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Dublin Dental University Hospital
Trinity College Dublin, the University of Dublin

"Designing sustainable kidney care through product innovation and life cycle assessment of dialysis pathways"

Declaration

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James Larkin

Abstract

This thesis investigates how society approaches the sustainability of kidney healthcare, using the example of dialysis pathways to map the environmental, social, practical and ethical complexities that define modern medicine. Kidney care, particularly haemodialysis (HD) and peritoneal dialysis (PD), is among the most resource intensive fields in medicine, requiring large volumes of energy, water and single-use plastics and generating substantial hazardous waste. With the number of patients needing life sustaining kidney replacement therapy (KRT) rising sharply due to global demographic and epidemiological trends, the environmental footprint of dialysis is growing at a rate that challenges not only health systems but the broader goals of climate neutrality, resource stewardship and social justice.

The thesis is situated within the KitNewCare project, a European wide collaborative effort supported by Horizon funding to decarbonise kidney treatment through innovation in clinical practice, product development and policy advocacy. The project's multi-disciplinary scope brings together designers, clinicians, engineers, data scientists and procurement officials to develop practical methods and tools that shape everyday decision making. Among the outputs of this thesis are educational toolkits and guidelines for clinicians, operational dashboards for environmental monitoring and methodological improvement in LCA analysis of healthcare systems at multiple scales. The work has been published in leading peer reviewed journals, influencing national and European strategy, procurement guidelines and greener pilot initiatives in hospitals.

Through a thorough and original programme of life cycle assessment (LCA), this thesis quantifies the impacts of dialysis modalities across multiple categories, including climate change, energy use, toxicity and resource depletion. The thesis also identifies the root cause of high environmental impacts within clinical procurement, manufacturing processes and service organisation, such as product specifications, costs, supplier location and waste classification rules. By mapping treatment pathways in detail, including material flows, energy consumption, transport, packaging and waste management, the work provides a comprehensive picture of the environmental burden of dialysis. It presents the first process based LCAs of PD and HD pathways at product, treatment and system level in a European setting and integrates social life

cycle assessment (S-LCA) to examine labour risk exposure in dialysis supply chains. The result is a robust evidence base that helps empower clinicians, hospital administrators and policymakers to identify specific products, practices and system designs that disproportionately contribute to emissions and resource consumption.

In investigating PD, the research demonstrates the significant influence of single use plastics, transport logistics and hazardous waste disposal on the total environmental burden. Through process based LCAs, the thesis reveals that consumables such as dialysate bags, tubing and packaging account for the majority of emissions and waste. Annual plastic consumption for a single PD patient can exceed one tonne, most of which is incinerated, producing toxins such as dioxins, heavy metals and greenhouse gases (GHG). These results raise practical questions about how PD equipment is specified and purchased. They suggest that procurement teams and manufacturers need to reconsider material choices, product configurations and packaging. The work looks at alternative pathways, such as on-site dialysate mixing, localised production and closed loop materials management, demonstrating the potential for substantial footprint reductions without compromising treatment success.

In HD, the thesis quantifies the high energy and water demands of hospital based treatments. An individual HD session requires hundreds of litres of water, much of which is wasted in the production of ultra-pure dialysate. The process is further burdened by the reliance on energy-intensive machines and complex, multi component disposable kits. The environmental impacts of transport and packaging are critical hotspots, especially for acid and bicarbonate concentrates. The research compares system innovations, such as centralised acid preparation and shows that replacing single use liquid bags with bulk powder or central preparation substantially reduces emissions and waste while streamlining logistics and improving operational resilience.

The quantitative output of this thesis is complemented and deepened by qualitative analysis. Semi structured interviews and thematic analysis engage over two dozen European stakeholders, including clinicians, hospital managers, procurement experts and policy advisors. Participants discuss tensions between infection control requirements, workload and

staffing, procurement rules and waste regulations and their wish to reduce environmental impacts. The interviews uncover motivators and barriers, from the perception of sustainability as a secondary concern in patient care to the need for clear information and leadership at multiple levels. Survey data supplement these insights, identifying gaps in awareness, training and engagement among healthcare students and clinicians and helping shape recommendations for future professional education and system change.

A unique contribution of this thesis is the integration of social life cycle assessment (S-LCA), which examines the ethical aspects of procurement and clinical systems. The research shows the presence of medium to high risk labour exposure embedded in the supply chains for dialysis products, many of which are manufactured or disposed of under conditions that challenge global standards for equity and environmental justice. By looking at environmental and social impacts together, the thesis advocates a triple bottom line approach to sustainability that foregrounds not only carbon and pollution reduction but also the fair distribution of risks and benefits.

The research highlights the complexity of turning environmental data into practice. Recognising the operational challenges of hospitals, the thesis proposes implementation pathways for sustainable procurement and waste treatment, explaining how environmental performance metrics can be embedded in tender evaluations, clinical dashboards and policy frameworks such as the NHS Net Zero Supplier Roadmap and the European Green Deal. The thesis makes the underlying life cycle assumptions and datasets as transparent as possible. It recommends that manufacturers and health systems share comparable product level data so that environmental performance can be routinely included in procurement and service planning. The participatory approach to data collection and tool development, involving clinicians, engineers and suppliers, ensures that findings are not only technically sound but institutionally feasible.

This thesis integrates design, environmental quantification, social ethics, professional training and policy strategy into a unified model, providing a platform from which science, clinical practice and public health policy can continue to evolve. By linking environmental and social

hotspots to specific products, processes and procurement decisions, this thesis offers a guide for greener kidney care that does not compromise patient safety or access. It provides recommendations for product redesign, waste reclassification, centralised fluid delivery and integration of LCA into procurement and education, supporting health system decarbonisation strategies.

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Abbreviations

AI - Artificial Intelligence

AOU - L'Azienda Ospedaliero-Universitaria di Modena

APD - Automated Peritoneal Dialysis

AVF - Arteriovenous Fistula

AVG - Arteriovenous Graft

CAPD - Continuous Ambulatory Peritoneal Dialysis

CKD - Chronic Kidney Disease

CO_2-eq - Carbon Dioxide Equivalent

CSH - Centre for Sustainable Healthcare

CSS - Central Bicarbonate Supply Systems

CVC - Central Venous Catheters

DALY - Disability-Adjusted Life Year

DEFRA - Department for Environment, Food and Rural Affairs

ECDC - European Centre for Disease Prevention and Control

EIA - Environmental Impact Assessment

EEA - European Environment Agency

EPD - Environmental Protection Declaration

EPR - Extended Producer Responsibility

ESKD - End-Stage Kidney Disease

ESRD - End- Stage Renal Disease

EU - European Union

FDI - FDI World Dental Federation

GDPR- General Data Protection Regulation

GFR - Glomerular Filtration Rate

GHG - Greenhouse Gas

HD - Haemodialysis

IEA - International Energy Agency

iHD - Incremental Haemodialysis

iPD - Incremental Peritoneal Dialysis

ISO - International Organisation for Standardization

KPIs - Key Performance Indicators

KRT - Kidney Replacement Therapy

LCA - Life Cycle Assessment

LCI - Life Cycle Inventory

LCIA - Life Cycle Impact Assessment

LLMs - Large Language Models

LMIC - Low and Middle Income Country

MJ - Megajoules

MRIO - Multi-Regional Input Output

NCES - National Clinical Environmental Sustainability

NHS - National Health Service

OLHDF- Online Haemodialysis

OECD - Organisation for Economic Co-operation and Development

PD - Peritoneal Dialysis

PET - Polyethylene

PLA - Polylactic Acid

PP - Polypropylene

PPAs - Power Purchase Agreements

PPE - Personal Protective Equipment

PSILCA - Product Social Impact Life Cycle Assessment

PVC - Polyvinyl Chloride

RCTs - Randomised Control Trials

RRT - Renal Replacement Therapy

RO - Reverse Osmosis

QALYS - Quality Adjusted Life Years

SDG - Sustainable Development Goal

S-LCA - Social Life Cycle Assessment

SME - Small and Medium-sized Enterprise

TPE - Thermoplastic Elastomers

UNEP - United Nations Environment Programme

WHO - World Health Organization

WEEE - Waste Electrical and Electronic Equipment

Publications

Some of the original work presented in this thesis has been published in international peer-reviewed journals, as listed below. Offprints of the publications are included in the Appendix:

Larkin, J., Alfano, G., Ligabue, G. *et al.* Green haemodialysis: comparison of dialysis bags versus Fresenius Granumix at the AOU Policlinico di Modena, Italy. *J Nephrol.* (2025a). https://doi.org/10.1007/s40620-025-02416-0

Larkin, J., Ligabue, G., Alfano, G. *et al.* A life cycle assessment of peritoneal dialysis procurement in Italy: environmental burden and opportunities for improvement. *J Nephrol.* (2025b). https://doi.org/10.1007/s40620-025-02409-z

Duane, B., Larkin, J., Caiazzo, M., et al. But how green is it actually? Calculating the environmental footprint of kidney care environmental optimizations within haemodialysis. *Clinical Kidney Journal.* (2025a). https://doi.org/10.1093/ckj/sfaf220

Yasar, A., Larkin, J., Steinbach, I. et al. Advancing green nephrology: a scoping review of sustainability interventions in kidney care. *Int Urol Nephrol.* (2025). https://doi.org/10.1007/s11255-025-04904-5

Duane B, Larkin J, Caiazzo M, et al. Using large language models to support carbon foot printing in dentistry: opportunities and risks for sustainable healthcare. *International Dental Journal*. (2026a). https://doi.org/10.1016/j.identj.2025.103979

Larkin, J., Ligabue, G., Morisi, N. et al. Comparing environmental footprints of haemodialysis and online haemodiafiltration in Italy. *Int Urol Nephrol.* (2026a). https://doi.org/10.1007/s11255-026-05033-3

Larkin J, Ligabue G, Alfano G, et al. Procurement and Waste in Haemodialysis: A Detailed Life Cycle Assessment to Reduce Environmental Impact. (2026b). Accepted for publication.

Larkin J, Ligabue G, Alfano G, et al. Sustainable kidney care: A life cycle assessment of the peritoneal dialysis pathways. *Peritoneal Dialysis International: Journal of the International Society for Peritoneal Dialysis.* (2026c). https://doi.org/10.1177/08968608251415439

Larkin J, Ligabue G, Alfano G, et al. Theoretically Redesigning Peritoneal Dialysis Products for Sustainability: A Life Cycle Inventory Approach. *The International Journal of Artificial Organs.* (2026d). https://doi.org/10.1177/03913988251415097

Larkin J, O'Dwyer C, et al. Trends, Challenges and Best Practices for Reducing the Environmental Impact of Healthcare: Insights from a Qualitative Expert Study with Focus on Kidney Care. (2026e). Accepted for publication.

Duane B, Larkin J, Alfano G, et al. Calculating the social footprint of kidney care: integrating social life cycle assessment into haemodialysis optimisation. (2026b). Manuscript under review.

Duane B, Larkin J, Caiazzo M, et al. Teaching life cycle assessment in healthcare: development of an educational toolbox for sustainable clinical practice. (2026c). Manuscript under review.

Data availability

This thesis makes use of primary and secondary datasets generated as part of the KitNewCare project and related studies on sustainable kidney care. Where possible, anonymised and non-identifiable data have been deposited in open repositories to support transparency, reuse and further research.

Quantitative LCA datasets, associated product information for PD and HD in Modena and Interview transcript data are available on Zenodo:

Larkin, J et al., (2025). Trends and Barriers for Qualitative Study [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16847707

Aycan, Y et al., (2025). Advancing Green Nephrology: A Scoping Review of Sustainability Interventions in Kidney Care [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15608021

Larkin, J et al., (2025). Sustainable Peritoneal Dialysis Product Redesign [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15526450

Duane, B et al., (2025). Life Cycle Assessment Dataset for Kidney Care Environmental Optimisations within Haemodialysis [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15075254

Larkin, J et al., (2025). Green Haemodialysis: Comparison of Dialysis Bags Versus Fresenius Granumix Water Recycling System at the AOU Policlinico di Modena, Italy [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14610055

Larkin, J et al., (2024). Life Cycle Assessment Dataset For Peritoneal Dialysis in Modena [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14414092

Larkin, J et al., (2024). Life Cycle Assessment Dataset For Haemodialysis in Modena [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14272816

Larkin, J et al., (2024). Product Images for Life Cycle Assessment Dataset For Peritoneal Dialysis and Haemodialysis in Modena [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14258920

Chapter 1: Introduction to sustainable kidney care

1.1 The sustainability challenge in kidney care

1.1.1 Global burden of kidney disease and dialysis

Chronic kidney disease (CKD) affects over 700 million people worldwide, with end stage kidney disease (ESKD) requiring dialysis or transplantation for the 1.2 million patients annually. These numbers are projected to double by 2030 due to rising diabetes, hypertension and ageing populations (Bello et al., 2022; Jager et al., 2019).

Kidney care, particularly haemodialysis (HD) and peritoneal dialysis (PD), is one of the most high resource demand areas in modern healthcare, relying on energy and water intensive technologies and large amounts of single use materials that generate substantial hazardous waste (J. W. Agar, 2015; Barraclough et al., 2017).

This resource intensity challenges healthcare's net zero goals amid EU Green Deal and NHS targets (Commission, 2019; NHS, 2020). As ESKD burden intensifies, life cycle assessment (LCA) becomes essential to quantify impacts and identify sustainable innovations preserving clinical outcomes (Chesnaye et al., 2024).

1.1.2 Environmental challenges in modern healthcare

Health systems are under growing pressure to reduce their environmental footprint while maintaining or improving quality of care, driven by policy frameworks such as the EU Green Deal, national net-zero targets and the broader planetary health agenda (Campbell-Lendrum et al., 2023; Commission, 2019). Healthcare activities contribute substantially to greenhouse gas (GHG) emissions, resource use and waste generation, with procurement of medicines, devices and equipment now recognised as a major source of impact (Healthcare Without Harm, 2020; NHS, 2020). Addressing these impacts requires not only technological innovation, but also changes in how services are designed, procured and managed at system level (Keil et al., 2023; Yeo et al., 2022).

Among renal replacement therapies (RRT), both PD and HD contribute significantly to healthcare related GHG emissions, plastic waste and resource consumption (Agar, 2015a;

Connor et al., 2010a). Procurement of dialysis related materials, machines and disposables is now widely identified as the single largest contributor to the environmental burden of kidney care, accounting for up to around 70-72% of the carbon footprint of some nephrology pathways (Al-Hadithy et al., 2024; NHS, 2020). The environmental implications of procurement choices remain poorly understood in practice, largely due to a lack of detailed, product level life cycle data within clinical settings (Connor et al., 2010b; Duane et al., 2025b).

This thesis is embedded within the KitNewCare project, a multidisciplinary programme supported by EU Horizon funding that aims to decarbonise kidney care by working across clinical practice, product design and health systems. KitNewCare develops evidence on environmental hotspots in dialysis pathways, redesigned products and waste pathways that reduce impact and tools, training and policy oriented outputs to support implementation in renal services (Duane et al., 2025b). The studies in this PhD align with these themes by quantifying environmental impacts of PD and HD at product, treatment and system level using LCA. The thesis aims to inform and evaluate sustainable product redesign and waste treatment options. It also aims to explore how procurement practices, clinical workflows and stakeholder perspectives can support wider system change in kidney care (Larkin et al., 2025a).

1.2 Background and rationale

1.2.1 The kidneys, dialysis and haemodialysis vs peritoneal dialysis

The anatomical position of the kidneys is illustrated in Figure 1.1. Each kidney receives a substantial proportion of cardiac output via the renal arteries and returns filtered blood to the systemic circulation through the renal veins. Figure 1.2 shows a cross-sectional view of the kidney, including cortex and medulla.

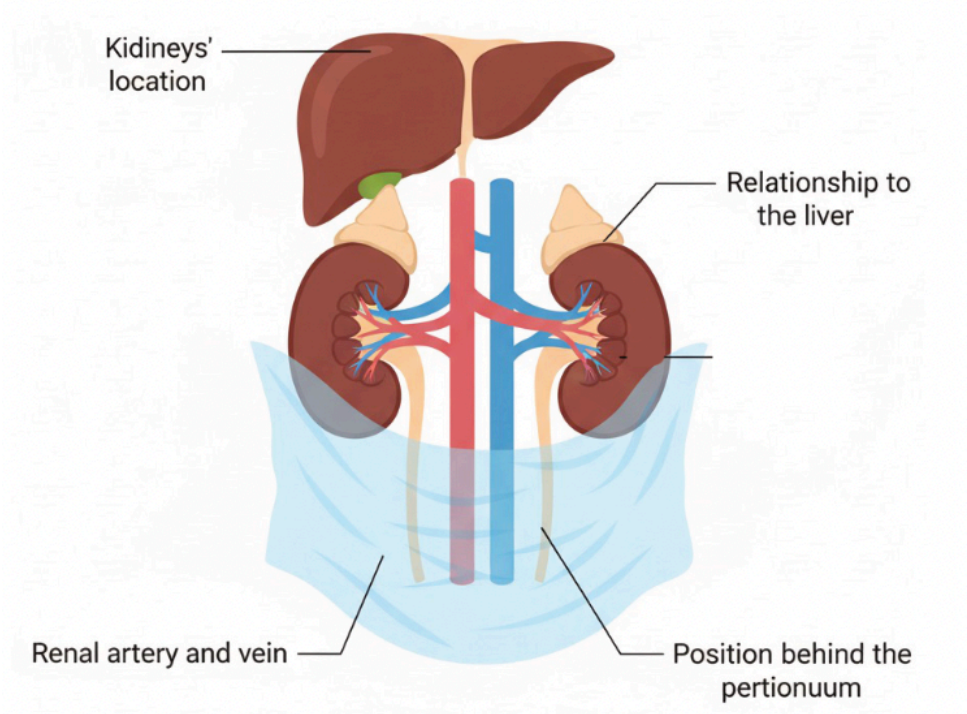

Figure 1. 1 Kidneys' location, relationship to the liver, adrenal glands, renal artery and vein and their position behind the peritoneum

The nephron comprises a glomerulus, where plasma is filtered and a series of tubular segments that reabsorb most water and solutes while secreting metabolic waste products. When glomerular filtration rate falls to advanced CKD and ESKD levels, these processes become insufficient, leading to uraemic symptoms, fluid overload, electrolyte disturbances and increased cardiovascular and mortality risk (Jager et al., 2019; Chesnaye et al., 2024). The nephron structure is summarised in Figure 1.3. Dialysis and transplantation are therefore required to replace a portion of kidney function and sustain life for the growing global population with kidney failure (Bello et al., 2022).

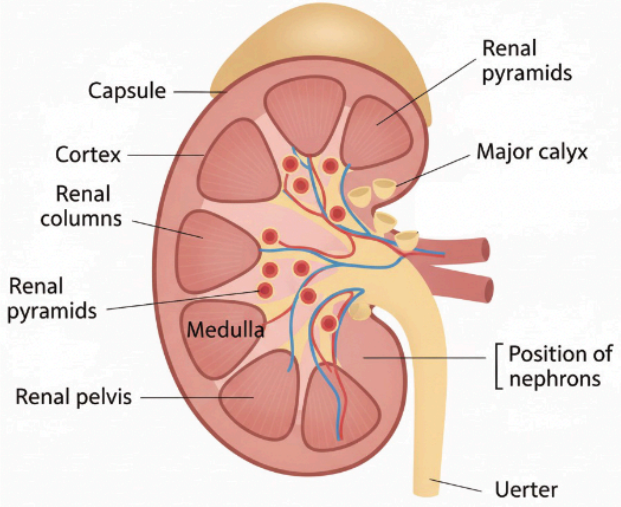

Figure 1. 2 Kidney cross section, distinguishing cortex, pyramids, columns, calyces, pelvis and the position of nephrons

HD replaces kidney function extracorporeally. Blood is pumped through a dialyser containing bundles of hollow fibres, separated from dialysis fluid by a semi permeable membrane, allowing solutes to diffuse down concentration gradients and excess water to be removed by ultrafiltration. Treatments are typically delivered in hospital or satellite units three or more times per week using HD machines, water treatment systems and single use consumables such as dialysers, bloodlines and dialysate concentrates. Vascular access is usually via an arteriovenous fistula (AVF), arteriovenous graft (AVG) or central venous catheter (CVC). Figure 1.4 depicts the HD circuit and dialyser, while Figure 1.5 compares AVF, AVG and CVC access types. A schematic comparison of HD and PD is shown in Figure 1.6 to highlight the broad differences in location of treatment, access route and fluid circuit. The design and operation of HD systems, including ultrapure water production and waste fluid management, have major implications for energy use, water consumption and material flows that are quantified in the LCAs in Chapter 3. The reliance on factory produced dialysate, packaging and single use consumables makes PD particularly relevant for LCA of plastics, transport and waste management.

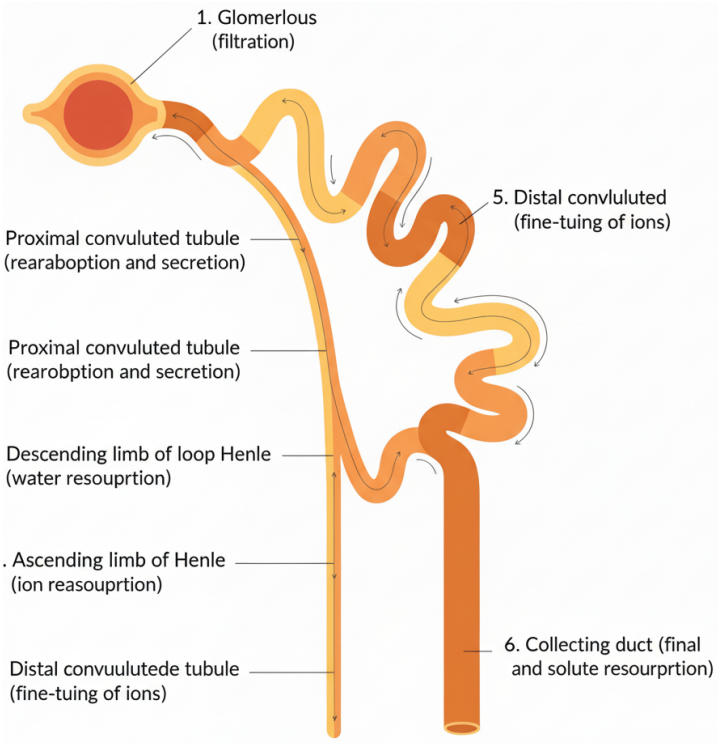

Figure 1. 3 Nephron's structure, with a schematic tracing glomerular filtration, tubular processes and the collecting duct

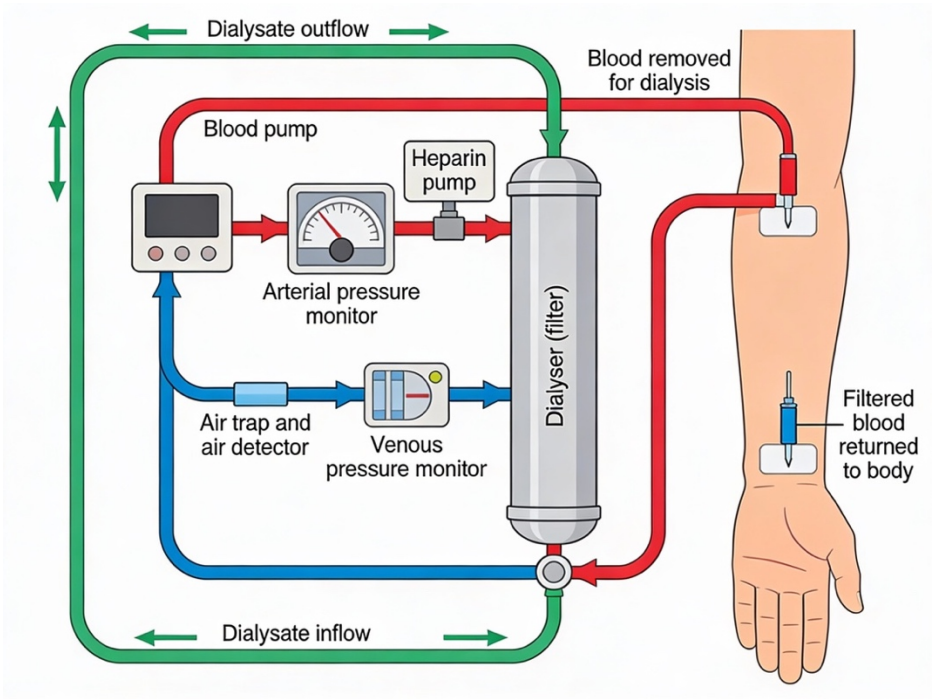

Figure 1. 4 HD circuit and the dialyser, including bloodline connectivity, dialysate inflow and outflow

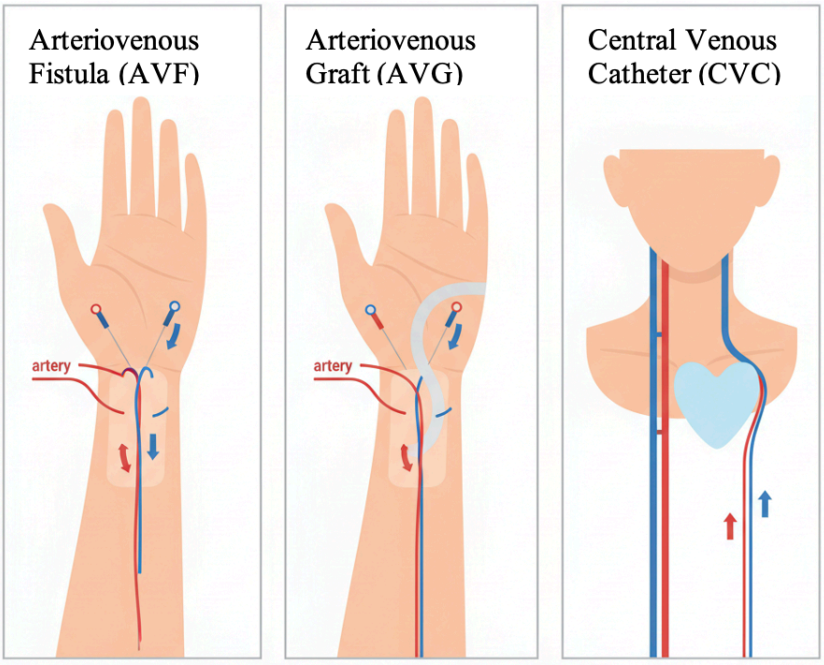

Figure 1. 5 Comparison of AVF, AVG and CVC

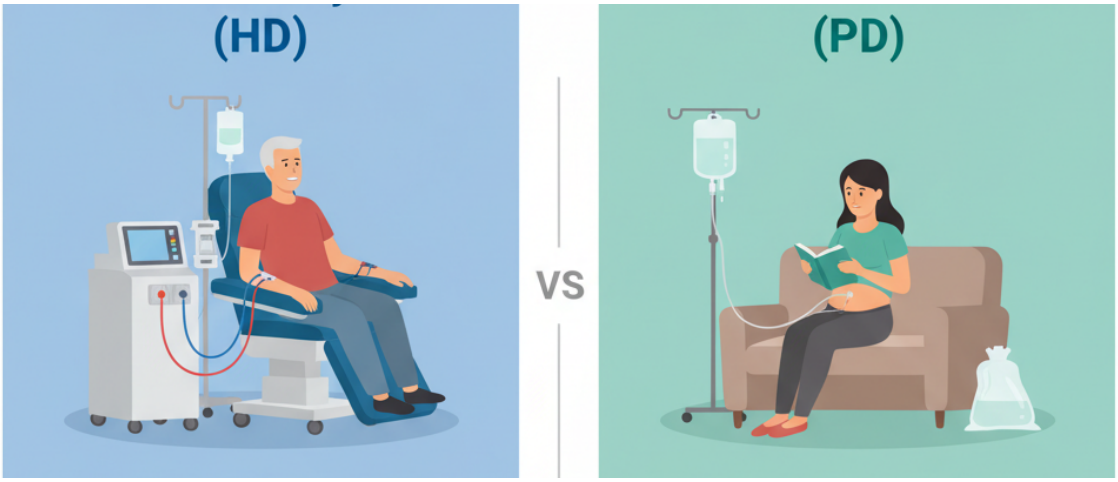

Figure 1. 6 Contrast HD with PD

PD uses the patient's peritoneal membrane as the semi permeable barrier for solute and fluid exchange. Sterile dialysate is infused into the peritoneal cavity through a permanently implanted catheter, allowed to dwell to permit diffusion and osmotically driven ultrafiltration across the peritoneum and then drained. In continuous ambulatory peritoneal dialysis (CAPD), patients perform manual exchanges several times per day, whereas automated peritoneal dialysis (APD) uses a cycler machine to perform multiple exchanges overnight. Figures 1.7 and 1.8 illustrate CAPD and APD set-ups respectively. PD relies heavily on factory produced

dialysate bags, tubing, connectors and packaging, all of which are typically single use and frequently managed as clinical or hazardous waste. These characteristics make PD a particularly important focus for LCA of plastics, transport and waste treatment in this thesis (Larkin et al., 2025b; Larkin et al., 2026b).

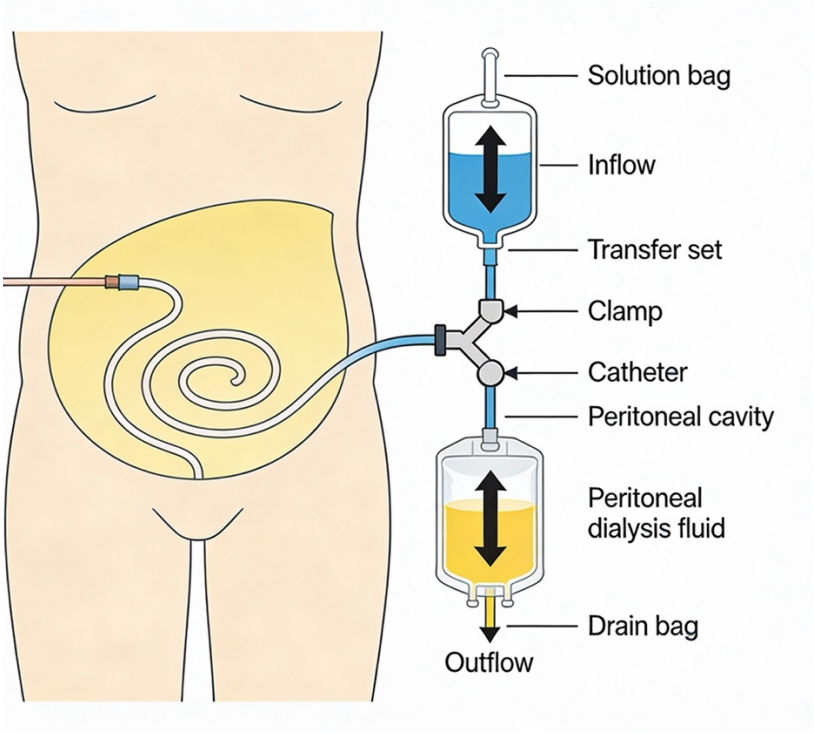

Figure 1. 7 CAPD Catheter setup, with view beneath the abdominal wall and position in the peritoneal cavity

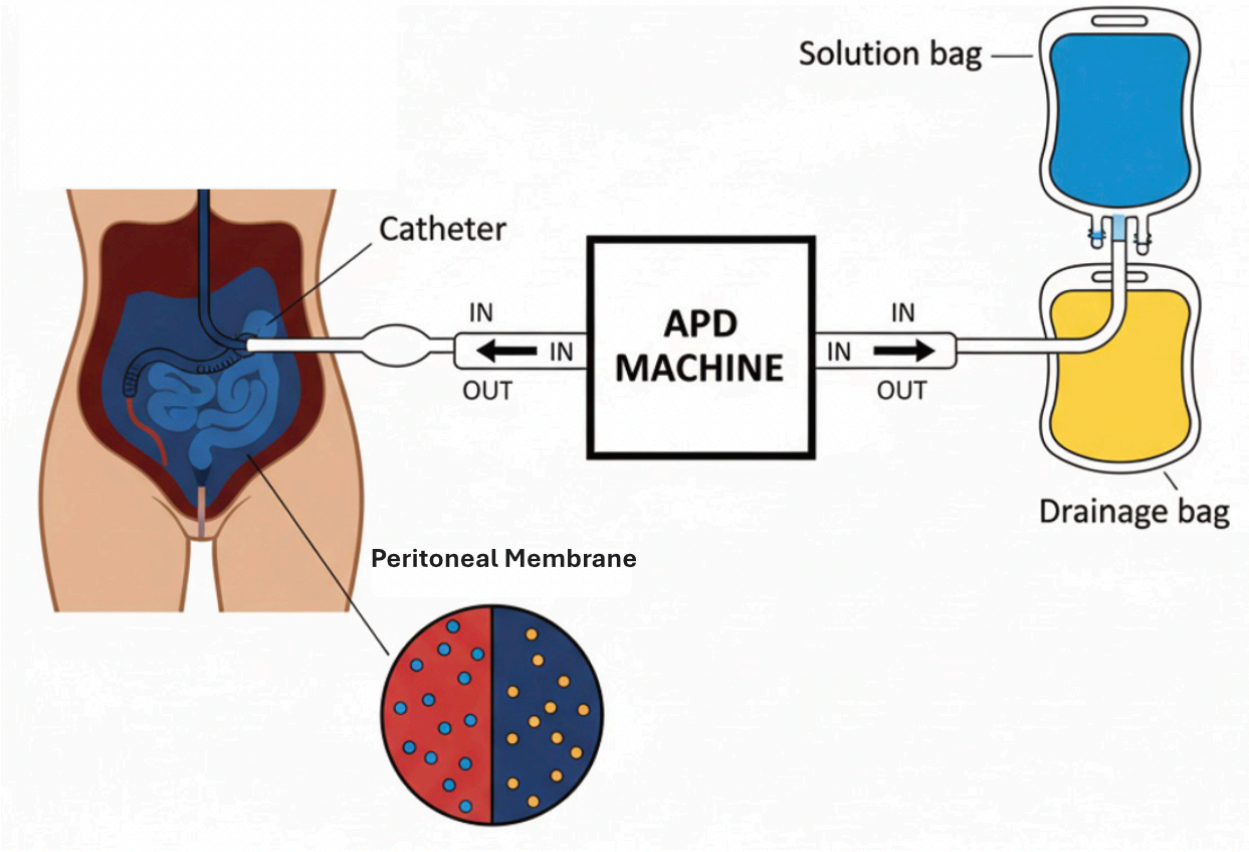

Figure 1. 8 APD overview: Dialysate solution flows from the solution bag through the APD machine and into the patient's peritoneal cavity via a catheter, where solute and fluid exchange occurs across the peritoneal membrane

Although dialysis can effectively control uraemic symptoms and prolong survival, it does not replace all renal functions. Pharmacological therapy and dietary modification are required alongside HD or PD to address anaemia, mineral bone disorder and blood pressure control (Chesnaye et al., 2024; Jager et al., 2019). From a sustainability perspective, the partial and technology intensive nature of dialysis means that each treatment includes substantial resource use and waste generation over many years of chronic therapy (Duane et al., 2025b; Yasar et al., 2025). Understanding the basic physiology of kidney failure and the technical principles of HD and PD therefore provides essential clinical context for the pathway level and product level LCAs presented in Chapter 3.

1.2.2 Current sustainability gaps in healthcare

Treatments for ESKD, including HD and PD demand high volumes of water, energy and materials and generate substantial waste, including clinical and hazardous waste streams. HD

is particularly associated with high carbon emissions. The most up to date research on HD and OLHDF indicates that conventional HD sessions consume approximately 430-510 litres of water and on average 11.2-13.1 kWh of electricity per treatment (Jiménez et al., 2024). OLHDF sessions tend to use more water and energy compared to standard HD, although the difference in water consumption is not statistically significant, while electricity consumption is noticeably higher in centres with a majority of OLHDF sessions.

Waste generation figures can vary, but improvements and operational changes have recently reduced plastic and hazardous waste by up to 65% and 63% respectively in certain clinics.

Across modalities, procurement, waste generation, transportation and electricity use remain the main contributors to environmental footprints (Martindale et al., 2024; NHS, 2020). Growing awareness of these impacts has given rise to the field of "green nephrology", which seeks to reduce the environmental burden of kidney treatments through LCA material innovations, water recycling technologies, renewable energy adoption and waste reduction strategies. Policy frameworks such as the EU Green Deal and NHS Net Zero targets are further pushing healthcare providers toward decarbonisation (NHS, 2020).

However, widespread implementation remains inconsistent, constrained by regulatory, clinical and infrastructural barriers (Yau et al., 2021). Understanding and addressing these challenges is critical for integrating sustainability into kidney care delivery systems. Recent studies highlight interventions like centralised acid systems and PD kit redesign, but implementation faces regulatory and infrastructural barriers (Yau et al., 2021). These gaps highlight the need for product level analysis and design innovation, explored in section 1.2.3.

Many studies focus on isolated interventions or single impact indicators, with limited integration of product level data, procurement systems and real world clinical constraints. This gap limits the ability of healthcare providers to turn environmental evidence into routine decision making.

1.2.3 Why product design and life cycle assessment matter

Procurement decisions influence dialysis environmental impacts, accounting for 70-72% of carbon footprints through single use consumables like dialysate bags, tubing sets and APD machines. However, the clinical understanding of these choices remains limited (NHS, 2020; Al-Hadithy et al., 2024). LCA excels at hotspot identification, revealing that within the studied pathways a small number of product categories account for the majority of procurement related CO_2eq emissions, highlighting precise redesign targeting (Larkin et al., 2025b).

Product design innovation addresses these hotspots directly. Material substitution (PVC to TPE/silicone), modular architectures and packaging lightweighting demonstrate 20-63% impact reductions across modelled PD redesigns, validated against ISO 10993 biocompatibility standards (Keil et al., 2023; Larkin et al., 2026d). Integrating LCA evidence into policy, as recommended by NHS/EU guidelines, change procurement from cost driven to sustainability optimised, aligning clinical safety with EU Green Deal ambitions (Commission, 2019). These analyses are not intended to prescribe universal solutions, but to demonstrate how structured life cycle evidence can inform design, procurement and service planning decisions in kidney care.

1.3 Life cycle assessment as a methodological tool

1.3.1 Life cycle assessment fundamentals and ISO standards

In health systems worldwide, LCA provides a robust, science driven framework for identifying environmental hotspots, quantifying impacts over multiple categories and guiding both policy and procurement toward sustainability goals (Duane et al., 2025a; McGain et al., 2014). This section looks at the methodological foundations, functional scope, key impact categories and application of LCA in the healthcare setting, giving particular attention to the broader context of impact factors and environmental indicators. Figure 1. 9 provides a visual overview of the key stages involved in LCA, illustrating how environmental impacts are tracked from resource extraction through processing, manufacturing, distribution and use to end of life disposal.

Figure 1. 9 Key Stages in LCA

LCA is defined by ISO 14040 and ISO 14044 as a systematic approach to assessing environmental burdens associated with a product, process, or service throughout its complete life cycle. It ranges from raw material extraction, manufacture, transport, clinical use and end of life disposal (14040, 2006; 14044, 2006). Its adoption in healthcare is advancing rapidly as the sector faces growing scrutiny for its role in climate change, waste generation and resource consumption (Duane et al., 2020; Karliner, 2020). The healthcare sector is estimated to account for almost 5% of global GHG emissions, with procurement, waste and energy intensive specialties such as surgery and nephrology among the primary contributors (Karliner, 2020; NHS, 2020). The specific implementation of these phases, functional units, system boundaries and impact categories in this thesis is described in detail in Chapter 2 and 3. In this thesis, ISO

standards are used as a guiding framework rather than a rigid template, reflecting the complexity and data constraints of real world healthcare systems.

1.3.2 Life cycle assessment in healthcare contexts

A typical healthcare LCA boundary includes raw material inputs, intermediate processing, manufacturing, packaging, transportation, use in clinical or patient settings (including energy, water and ancillary products) and waste management at end of life (Guinee, 2011). Figure 1. 10 illustrates a generic cradle to grave boundary for a medical intervention, highlighting typical stages considered in health sector analyses.

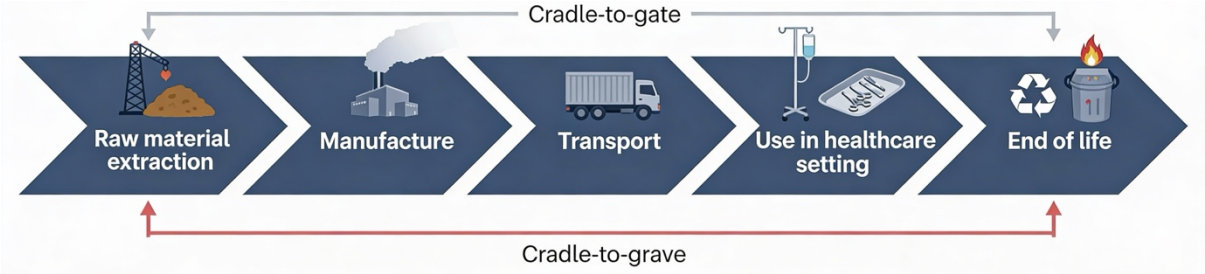

Figure 1. 10 Example of LCA system boundaries applied to healthcare: arrows connect extraction, manufacture, transport, use and end of life

Environmental impact factors in LCA span a diverse spectrum, with the European Commission and ILCD handbook recommending assessments beyond climate change to include acidification, eutrophication, ecotoxicity, resource depletion, water use, photochemical ozone formation, particulate matter, human toxicity and more (Commission, 2019; Hauschild, 2024). Each impact category is represented by normalised metrics. Assessing multiple categories provides an overview of system harms and enables more subtle optimisations (Hauschild, 2024).

For example, the manufacture and single use disposal of plastic based medical products, international freight of consumables and energy use by clinical equipment are the most common hotspots in medical LCAs (Al-Hadithy et al., 2024; McAlister et al., 2024b). In nephrology, procurement of dialysate and consumables has been shown to account for up to

72% of the carbon and resource footprint in some modalities, a pattern mirrored in surgical and anaesthetic LCAs (Larkin et al., 2025b; Sherman et al., 2012).

Impact factor selection is both scientific and policy driven. Carbon footprint (climate change) is most frequently reported, as healthcare systems now align with national or international goals such as the EU Green Deal, NHS Net Zero, or the Sustainable Development Goals (Commission, 2019; NHS, 2020). However, focusing on carbon alone risks neglecting critical impacts such as freshwater depletion, ecotoxicity, or particulate pollution (Tennison et al., 2021). A recent global review of LCAs in dentistry revealed wide variation in scope, with some studies limited to waste weight or energy use, while others employed full multicategory impact analysis (Borglin et al., 2021). The latter approach provides a more robust scientific basis for decision making and innovation.

Data quality and transparency highlight LCA credibility. Primary data collection, such as dismantling and weighing medical products, measuring resource use in clinical settings and mapping procurement pathways, improves model uniqueness and trustworthiness (Larkin et al., 2025b). Background inventory data relies on databases like Ecoinvent, ensuring comparability and international standardisation (Ecoinvent, 2024). Figure 1. 11 provides an example of a process flow diagram used to map inputs and outputs for a medical intervention's LCA, serving as a visual aid for inventory compilation and stakeholder discussion. Wherever possible, primary data were prioritised to reduce uncertainty and improve contextual relevance, with background databases used to support comparability and completeness.

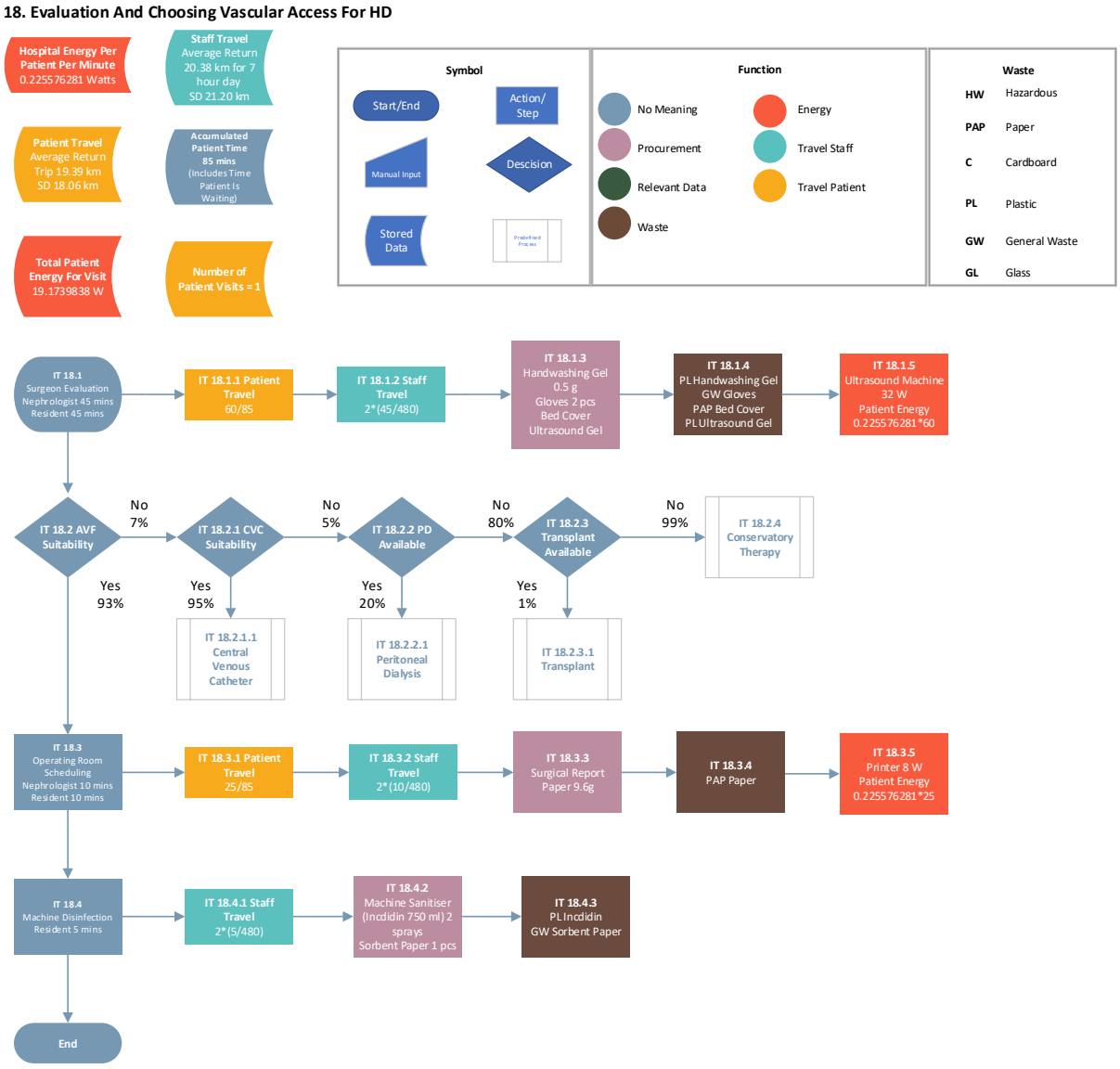

Figure 1. 11 Example flow diagram for mapping inputs/outputs in a healthcare LCA, shown here for pathway 18, one of the numbered dialysis pathways used in this thesis *(Larkin et al. 2026a)*

In addition to environmental quantification, modern LCAs may integrate social and ethical aspects. Social LCA (S-LCA) extends ISO methodology by incorporating indicators for labour rights, equity, forced labour risk and occupational health (Alsamawi et al., 2019; Benoît Norris et al., 2020). The PSILCA or Soca v2 databases enable modelers to estimate medium risk labour hours embedded in healthcare supply chains, highlighting risks and opportunities for ethical procurement (Hamed et al., 2025).

Recent applications of LCA in healthcare have spanned:

- Comparative studies of reusable vs single use surgical equipment (McGain et al., 2014).

- Carbon intensity of anaesthetic gases, identifying desflurane as a climate hotspot and guiding low carbon protocols (Sherman et al., 2012).

- Analysis of different hospital waste management systems (Lee et al., 2022).

- Mapping of telemedicine, transport and digital service impacts for decarbonisation (Tennison et al., 2021).

In nephrology and dialysis, detailed LCAs have highlighted that single use products, procurement logistics and hazardous waste management are the main causes of environmental harm (Al-Hadithy et al., 2024; Larkin et al., 2025b). Comparative research showed that material substitutions in packaging, modular product designs and switching from concentrated acid bags to centralised acid delivery can yield up to 30% reductions in carbon emissions and significant improvements across toxicological categories (Larkin et al., 2025a; Murcutt et al., 2024).

Figure 1.12 displays typical normalised impact category results, pinpointing which areas such as energy use, freshwater ecotoxicity, or particulate matter require priority management. Focusing on multiple impact categories is particularly important in kidney care, where interventions that reduce carbon emissions may simultaneously increase water use or toxicological burdens.

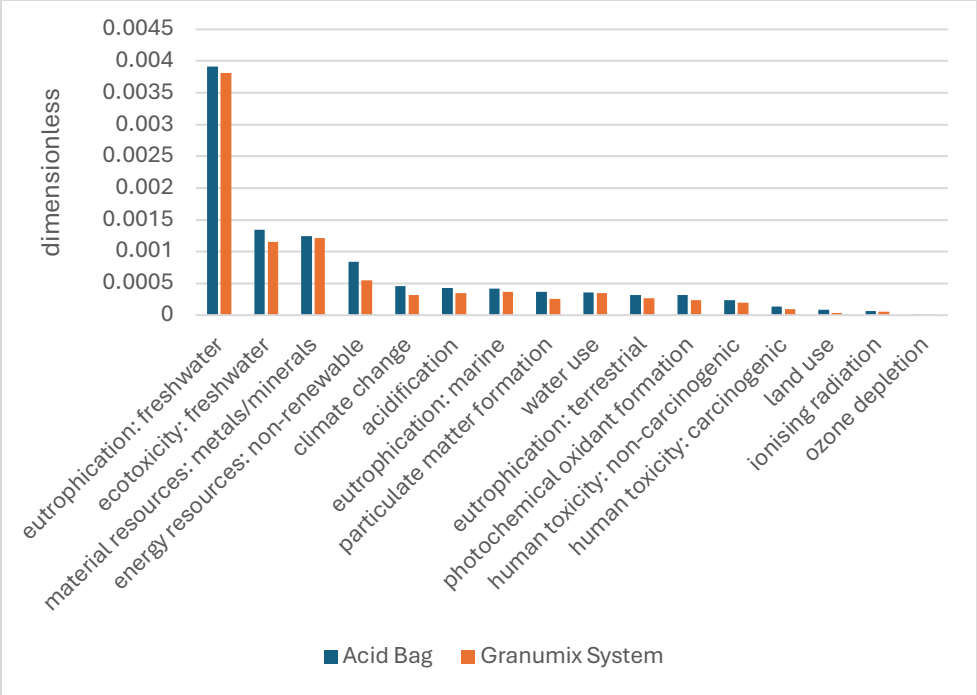

Figure 1. 12 Example bar graph: Normalised LCA results for a healthcare intervention, showing various category scores per functional unit (Larkin et al. 2025a)

1.3.3 Scope of life cycle assessment in this thesis

While alternative approaches such as environmentally extended input output modelling are valuable for national or sector wide assessments, they lack the resolution required to evaluate specific products and clinical pathways. Process based LCA was therefore selected to support detailed analysis of dialysis consumables, technologies and procurement decisions. LCA supports evidence based innovation and procurement reform. By developing clear system maps and hotspot matrices, institutions can compare alternative interventions, set priorities and engage suppliers in sustainable design initiatives (Keil et al., 2023). Embedded LCA requirements within procurement tenders, as called for in NHS and EU guidance, are increasingly common ways for reducing sectoral carbon and material footprints (Al-Hadithy et al., 2024; Commission, 2019). Table 1.1 summarises sustainable procurement interventions supported by LCA evidence.

Table 1. 1 Sustainable Procurement Interventions

Intervention	**LCA Evidence**	**Typical Outcome**	**Reference**

Centralised acid delivery in HD	Lower emissions, packaging, transport impact	30% reduction in CO_2 eq	(Larkin et al., 2025a)
Modular/recyclable PD kits	Decreased fossil plastic use, waste, transportation	Lower resource/treatment	(Keil et al., 2023)
Material substitution in packaging	Lower fossil carbon, better recyclability	20% circularity increase	(Lithner et al., 2011)
Reusable surgical textiles	Less water/energy/waste than single use	60% savings (multi use)	(McGain et al., 2014)
Telemedicine vs in person visits	Lower travel, facility energy, higher digital energy	Net carbon reduction	(Tennison et al., 2021)

Beyond technical modelling, LCA helps direct qualitative and participatory research, which explores technical, policy and human behaviour barriers to sustainability (Greenhalgh et al., 2018). Qualitative interviews and scoping reviews contextualise LCA findings, lending practical meaning as hospitals and clinicians grapple with operational challenges, regulatory barriers and patient needs (Yau et al., 2021).

The future agenda for LCA and environmental impact analysis in healthcare includes broadening supply chain data transparency, expanding social and ethical metrics, linking reporting standards and advancing digital and circular frameworks. Integration with organisational, policy and design innovation is key. For health professionals and policymakers, LCA provides a structured method for comparing environmental trade-offs across complex systems. It is an enabler for measurable sustainability, ethical stewardship and responsible healthcare transformation, aligned with global climate and social justice goals (Benoît Norris et al., 2020; Commission, 2019). Together, these methodological choices define the analytical boundaries within which the research questions of this thesis are addressed.

1.4 Aims and research objectives

1.4.1 Overall thesis aim

The overarching aim of this PhD research is to evaluate the environmental impact of kidney care using LCA, with a focus on procurement, product design and system level innovation. This work contributes to the growing field of sustainable healthcare and responds to global calls for decarbonising medical services in line with the EU Green Deal and national climate targets (Commission, 2019; Tennison et al., 2021). The research prioritises understanding and comparison of environmental impacts rather than optimisation of clinical outcomes, which remain outside the scope of this thesis.

The research is structured around a series of studies that map the environmental footprint of PD and HD pathways, quantify the impact of specific products and procurement practices and propose evidence based interventions to reduce emissions, waste and resource use.

1.4.2 Research questions and objectives by chapter

The six research objectives systematically address the thesis aims, with each linking directly to specific chapters as follows:

1. To quantify the environmental footprint of PD and HD pathways using process based LCA, capturing impacts across multiple categories including climate change, ecotoxicity, acidification and water use (14040, 2006; Connor et al., 2010b) [addressed primarily in Chapters 2 & 3].
2. To identify environmentally significant products and processes within dialysis pathways, with particular attention to procurement related impacts (Al-Hadithy et al., 2024; Universities, 2022) [addressed primarily in Chapters 3 & 5].
3. To compare traditional dialysis delivery systems with sustainable alternatives, such as centralised acid delivery (e.g. Fresenius Granumix) and evaluate their potential to reduce environmental impacts (Di Chiaro et al., 2024; Murcutt et al., 2024) [addressed primarily in Chapters 3].

4. To explore the potential environmental implications of design led interventions, including material substitution and modular product architectures (Keil et al., 2023; Lithner et al., 2011) [addressed primarily in Chapters 3 & 5].
5. To investigate stakeholder perspectives and barriers to sustainable kidney care, through qualitative methods including semi structured interviews with healthcare professionals, sustainability experts and policymakers (Aboueid et al., 2023; Yau et al., 2021) [addressed primarily in Chapters 4].
6. To analyse findings across studies in order to inform future integration of environmental sustainability into procurement, policy and clinical decision making (Coalition, 2023; NHS, 2020) [addressed primarily in Chapters 6].

Together, these objectives are addressed through a combination of quantitative modelling, qualitative inquiry and analysis across interconnected studies. These objectives are addressed through a collection of published and in progress research papers, forming the core of this PhD thesis. Collectively, they aim to generate actionable evidence that supports the transformation of kidney care into a more environmentally sustainable area.

1.5 Thesis structure and contribution to knowledge

1.5.1 Chapter outline

This thesis is presented in a thesis by publication format, with all chapters linked through a common analytical focus on dialysis pathways, procurement systems and LCA. Each paper investigates the environmental impact of kidney care using LCA methodologies, supported by primary data collection in a clinical context. The work is complemented by systematic and scoping reviews, quantitative and qualitative analysis which collectively form a comprehensive assessment of sustainability challenges and solutions in nephrology.

The thesis is organised into six chapters:

- Chapter 1: Introduction
  Provides background context on the climate crisis, kidneys and dialysis, sustainable healthcare and the specific challenges associated with environmental sustainability in kidney care. It introduces LCA as a key methodology and outlines the overall aims, objectives and research questions.
- Chapter 2: Methodology
  Describes the overarching research approach, detailing data collection methods, LCA modelling in OpenLCA, stakeholder engagement and how each study aligns with ISO 14040/14044 standards (14040, 2006; 14044, 2006). Ethical considerations and the use of secondary datasets are also addressed.
- Chapter 3: Environmental Impacts in Dialysis Modalities
  Presents six dialysis related LCA studies covering PD and HD. Key findings highlight procurement and waste as major impact areas and assess alternative systems such as Granumix.
- Chapter 4: Qualitative Insights on Sustainable Kidney Care
  Reports findings from interviews with over 25 European experts in kidney care and sustainability. Explores challenges, innovations and policy gaps in implementing sustainable practices. Integrates with Chapter 3 to provide real world context for LCA results.

- Chapter 5: Broader Contributions and Collaborative Research
  Summarises coauthored and lead author studies beyond dialysis LCA, including reviews, product redesign, waste treatment and disinfection processes. Demonstrates the importance of transdisciplinary collaboration and design thinking. Emphasises how broader work supports the thesis's central arguments.
- Chapter 6:Discussion and Conclusions
  Provides a comprehensive discussion and combination of all major findings and insights across the thesis, integrating evidence from both PD and HD modalities as well as the full suite of sustainability interventions. Evaluates the significance of results for clinical practice, health systems and policy and identifies key priorities for future research and implementation in sustainable kidney care.

To visually summarise these contributions, Figure 1. 13 provides an overview of the thesis structure, highlighting the interconnected studies across PD, HD, product design, procurement and sustainability interviews. Each component contributes to a wider framework for integrating environmental evidence into kidney care through LCA, policy alignment and actionable clinical recommendations. The diagram illustrates how primary data collection, comparative analysis and stakeholder engagement collectively advance a more sustainable approach to RRT. Although presented as separate studies, the chapters are analytically connected through shared system boundaries, datasets and sustainability questions.

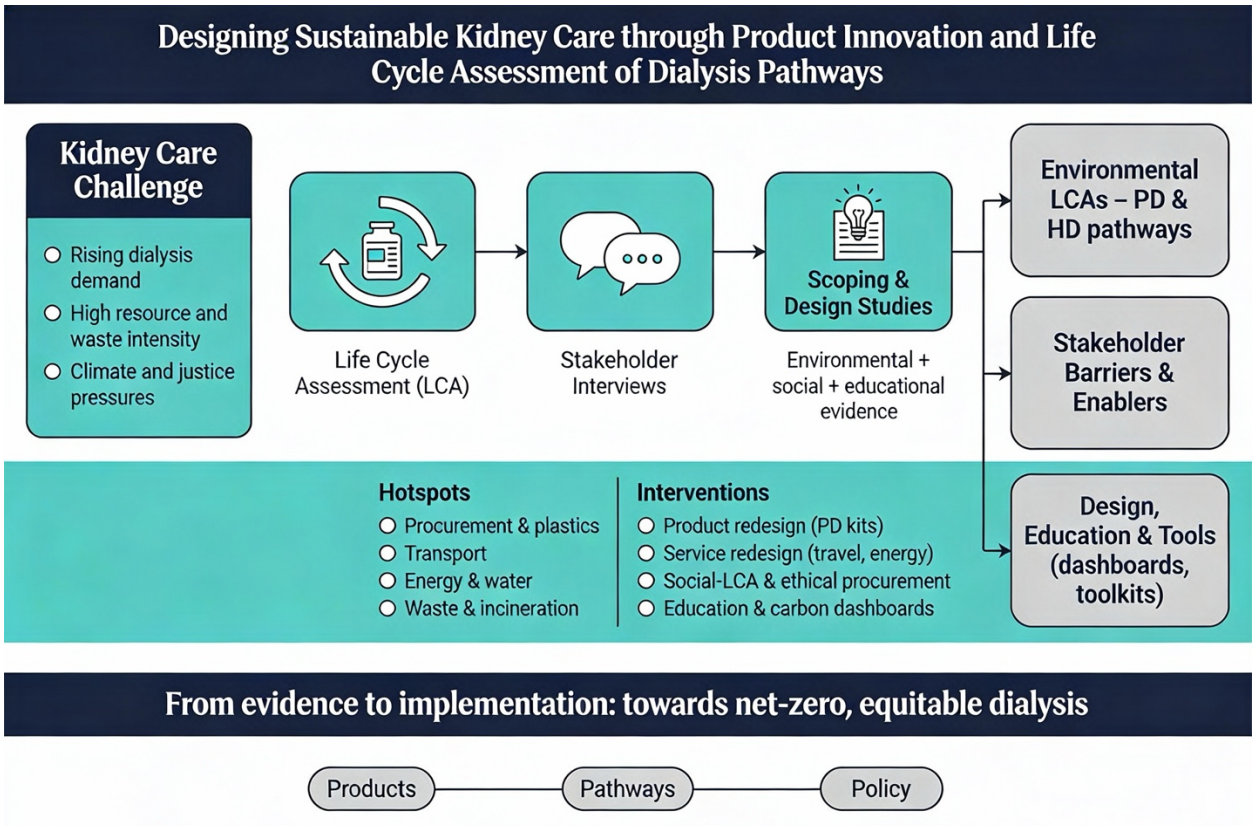

Figure 1. 13 Summary of Thesis

1.5.2 Key contributions (Procurement, life cycle assessment methods, design innovation, policy alignment)

This thesis provides original contributions to the field of sustainable healthcare by improving the environmental understanding of kidney treatment pathways, particularly PD and HD, through detailed LCA. Using primary data collected in clinical settings, this research offers new insights into the environmental impacts of dialysis products, systems and procurement practices and delivers practical solutions to reduce those impacts. The principal contributions of this thesis lie in methodological development, important evidence generation and practical changes for sustainable kidney care. These contributions are outlined below:

- First full LCA of PD using primary clinical data

- Procurement teardown and identification of high impact products

- Comparative LCA of acid concentrate delivery systems

- Modality wide environmental mapping of HD

- Integration of environmental impact into procurement and Ecodesign

- Policy relevance and alignment with EU Green Deal and NHS Net Zero

Together, these contributions establish a detailed evidence database for sustainable nephrology and demonstrate how detailed environmental data can drive improvements in clinical practice, procurement and system design. Together, these contributions extend existing sustainability research in nephrology by moving beyond conceptual discussion toward operationally relevant evidence.

1.5.3 Significance and novelty

This thesis investigates the environmental impacts of kidney care by including internationally recognised LCA methodologies with direct stakeholder input, analysing both PD and HD modalities through detailed mapping of material, energy and waste flows at every stage of the treatment pathway. By combining quantitative environmental data from dismantled products, measured resource consumption and independent clinical audits with qualitative insights gathered from interviews and policy reviews, the research identifies the wasteful processes, resource intensive practices and key barriers faced by clinicians and health systems. Drawing on this evidence, the thesis presents a coherent set of practical, data driven recommendations with the aim of reducing emissions, water and energy consumption and hazardous waste, while promoting recyclability, procurement reform and sustainable innovation in kidney care that supports high quality patient outcomes alongside ambitious climate and public health goals.

This body of work represents one of the first comprehensive LCA based investigations of both PD and HD pathways within European healthcare settings. By combining primary data collection, design thinking and environmental modelling, the thesis provides a practical and scientific foundation for advancing sustainability in kidney care. The novelty of this work lies

not in a single technique, but in the integration of environmental quantification, social assessment and design led interpretation within a clinical context.

Building on the significance and novelty outlined above, the following chapter sets out the theoretical and methodological framework used throughout the thesis. Chapter 2 explains how LCA was positioned within healthcare sustainability research and describes the analytical choices, system boundaries and data collection strategies adopted. This framework highlights all subsequent analyses and provides the methodological basis through which environmental and social impacts of kidney care were examined in later chapters.

Chapter 2: Theoretical framework for healthcare sustainability assessment

2.1 Positioning life cycle assessment within healthcare sustainability

2.1.1 LCA Framework

Building on the LCA framework introduced in Chapter 1, this section situates LCA within the broader context of healthcare sustainability and explains how the methodology was applied across the studies presented in this thesis. It introduces the theoretical positioning of LCA within healthcare sustainability and outlines how environmental, social and qualitative methods were integrated to support interpretation and implementation across the studies presented.

The healthcare sector is estimated to account for nearly 5% of global carbon emissions and procurement, waste and energy intensive processes such as dialysis and surgery are among the key contributors (Karliner, 2020; NHS 2020). In the context of sustainable healthcare, LCA helps bridge the gap between clinical needs and environmental responsibility.

Healthcare applications of LCA have included the assessment of reusable vs single use surgical equipment (McGain et al., 2014), low carbon anaesthetic alternatives and hospital waste management strategies (Lee et al., 2022; Sherman et al., 2012). In nephrology specifically, LCA has been used to examine the environmental impacts of HD and PD, revealing that consumables and procurement accounts for the majority of the environmental footprint (Agar, 2015a; Larkin et al., 2025b).

The strength of LCA lies in its capacity to generate insights across a broad set of impact categories, not just carbon emissions, but also water use, toxicity, land use and resource depletion. The method enables comparisons of alternative products or pathways, thus informing clinical decision making, procurement policy and design innovation (Hillege, 2019). The increasing adoption of LCA in healthcare supports a transition toward environmentally sustainable systems aligned with global climate targets and circular economy goals (WHO, 2022).

In this thesis, LCA is positioned as a comparative decision support method rather than a predictive or optimisation tool. The analysis is used to identify relative environmental hotspots

and compare alternative configurations of dialysis pathways, rather than to produce absolute emission values for regulatory or accounting purposes.

2.1.2 Methodological Pathway Overview

This thesis examines an integrated methodological framework combining LCA, S-LCA, semi-structured interviews and design-led analysis. Figure 2.1 illustrates the methodological pathway, showing how primary data collection (product teardowns, clinical audits) feeds into OpenLCA modelling (Chapters 3, 5), which is contextualised by stakeholder perspectives (Chapter 4) and analysed for policy/procurement recommendations (Chapter 6).

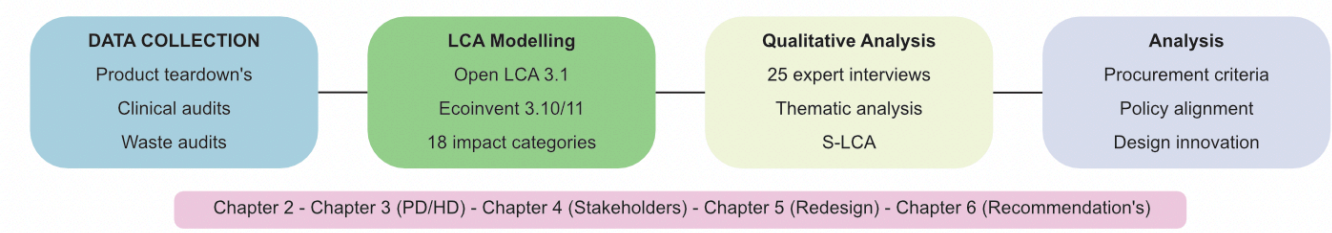

Figure 2. 1 Methodological Pathway Flowchart

The pathway begins with ISO 14040/14044-compliant LCA (Section 2.2), progresses through modality-specific studies (Chapter 3: PD/HD pathways; Chapter 5: product redesign), incorporates qualitative validation (Chapter 4), and culminates in transdisciplinary synthesis (Chapter 6). Each stage builds on the previous, ensuring methodological coherence across the KitNewCare project's sustainability objectives.

2.2 Life cycle assessment framework

2.2.1 ISO 14040/14044 and functional units

The methodological foundation of this thesis is based on the internationally recognised LCA standards, ISO 14040 and ISO 14044. These standards, developed by the International Organisation for Standardisation, define the principles, framework, requirements and guidelines for conducting an LCA (14040, 2006). They ensure transparency, reproducibility and scientific credibility in environmental assessments across sectors, including healthcare.

In this thesis, these phases are applied to dialysis pathways and products using primary data collection and OpenLCA modelling, as described in Sections 2.2 and 2.3.

ISO 14044 further details the methodological requirements and choices for each stage, including impact category selection, data quality requirements, allocation procedures and sensitivity analyses (14044, 2006). Following these standards enables consistent application of LCA and allows comparisons between different studies and systems.

The functional unit is a quantified description of the service provided by the system under study. It ensures comparability between different processes or products by standardising the output of interest (14040, 2006). The functional units were selected to reflect routine clinical practice and to enable meaningful comparison between dialysis modalities, rather than to estimate population level environmental burden. In this thesis, the functional units are aligned with clinical practice and vary depending on the dialysis modality studied:

- For PD studies, the functional unit is defined as the complete PD treatment for one patient over one year, reflecting the annual material, energy and waste burdens per patient.
- For HD studies, functional units are either defined as one dialysis session or one patient's treatment over a year, depending on the comparison being made (e.g. treatment pathways or product systems).

This approach allows meaningful interpretation of environmental impacts per patient and supports direct comparison between alternative products or treatment configurations. These

choices ensured consistency across comparative scenarios while maintaining clinical relevance.

2.2.2 Life cycle assessment software and modelling approach

In this research, the LCA studies were conducted using OpenLCA, an open source software designed for modelling and analysing environmental impacts in accordance with ISO 14040/14044. OpenLCA was selected due to its transparency, suitability for process based modelling and its ability to explicitly analyse clinical data alongside background supply chain datasets. For this thesis, the Ecoinvent 3.10 and Ecoinvent 3.11 databases were used as the primary background datasets, providing high quality life cycle inventory data on global energy, materials and waste management systems (Ecoinvent, 2024). The use of Ecoinvent allowed consistent modelling of manufacturing, energy production and waste treatment processes while maintaining comparability with published healthcare LCAs. The complete OpenLCA project files and underlying life cycle inventory datasets used for these analyses are archived on Zenodo (Aycan, 2025; Duane, 2025; Larkin, 2025a; Larkin, 2025b; Larkin, 2025c; Larkin, 2024a; Larkin, 2024b; Larkin, 2024c). The modelling approach prioritised clarity and traceability of assumptions over model complexity. This ensured that individual products, processes and procurement decisions could be directly linked to observed environmental hotspots, supporting interpretation and practical relevance rather than optimisations alone.

2.2.3 System boundaries and allocation methods

For all LCA studies in this thesis, a cradle to grave system boundary was applied. System boundaries were defined to balance analytical completeness with data availability, with emphasis placed on processes most relevant to dialysis delivery, procurement and waste management. This includes:

- Raw material extraction.
- Manufacturing and assembly.
- Packaging.
- Transportation (international and last mile delivery).

- Use phase (including electricity and consumables, where applicable).
- End of life disposal, such as incineration, landfill, or recycling.

The included processes represent the main material and energy flows associated with routine dialysis treatment and were applied consistently across all comparative scenarios. Figure 2. 2 illustrates a representative system boundary applied across dialysis LCAs in this thesis. Where changes from this boundary were required for specific case studies, these are clearly described within the relevant chapter.

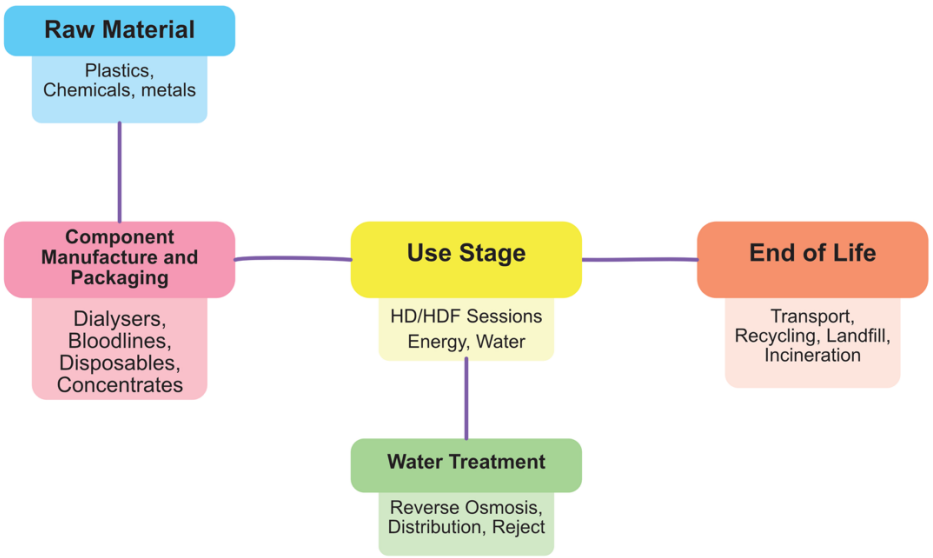

Figure 2. 2 Example System Boundary (Larkin et al. 2026a)

2.2.4 Primary data collection: Product weighing and teardown

Primary data collection forms the basis of the LCI phase in this thesis, ensuring high quality, site specific inputs for OpenLCA models. Primary data collection was undertaken to reduce reliance on generic secondary datasets and to improve representativeness of dialysis specific materials, packaging and waste streams within the LCI. Fieldwork at AOU Policlinico di Modena (April-July 2024) involved systematic dismantling (teardown) and weighing of dialysis consumables. All product weighing and teardown activities were conducted on unused disposable items under controlled conditions prior to clinical use.

Dialysis consumables were dismantled using a consistent non-destructive teardown approach to separate major material components. Individual components and associated packaging were weighed using calibrated laboratory scales and materials were classified based on manufacturer information and visual inspection. Data were recorded in structured templates to ensure consistency across products and treatment modalities. It is important to note that measured weights reflect pre-use conditions and do not account for residual liquids or contamination present in real world post use waste. In clinical settings, dialysis consumables such as bags, cartridges and tubing often retain fluid after use, which increases total waste mass and may influence waste treatment impacts. Figure 2. 3 displays photos of the researcher dismantling dialysis consumables during primary data collection at AOU Modena.

Figure 2. 3 Product teardown process of HD Dialyser at AOU Policlinico di Modena

Results fed directly into LCI datasets (e.g., 1.2kg average PD bag weight, 72% plastics), enabling allocation to hotspots such as PVC incineration and transport. However, as weights were derived from unused products, waste-related impact estimates may be conservative where residual fluids increase post-use mass in practice. This should be considered when interpreting waste management results. Primary datasets were incorporated directly into LCI models, allowing for explicit representation of material composition, packaging ratios and waste treatment pathways. Datasets archived on Zenodo ensure reproducibility (Larkin, 2024; Larkin, 2025). Archiving of datasets supports transparency and enables reuse in future healthcare sustainability research.

2.2.5 Data quality, uncertainty and sensitivity analysis

Data quality is a critical consideration in LCA, particularly within healthcare systems where primary data availability is often limited and practice varies across sites. In this thesis, data quality was addressed through a combination of primary data collection, transparent documentation of assumptions and structured sensitivity analysis.

Primary data was prioritised wherever possible, particularly for dialysis consumables, packaging and waste, to improve representativeness of the studied pathways. Where primary data was unavailable, secondary data from the Ecoinvent database was used to model manufacturing, energy production and waste treatment processes. These datasets were selected due to their widespread use in healthcare LCA studies and their provision of consistent background inventories.

Uncertainty within the models arises from several sources, including variability in product composition, differences in clinical practice and assumptions regarding waste treatment routes. Rather than attempting to eliminate uncertainty, this research sought to manage it through transparency and consistency. All assumptions applied within each model were documented and applied uniformly across comparative scenarios to support internal validity.

Sensitivity analyses were conducted for parameters expected to influence results, including transport distances, waste treatment pathways and alternative product configurations. These analyses were used to assess the robustness of hotspot identification and to determine whether relative comparisons between scenarios remained stable under reasonable parameter variation.

The purpose of uncertainty and sensitivity analysis within this thesis was not to generate precise emission values, but to evaluate confidence in comparative findings and identify parameters with the greatest influence on environmental outcomes. This approach aligns with ISO 14044 guidance, which emphasises interpretation and transparency over numerical precision in comparative assessments (ISO 14044, 2006).

By combining primary data, consistent modelling assumptions and targeted sensitivity testing, the LCA presented in this thesis provide a robust basis for identifying environmental hotspots and informing decision making within dialysis care pathways.

2.3 Ethical considerations in environmental research

2.3.1 Data integrity and transparency

Ethical considerations in this thesis relate primarily to responsible data use, transparency of assumptions and protection of participants involved in qualitative research. Ensuring that data is collected accurately, presented transparently and analysed appropriately is essential for producing valid results. In the context of LCA, this involves documenting the entire data collection process, including the sources, assumptions and limitations of the inventory data. It is also vital to ensure the reproducibility of results by using widely accepted databases and methodologies (Guinee, 2011). Transparency was prioritised to reduce the risk of misinterpretation or inappropriate use of environmental results in clinical or policy contexts.

In this thesis, all work involving human participants or clinical data underwent formal research ethics review at the relevant institutions. This covered the qualitative interview study with clinicians and sustainability experts. It also included the use of anonymised clinical audit data and procurement records linked to dialysis treatments. Modena specific LCA studies drew on existing operational and procurement information, but ethics constraints on direct clinical data access meant that Irish travel data had to be used for some transport modelling, rather than site specific patient level data from Italy (Kennedy et al., 2018). Ethics approvals defined the purpose of the research, data handling procedures and safeguards to minimise risk to patients, staff and participating organisations. Ethics approval ensured that participation was voluntary, informed consent was obtained and no clinical decision making was influenced by study involvement.

Data protection and confidentiality followed the General Data Protection Regulation (GDPR) and local institutional policies. Patient related information used for environmental analyses was not required for LCA models. No identifiable clinical details were stored in OpenLCA project files. Interview transcripts were pseudonymised and kept on encrypted institutional servers with controlled access. Any external sharing via open repositories used deidentified material in line with participant consent and ethics approvals (Commission, 2019). Together,

these measures ensured that environmental modelling and qualitative research were conducted in a manner consistent with institutional, legal and professional ethical standards.

2.3.2 Stakeholder engagement

Stakeholder engagement within this research focused primarily on healthcare professionals involved in dialysis delivery, procurement and sustainability initiatives. Engagement was undertaken to ensure that environmental modelling reflected real world clinical practice and operational constraints. Clinician input informed interpretation of treatment pathways, validation of system boundaries and feasibility assessment of proposed sustainability interventions. Stakeholder engagement was consultative rather than directive and did not influence patient care or clinical decision making. The research in healthcare sustainability, particularly in dialysis systems, directly impacts patients and healthcare staff.

As LCA can highlight potential cost savings through reduced environmental impacts, it is crucial to assess whether these cost savings are passed on to patients or healthcare systems in the form of better care or reduced costs. An ethical research approach involves advocating for environmental improvements that do not exacerbate social inequalities or create unintended negative consequences for vulnerable populations (Jennings et al., 2015). No direct patient participation was undertaken as part of the environmental modelling studies and patient level decision making remained outside the scope of this research.

2.3.3 Long term policy and community impact

Ethical considerations related to long term impact in this thesis focused on responsible communication of findings and protection of sensitive healthcare data used for environmental modelling and qualitative analysis. In healthcare, this is particularly important when dealing with patient data, which must be handled in accordance with data protection regulations such as the GDPR in Europe (Commission, 2019; GDPR, 2016; Union, 2016). Research studies that involve data collection from healthcare settings, such as those examining environmental impacts of dialysis treatments, must ensure that patient identities and health details are anonymized and that the data is securely stored. This is essential to maintain public trust in

scientific research and to ensure compliance with legal and ethical standards. All data handling procedures were designed to comply with relevant European and institutional data protection requirements.

In this thesis, confidentiality was protected by removing direct identifiers and pseudonymised data for all analyses. Patient level variables used in LCA models were reduced to non-identifiable parameters such as treatment frequency, modality mix or typical transport distances. These were never linked to names, addresses or hospital numbers. Interview transcripts were pseudonymised at the point of transcription and stored on encrypted institutional servers with access restricted to the research team. These measures ensured that environmental findings could be disseminated responsibly without compromising confidentiality, institutional trust or participant privacy.

2.4 Complementary methods

2.4.1 Environmental impact categories

Multiple environmental impact categories were assessed to avoid reliance on carbon footprint alone and to reduce the risk of burden shifting between environmental impacts. The impact categories selected reflect environmental pressures most relevant to dialysis treatment pathways, particularly those associated with plastics production, energy use, water consumption and waste treatment. The impact categories used in the thesis include:

- Climate Change
- Acidification Potential
- Eutrophication Potential
- Freshwater Ecotoxicity
- Human Toxicity
- Photochemical Ozone Formation
- Resource Depletion – Fossil and Mineral
- Water Use
- Particulate Matter Formation
- Ozone Depletion
- Ionising Radiation
- Land Use

Not all impact categories were reported for every study, as selection was guided by data availability, methodological suitability and clinical relevance. These categories were selected to capture not only GHG emissions but also broader ecological and human health impacts, providing a more complete understanding of dialysis related burdens.

Chapters 3 and 5 specify which subsets of these categories are reported for each study, based on data availability and clinical relevance. The rationale for category selection and reporting is described within each results chapter.

2.4.2 Qualitative interviews

Qualitative interviews were conducted to complement LCA by exploring organisational, operational and institutional factors influencing the implementation of environmental sustainability in kidney care. Semi structured interviews were undertaken with stakeholders involved in dialysis delivery, procurement and sustainability governance, including clinical directors, sustainability leads and procurement professionals. Interviews focused on perceived barriers and enablers to implementation of environmentally preferable practices identified through LCA findings. Each method complements the LCA approach by addressing aspects that quantitative environmental modelling cannot capture, particularly social experiences, perceptions, policy contexts and system wide trends. No patient interviews were conducted as part of this study.

Interview data were analysed using thematic analysis, following iterative coding to identify recurring patterns related to feasibility, governance, infrastructure and procurement processes.

In the context of sustainable kidney care, semi structured interviews are used to explore barriers and enablers to environmental optimisation in clinical settings and institutional or cultural factors affecting change implementation.

These interviews add real world detail that shows how the LCA findings play out in everyday kidney care practice. For example, why high impact interventions may be difficult to implement despite their environmental benefits.

In this thesis, interviews were undertaken with 25 stakeholders across Europe, including sustainability officers, clinical directors and procurement professionals, to map systemic challenges and opportunities for greening kidney care. Qualitative findings are presented alongside quantitative results to support interpretation rather than to generate generalisable behavioural conclusions. An anonymised, deidentified version of the interview dataset has been deposited on Zenodo (Larkin, 2025c). Access is provided in line with ethical approvals and participant consent.

2.4.3 Scoping review

A scoping review is used in this thesis to map existing evidence on:

- Sustainability interventions in kidney care, including innovations, practice changes and policy reforms (scoping review).

The scoping review uses the Arksey and O'Malley framework to examine a broader and more exploratory research question (O'Malley, 2003). What interventions have been implemented across the globe to reduce the environmental impact of kidney care? This approach helps contextualise the findings of the LCAs within the larger landscape of innovation, demonstrating where change is already happening and where gaps remain.

2.4.4 Integration and complementarity

Integration of quantitative and qualitative methods was used to support interpretation of LCA findings and to contextualise environmental results within operational and organisational areas of kidney care. The following methods were used to:

- support interpretation of LCA results within clinical and procurement contexts
- identify organisational and infrastructural factors influencing implementation
- inform development of practical and context sensitive recommendations

The qualitative components were not intended to validate quantitative results, but to provide explanatory insight into why environmentally preferable options may or may not be feasible within existing healthcare systems. This chapter has established the methodological foundation for the thesis, detailing the ISO-aligned LCA framework, ethical considerations and complementary qualitative methods used throughout. This supports a methodological framework across the thesis while maintaining clear distinctions between scientific approaches.

Chapter 3 applies this framework to generate original LCA data on PD and HD, quantifying environmental hotspots across dialysis pathways using primary and secondary data from European renal units.

Chapter 3: Environmental life cycle assessment of dialysis pathways

3.1 Introduction

3.1.1 Dialysis as a resource intensive medical intervention

With CKD as a major global health challenge, more than 3.9 million individuals with kidney failure require kidney replacement therapy (KRT) such as dialysis or transplantation globally (Bello et al., 2022). The burden of disease is increasing due to population ageing, rising prevalence of diabetes, hypertension and improved access to healthcare services in low and middle income countries (Chesnaye et al., 2024).

HD is more prevalent in high income countries where hospital based infrastructure is available, whereas PD is often promoted in regions with resource constraints due to its home based nature and lower clinical staffing needs (Teakell et al., 2022). In some health systems, reimbursement structures and profit driven incentives within private insurance models have also favoured incentre HD over PD (van der Tol et al., 2019). These structural differences in treatment delivery have important implications for material use, energy demand and waste generation.

The global dialysis population is projected to double by 2030 (Jager et al., 2019), posing not only clinical and economic challenges but also profound environmental and sustainability concerns. The scale and projected growth of dialysis activity increases the importance of understanding environmental impacts at both product and treatment pathway level.

For these reasons, dialysis provides a suitable context for detailed LCA of healthcare environmental impacts, as presented in the remainder of Chapter 3.

3.1.2 Environmental challenges in haemodialysis and peritoneal dialysis

Previous studies have demonstrated that both HD and PD are associated with substantial environmental impacts, with the main contributions arising from water treatment, energy use and single use medical products. These findings provide a foundation for detailed pathway level analysis.

Building on this evidence, existing LCAs have identified consistent environmental hotspots across dialysis modalities.

- In HD: water treatment, dialyser manufacture and single use acid/bicarbonate containers (McAlister et al., 2024b; Zawierucha et al., 2023).
- In PD: production and transport of dialysate bags, plus disposal of PVC based sets (Larkin et al., 2026c; Chen et al., 2017).

By mapping these pathways, LCAs not only identify key causes of environmental harm but also inform targeted interventions, such as product redesign, packaging reform and alternative waste treatment technologies (Sharma et al., 2024).

The following sections present six interrelated LCA studies examining PD and HD pathways in detail. These include whole pathway modelling, procurement based analyses, product redesign scenarios and evaluation of alternative dialysis technologies. Together, these studies provide the basis for interpretation and analysis in Section 3.5.

3.1.3 Research questions for pathway level analysis

The six studies examine environmental impacts across PD and HD delivery systems, spanning full treatment pathways, procurement hotspots, product level analyses and delivery system innovations.

PD Pathway LCA: Comprehensive cradle to grave analysis of APD and CAPD treatment pathways at Modena (Larkin et al., 2026c).

PD Procurement LCA: Product level analysis isolating individual consumables from the broader pathway to enable detailed hotspot identification and procurement optimisation (Larkin et al., 2025b).

PD Product Redesign LCA: Comparative assessment of optimised PD consumable against manufacturer baseline specifications. This design led study examines potential environmental

implications of material substitution, component rationalisation and manufacturing process modifications (Larkin et al., 2026d).

HD vs OLHDF Comparison: Environmental performance comparison of high flux HD versus OLHDF under routine clinical operation at Modena's main dialysis unit (Larkin et al., 2026a).

HD Procurement LCA: Consumables focused analysis prioritising the highest impact items identified through prior screening (Larkin et., 2026b).

Acid Concentrate (Granumix) LCA: Delivery system comparison of traditional acid concentrate bags versus Fresenius' centralised Granumix/Diamix system (Larkin et al., 2025a).

Together, these studies form an integrated pathway level analysis in which whole system modelling is combined with targeted product and technology assessments to support interpretation of environmental hotspots and intervention potential. Based on this structure, through these 6 studies, the chapter addresses the following questions:

- What are the main environmental burdens of HD and PD pathways across multiple impact categories (climate change, water use, toxicity, resource depletion)?

- Which products and processes within procurement, manufacturing, transport, use and waste management contribute most significantly to these burdens?

- How do innovative alternatives such as centralised acid preparation (Granumix) compare environmentally to conventional systems and what are the implications for clinical procurement practice?

3.2 Methods and system boundaries

3.2.1 Life cycle assessment approach for peritoneal dialysis and haemodialysis

This section describes the methodological approach used to model PD and HD pathways for the six studies presented in this chapter. The aim was to ensure consistent system boundaries and data collection procedures while allowing modality specific parameters to be represented accurately. Unlike HD's facility based resource demands, PD's footprint centres on procurement of large volume consumables including dialysate bags, tubing sets, drainage systems and cassettes shown in Figure 3.1 (Al-Hadithy et al., 2024; Larkin et al., 2025; Lee et al., 2022; Lithner et al., 2011). The PD studies investigate PD pathways at product, treatment and annual scales.

HD accounts for the vast majority of patients (89% patients) requiring three times weekly 3-5hr sessions with extracorporeal blood dialysate exchange (Jager et al., 2019; Bello et al., 2022). Resource intensity is extreme. 120-500L water/session (RO reject), 9-12kWh electricity, plus dialysers, bloodlines, bicarbonate/acid containers (shown in Figure 3. 2) creating massive single use waste (Agar, 2010; Arias-Guillen et al., 2024; Barraclough et al., 2022) (Larkin et al., 2026a). The HD studies examine HD from process hotspots to procurement impacts. Separate models were developed for PD and HD to reflect differences in treatment delivery, consumable use and infrastructure requirements.

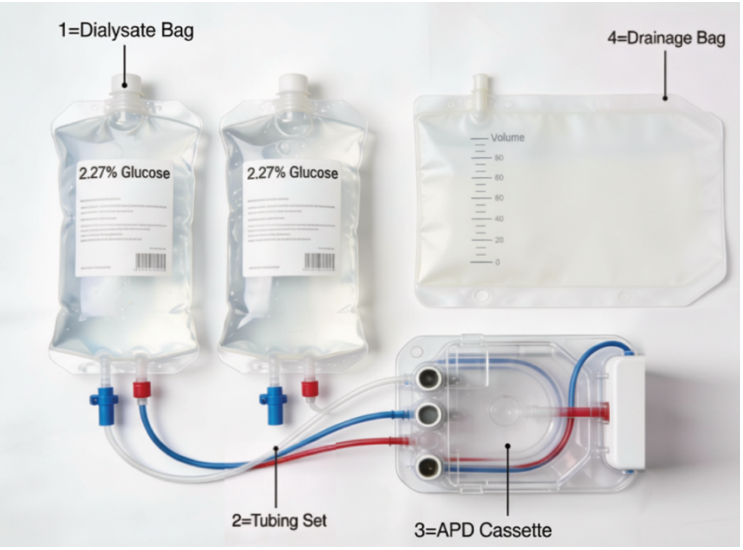

Figure 3. 1 Example of PD Consumables

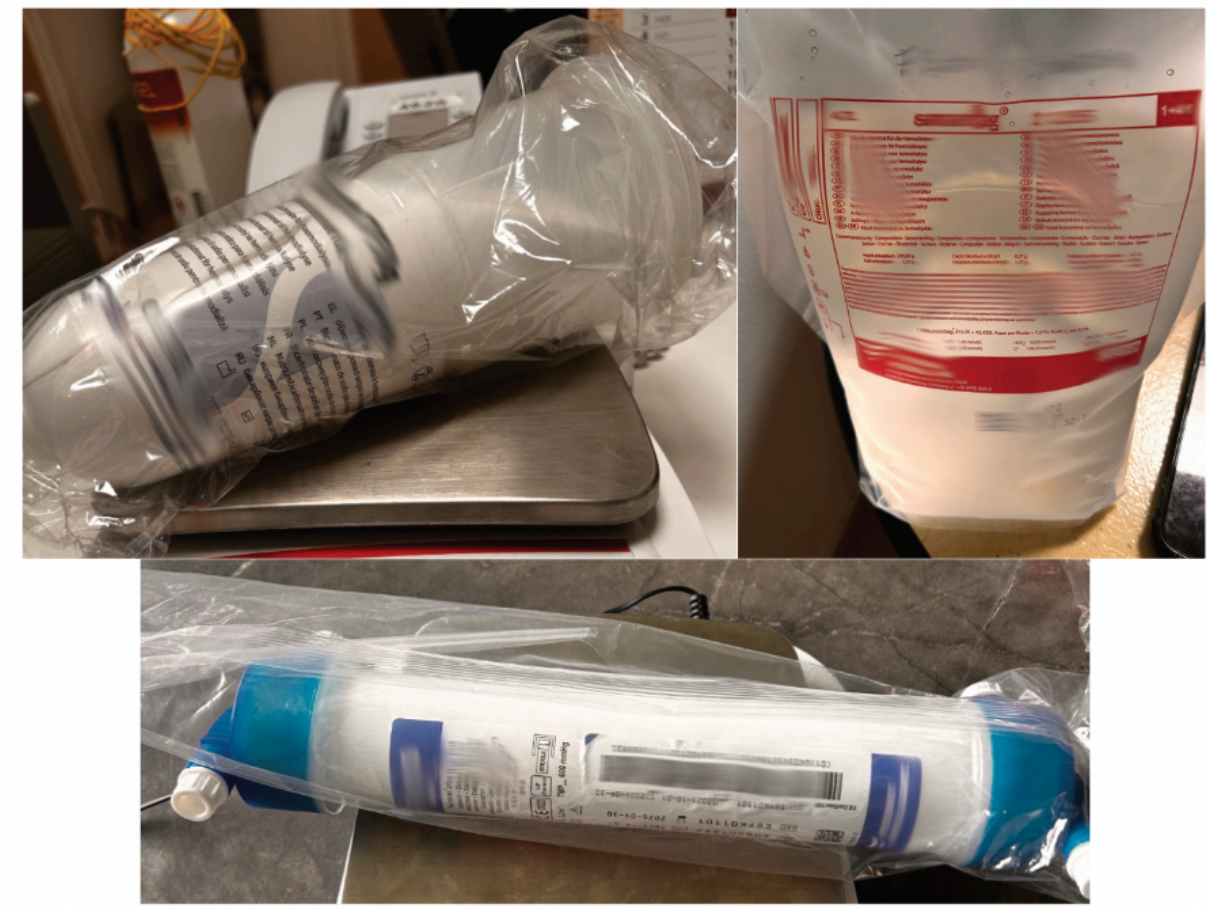

Figure 3. 2 Example HD Consumables

Primary data was collected to improve representativeness of key operational parameters within both modalities:

- Electricity: Plug meter on a HD machine shown in Figure 3. 3 which captured active treatment, thermal disinfection, standby (Larkin et al., 2026a). For PD, a plug meter was placed on an APD machine shown in Figure 3. 4 to capture electricity during APD treatment (Larkin et al., 2025b).
- Water: RO product water directly measured HD 382L vs OLHDF 409L (+27L substitution), baseline 65% recovery, scenarios 50-70% (Bendine et al., 2020; Tattersall et al., 2013)
- Procurement: Onsite dismantling/weighing of all consumable packs (bags, dialysers, lines), supplier specifications gap filled.

- Waste: Streams/treatments verified with contractor (autoclave/incineration/landfill pathways).
- Travel: 29km roundtrip average derived from Irish in centre patterns (Italian data protection proxy), geography validated (Kennedy et al., 2018). Travel distances were incorporated to reflect patient attendance patterns.

Figure 3. 3 Example of a HD Dialysis Machine

Figure 3. 4 Example of an APD Machine

All inventories were modelled using measured or site specific data where available. The modelling was conducted using OpenLCA v2.5.0 with the Ecoinvent 3.11 database, applying European averages for plastics and freight processes alongside an Italy specific electricity grid emission factor of 0.25 $kgCO_2/kWh$ (Ecoinvent, 2024). This included Operational litres

reported alongside LCIA water (scarcity not equal to volume) (McAlister et al., 2024; Rockström et al., 2009).

OLHDF: +5.7% electricity (substitution pump), 27L product water/session, bloodlines + integrated substitution lines, quarterly dialysate ultrafilters (Bendine et al., 2020; Care, 2025). Inventories were compiled in Excel using measured weights of bags, cartons and pallets alongside manufacturer bill of materials and safety data sheets.

Detailed system boundaries and parameter values specific to each study are described within the corresponding results sections.

3.2.2 Functional unit and system definition

This section defines the functional units and system boundaries applied across the pathway level and product specific LCA studies presented in this chapter. Separate system definitions were required to reflect differences in treatment modality, delivery model and what the analysis focused on. The functional unit was defined as one year of PD for a single patient, based on the most common prescription at Modena (Larkin et al., 2026c).

To support transparency and consistency across pathway modelling, process flow diagrams were developed for each dialysis modality (Figure 3. 5). Each diagram includes key processes such as patient setup, product procurement, waste generation and energy use. Standardised symbols were used to indicate procurement, energy consumption, transport and waste, offering a clear, structured visual reference for the LCA modelling process in OpenLCA.

1. Education Renal Replacement Therapy PD

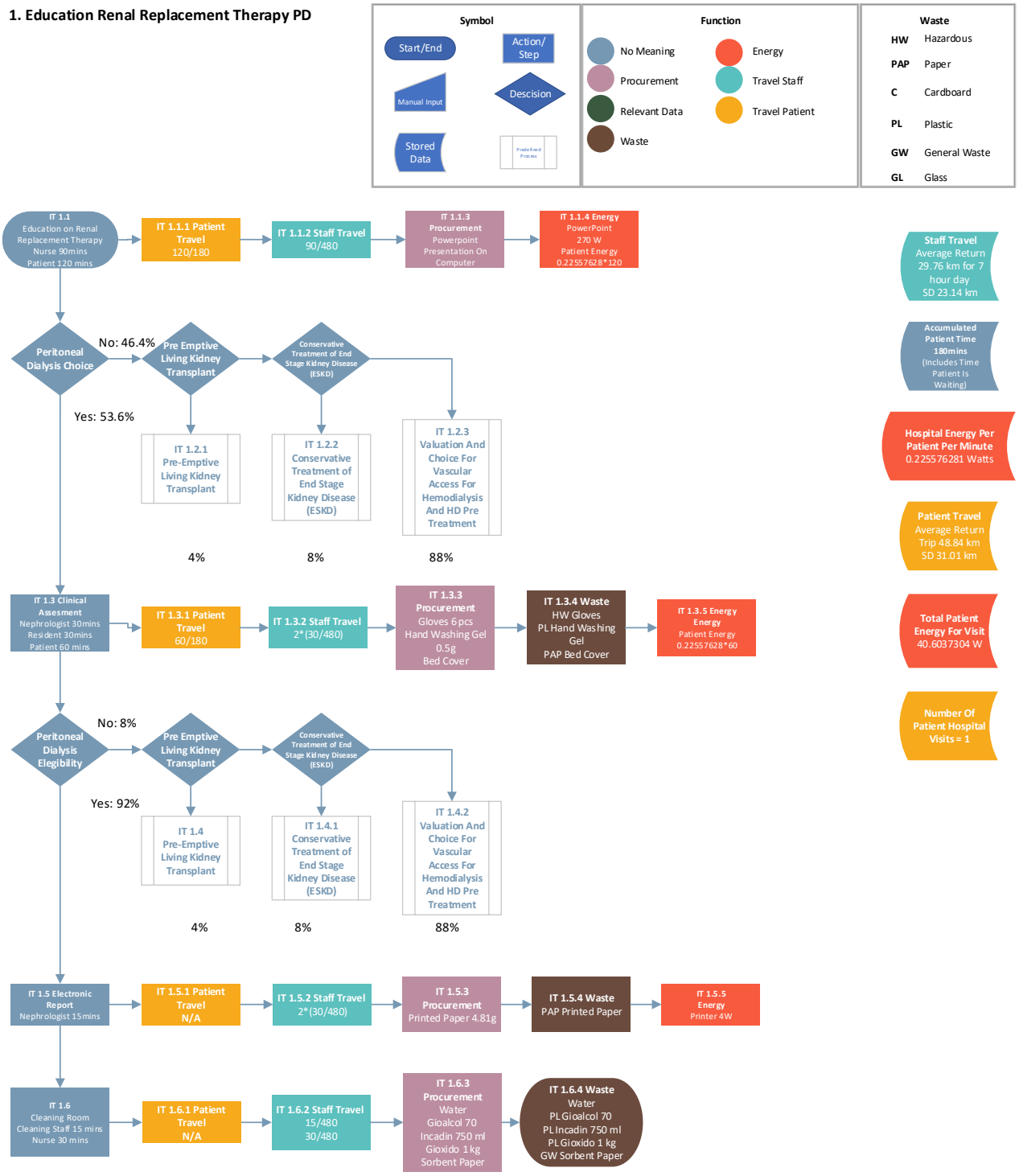

Figure 3. 5 Sample Flow Diagram, First pathway in PD (Larkin et al. 2026c)

The PD pathway system boundary adopted a cradle to grave approach, including all key life cycle stages from raw material extraction through to final disposal. As illustrated in Figure 3. 6, this includes the following stages:

- Raw Materials: Inputs including plastics and chemical components.
- Manufacturing: These raw materials undergo specific manufacturing processes such as injection moulding, blow moulding, extrusion, fluid production and machine assembly.
- Product Formation: The resulting components include dialysate bags, tubing, cassettes, connectors, packaging and machines required for both CAPD and APD.
- Transport and Logistics: All products are shipped through international and regional freight systems to hospitals and patients' homes.
- Use Stage: The PD treatment is carried out either at home or in a hospital, depending on the context. Each treatment cycle involves the consumption of fluid, plastic, energy (for APD) and packaging.
- Disposal: End of life impacts include incineration (for medical waste), landfill (for mixed plastics and packaging) and minor recycling where applicable.

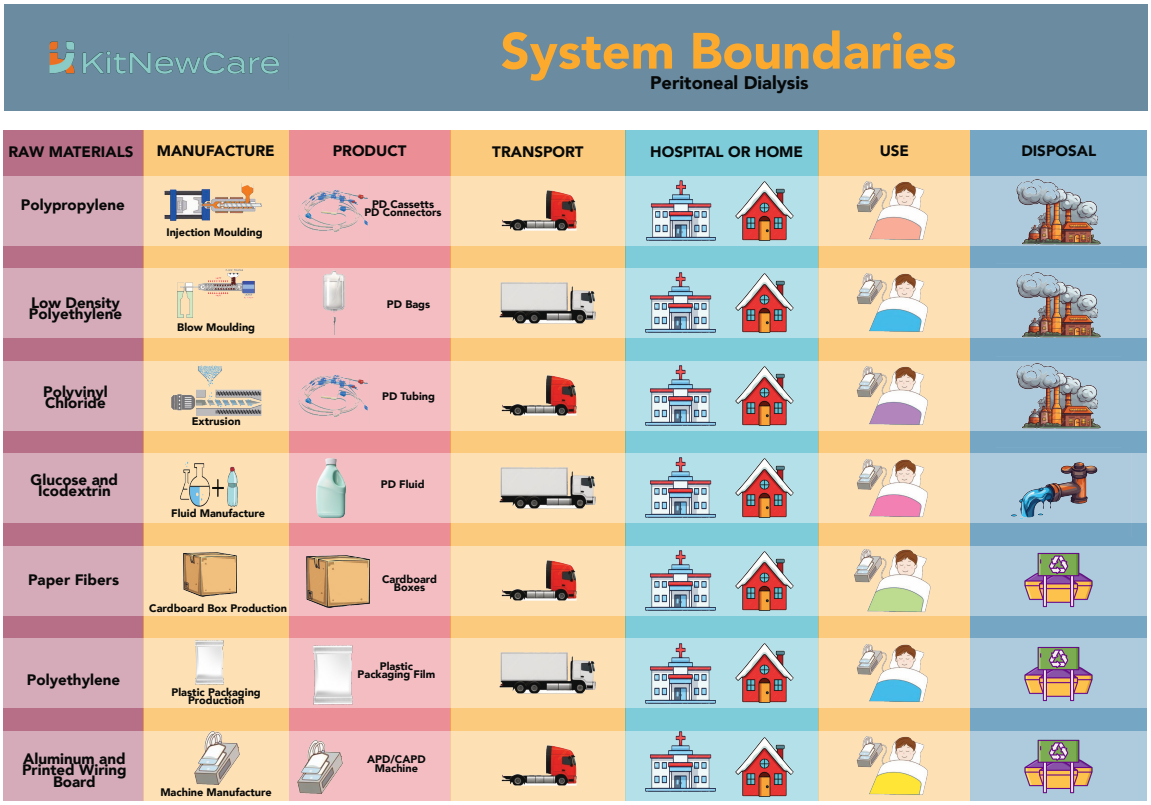

Figure 3. 6 System boundaries for PD. APD and CAPD are both included. The system boundary shows the "cradle to grave" analysis of the LCA (Larkin et al. 2026c)

A separate system boundary was designed for the PD procurement LCA to enable product level detail and isolate individual consumables from pathway level processes. This system boundary is illustrated in Figure 3. 7. This cradle to grave boundary included raw material extraction, manufacturing, packaging, international and domestic transport, product use and waste disposal. Household waste collection and disposal were included to reflect home dialysis waste pathways. (Larkin et al., 2025b; Lee et al., 2022). Travel was included within the system boundary due to its potential contribution to total impacts.

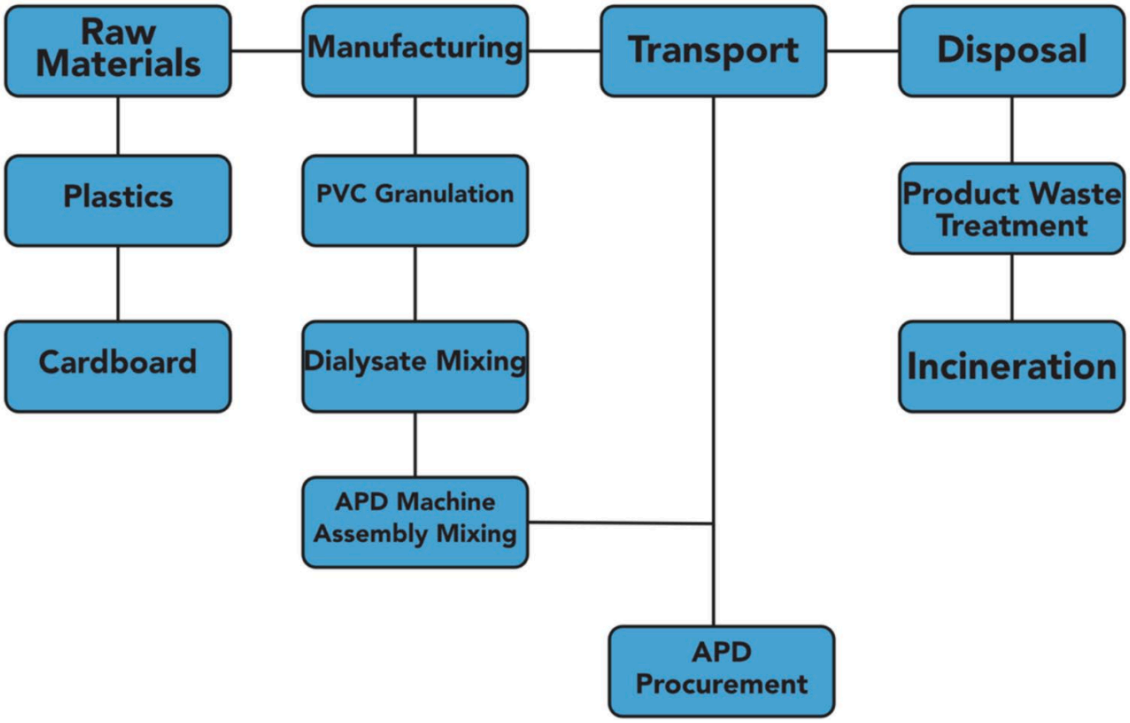

Figure 3. 7 System boundary. PVC Polyvinylchloride, APD Automated Peritoneal Dialysis (Larkin et al. 2025b)

The functional unit included one patient year of in centre therapy (156 sessions, three times a week), with per session reporting for interpretability (Larkin et al., 2026a).

Figure 3. 8 illustrates the HD system boundary, which follows a cradle to grave approach including:

- Procurement: dialysers, bloodline sets (HD vs HDF-specific), needles, concentrates, packaging, inbound freight.
- Water systems: RO generation and distribution, ultrafiltration for ultrapure water (Tattersall et al., 2013) pipeline disinfection excluded due to data unavailability.
- Session operations: dialysis machine energy (treatment + thermal disinfection + standby), dialysate preparation.
- Waste: separation, internal handling, transport and treatment (hazardous/non-hazardous).
- Travel: patient trips and staff commuting (Kennedy et al., 2018; Stephens et al., 2013).

Vascular access procedures were excluded as they fall outside the product/facility boundary, while capital equipment manufacturing was excluded due to its conventionally minor contribution (<5% in high-intensity therapies) (McGain et al., 2014; Sherman et al., 2018).

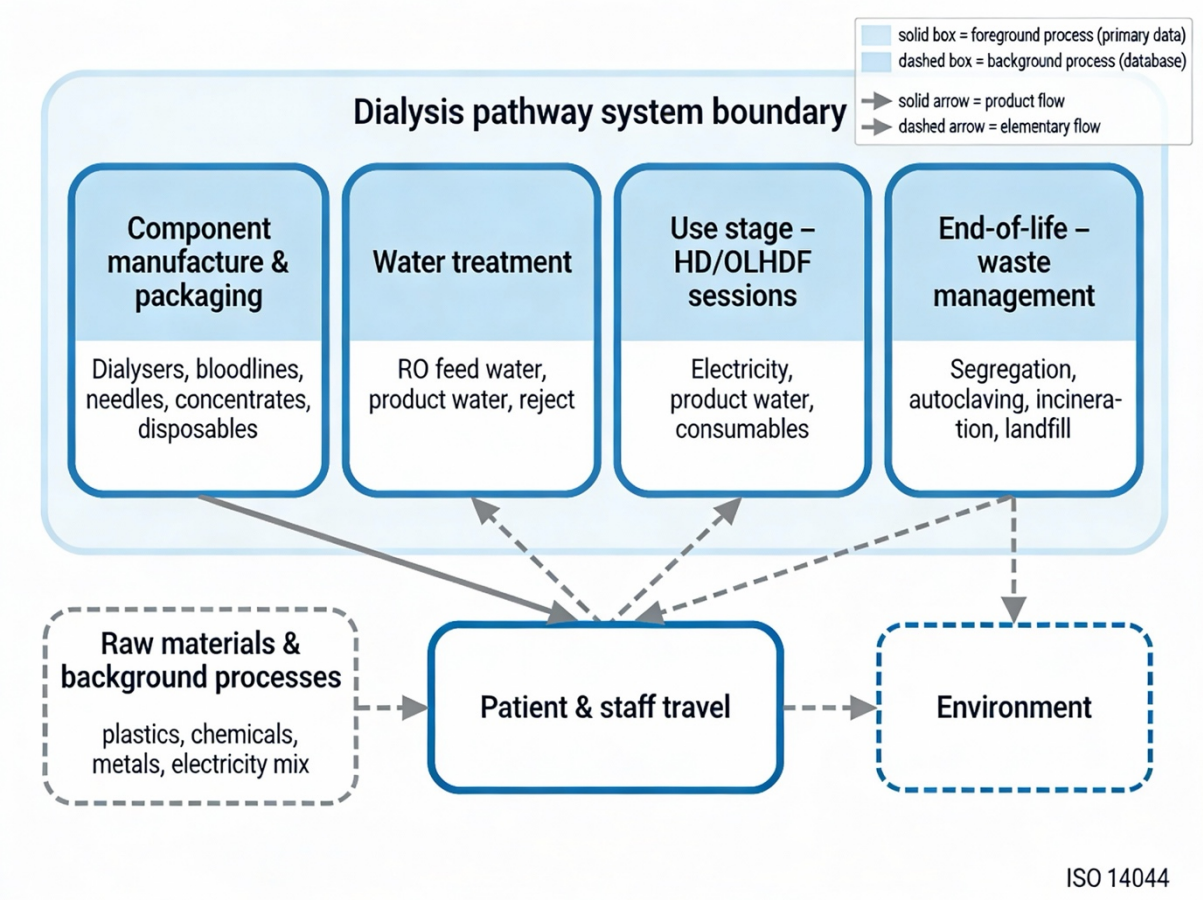

Figure 3. 8 System boundary (ISO 14044 aligned) (Larkin et al. 2026a)

The system boundary for the HD Procurement study adopted a cradle to grave approach, including procurement of consumables, electricity and water use, transport and waste disposal. Similar to the HD vs OLHDF study, the functional unit was defined as the complete HD treatment for a single patient over one year, corresponding to 156 sessions (three sessions per week). All consumables and associated packaging required to deliver this annual course of treatment were included, along with included impacts of the HD machine (spread over its expected service life) and the electricity consumed during operation (Larkin et al., 2026b).

Waste management pathways were modelled according to practices at AOU Modena, where most consumables are classified as hazardous clinical waste and treated through incineration (Larkin et al., 2026b). Alternative scenarios, including autoclaving or separating into nonclinical waste streams, were modelled separately to explore optimisation potential.

Figure 3. 9 illustrates the system boundaries applied in this study. The diagram shows the inclusion of raw material investment, manufacturing, packaging, transport, hospital use phase and end of life disposal, ensuring that the analysis represents a full cradle to grave perspective. This figure is adapted from the system boundary diagram used in the Modena HD procurement study (Larkin et al., 2026b).

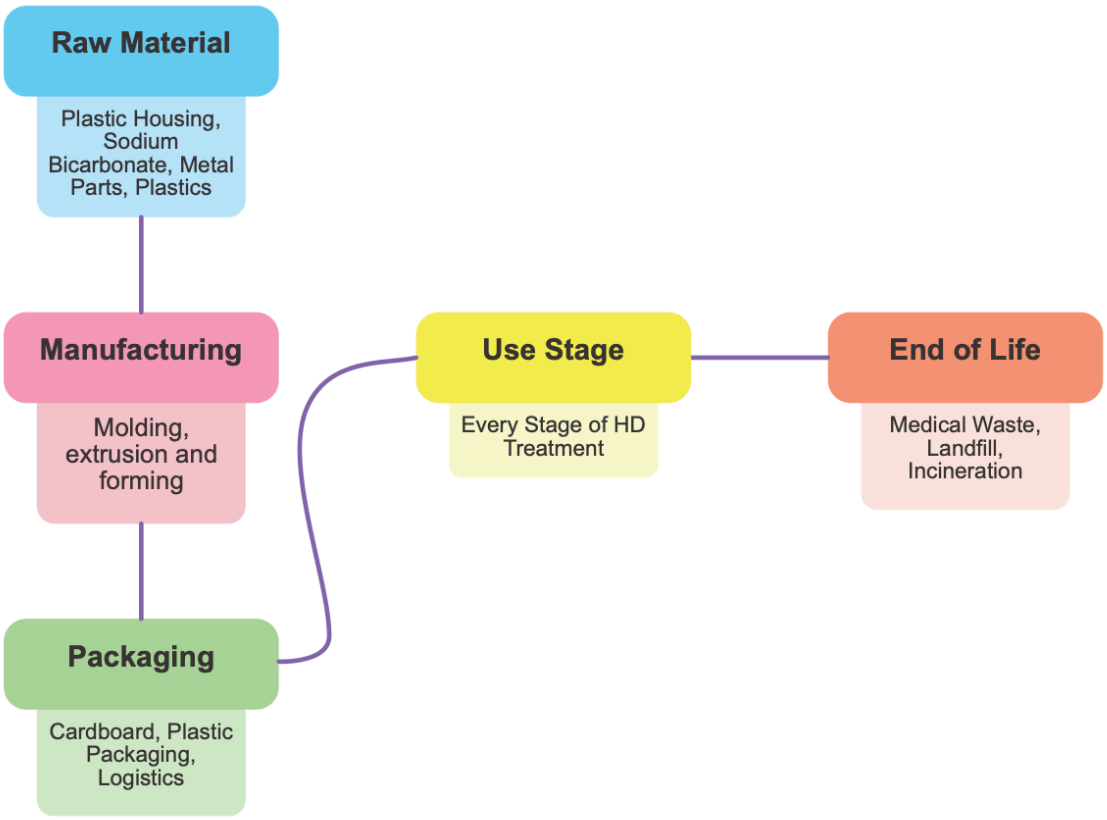

Figure 3. 9 System Boundary (Larkin et al. 2026b)

For the Acid concentrate study, the functional unit was one standard HD treatment for one patient. The session length was four hours. Dialysate flow was 500 millilitres per minute. Total dialysate volume was 120 litres per treatment.

Data collection took place between April and September 2024 at AOU Policlinico di Modena (Larkin et al., 2025a).

Primary measurements captured pack weights, observed residual acid per used bag, counts of Diamix containers and reuse cycles, filter bill of materials and change frequency and waste routing to the contracted waste operator (Mehta et al., 2019). Transport distances were calculated with Google Maps for road legs and Fluent Cargo for sea legs (Google., n.d.). Bicarbonate supply was excluded from the comparison because the bicarbonate process chain is the same in both arms and would add noise without affecting the relative difference in the acid subsystem (Larkin et al., 2025a).

The system boundary included raw material production, manufacturing, packaging, international and domestic transport, on site preparation, use phase processes and end of life treatment for both acid delivery systems as shown in Figure 3. 10 (Larkin et al., 2025a).

Detailed inventories and parameter values specific to each study are presented within the corresponding results sections.

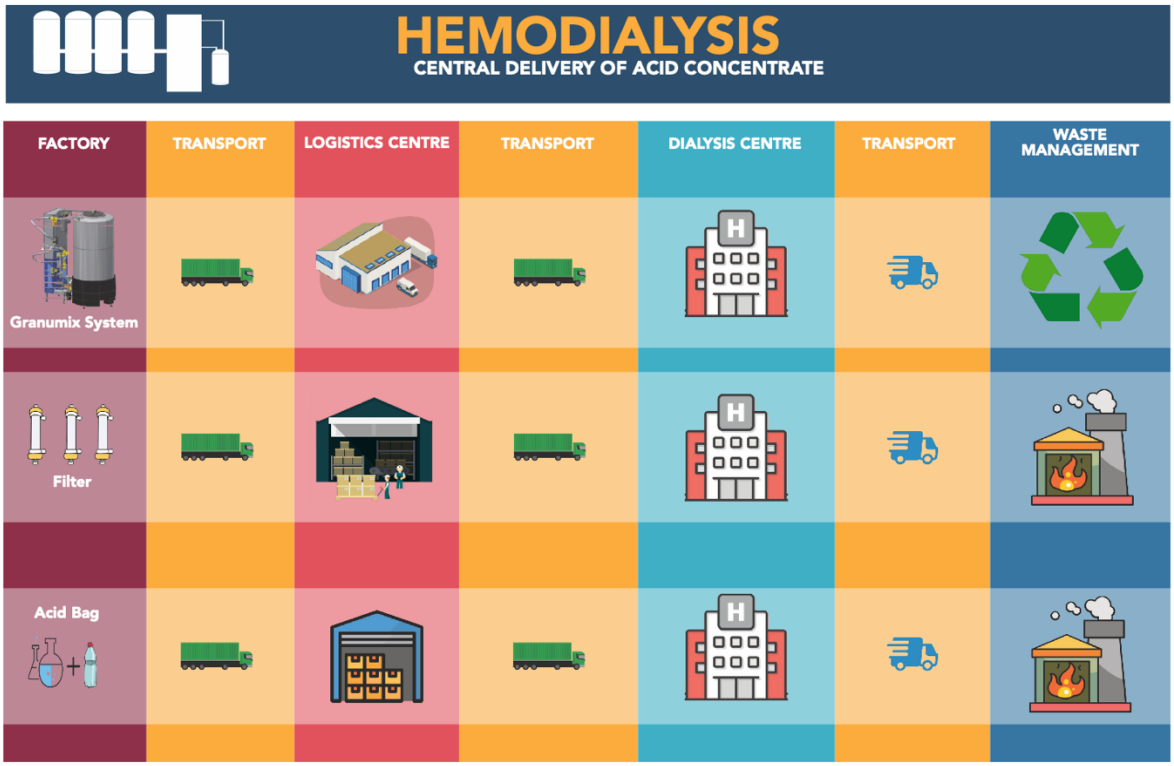

Figure 3. 10 System boundaries for Acid Concentrate Bags and the Fresenius Granumix System. The system boundary shows the "cradle to grave" analysis of the LCA (Larkin et al. 2025a)

3.3 Peritoneal dialysis pathway: Life cycle assessment results

3.3.1 Multi-category impact analysis

The annual environmental footprint of PD was quantified across multiple impact categories. Climate change impacts were estimated at approximately 2.9 tonnes CO_2-equivalent per patient per year. Total non-renewable energy demand exceeded 34,000 MJ, while water use approached 362 m^3 world-equivalent deprived (Larkin et al., 2026c).

Results are presented using normalised values, which compare the impacts associated with one year of PD treatment to the average annual environmental footprint of one individual in the reference population. Normalisation supports interpretation across impact categories by indicating the relative magnitude of burdens at a patient level (Larkin et al., 2026c).

Among the assessed impact categories (see Table 3. 1), the highest normalised burdens were in:

- Non-renewable energy use (normalised score 2.63).
- Freshwater ecotoxicity (1.59).
- Climate change (1.38).
- Photochemical oxidant formation (1.29).
- Acidification (1.05).
- Particulate matter formation (0.99).

Table 3. 1 LCA Results Across 16 Impacts (Larkin et al. 2026c)

Impact Category	**Impact Assessment Result**	**Unit**
Acidification	11.716775	mol H^+-Eq
Climate change	2230.69738	kg CO_2-Eq
Ecotoxicity (freshwater)	13564.4985	CTUe

Energy use (non-renewable)	34256.0595	MJ (net calorific value)
Eutrophication (freshwater)	0.26351371	kg P-Eq
Eutrophication (marine)	3.24341716	kg N-Eq
Eutrophication (terrestrial)	32.4510544	mol N-Eq
Human toxicity (carcinogenic)	1.30E-06	CTUh
Human toxicity (non-carcinogenic)	1.89E-05	CTUh
Ionising radiation	40.1352328	kBq U235-Eq
Land use	50457.6262	dimensionless
Material use (metals/minerals)	0.00438602	kg Sb-Eq
Ozone depletion	1.69E-04	kg CFC-11-Eq
Particulate matter	1.18E-04	disease incidence
Photochemical oxidants (human health)	10.4932758	kg NMVOC-Eq
Water use	362.027239	m^3 world eq. deprived

Across categories, the highest absolute contributions were associated with energy use, material production, transport and waste treatment processes (Table 3. 1). Key contributors to these burdens were freight transport, electricity use for equipment and APD machines, hazardous waste incineration and the production and transport of consumables (Larkin et al., 2026c).

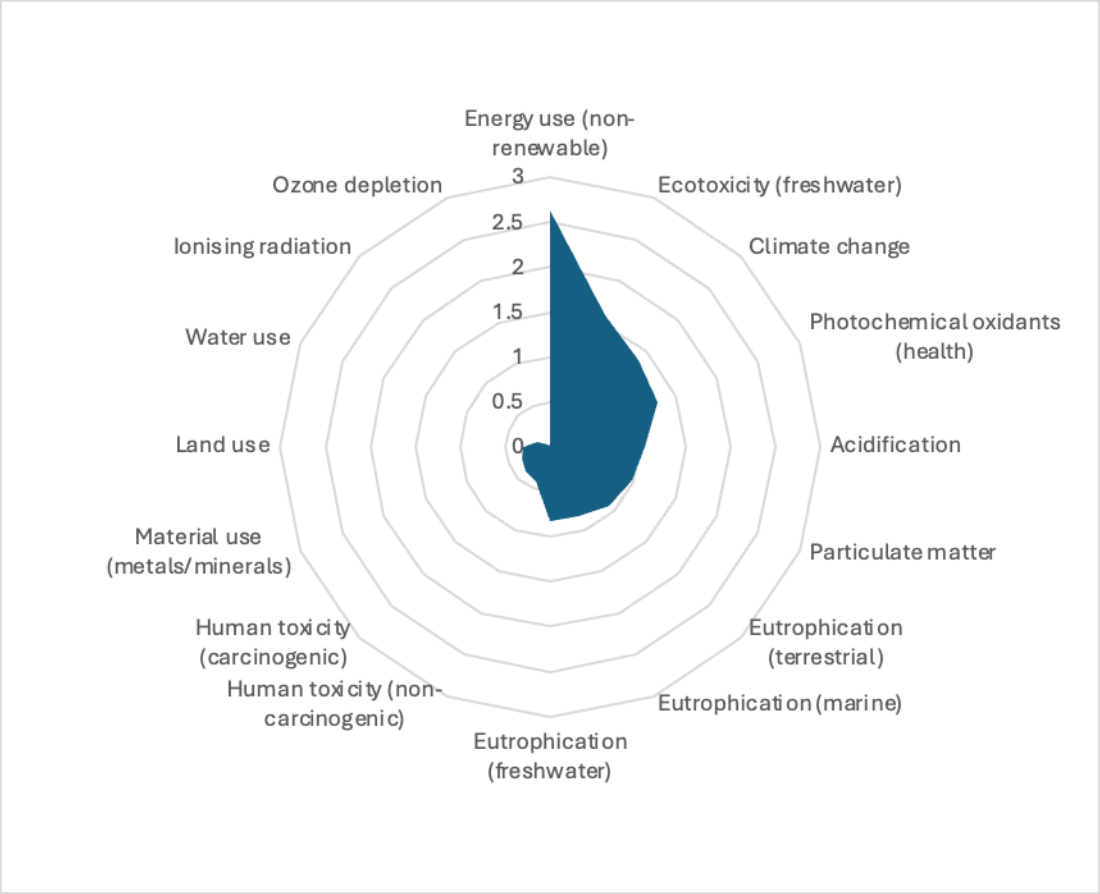

Figure 3. 11 Normalised scores across 15 impacts (Larkin et al. 2026c)

Figure 3. 12 to Figure 3. 16 present contribution analyses for APD and CAPD across the most environmentally significant impact categories, highlighting differences in the main processes between modalities.

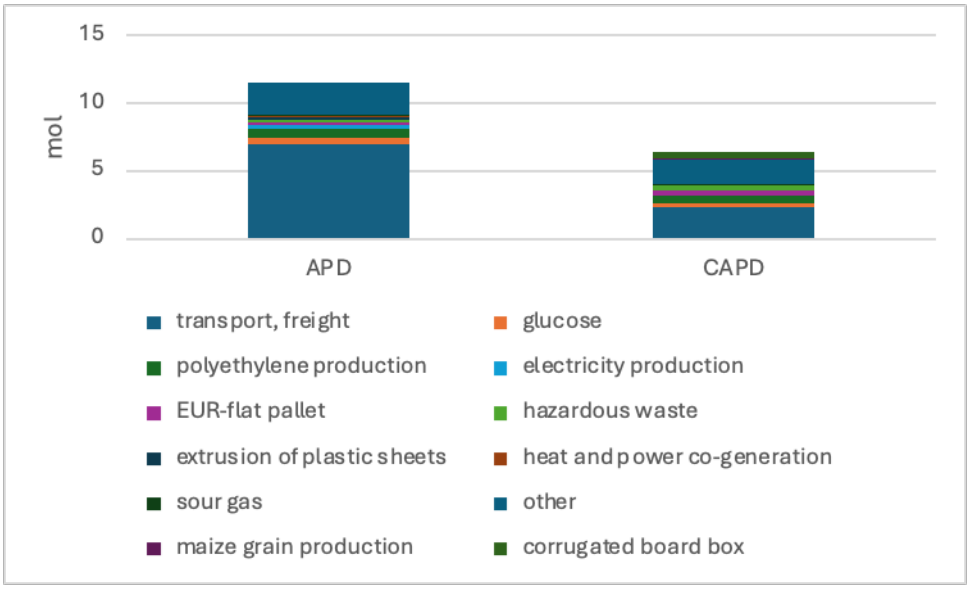

Figure 3. 12 Contribution Analysis of PD Treatment (Acidification) (Larkin et al. 2026c)

Figure 3. 12 shows that acidification impacts in PD treatment are driven mainly by freight transport and PVC production, with smaller contributions from dialysate manufacture and waste management (Larkin et al., 2026c).

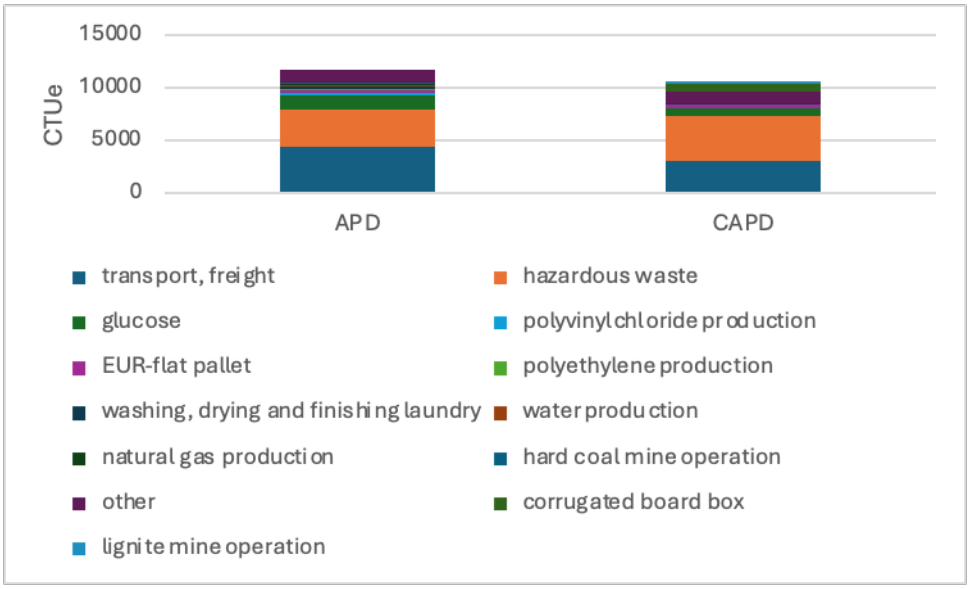

Figure 3. 13 Contribution Analysis of PD Treatment (Ecotoxicity) (Larkin et al. 2026c)

Figure 3. 13 presents freshwater ecotoxicity for PD, where emissions linked to plastic production and hazardous waste incineration are highest (Larkin et al., 2026c).

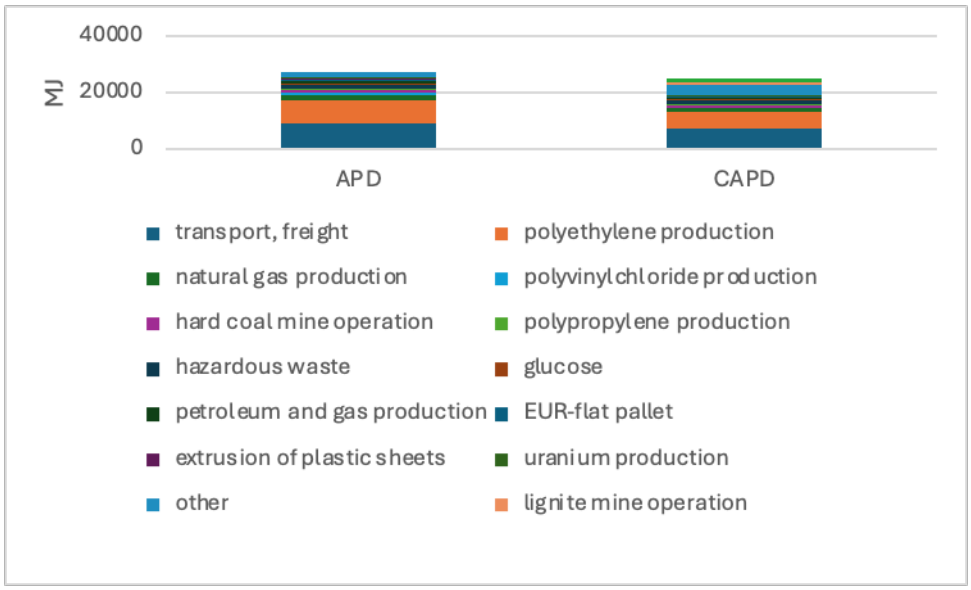

Figure 3. 14 Contribution Analysis of PD Treatment (Ecotoxicity) (Larkin et al. 2026c)

Figure 3. 14 provides a complementary view of ecotoxicity, separating contributions by process and showing that dialysate bags and associated packaging are the main sources of toxic releases (Larkin et al., 2026c).

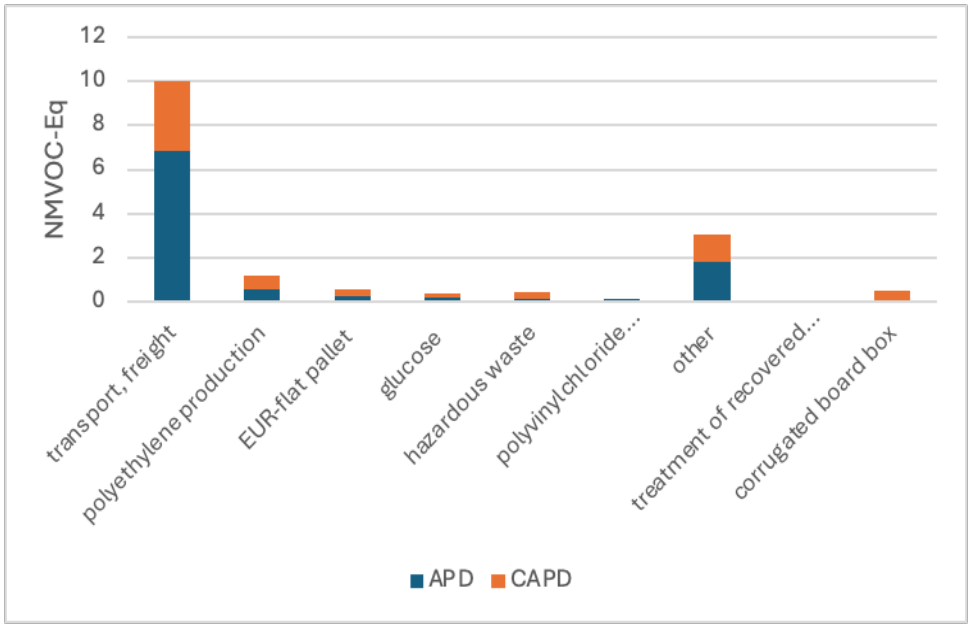

Figure 3. 15 Contribution Analysis of PD Treatment (Photochemical Oxidant Formation) (Larkin et al. 2025b)

Figure 3. 15 shows contributions to photochemical oxidant formation, where combustion from international and domestic transport is the main factor (Larkin et al., 2026c).

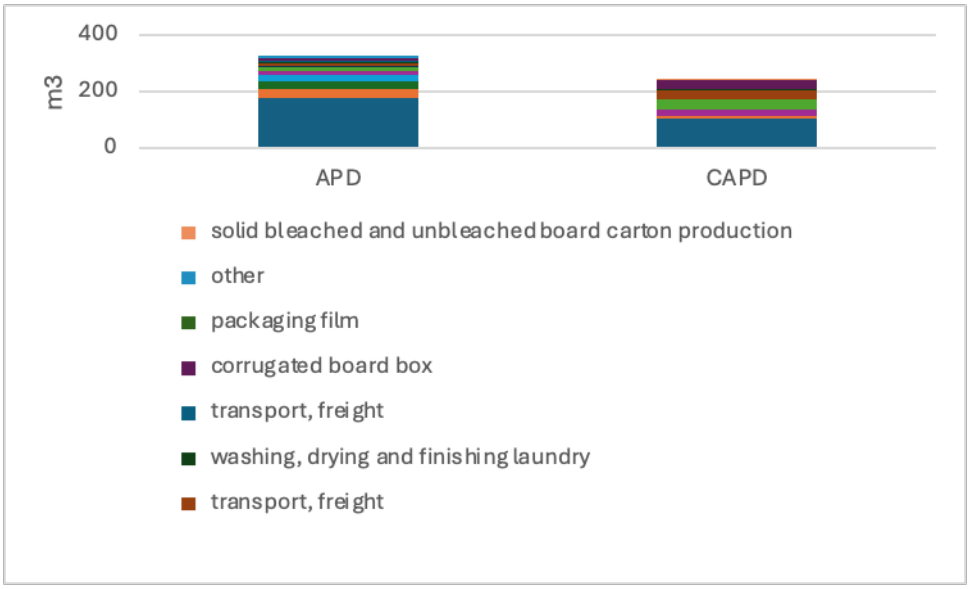

Figure 3. 16 Contribution Analysis of PD Treatment (Water Use) (Larkin et al. 2026c)

Figure 3. 16 illustrates water use across PD treatment, with product transport accounting for most of the demand (Larkin et al., 2026c).

Figure 3. 17 to Figure 3. 28 explore procedure level impacts for the five most intensive pathways across six key impact categories. The monthly examination pathways highlighted the highest impacts across all assessed categories, largely driven by travel related processes. For example:

- Climate change: Monthly visits produced 135.65 kg CO_2-eq per year.
- Acidification: Highest at 0.299 mol H^+-Eq, driven by car and freight travel.
- Freshwater ecotoxicity: Accounted by benzene and petroleum related substances at 259.39 CTUe.
- Energy resource use: Topped the list at 2532.70 MJ per year.
- Photochemical oxidants: Emissions reached 0.281 kg NMVOC-Eq, primarily from combustion related travel.
- Water use: A significant 49.05 m^3 world eq. deprived, with textile procurement as a key impact.

Procedures like PET, training and catheter changes showed much lower yet non negligible impacts. These results collectively support a view that while PD treatment contributes to

material intensity, in centre procedures, especially those requiring regular travel, introduce avoidable emissions (Larkin et al., 2025b; Larkin et al., 2026c).

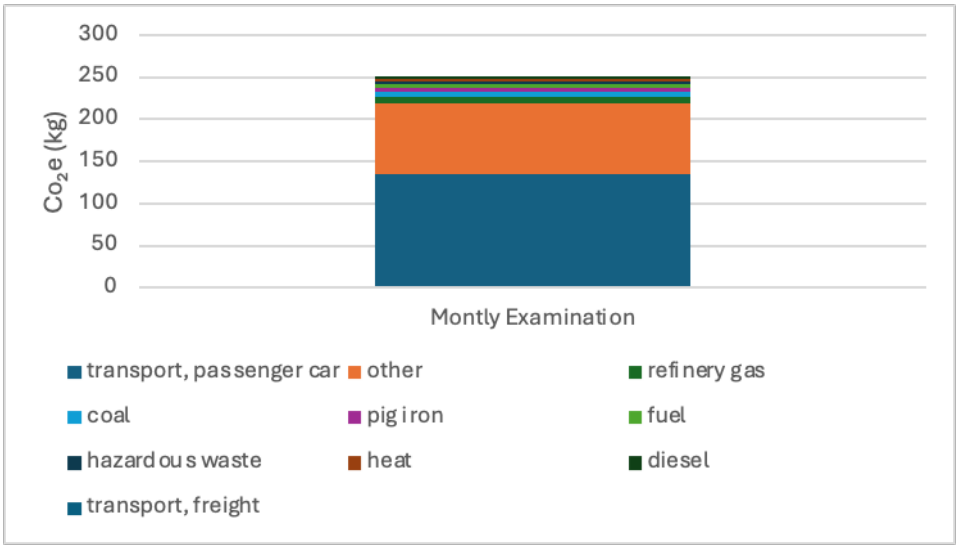

Figure 3. 17 Contribution Analysis of Monthly Examination (Climate Change) (Larkin et al. 2026c)

Figure 3. 17 focuses on climate change impacts from the monthly examination pathway, showing that patient travel and freight transport together account for most emissions (Larkin et al., 2026c).

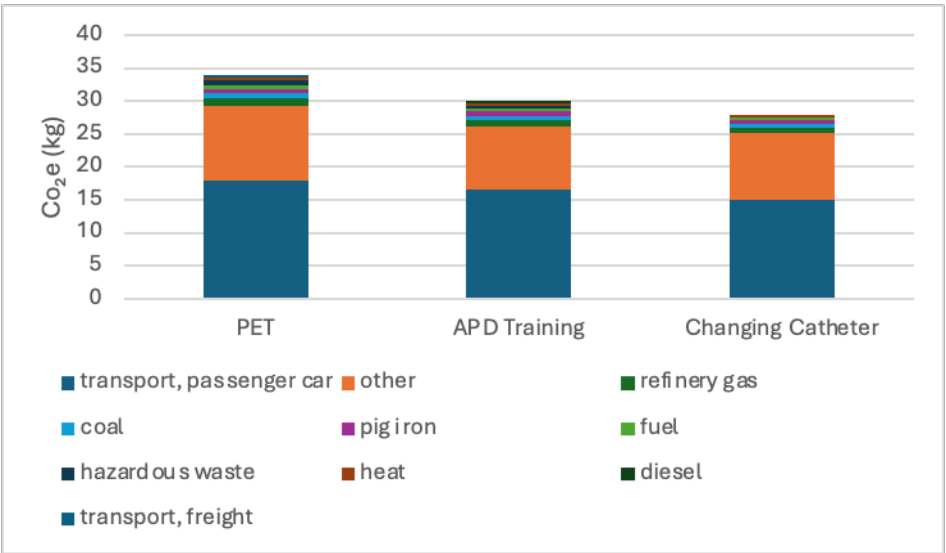

Figure 3. 18 Contribution Analysis of 3 PD Procedures (Climate Change) (Larkin et al. 2026c)

Figure 3. 18 compares climate change impacts across three PD procedures, demonstrating that monthly examinations exceeds PET and training in emissions (Larkin et al., 2026c).

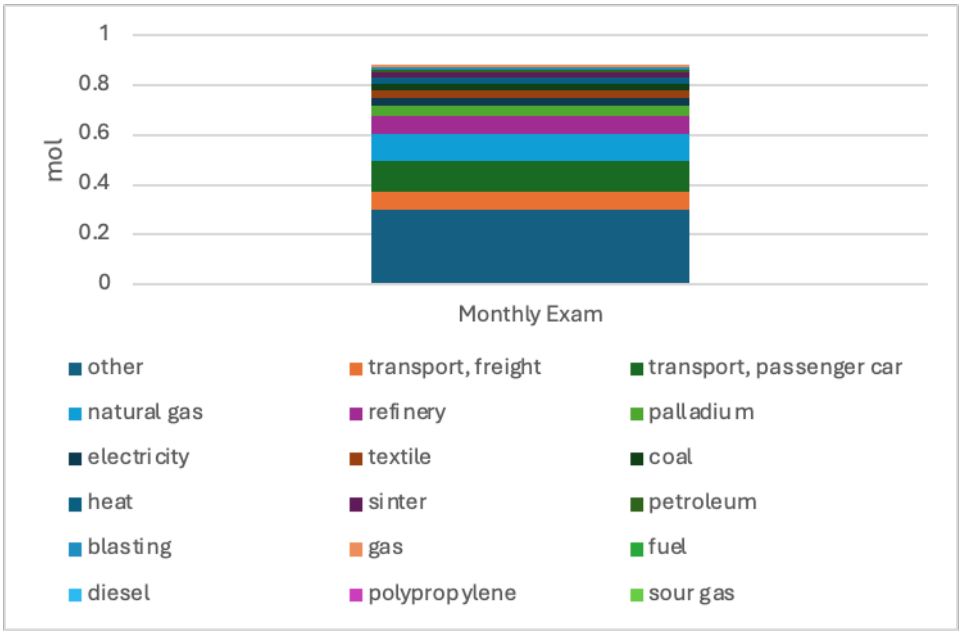

Figure 3. 19 Contribution Analysis of Monthly Examination (Acidification) (Larkin et al. 2026c)

Figure 3. 19 presents acidification impacts for monthly examinations, again with car travel and logistics as the main contributors (Larkin et al., 2026c).

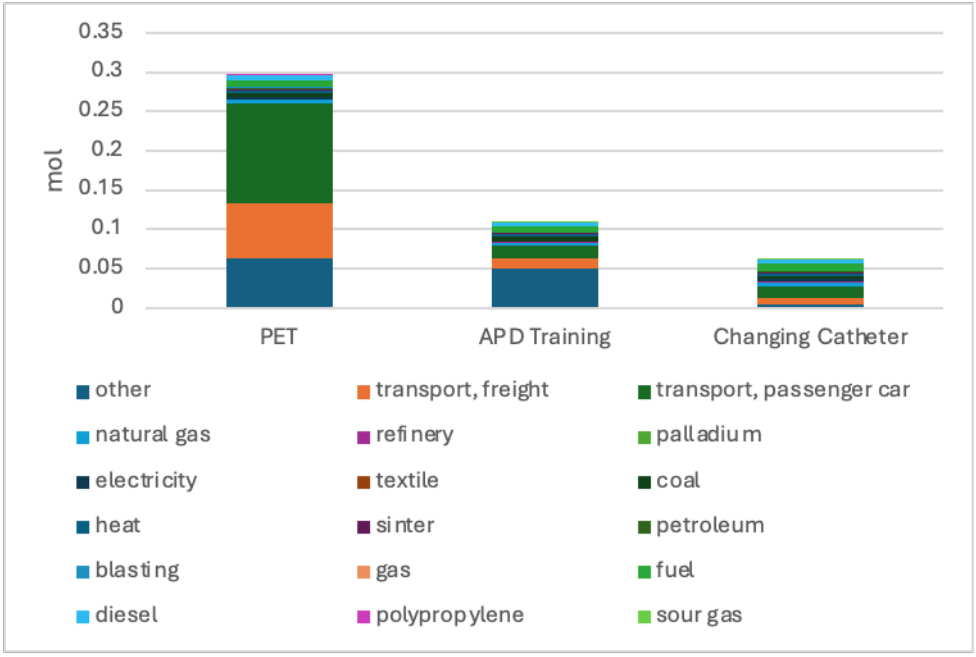

Figure 3. 20 Contribution Analysis of 3 PD Procedures (Acidification) (Larkin et al. 2026c)

Figure 3. 20 compares acidification across three PD procedures, where monthly examinations are clearly highest, followed by PET and training (Larkin et al., 2026c).

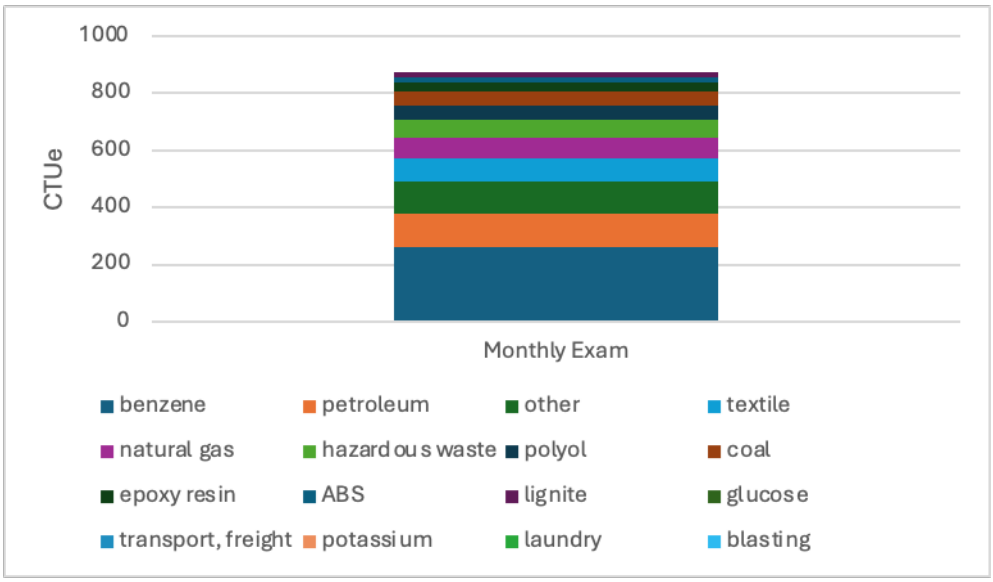

Figure 3. 21 Contribution Analysis of Monthly Examination (Ecotoxicity: Freshwater) (Larkin et al. 2025b)

Figure 3. 21 shows freshwater ecotoxicity for monthly examinations, with petroleum related substances and benzene derivatives influencing the impact (Larkin et al., 2026c).

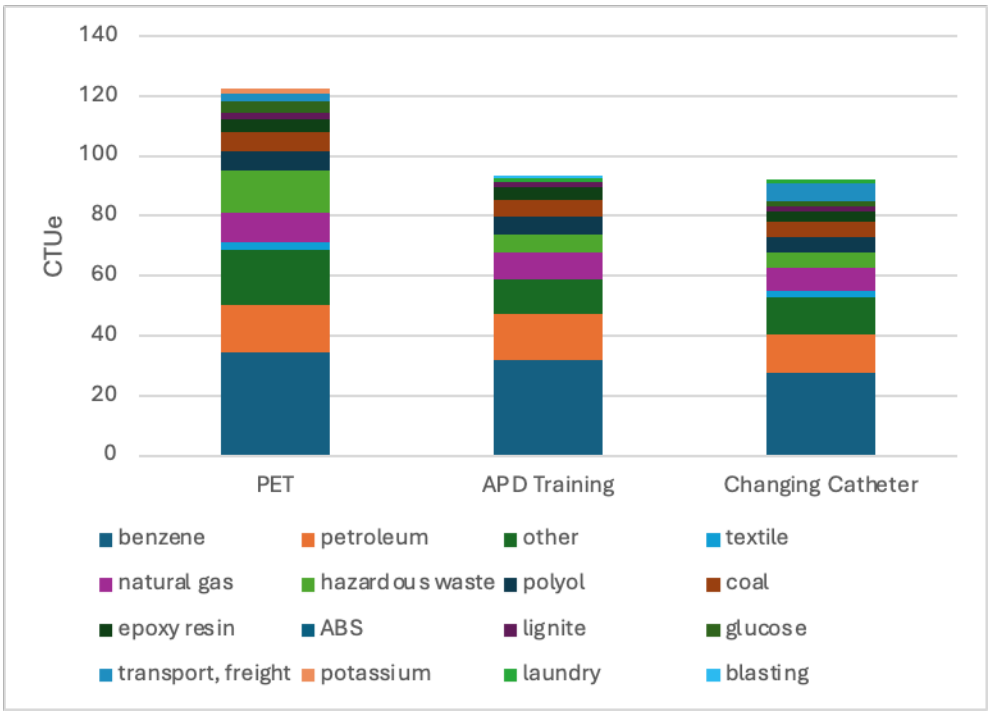

Figure 3. 22 Contribution Analysis of 3 PD Procedures (Ecotoxicity: Freshwater) (Larkin et al. 2026c)

Figure 3. 22 compares ecotoxicity across PET, training and monthly examinations, confirming that routine visits contribute the largest toxic load, while the other procedures remain lower but not negligible (Larkin et al., 2026c).

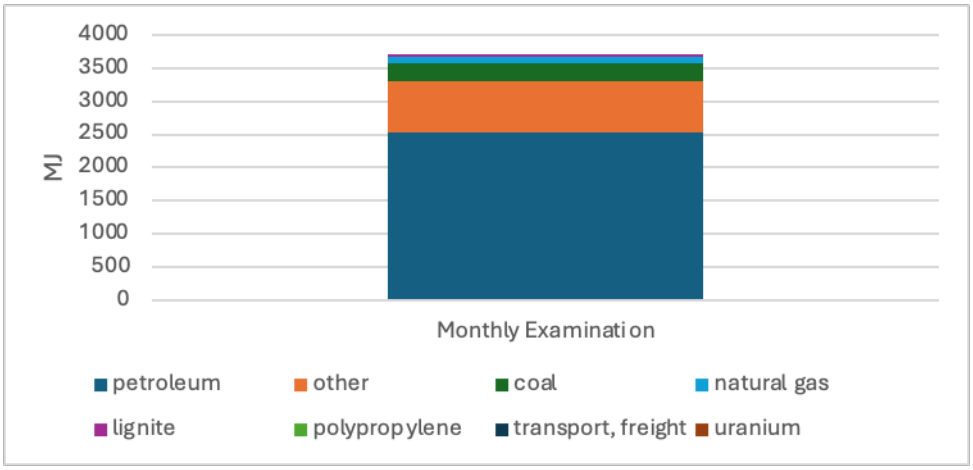

Figure 3. 23 Contribution Analysis of Monthly Examination (Energy Resources) (Larkin et al. 2026c)

Figure 3. 23 presents energy resource use for monthly examinations, with fossil fuels from car and freight travel as the leading contributor (Larkin et al., 2026c).

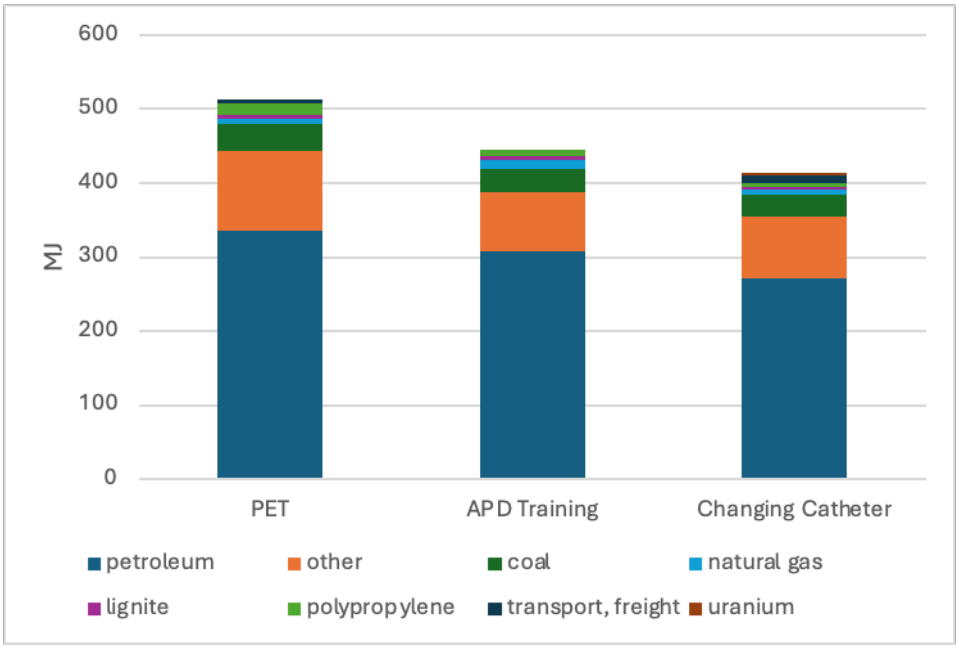

Figure 3. 24 Contribution Analysis of 3 PD Procedures (Energy Resources) (Larkin et al. 2026c)

Figure 3. 24 compares energy resource use across three PD procedures, again showing monthly examinations at the top of the distribution (Larkin et al., 2026c).

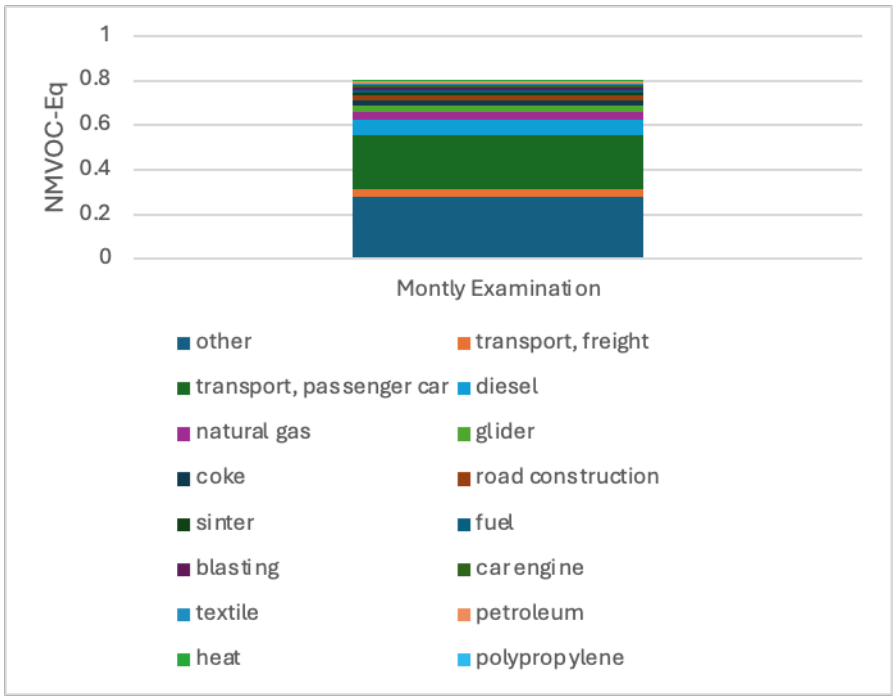

Figure 3. 25 Contribution Analysis of Monthly Examination (Photochemical Oxidant Formation) (Larkin et al. 2026c)

Figure 3. 25 displays photochemical oxidant formation for monthly examinations, where vehicle exhaust and fuel production are highest (Larkin et al., 2026c).

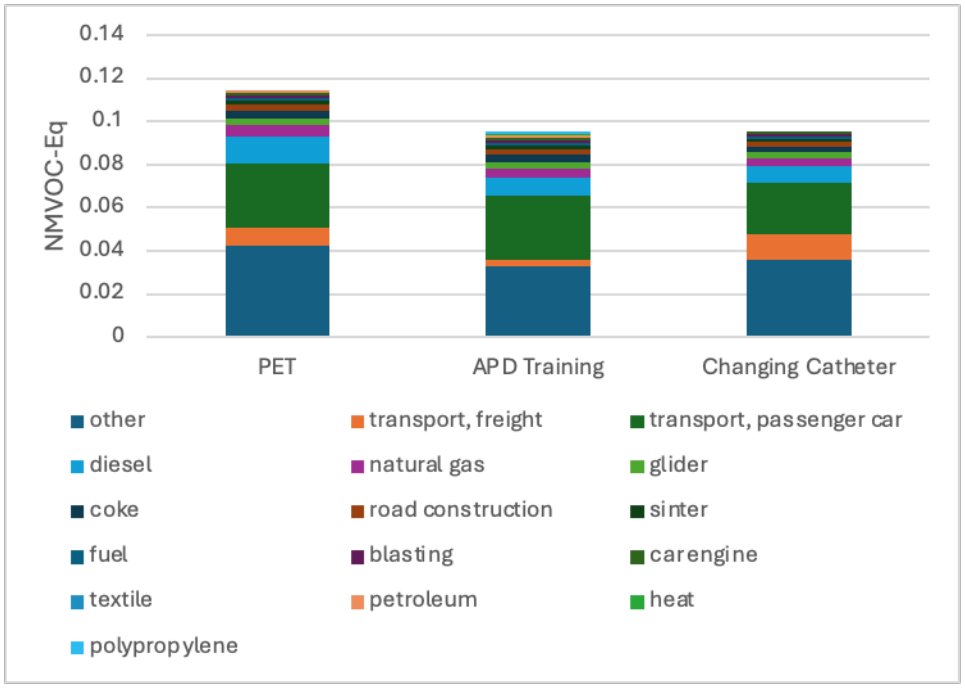

Figure 3. 26 Contribution Analysis of 3 PD Procedures (Photochemical Oxidant Formation) (Larkin et al. 2026c)

Figure 3. 26 compares photochemical oxidant formation across PET, training and monthly examinations, with monthly examinations again producing the highest emissions (Larkin et al., 2026c).

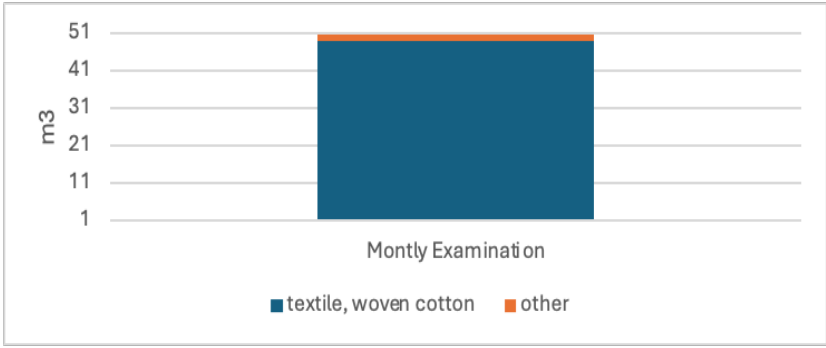

Figure 3. 27 Contribution Analysis of Monthly Examination (Water Use) (Larkin et al. 2026c)

Figure 3. 27 shows water use for the monthly examination pathway, highlighting textile procurement and fuel production as the key contributors (Larkin et al., 2026c).

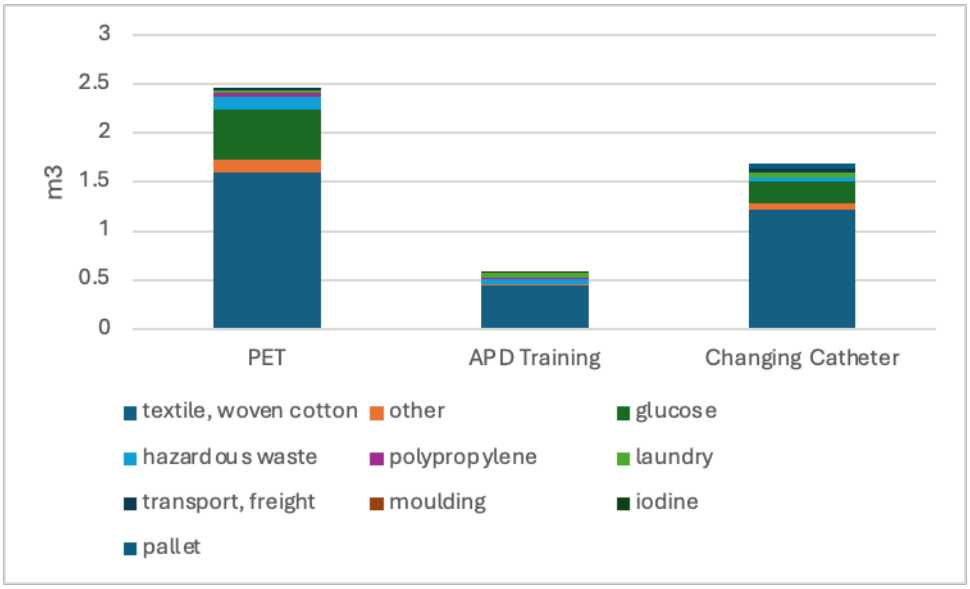

Figure 3. 28 Contribution Analysis of 3 PD Procedures (Water Use) (Larkin et al. 2026c)

Figure 3. 28 compares water use for three PD procedures, with monthly examinations again highest, followed by PET and training (Larkin et al., 2026c).

3.3.2 Pathway level environmental impacts

PD treatment accounted for the largest share of the patient journey carbon footprint at 83% (1,810 kg CO_2-eq per patient-year), followed by monthly centre visits (11%, 250 kg CO_2-eq)

and training activities (APD: 28 kg, CAPD: 19 kg). Support procedures such as RRT education (17 kg CO_2-eq) and catheter placement (7 kg CO_2-eq) showed comparatively minor but essential contributions (Larkin et al., 2026c). Table 3. 2 quantifies all 17 chronological pathways within PD.

Table 3. 2 Carbon Footprint patient pathways CO_2 emissions (Larkin et al. 2026c)

Pathway	**Description**	**Total result [kg CO_2 - Eq]**
1. Education For Renal Replacement Therapy	This pathway begins with education provided by a dedicated nurse to patients with end stage kidney disease about their available treatment options: PD, HD, kidney transplantation and conservative care. Patients who decline kidney replacement therapy may opt for conservative care. After receiving this information, patients typically take one to two weeks to decide on their preferred treatment. This pathway also records the percentage of patients who ultimately choose PD, HD, conservative care, or transplantation. For those who select PD, an eligibility assessment is carried out by a nephrologist and the percentage of patients deemed suitable for PD is documented.	17
2. Surgical Evaluation for PD Suitability	Patients considered suitable for PD by the nephrologist are referred to the surgeon for the feasibility of peritoneal catheter placement.	7
3. Patient Home Suitability	Patients considered suitable for PD by the nephrologist and the surgeon receive a home visit by PD nurses to verify that the home environment is also suitable for the carrying out of PD.	11

4. Pre Surgery Evaluation	Once all the patient's requirements have been verified, glomerular filtration rate (GFR) is close to dialysis start, it is necessary to conduct preoperative examinations during which the surgeon, anaesthesiologist and nurse perform several tests.	4
5. Peritoneal Catheter Placement Local Aesthetic	The surgical procedure of catheter insertion is performed in two ways: using local anaesthesia (pathway 5) or by laparoscopic surgery (pathway 6). In pathway 5, the procedure using local anaesthesia is described. The day after surgery, the patient, still admitted in the surgical ward, came to the PD office to check the function of the catheter as occur in pathway 8.	7
6. Surgical Placement of PD Catheter Laparoscopy	The surgical procedure of catheter insertion by laparoscopic surgery is described.	0.6
7. Post Catheter Surgical Evaluation	This pathway is carried out for patients after surgery. The surgeon conducts fast check of the surgical wound.	4
8. PD Pre Training Visit	The nurse performs a low volume abdominal dwelling, to check the function of the catheter. It is always performed by a 2L bag regardless of APD or CAPD.	9
9. CAPD Training	If the peritoneal catheter works well, 15 days after insertion, the patient trained to perform either CAPD (pathway 9) or APD (pathway 10). If not, training continues.	19
10. APD Training	If the peritoneal catheter works well, 15 days after insertion, the patient trained to perform either CAPD (pathway 9) or APD (pathway 10). If not, training continues.	28

11. PD Treatment	The actual PD Treatment	1810
12. Monthly Examination	Every month the patient comes back to the centre for blood tests, clinical evaluation by the nephrologist and nursing assessment.	250
13. PET	Once a year the patient has a PET to check the function of the peritoneal membrane.	34
14. Change Terminal Catheter Set	Every 6 (if performing APD) or 12 months (if performing CAPD) the terminal set of the catheter is changed.	30
15. Malfunctioning Catheter	Outlines the step by step approach taken when a PD catheter is not functioning properly. A series of troubleshooting procedures are followed in a specific order and if catheter function is restored at any stage, subsequent steps are not performed.	0.4
16. Peritonitis Procedure	If peritonitis is suspected, the patient comes to the centre and first has an examination with the nephrologist and blood tests with the nurse. Then the procedure may be different if the patient arrives at the hospital with an empty abdomen (it is necessary to fill it) or with a full abdomen (there are options in both cases for both Baxter and Fresenius). Another variable is the presence of turbidity in the peritoneal fluid which makes it necessary to perform cultures and start intraperitoneal antibiotic therapy.	0.6
17. Catheter Removal	Procedure for catheter removal.	0.4

*Table shows order of care by patient pathway, top 5 pathways are highlighted in red.

While several early-stage and support procedures contribute relatively small emissions individually, their inclusion provides a complete representation of the patient journey. Notably, incremental PD (iPD) approaches, where patients begin with reduced dialysis frequency, demonstrated significantly lower carbon footprints. Incremental APD resulted in 1642 kg CO_2-eq and incremental CAPD just 1517 kg CO_2-eq, almost halving the emissions compared to full dose APD or CAPD (Table 3. 3) (Larkin et al., 2026c).

Table 3. 3 APD vs CAPD vs Incremental Approach (1Year) (Larkin et al. 2026c)

Process	**kg CO_2 eq**
APD	3267
CAPD	2975
Incremental APD	1642
Incremental CAPD	1517

3.3.3 Clinical process & waste hotspots

In Pathway 11, more than 70% of the total carbon footprint came from procurement and material manufacturing processes, including plastic components, medical textiles and device related manufacturing (Table 3. 4). The main contributing processes were:

- Plastic production accounted for 740 kg CO_2-eq.
- Procurement related transport contributed 553 kg CO_2-eq.
- Electricity use for running APD machines added 90 kg CO_2-eq.
- Waste generation (mostly healthcare waste) accounted for 279 kg CO_2-eq.

Table 3. 4 Pathway 11: PD treatment by process (including 30% APD, 4% CAPD, 30% incremental APD and 36% incremental CAPD) (Larkin et al. 2026c)

Process	**Kg CO_2 eq**

Staff Travel	No staff travel required for this treatment at home
Patient Travel	No patient travel required for this treatment at home
Energy (Building Energy)	Not taken into account for this treatment at home
Waste	279
Procurement Transport	553
Plastic (material used in products)	740
Other Materials (textiles, metals, cardboard)	44
Electricity (running of machine)	90
Manufacturing Methods (Products)	103

Building energy use was excluded for home based treatment. Staff and patient travel were also negligible for PD sessions carried out at home, This reflects the absence of direct building energy and travel related emissions for home based treatment.

In contrast, monthly examinations (Pathway 12), which require in centre visits, were highly impacted by patient travel emissions (208 kg CO_2-eq), followed by staff travel (28 kg CO_2-eq) and minimal emissions from procurement, electricity and waste (Table 3. 5). Transport related emissions were the main impact in this (Larkin et al., 2026c).

Table 3. 5 Pathway 12: Monthly examination (Larkin et al. 2026c)

Process	**Kg CO_2 eq**
Staff Travel	28
Patient Travel	208
Energy (Building Energy)	0.128
Waste	4
Procurement Transport	0.2
Plastic (material used in products)	3

Other Materials (textiles, rubber, cardboard)	4
Electricity (blood exam and vital signs)	2
Manufacturing Methods (Products)	2

Material consumption and waste profiles differed between modalities. CAPD produced more plastic waste in terms of PET use (310g vs 275g in APD), while APD involved higher use of PVC (44g vs 1g in CAPD) and PP (43g vs 30g), as shown in Figure 3. 29 (Larkin et al., 2026c).

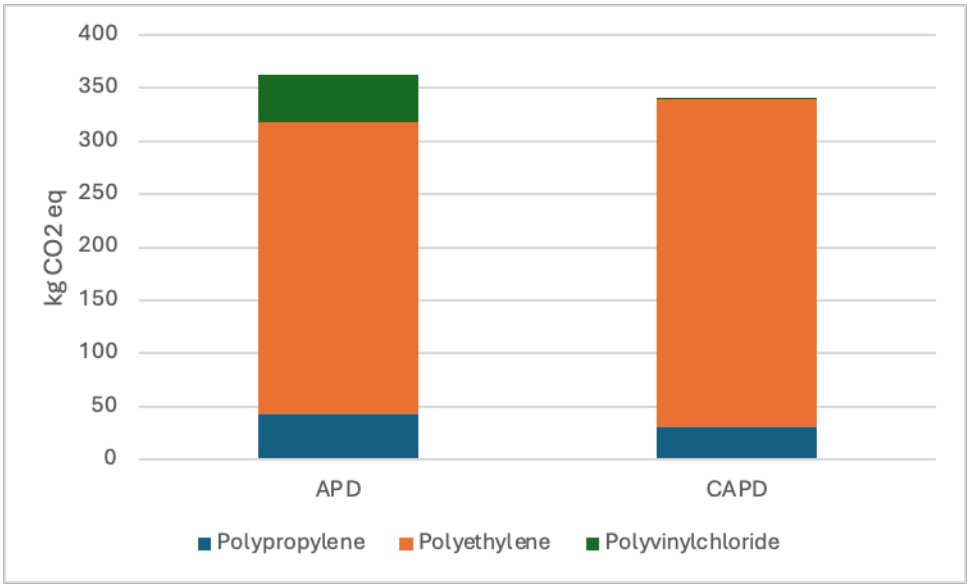

Figure 3. 29 Plastic Material in APD and CAPD (Larkin et al. 2026c)

Waste related impacts were higher in CAPD, which generated 320 kg of healthcare waste resulting in 810 kg CO_2-eq, compared to 145 kg and 374 kg CO_2-eq for APD (Table 3. 6 and Table 3. 7). CAPD also generated more cardboard and paper waste, largely due to the more frequent manual exchanges and associated packaging.

Table 3. 6 Waste (APD) (Larkin et al. 2026c)

Process	**kg**	**kg CO_2**
Cardboard Waste	448	4.82E-04
Healthcare Waste	145	3.74E+02

Paper Waste	16	1.80E-05
Plastic Waste	7	7.36E-06

Table 3. 7 Waste (CAPD) (Larkin et al. 2026c)

Process	**kg**	**kg CO_2**
Cardboard Waste	538	4.82E-04
Healthcare Waste	320	8.10E+02
Paper Waste	45	1.80E-05
Plastic Waste	15	1.61E-06

3.3.4 Procurement level analysis

While section 3.3.3 examined clinical processes and waste flows, this section examines procurement related contributions to environmental impacts across PD pathways. Three product groups accounted for the largest share of the environmental footprint. The 5 L dialysate bags, 2 L dialysate bags and the automated drainage and PD sets. Together these accounted for more than three quarters of the annual emissions for one patient on APD. Figure 3. 30 shows the total annual carbon footprint by product group, clearly demonstrating the impact of the 5 L dialysate bag, which contributed 1,515 kg CO_2-eq annually. The 2 L dialysate bag followed at 457 kg CO_2-eq, the automated drainage system at 286 kg CO_2-eq and the APD set at 186 kg CO_2-eq. Smaller items such as hand gel, disinfectant sprays and medical kits each contributed less than 30 kg CO_2-eq individually but added cumulatively to the total (Larkin et al., 2025b).

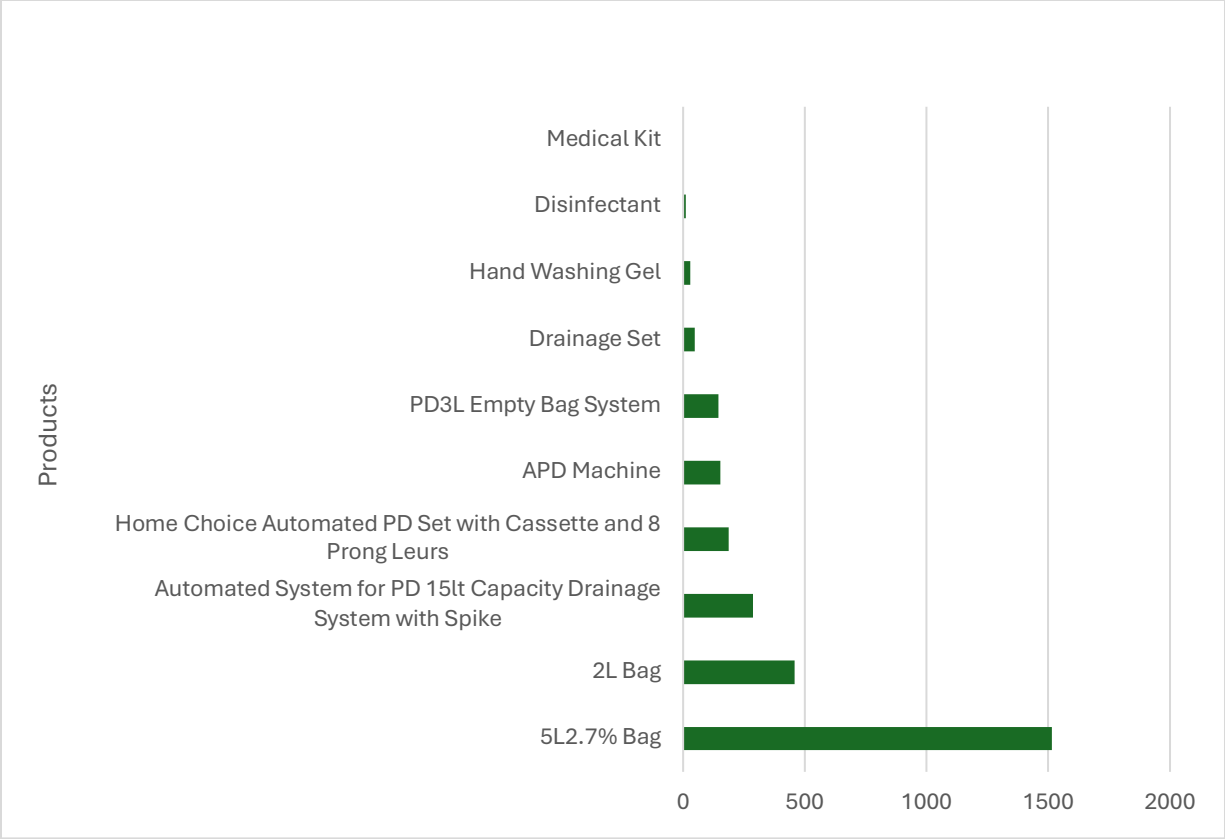

Figure 3. 30 CO_2-eq Impact (Larkin et al. 2025b)

Although the 5 L bag was the single largest source of emissions in absolute terms, it was more efficient per litre of dialysate delivered. Its impact was 0.415 kg CO_2-eq/L compared to 0.626 kg CO_2-eq/L for the 2 L bag. This reflects the additional packaging and distribution burdens associated with smaller bags. McAlister et al., (2024) reported similar findings in Australia, showing that larger bag formats reduced per litre emissions, largely due to reduced packaging mass and improved transport efficiency (McAlister et al., 2024b). Larger bag formats demonstrated lower emissions per litre of dialysate delivered, reflecting differences in packaging mass and transport efficiency (Larkin et al., 2025b).

Figure 3. 31 also presents a contribution analysis of emissions by product and lifecycle stage. For the 5 L bag, international freight was the single largest contributor, responsible for 764 kg CO_2-eq annually. Secondary packaging, primarily corrugated cardboard, contributed more than 300 kg CO_2-eq per patient year and plastics (PET and PVC) added 135 kg CO_2-eq. Similar profiles were observed for the 2 L bag, with higher proportional packaging impacts per litre.

These results indicate that logistics and packaging contribute substantially to total procurement related emissions (Larkin et al., 2025b).

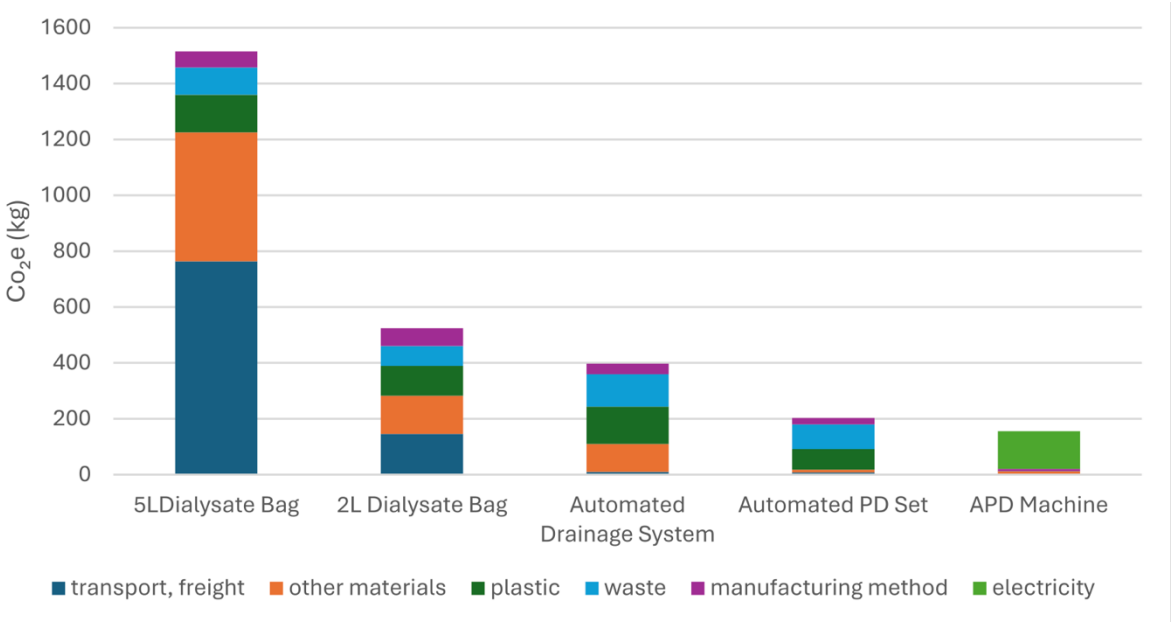

Figure 3. 31 Contribution Analysis (Carbon Emissions) (Larkin et al. 2025b)

Figure 3. 31 separates the 5 L bag's impacts by lifecycle stage, showing that transport and packaging together accounted for more than half of total emissions, followed by plastics, manufacturing energy and waste incineration. This pattern is consistent with previous healthcare LCAs reporting large procurement and supply chain contributions to total emissions (Al-Hadithy et al., 2024; Larkin et al., 2025b).

The automated drainage system (286 kg CO_2-eq) and APD set (186 kg CO_2-eq) were also significant contributors, largely due to their high PVC content. Incineration of PVC releases dioxins and furans, contributing to both human toxicity and freshwater ecotoxicity categories (Frischknecht, 2000; Lithner et al., 2011). Their multi material complexity further complicates recycling (Larkin et al., 2025b).

The APD machine, annualised over a five year service life, contributed 152 kg CO_2-eq annually, with electricity use during operation (134.5 kg CO_2-eq) as the main impact. Electricity use during operation represented the main contributor within this product category.

Figure 3. 32 demonstrates some of the smaller consumables such as hand gel (29.9 kg CO_2-eq), disinfectant sprays (11.5 kg) and medical kits (3.3 kg) which were minor in isolation, but their cumulative impact was non negligible, especially given their frequency of use and packaging inefficiencies (Larkin et al., 2025b).

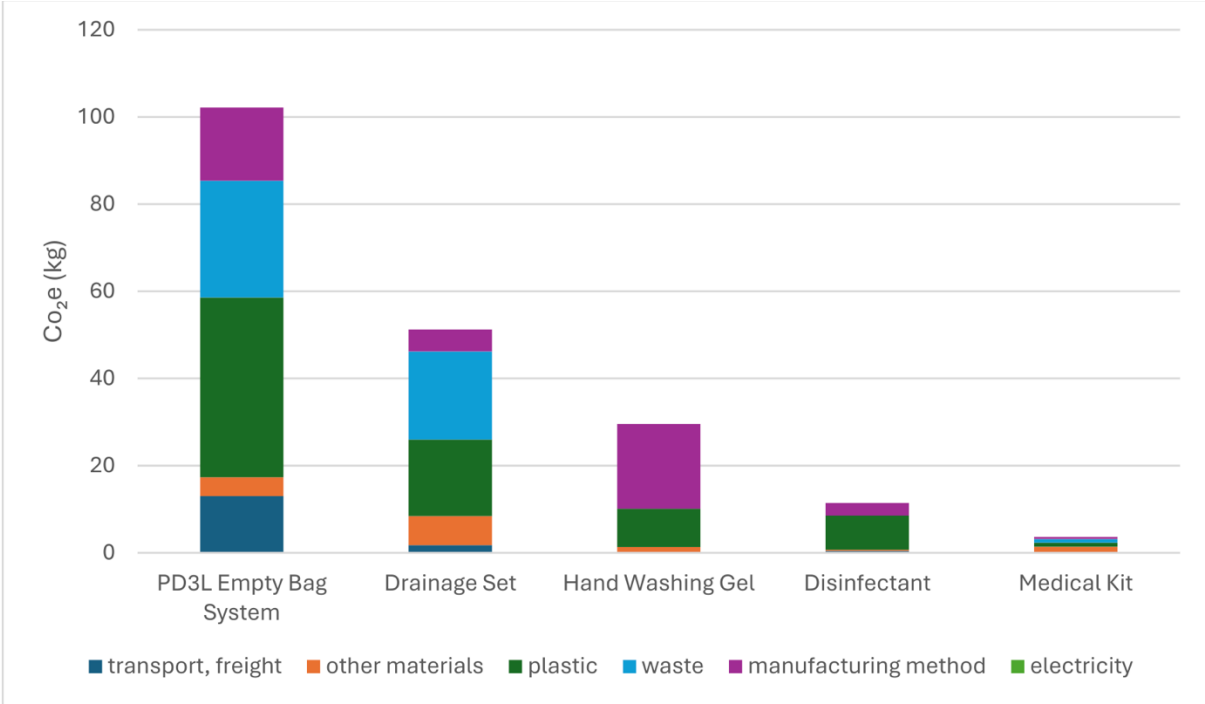

Figure 3. 32 Contribution Analysis (Carbon Emissions) (Larkin et al. 2025b)

Table 3. 8 summarises the procurement related environmental impacts by product category across four key indicators.

Table 3. 8 Procurement related environmental impacts by product category across four key indicators (Larkin et al. 2025b)

Product group	**Carbon (kg CO_2-eq/year)**	**Energy (MJ/year)**	**Water (m^3/year)**	**Key toxicity issues**
5 L Dialysate bag	1,515	10,648	239	PET, PVC incineration

2 L Dialysate bag	457	2,119	48	PET, PVC incineration
Automated drainage system	286	2,050	26	PVC tubing, connectors
APD set	186	2,000	22	PVC, multi material incineration
APD machine	152	1,800	19	Electricity (grid mix)
Hand gel	30	450	5	Packaging inefficiencies
Disinfectant spray	12	120	3	Packaging inefficiencies
Medical kit	3	75	2	Mixed consumables

Across complete PD pathways, dialysate production, transport and disposal drive the majority of climate, energy and water impacts, with APD regimens generally more resource intensive than CAPD because of higher fluid volumes and equipment needs (Larkin et al., 2025b; Larkin et al., 2026a). Patient travel and clinic visits contribute relatively little compared with dialysate and consumables, indicating that procurement and product design changes offer greater mitigation potential than scheduling or minor logistical adjustments. iPD strategies can lower environmental burdens per patient year, but only when optimised fluid prescriptions are combined with more efficient product and waste management systems.

Assessing procurement related emissions through carbon footprint analysis alone is insufficient to capture the broader environmental consequences of PD. Dialysis products are resource intensive, involving plastics, complex packaging and international logistics chains, all of which have impacts across multiple categories including energy demand, water consumption and toxicity. By expanding the analysis beyond GHG emissions, a more inclusive picture emerges of the environmental burden imposed by procurement in APD (Larkin et al., 2025b).

Energy use is one of the clearest indicators of resource intensity in PD consumables. Figure 3. 33 presents the annual primary energy demand for major products used by one APD patient.

The 5 L dialysate bag consumed 10,648 MJ annually, more than four times higher than the 2 L bag (2,119 MJ) and considerably higher than the automated drainage system (2,872 MJ) or the APD set (2,278 MJ) (Larkin et al., 2025b).

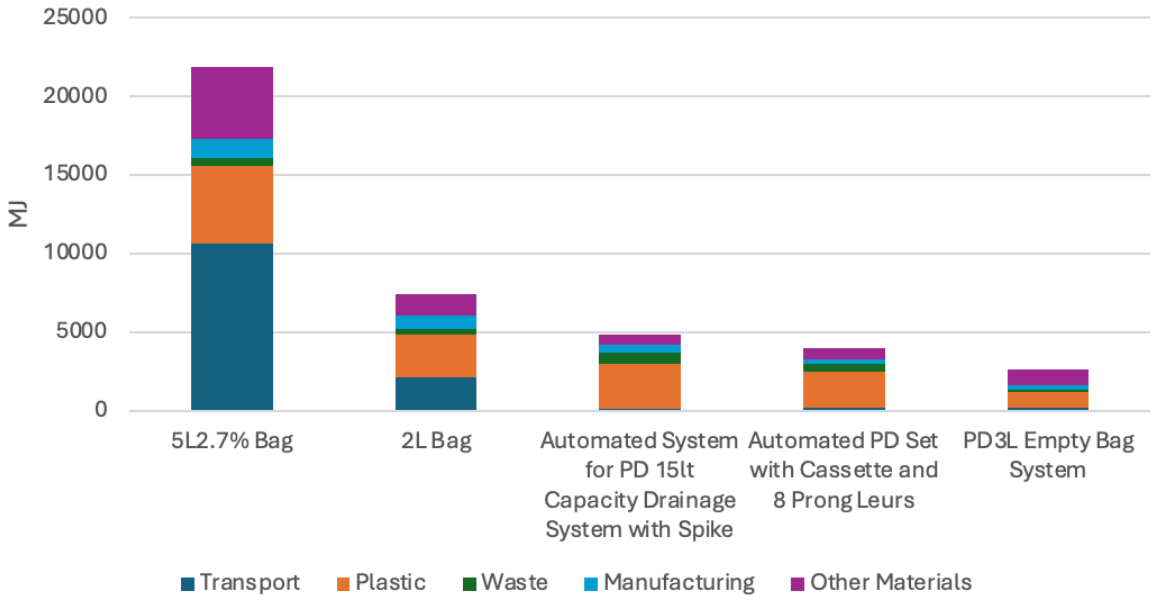

Figure 3. 33 Contribution Analysis (MJ) (Larkin et al. 2025b)

Separating the 5 L bag's energy use reveals that transport accounted for nearly half of its footprint (4,958 MJ), with secondary packaging materials, particularly corrugated cardboard, contributing 4,621 MJ. Plastics and manufacturing energy added 463 MJ and 1,202 MJ, respectively. These results are consistent with life cycle studies showing that logistics and packaging are major impacts of energy use in healthcare procurement (Larkin et al., 2025b).

In contrast, the 2 L bag demonstrated a different profile. Plastics accounted for the largest share of its energy demand, contributing 2,737 MJ, compared to 2,119 MJ from transport. This confirms the inefficiencies associated with smaller bag formats, which require relatively more polymer per litre of dialysate delivered, as well as more packaging per unit volume. The environmental penalty of small volume bags is therefore evident not only in carbon intensity per litre but also in energy demand (Larkin et al., 2025b).

The automated drainage system and APD set each required more than 2,000 MJ of energy per patient annually. Plastics were again the main contributor (2,872 MJ for the drainage system, 2,278 MJ for the APD set), while transport, manufacturing and secondary packaging made smaller but non trivial contributions. The APD machine itself had an annualised energy demand of 2,608 MJ, with the majority attributable to the production of "other materials" (2,196 MJ) such as metals, composites and electronics. Electricity use during operation also contributed significantly, 412 MJ electricity use represented the main contributor within this product category (Larkin et al., 2025b).

Smaller consumables as seen in Figure 3. 34, while less significant in absolute terms, still carried energy burdens relative to their size. For instance, hand washing gel required nearly 500 MJ annually to produce, largely due to the production of the plastic container and waste processing, while disinfectant sprays required 339 MJ for similar manufacturing. Even the small medical kit contributed 65 MJ, primarily from the production of other materials such as sterile packaging (Larkin et al., 2025b).

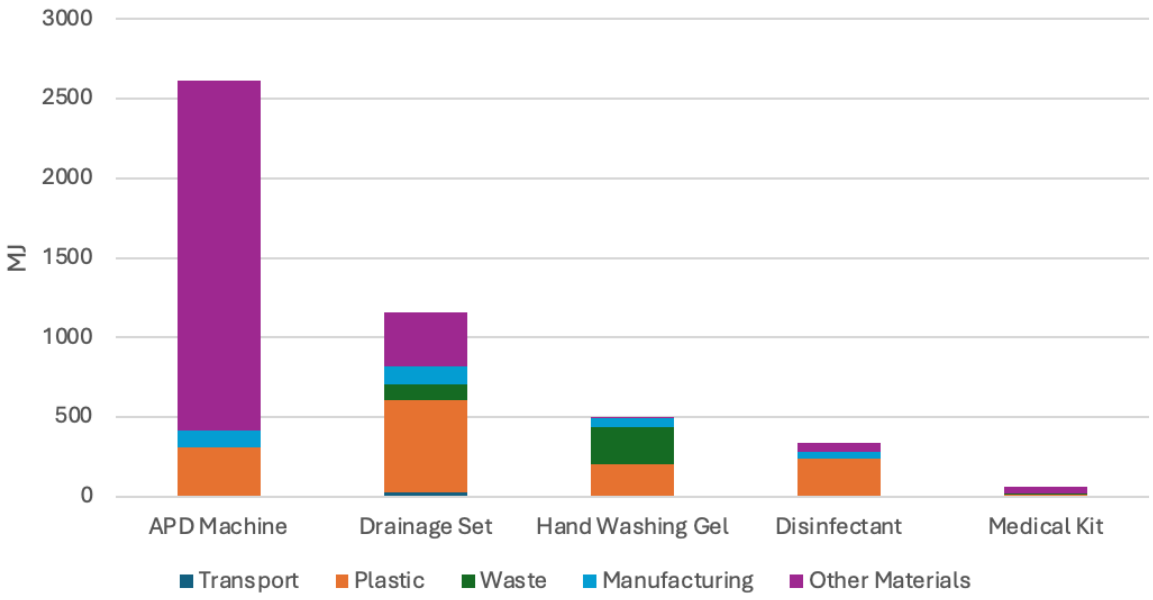

Figure 3. 34 Contribution Analysis (MJ) (Larkin et al. 2025b)

These results show that while the dialysate bags contributed significantly to overall energy demand, secondary products also impose considerable energy costs. In line with studies of

dialysis procurement in Australia and China, this analysis confirms that both high volume consumables and multi material devices are energy intensive (McAlister et al., 2024b; Chen et al., 2017). Targeting reductions in transport, packaging and material use could therefore yield significant improvements in energy efficiency across the system (Larkin et al., 2025b).

Water consumption in raw material extraction, polymer production and product manufacture is another critical indicator, particularly given global concerns about water scarcity and the reliance of polymer production on water intensive processes. Figure 3. 35 presents the water use results for major PD products (Larkin et al., 2025b).

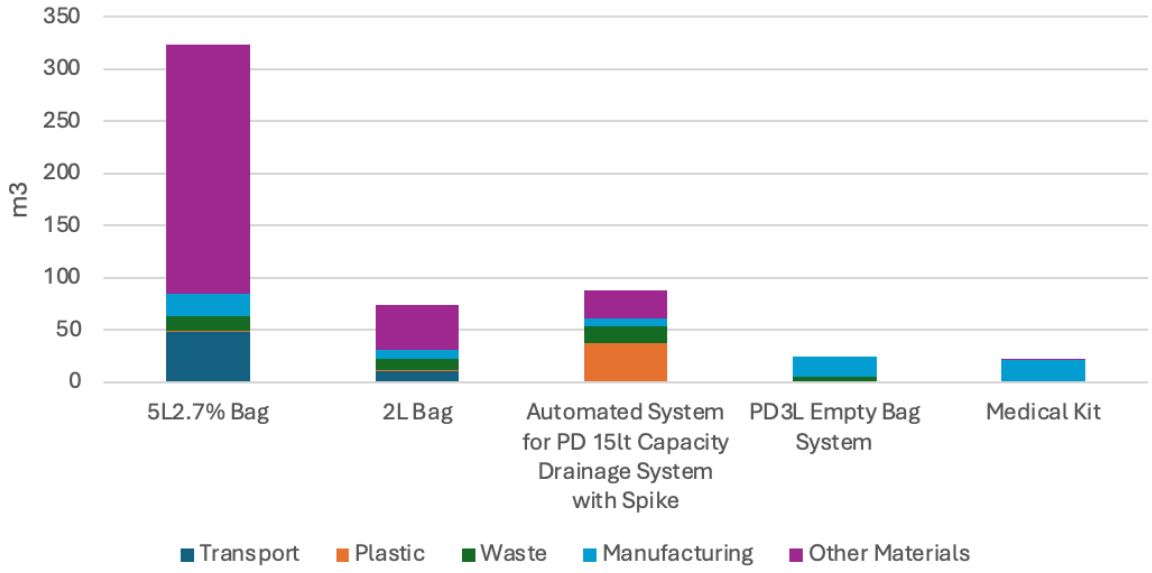

Figure 3. 35 Contribution Analysis (m3) (Larkin et al. 2025b)

The 5 L dialysate bag accounted for the largest share of the water footprint, requiring 323 m³ annually per patient. Most of this burden was linked to other materials (239 m³), specifically packaging, while transport added 48 m³ and manufacturing 21 m³. This demonstrates that packaging has a disproportionately high water footprint relative to the weight of the manufactured product, due to the water intensive nature of paperboard and cardboard production (Larkin et al., 2025b).

The 2 L bag consumed 74 m³ of water annually, this amount consisted mainly of packaging (43 m³) and manufacturing (9 m³). The automated drainage system and APD set required 26

m³ and 13 m³, respectively. Notably, water use in the APD set was heavily associated with waste incineration (12 m³), demonstrating that end of life treatment processes can have significant indirect water impacts (Larkin et al., 2025b).

Smaller consumables, while low in absolute terms, showed relatively high impacts per kilogram of product, reflecting the fixed burdens of packaging, sterilisation and logistics for very small masses of material. For example, the medical kit used only 0.2 m³ of water in total but most of this was attributable to manufacturing, which turned into over 20 m³ per kilogram of product. Similarly, hand washing gel consumed 9 m³, nearly all linked to manufacturing, while disinfectant sprays required 0.3 m³. These results highlight the high water consumption associated with manufacturing low volume products, which often require the same water intensive cleaning, sterilisation and packaging steps regardless of batch size.

Together, Figure 3. 35 and Figure 3. 36 show that dialysate production and packaging account for the largest share of water consumption, but smaller consumables and sets show inefficiencies that are significant on a per mass or per function basis (Larkin et al., 2025b).

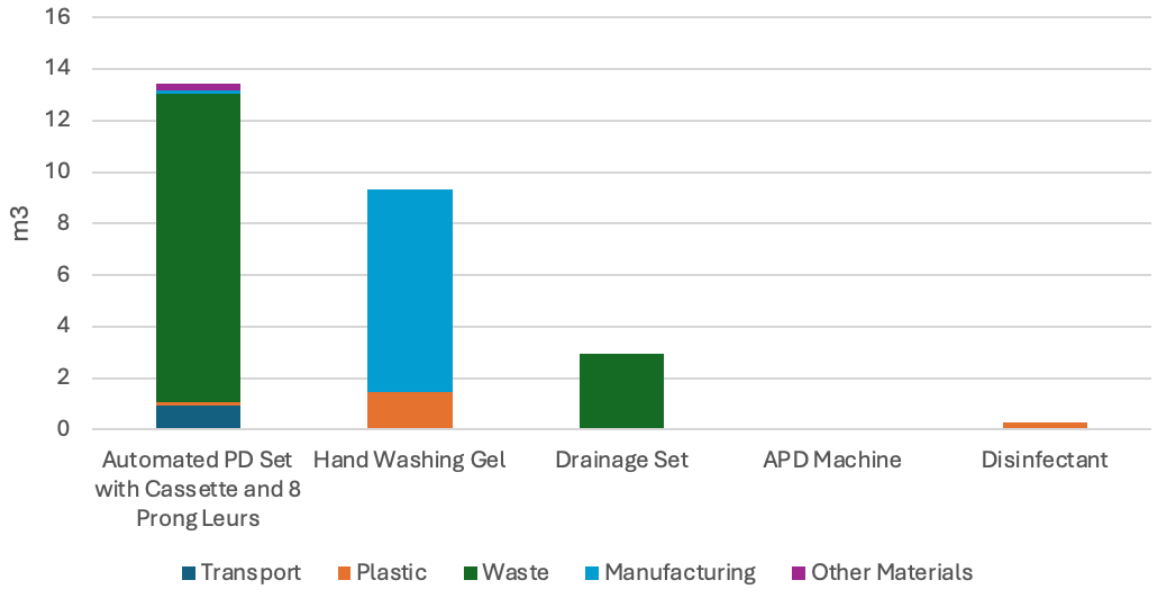

Figure 3. 36 Contribution Analysis (m3) (Larkin et al. 2025b)

Toxicity related impacts, although less visually prominent in the contribution charts, represent a critical area of concern in dialysis procurement. PVC based products, such as tubing, drainage

systems and APD sets, were found to be major contributors to human toxicity and ecotoxicity categories. When incinerated, PVC releases dioxins, furans and heavy metals, which persist in the environment and pose risks to human health (Frischknecht, 2000; Larkin et al., 2025b; Lithner et al., 2011).

The reliance on PVC in medical devices is well documented. In Australia, McAlister et al., (2024) reported that recycling PVC could reduce dialysis related emissions by up to 30%, though such schemes are rarely implemented in clinical practice (McAlister et al., 2024b). In Europe, small pilot initiatives have trialled the collection and recycling of IV bags and tubing, but these remain exceptions. Recent work from a UK plastic recycling facility showed that millions of microplastic particles per cubic metre of wash water can be released to receiving waters even after filtration, with up to an estimated 13% of processed plastic leaving the plant as microplastics, raising concerns about unintended pollution from large scale recycling (Brown et al., 2023). In the Italian context of this study, all PVC containing products are incinerated under clinical waste protocols, reinforcing toxicity burdens (Larkin et al., 2025b).

The toxicity impacts are particularly relevant in the context of the automated drainage system and APD sets, which contain high proportions of PVC. Their end of life incineration not only adds to carbon emissions but also creates persistent organic pollutants. Alternative materials such as thermoplastic elastomers and silicone have been proposed (Hosseini et al., 2021), but challenges remain in achieving regulatory approval, maintaining clinical performance and developing recycling pathways for these polymers (Larkin et al., 2025b).

Table 3. 9 integrates the results across categories, highlighting the main contributors in each case.

Table 3. 9 Integrated results across categories (Larkin et al. 2025b)

Product group	**Energy demand (MJ/year)**	**Largest energy contributor**	**Water use (m^3/year)**	**Largest water contributor**	**Toxicity risk**

5 L Dialysate bag	10,648	Transport & packaging (9,579 MJ)	239	Packaging ("other materials")	PVC, PET incineration
2 L Dialysate bag	2,119	Plastics (2,737 MJ)	74	Packaging & manufacturing	PVC incineration
Automated drainage system	2,873	Plastics (2,872 MJ)	26	Plastics & packaging	High PVC tubing content
Automated PD set	2,278	Plastics (2,278 MJ)	13	Waste incineration	PVC connectors, toxic incineration
APD machine	2,608	Other materials & electricity	<1	Minor contributions only	Metals, electronics (low recyclability)
Hand washing gel	495	Plastics & waste	9	Manufacturing	Packaging waste
Disinfectant spray	339	Plastics & packaging	0.3	Plastics	Packaging waste
Medical kit	65	Other materials	0.2	Manufacturing	Mixed single use plastics

5 L and 2 L dialysate bags are the main contributors to energy demand, water use and toxicity because of their volume, plastics and packaging. Automated drainage systems and APD sets add further burdens, particularly for toxicity, due to their high PVC content and clinical-waste incineration. Smaller consumables and multi material devices are less important in absolute terms but inefficient when normalised by mass or function. Packaging consistently emerges as a hidden impacts across categories, indicating that bag design, packaging reduction and drainage system optimisation are high priority targets for PD procurement (Larkin et al., 2025b).

Across impact categories, dialysate bags, drainage systems and APD sets were consistently identified as the main contributors.

3.3.5 Opportunities for redesign and optimisation

As previously reported in Larkin et al., (2026), a redesign study modelled the effects of substituting PVC and virgin PET with recycled polymers or alternative materials (Larkin et al., 2026d). Reductions of up to 63% were observed for the automated PD set and 54% for the 2 L dialysate bag relative to baseline designs (Larkin et al., 2026d). Figure 3. 37 presents the modelled GHG emissions for baseline and redesigned PD products.

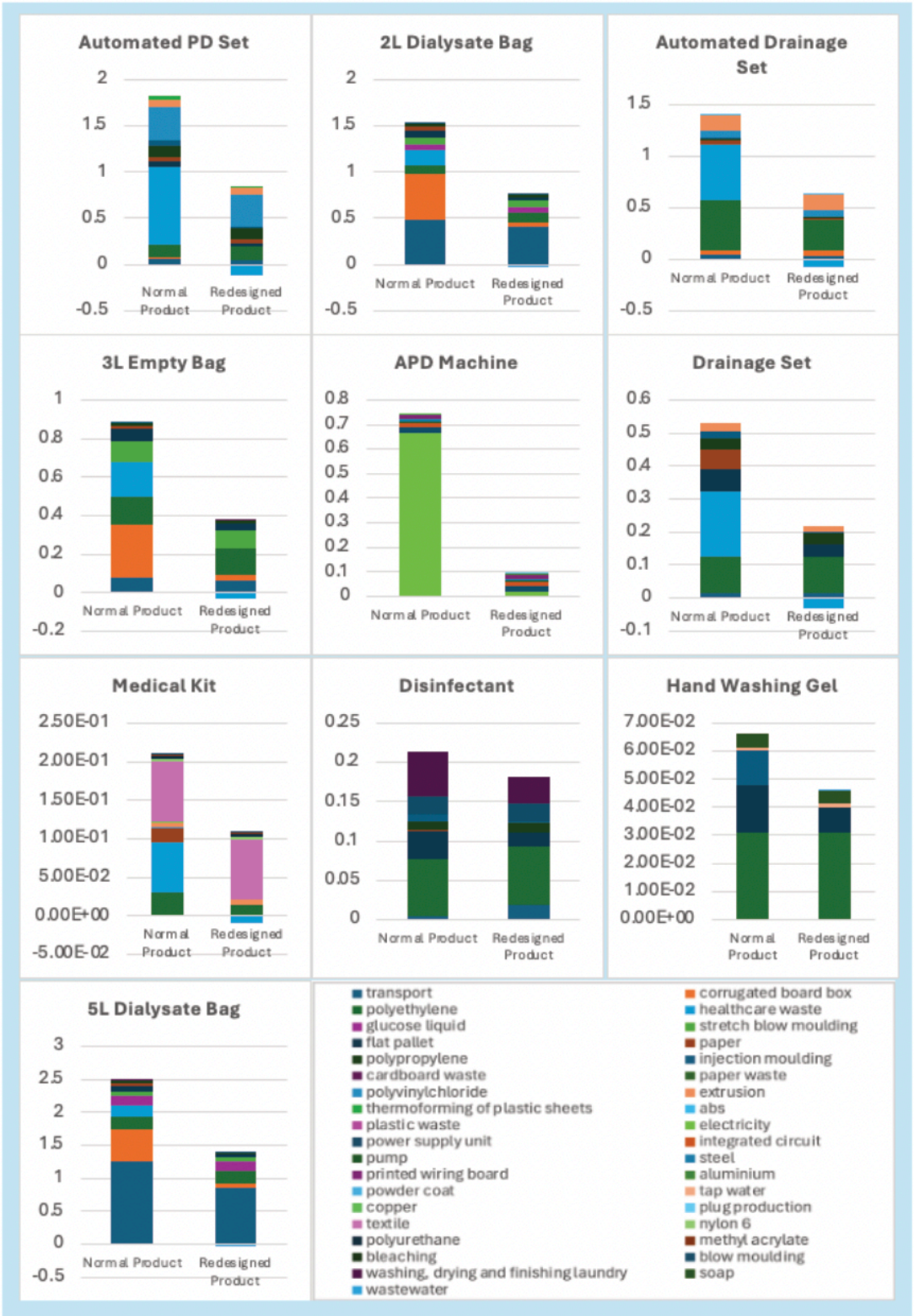

Figure 3. 37 Baseline vs Redesigned PD Product GHG Emissions (Larkin et al., 2026d)

Packaging interventions contributed a substantial proportion of the overall reductions. Substitution of recycled board in the 5 L dialysate bag reduced its footprint from 2.37 to 1.36 kg CO_2-eq per unit, representing a 42% decrease (Larkin et al., 2026d). Across the ten redesigned products, packaging interventions accounted for between 6% and 13% of total emission reductions.

Transport was the largest contributor to the 5 L dialysate bag footprint, accounting for 764 kg CO_2-eq per patient year. This burden was associated with long distance freight and the mass and volume of liquid dialysate, which limits pallet density efficiency (Larkin et al., 2026d).

Scenario modelling indicated that replacing prefilled dialysate bags with cartridge based dialysate mixing systems could reduce procurement related emissions by up to 35% per patient year, primarily through reductions in freight and packaging requirements (Larkin et al., 2026d).

3.4 Haemodialysis pathway: Life cycle assessment results

3.4.1 Overview of haemodialysis treatment modalities

HD and OLHDF together form the core of incentre KRT in high income health systems. OLHDF has gained adoption because it combines diffusive and convective clearance and is associated with improved survival and cardiovascular outcomes compared with high flux HD in pooled randomised evidence and a large pragmatic trial (Blankestijn et al., 2023; Maduell et al., 2013; Peters et al., 2016). Yet the shift to OLHDF brings concerns about environmental intensity: additional convective flows, higher product water demand for online substitution and HDF specific bloodlines may increase energy, water, materials and waste. As health systems operationalise net zero commitments (Commission, 2019; NHS, 2020), modality comparisons must be grounded in robust LCA, not assumptions.

This section presents a process based LCA to quantify and compare the environmental profiles of HD and OLHDF under real world operating conditions (Larkin et al., 2026a). The analysis is ISO aligned (14040, 2006; 14044, 2006), models background processes with Ecoinvent (Wernet et al., 2016) and reports three midpoint categories central to dialysis sustainability. These include climate change (kg CO_2-eq), energy resources (MJ, NCV) and water use (m^3 world-eq deprived) supplemented by reported operational water litres for interpretability (McAlister et al., 2024a; Rockström et al., 2009).

The European Green Deal and national net zero health strategies (e.g., NHS England's 2040 target) require service level decarbonisation without compromising outcomes (Commission, 2019; NHS, 2020). Dialysis, among the most energy and water intensive specialities, is a priority for transparent footprinting, procurement reform and infrastructure upgrades (Agar, 2015b; Barraclough et al., 2024).

3.4.2 Treatment process hotspots

The annual pathway footprint for a patient treated within the Modena dialysis centre, weighted by the observed modality mix, was estimated at 4,469 kg CO_2-eq per patient year. Corresponding resource use amounted to 60,290 MJ of non-renewable energy and 1,364 m^3

world-equivalent water deprived. When expressed per treatment session, impacts averaged 28.6 kg CO_2-eq, 386 MJ and 8.7 m^3 world-equivalent water (Larkin et al., 2026a).

Figure 3.38 presents the contribution analysis of annual greenhouse gas emissions by process. Patient travel was the main contributor, accounting for 2,548 kg CO_2-eq per patient year (57%). Staff commuting contributed a further 615 kg CO_2-eq (14%). Procurement of consumables represented 919 kg CO_2-eq (21%), with similar values observed for HD and OLHDF. Energy consumption associated with dialysis machines and RO systems contributed 203 kg CO_2-eq, while water production and healthcare waste accounted for smaller proportions (Larkin et al., 2026a).

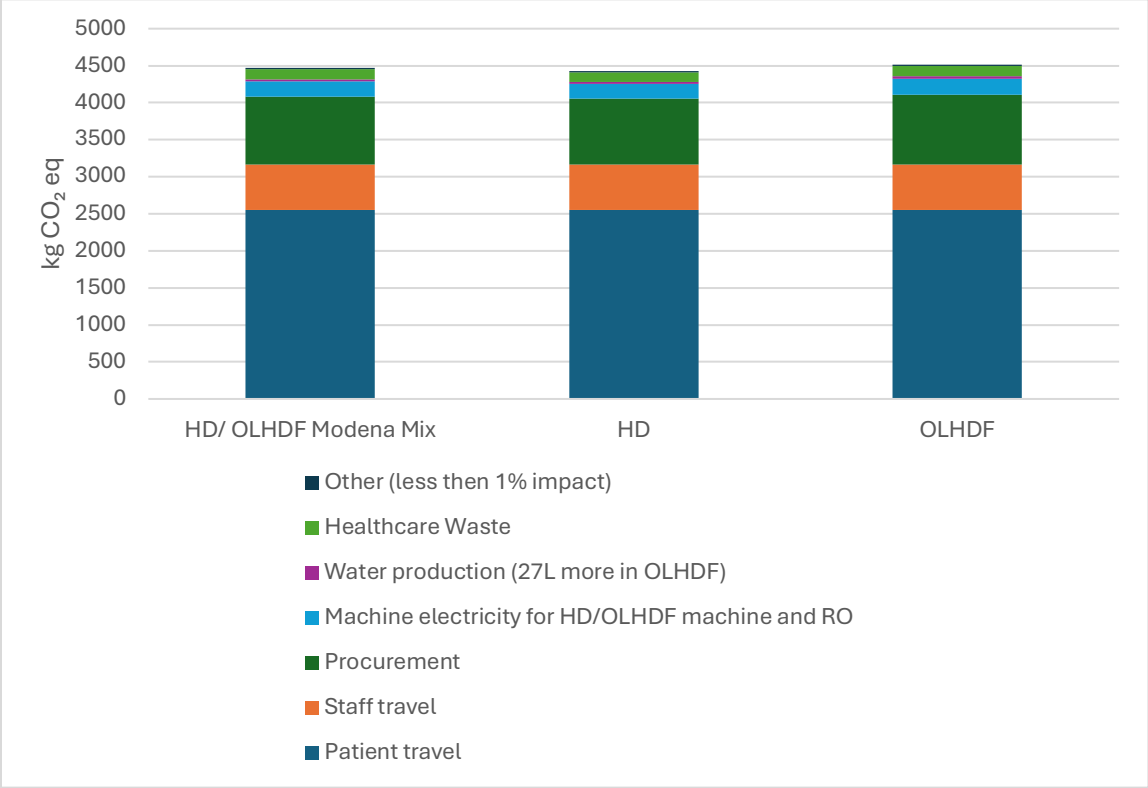

Figure 3. 38 Stacked contributions per modality (CO_2-eq) (Larkin et al., 2026a)

Comparison of treatment modalities showed modest differences in overall pathway impacts. Annual emissions for HD alone were estimated at 4,427 kg CO_2-eq per patient year, compared with 4,548 kg CO_2-eq for OLHDF. This corresponded to per session values of 28.38 kg CO_2-

eq for HD and 29.16 kg CO_2-eq for OLHDF, representing an increase of 2.73% under OLHDF operation (Larkin et al., 2026a).

A series of one-way sensitivity analyses was undertaken to assess the influence of key modelling assumptions on pathway results. Parameters tested included modality share, annual session count, electricity grid emission factor, reverse osmosis recovery rate and reduced-flow OLHDF prescriptions. Each parameter was varied within clinically and operationally plausible ranges while all other inputs were held constant (Canaud et al., 2024; Tattersall et al., 2013; Larkin et al., 2026, awaiting publication).

Across scenarios, variation in modality share between HD and OLHDF altered annual CO_2-eq values by less than 3%. Changes in session frequency within typical clinical ranges produced similarly small differences. Adjustments to electricity grid intensity and RO recovery rates affected total emissions modestly but resulted in substantial changes in absolute water volumes at unit scale. Reduced-flow OLHDF prescriptions lowered product water demand and produced small reductions in annual CO_2-eq while remaining within reported adequacy ranges.

The relative ranking of main contributors remained stable across all sensitivity analyses. Transport, procurement and water system performance consistently accounted for the largest shares of environmental impact. The magnitude of variation associated with these parameters is summarised in Figure 3.39, which presents percentage changes in annual CO_2-eq and water use across tested scenarios.

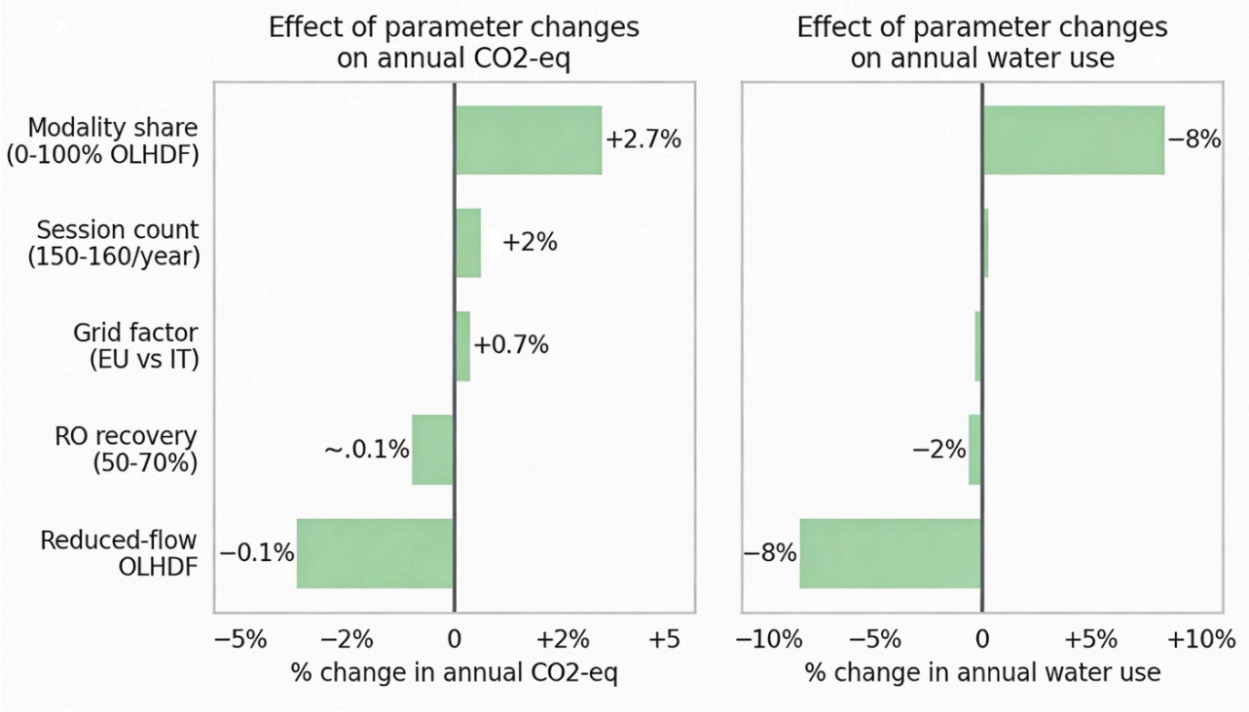

Figure 3. 39 Sensitivity of annual CO_2 eq and water use to key HD factors (Larkin et al., 2026a)

3.4.3 Procurement and material hotspots

Procurement of consumables represented the main contributor to the HD environmental footprint, accounting for approximately 70% of total annual GHG emissions per patient. Electricity use contributed around 20%, while water production and treatment contributed a smaller share of climate change impacts but remained important in water scarcity and related impact categories. Waste treatment, primarily high temperature incineration, was a major contributor to toxicity related outcomes due to the combustion of plastic based materials (Larkin et al., 2026b).

Products were selected for detailed analysis based on their relative contribution to the total procurement footprint identified during initial screening. A limited number of consumables accounted for the majority of impacts and were therefore prioritised for further investigation. These included dialysers, bloodline sets, acid concentrate bags and bicarbonate cartridges. Additional high frequency items such as saline bags, syringes, drapes and sterile gauze were

included to capture cumulative effects associated with repeated use across annual treatment schedules.

The procurement LCA identified dialysers as the single largest contributor to procurement related emissions. Each patient required approximately 156 dialysers per year, resulting in an annual footprint of approximately 200 to 220 kg CO_2-eq per patient. Dialysers were also associated with high primary energy demand and water use due to polymer processing and sterilisation requirements. Material composition included Polysulfone membranes, polycarbonate housings and PVC components, which contributed to both climate change and toxicity categories through end of life incineration (Larkin et al., 2026b).

Bloodline sets represented the second largest consumable contributor, with an annual footprint of approximately 145 kg CO_2-eq per patient. Their impact was driven primarily by the mass of PVC tubing required for each session and the requirement for disposal via hazardous waste incineration. Although individual bloodline sets had lower per unit impacts than dialysers, their use in every treatment session resulted in substantial cumulative burdens over a full patient year.

Acid concentrate bags were identified as a further major hotspot, contributing approximately 350 kg CO_2-eq annually per patient. These impacts were largely associated with transport and packaging due to the high weight and volume of liquid products. Transport emissions related to acid concentrate delivery exceeded 25 kg CO_2-eq per patient year in the Modena pathway, reflecting the inefficiency of long distance freight of pre diluted solutions (Larkin et al., 2026b).

Bicarbonate cartridges also contributed significantly, with annual emissions of approximately 110 kg CO_2-eq per patient. Sodium bicarbonate production was associated with high energy and water demand, while plastic cartridge housings contributed additional burdens at end of life.

Saline solution bags used during HD sessions contributed approximately 47 kg CO_2-eq annually per patient. Although smaller in scale than dialysers or concentrates, their frequent use and reliance on plastic packaging resulted in meaningful cumulative impacts.

Smaller consumables such as syringes, drapes and sterile gauze each contributed between 18 and 24 kg CO_2-eq per patient year. Sterile gauze was associated with particularly high water use, exceeding 300 m^3 annually per patient, due to the intensive water requirements of cotton cultivation and processing. These results highlight the importance of considering multi category impacts alongside GHG when evaluating procurement hotspots.

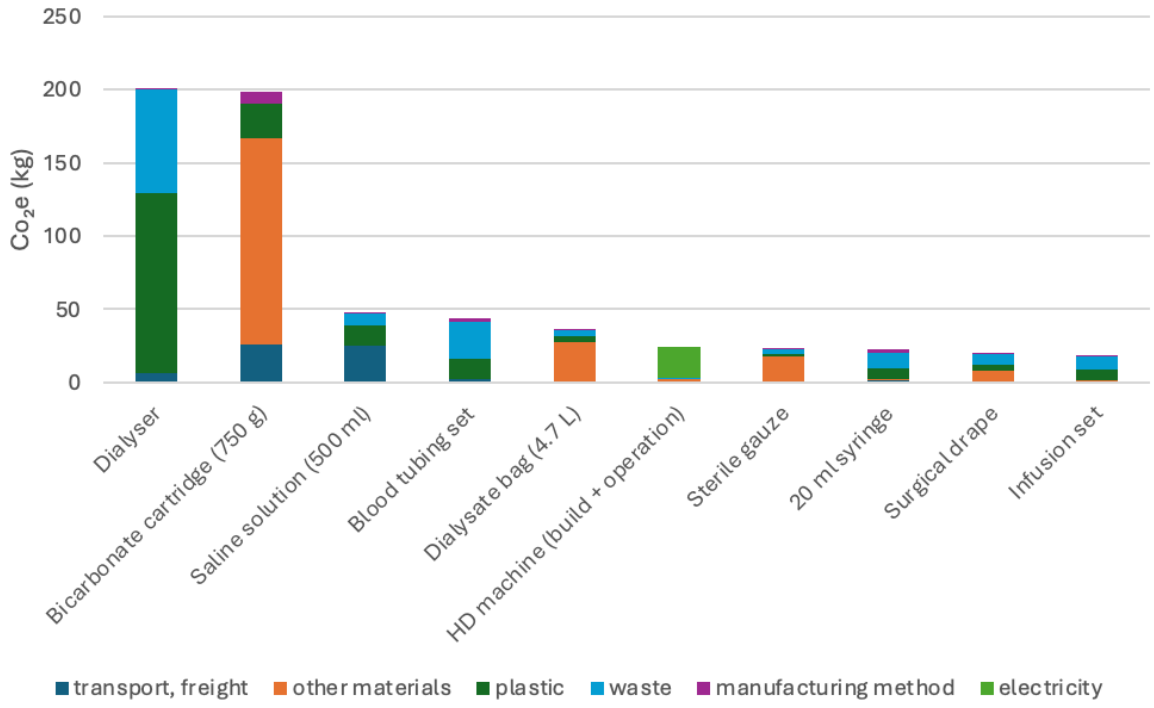

Figure 3. 40 Contribution Analysis (Carbon Emissions) (Larkin et al. 2026b)

The relative contributions of major consumables are illustrated in Figure 3.40. Dialysers, bloodlines and acid concentrate bags accounted for the largest shares of procurement related emissions, reflecting their polymer content, transport intensity and end of life treatment pathways. Table 3.10 summarises the carbon, energy and water impacts of the principal HD consumables on an annual per patient basis.

Table 3. 10 Procurement related environmental impacts of major HD consumables (per patient, per year) (Larkin et al. 2026b)

Product	**Carbon footprint (kg CO_2-eq)**	**Water use (m^3)**	**Energy use (MJ)**	**Notes**

Dialyser	220	12	800	PVC, polycarbonate
Bloodline set	145	8	500	PVC tubing
Acid bag (3.5 L)	350	18	1200	Transport heavy
Bicarbonate cartridge	110	7	400	Widely used

Waste treatment practices strongly influenced procurement related environmental burdens. At the Modena centre, the majority of dialysis consumables were classified as hazardous clinical waste and treated through high temperature incineration. Incineration contributed substantially to climate change impacts and accounted for the majority of toxicity related categories due to the combustion of PVC and polyurethane materials. End of life processes alone accounted for close to one fifth of the total environmental burden associated with consumable use (Larkin et al., 2026b).

Secondary packaging also emerged as a notable contributor. Corrugated cardboard outer packaging associated with consumables contributed more than 300 kg CO_2-eq annually per patient. Although theoretically recyclable, packaging was frequently disposed of through clinical waste streams due to limited separation, resulting in avoidable emissions and additional incineration burdens.

Energy and water use associated with major HD consumables are presented in Figures 3.41 and 3.42. Dialysers demonstrated the highest primary energy demand, exceeding 2,700 MJ per patient year, driven by polymer production and manufacturing processes. Bicarbonate cartridges also show high energy requirements. Sterile gauze and bicarbonate cartridges accounted for the largest share of water use, highlighting the influence of agricultural and chemical processes rather than direct clinical use.

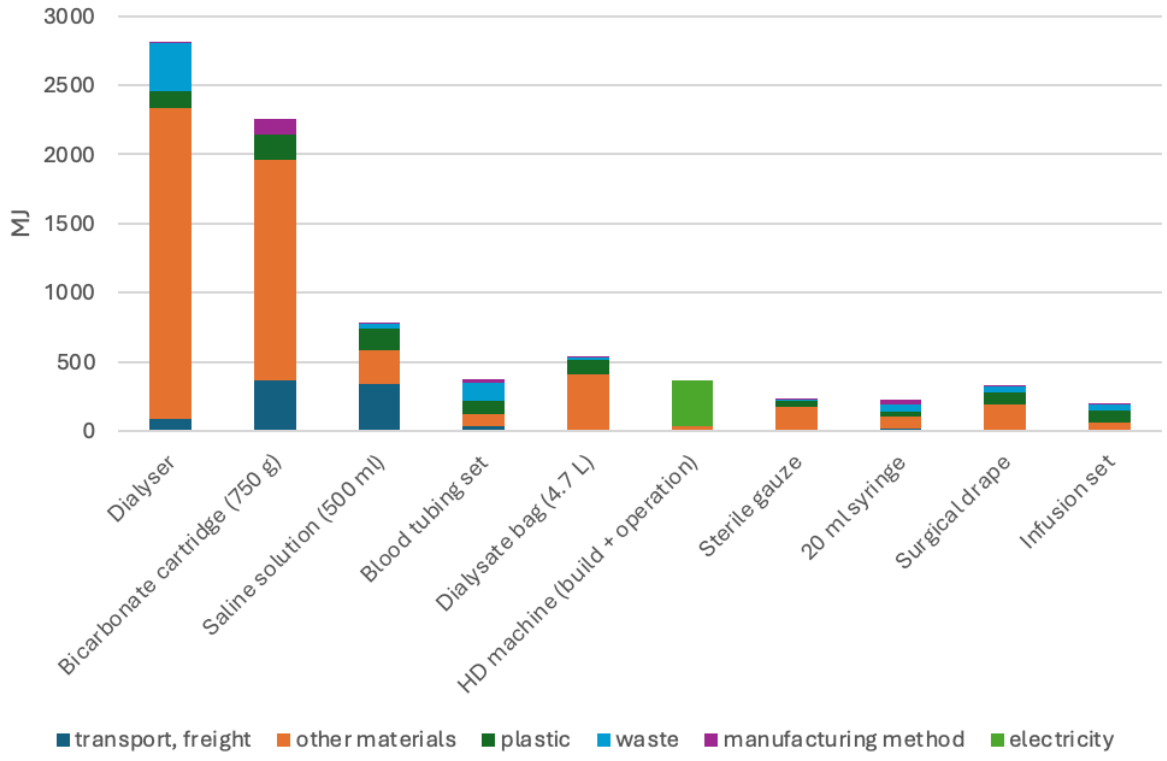

Figure 3. 41 Energy resource use of major HD consumables (Larkin et al. 2026b)

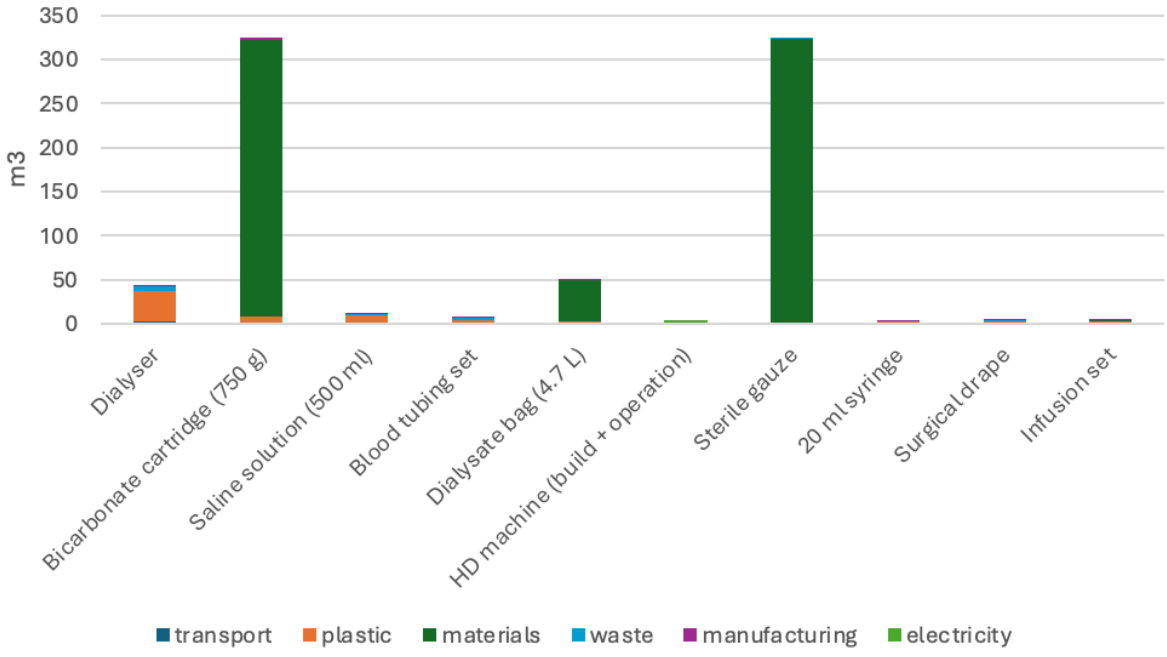

Figure 3. 42 Water use of major HD consumables (Larkin et al. 2026b)

Across all procurement categories, material composition, packaging requirements, transport intensity and end of life incineration consistently emerged as the root cause of environmental impacts. These findings confirm procurement and waste management as critical hotspots within the HD pathway and provide a quantitative basis for subsequent analysis of optimisation strategies presented in later chapters.

3.4.4 Innovations in haemodialysis sustainability: The Granumix case

This section presents a comparative LCA of two approaches to acid concentrate delivery in HD. The analysis evaluates the conventional use of single use liquid acid bags against a centralised dry powder preparation system, Granumix, implemented at the AOU Policlinico di Modena. Acid concentrate delivery represents one of the most material and logistics intensive subsystems within HD due to the transport of water based liquids, extensive packaging and hazardous waste disposal.

In the pathway, acid concentrate is supplied in single use liquid bags. These are transported as heavy water based products, stored onsite, connected to dialysis machines, partially emptied and disposed of with residual liquid and contaminated packaging. In contrast, the Granumix system prepares acid onsite from dry powder, distributes it through a fixed delivery loop and uses reusable containers with extended service lives (Di Chiaro et al., 2024; Ghimire et al., 2024; Larkin et al., 2025a; Murcutt et al., 2024; Tsai et al., 2025; Zawierucha et al., 2023).

Figure 3. 43 illustrates the central preparation system installed in Modena, including powder storage tanks, automated mixing units and distribution lines to dialysis stations.

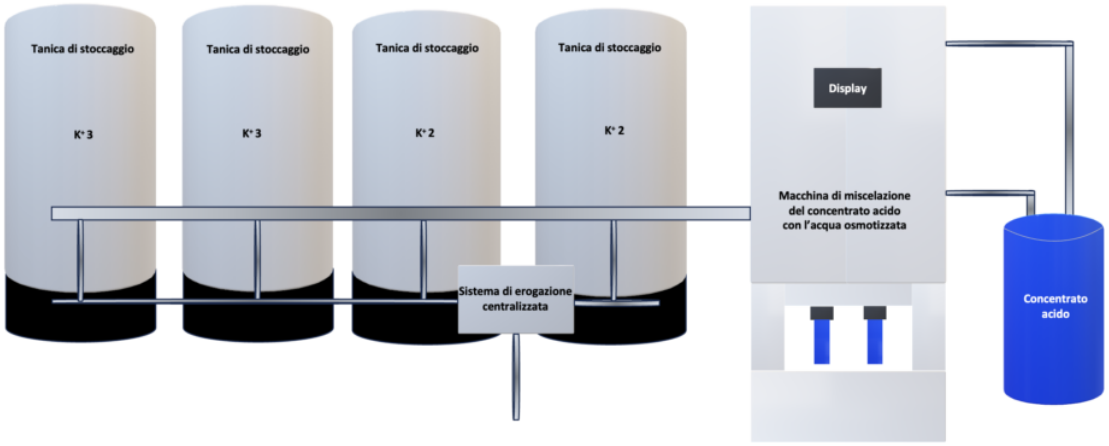

Figure 3. 43 Schematic of a Centralised Acid Concentrate Preparation and Delivery System for HD (Granumix Model, AOU Policlinico di Modena) (Di Chiaro et al. 2024)

The LCA compared both delivery pathways at the functional unit of one HD treatment. Primary measurements were collected at Modena and modelled using OpenLCA with Ecoinvent data. Fifteen midpoint impact categories were assessed, including climate change, energy resources, water use and toxicity related indicators (Larkin et al., 2025a).

Table 3.11 presents the per treatment results across all impact categories. Climate change decreased from 3.74 kg CO_2 eq per treatment using acid bags to 2.63 kg CO_2 eq with the Granumix system, representing a 30% reduction. Acidification declined by 17%. Freshwater ecotoxicity decreased by 14%. Human toxicity indicators showed reductions of 32% for carcinogenic effects and 15% for non-carcinogenic effects. Land use decreased by 61%, reflecting reduced demand for corrugated board and pallets. Water use declined modestly from 4.12 to 3.97 cubic metres world equivalent deprived.

Table 3. 11 LCA Results Across 15 Impacts (Larkin et al. 2025a)

Impact Categories	**Unit**	**Acid Bag**	**Granumix system**	**% Reduction**
Acidification	mol H+-Eq	2.36E-02	1.97E-02	17%
Climate change	kg CO_2 eq	3.74E+00	2.63E+00	30%

Ecotoxicity: freshwater	CTUe	5.70E+01	4.90E+01	14%
Eutrophication: freshwater	kg P-Eq	6.29E-03	6.12E-03	3%
Eutrophication: marine	kg N-Eq	8.29E-03	7.33E-03	12%
Eutrophication: terrestrial	mol N-Eq	5.68E-02	4.78E-02	16%
Human toxicity: carcinogenic	CTUh	2.35E-09	1.60E-09	32%
Human toxicity: non-carcinogenic	CTUh	5.42E-08	4.60E-08	15%
Ionising radiation: human health	kBq U235-Eq	2.75E-01	2.42E-01	12%
Land use - soil quality index	dimensionless	6.99E+01	2.73E+01	61%
Material resources: metals/minerals	kg Sb-Eq	7.87E-05	7.68E-05	3%
Ozone depletion	kg CFC-11-Eq	4.60E-07	4.04E-07	12%
Particulate matter formation	disease incidence	2.20E-07	1.56E-07	29%
Photochemical ozone formation	kg NMVOC-Eq	1.29E-02	9.55E-03	26%
Water use	m3 world eq. deprived	4.12E+00	3.97E+00	4%

Across categories, reductions were consistently observed for the central delivery system.

The contribution analyses showed several recurring root causes between pathways. Single use plastics were eliminated in the central system, removing repeated PET and packaging contributions present in the bag pathway. Secondary packaging was substantially reduced, lowering impacts linked to cardboard production and pallet transport. Hazardous waste incineration was avoided for most packaging and residual liquid, reducing contributions to acidification, ecotoxicity and particulate matter formation. Liquid freight was reduced due to transport of dry powder rather than pre mixed solutions. Additional material inputs associated with the central equipment were small on a per treatment basis due to long equipment lifetimes and infrequent replacement (Larkin et al., 2025a).

Normalised results are presented in Figure 3.44. These showed that both delivery pathways contributed most strongly to freshwater ecotoxicity and eutrophication categories, reflecting chemical production common to both systems. However, the acid bag pathway displayed consistently higher normalised values across most categories, particularly climate change,

toxicity and particulate matter formation. The Granumix system demonstrated lower normalised scores across nearly all categories (Larkin et al., 2025a).

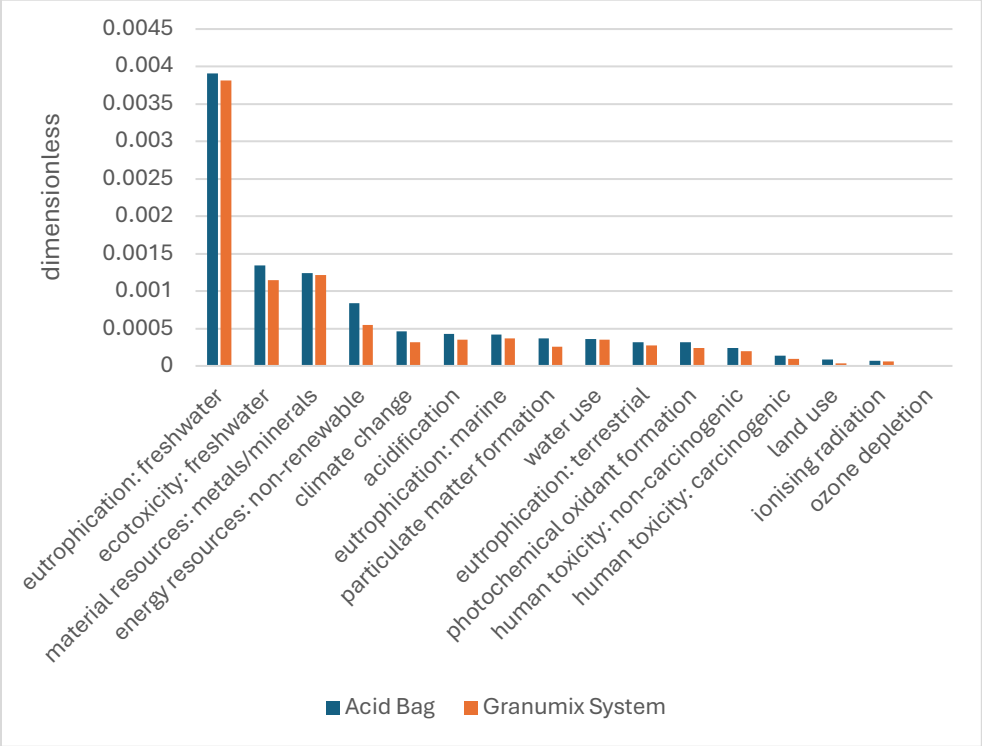

Figure 3. 44 Normalised Scores Across All Impacts (Larkin et al. 2025a)

Figure 3. 45 to Figure 3. 60 present contribution analyses for individual impact categories. Across climate change, energy resources, acidification, ecotoxicity and photochemical oxidant formation, reductions were primarily associated with removal of packaging, incineration and liquid freight processes. Water use reductions were smaller, as glucose production and ultrapure water requirements were shared between pathways.

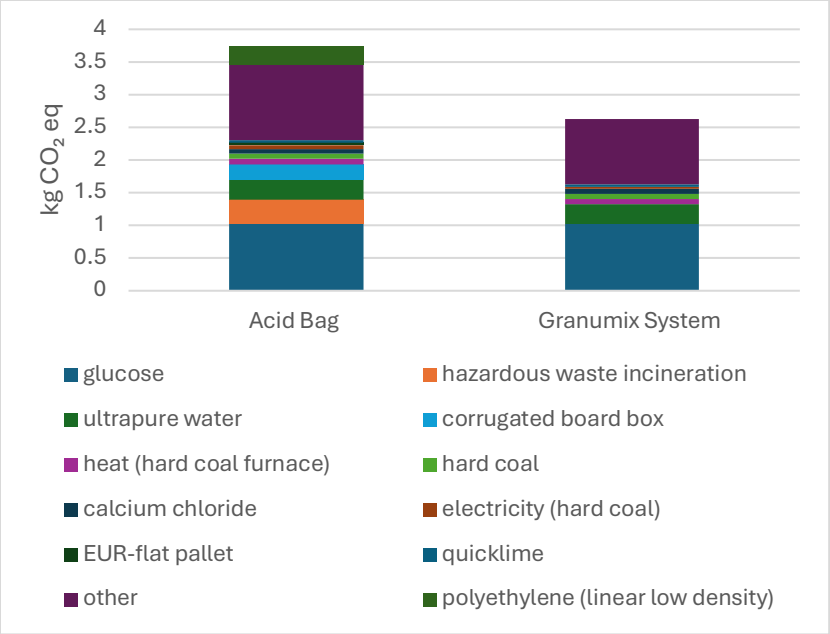

Figure 3. 45 Contribution Analysis, GHG emissions (Larkin et al. 2025a)

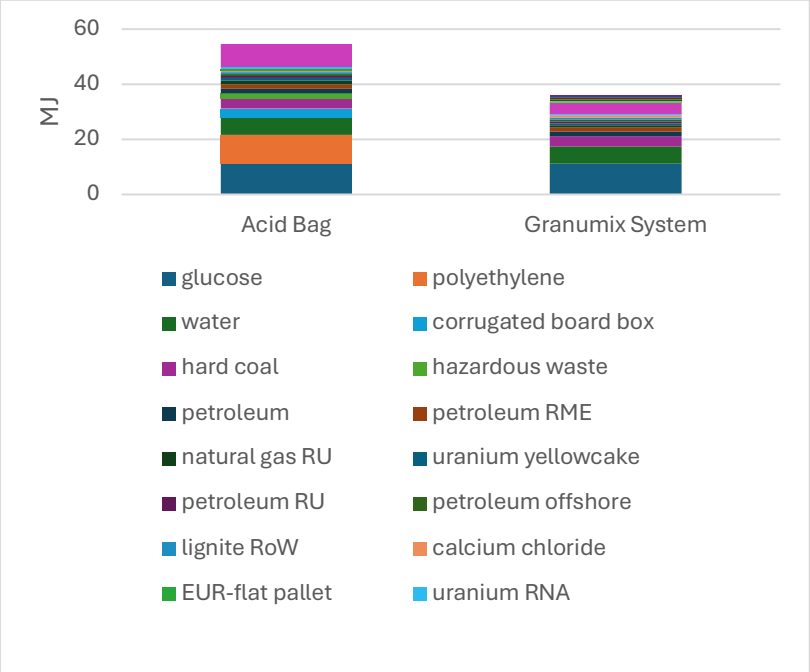

Figure 3. 46 Contribution Analysis, Energy Resources (Larkin et al. 2025a)

Non-renewable energy resources. For the bag pathway the inventory shows PET at 10.51 MJ and corrugated board at 3.17 MJ per treatment, with hazardous waste at 1.76 MJ and a range of petroleum and gas entries linked to plastics, freight and waste. The central pathway removes

bag film and board and lowers petroleum linked impacts. Residual energy for glucose and ultrapure water remains the same (Larkin et al., 2025a).

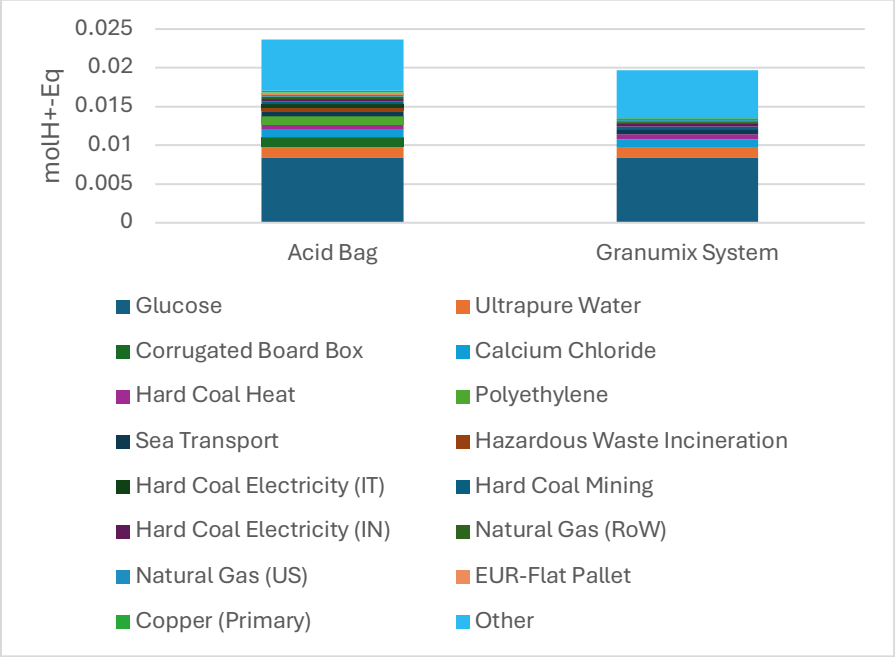

Figure 3. 47 Contribution Analysis, Acidification (Larkin et al. 2025a)

Acidification. The bag pathway includes contributions from glucose at 0.00836, ultrapure water at 0.00142, corrugated board at 0.00126, PET at 0.00102, hazardous waste incineration at 0.00052 and sea transport at 0.00065 mol H plus equivalent per treatment. The central pathway keeps glucose and water identical, removes PET and corrugated board and removes incineration for this subsystem. The result is a 17% reduction per treatment (Larkin et al., 2025a).

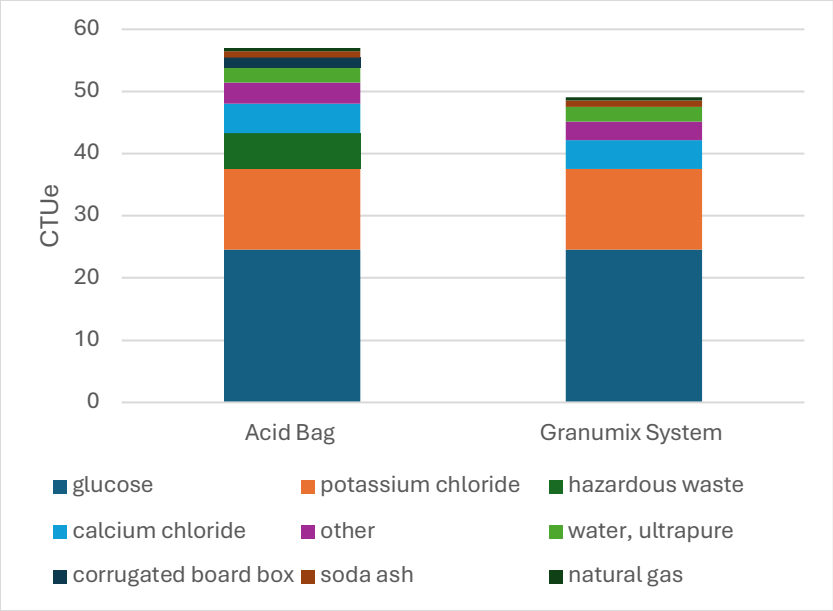

Figure 3. 48 Contribution Analysis, Ecotoxicity (Larkin et al. 2025a)

Freshwater ecotoxicity. The main contributions are glucose and potassium chloride. The bag pathway overlays these with hazardous waste at about 5.80 CTUe and corrugated board at 1.63 CTUe. The central pathway removes those additions, which produces a reduction of about 14%. This aligns with known ecotoxicity impacts from incinerator emissions and from production of pulp and paper for cartons (Larkin et al., 2025a).

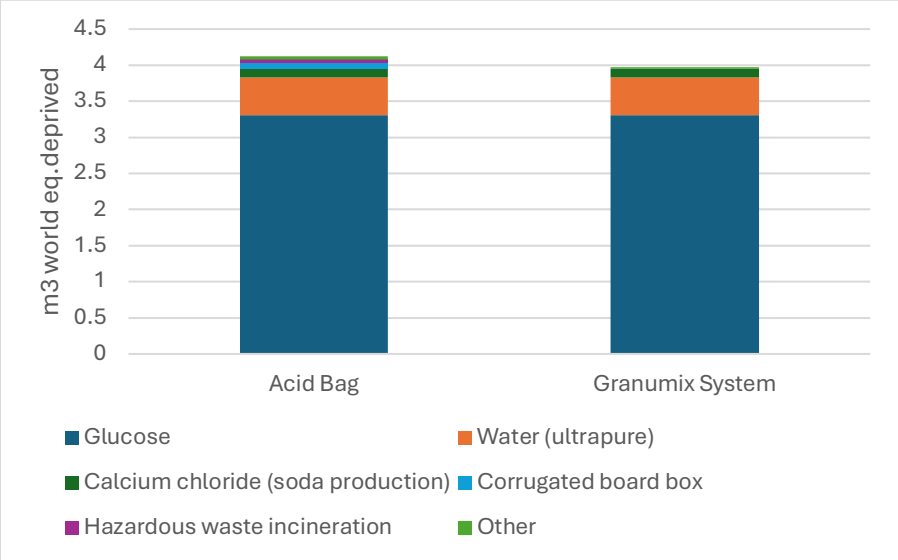

Figure 3. 49 Contribution Analysis, Water Use (Larkin et al. 2025a)

Water use. Water use decreases modestly. Both arms carry significant burdens for glucose production and ultrapure water for the dialysate recipe. Removal of corrugated board and incineration reduces the central pathway total from 4.12 to 3.97 cubic metres world equivalent deprived (Agar, 2015a; Gauly et al., 2022).

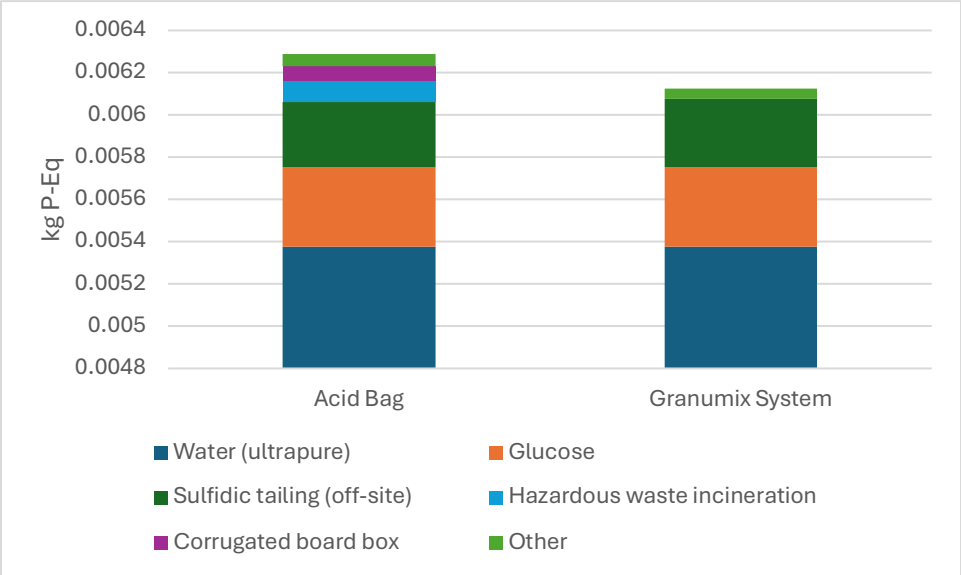

Figure 3. 50 Contribution Analysis, Eutrophication: Freshwater (Larkin et al. 2025a)

Freshwater eutrophication is driven mainly by glucose production and ultrapure water in both pathways, with additional contributions from corrugated board, PET and hazardous waste incineration in the bag scenario (Larkin et al., 2025a).

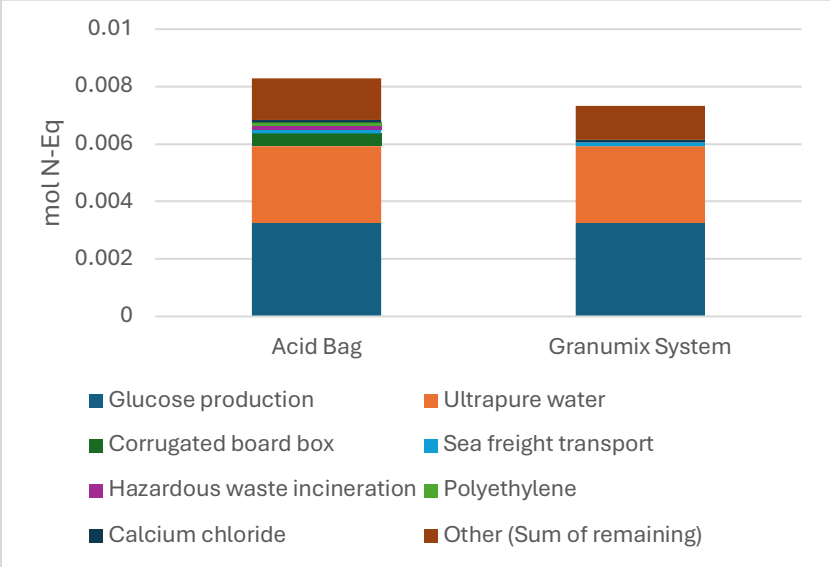

Figure 3. 51 Contribution Analysis, Eutrophication: Marine (Larkin et al. 2025a)

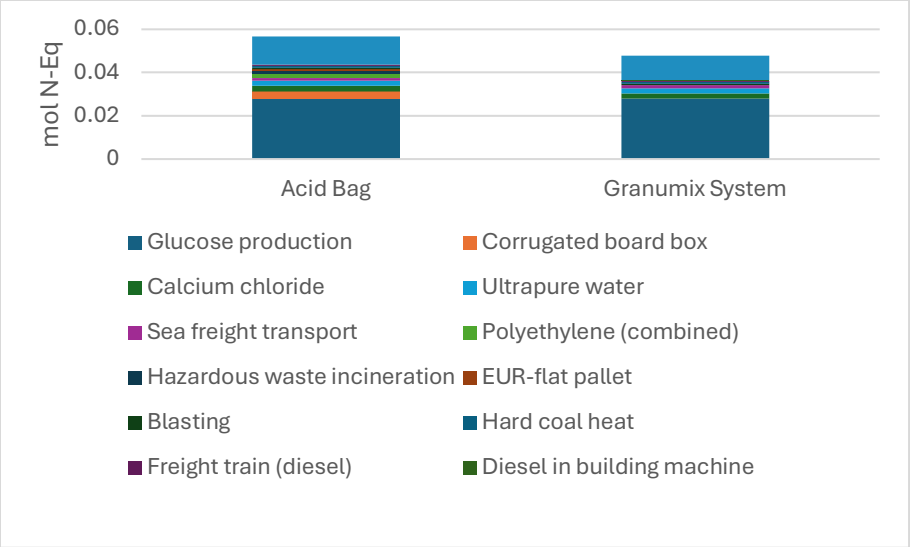

Figure 3. 52 Contribution Analysis, Eutrophication: Terrestrial (Larkin et al. 2025a)

Eutrophication in marine and terrestrial compartments. The bag pathway includes corrugated board, sea freight, PET, pallets and incineration on top of glucose and ultrapure water. The central pathway removes most of those additions. Marine eutrophication decreases from 8.29E 03 to 7.33E 03 kilograms nitrogen equivalent per treatment. Terrestrial eutrophication drops from 5.68E 02 to 4.78E 02 mol nitrogen equivalent.

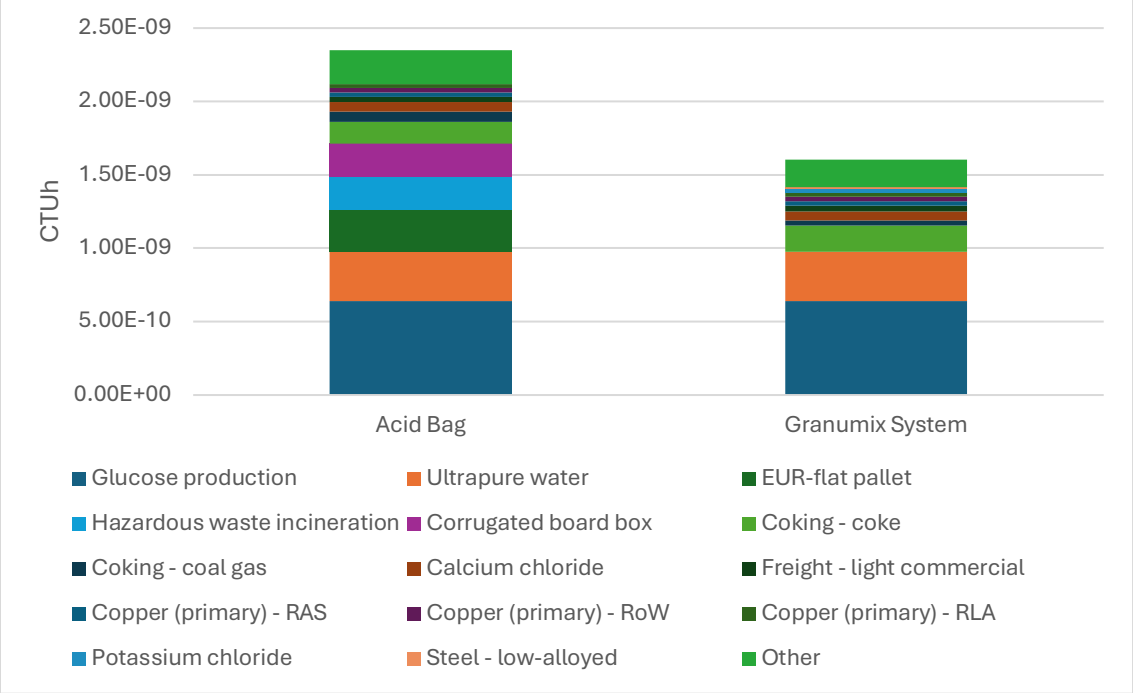

Figure 3. 53 Contribution Analysis, Human Toxicity: Carcinogenic (Larkin et al. 2025a)

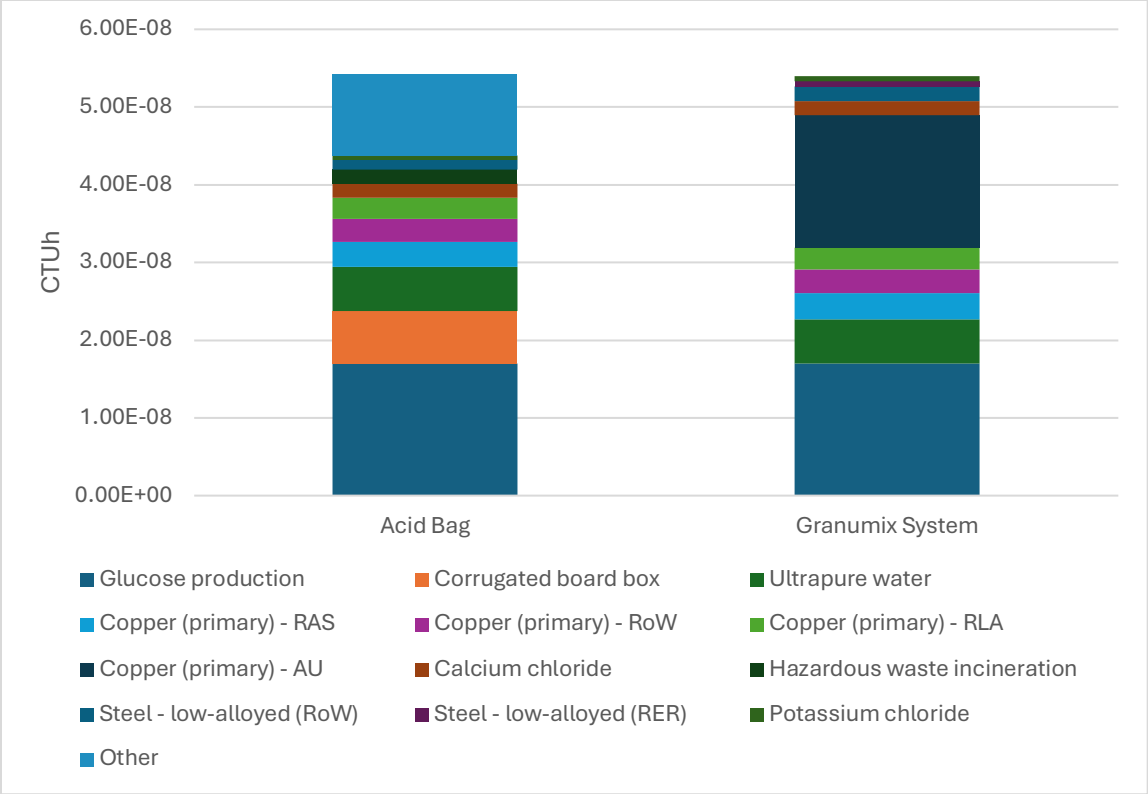

Figure 3. 54 Contribution Analysis, Human Toxicity: Non-Carcinogenic (Larkin et al. 2025a)

Within human toxicity, carcinogenic and non-carcinogenic categories show lower values due to the removal of incineration terms, corrugated board and some petroleum linked processes. There are small contributions from copper and steel that appear in both pathways.

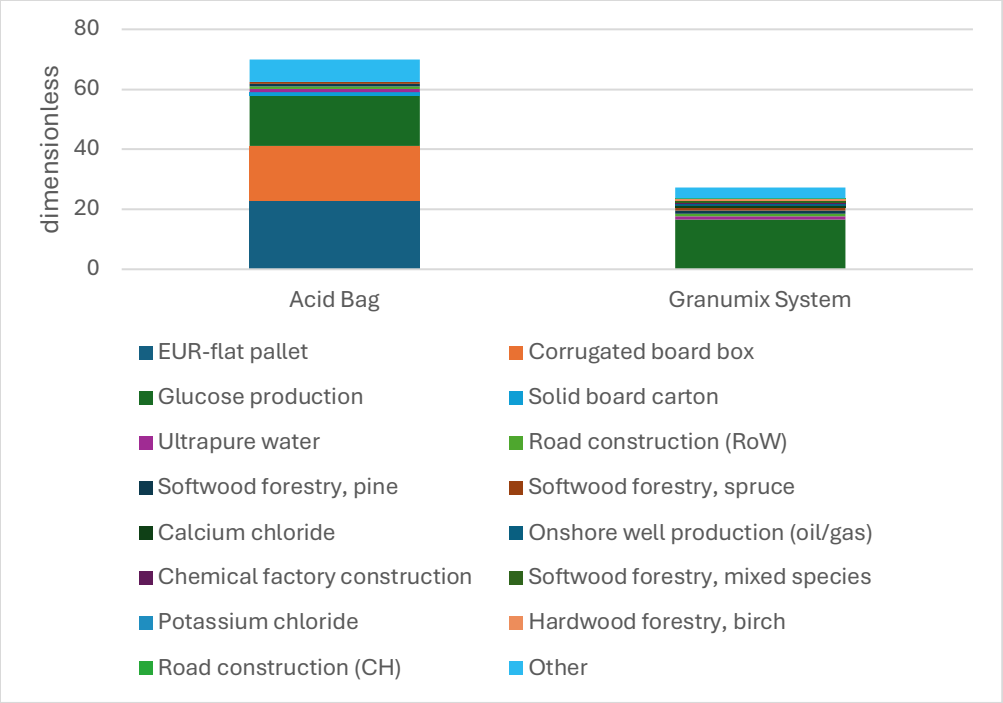

Figure 3. 55 Contribution Analysis, Land Use (Larkin et al. 2025a)

Land use impacts are primarily associated with forestry for corrugated cardboard and, to a lesser extent, with agricultural inputs of dialysate components (Larkin et al., 2025a). The bag pathway therefore has higher land use scores because it relies on single use cartons and pallets, whereas the central pathway lowers land occupation indicators by reducing packaging demand per treatment and shifting part of the burden towards reusable infrastructure (Larkin et al., 2025a).

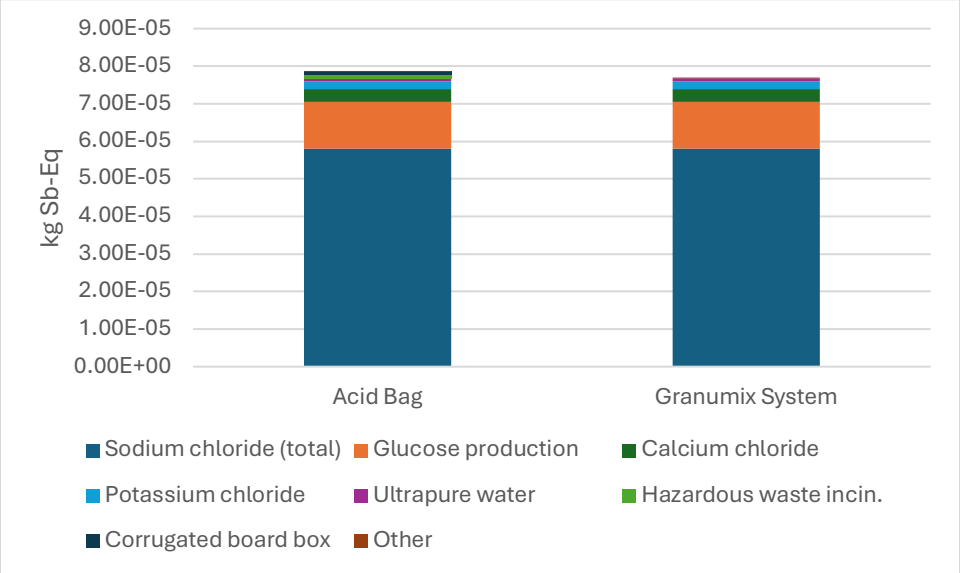

Figure 3. 56 Contribution Analysis, Material Resources: Metals/Minerals (Larkin et al. 2025a)

Material resource use for metals and minerals is relatively low compared with other categories and is linked mainly to steel, copper and other metals in machinery, valves and reusable containers present in both systems (Larkin et al., 2025a). Differences between the bag and central pathways are small, but the central system shows a slight advantage because metals are amortised over many reuses and more likely to enter recycling loops, whereas the bag pathway embeds additional mineral demand in one way packaging components (Larkin et al., 2025; Sherman et al., 2018).

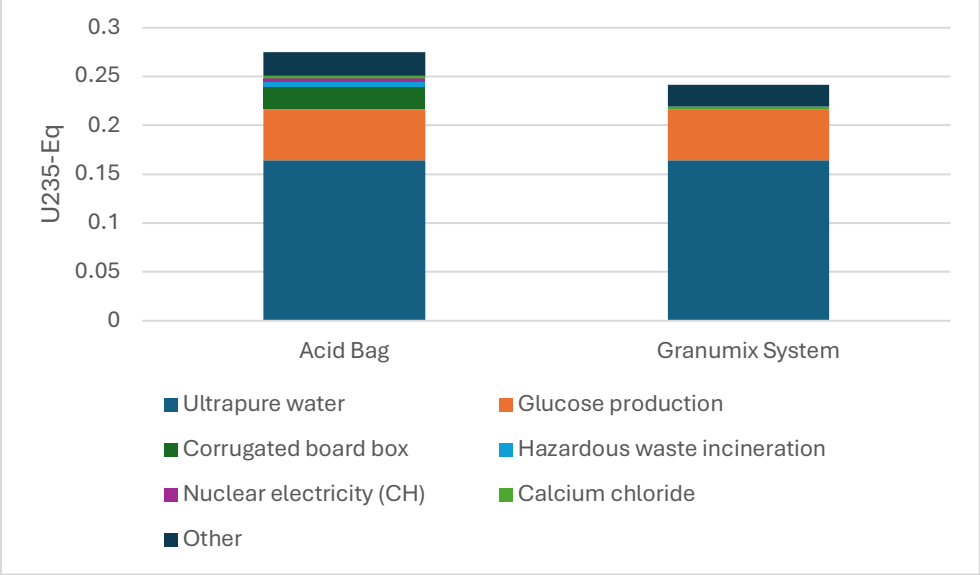

Figure 3. 57 Contribution Analysis, Ionising Radiation (Larkin et al. 2025a)

Ionising radiation, ozone depletion, particulate matter and photochemical oxidants. The bag pathway produces higher values across these categories through nuclear linked electricity in background processes for pulp and packaging, plastics and waste management, as well as through added transport. The central pathway reduces these impacts because it eliminates most packaging and incineration and reduces liquid freight (Larkin et al., 2025a).

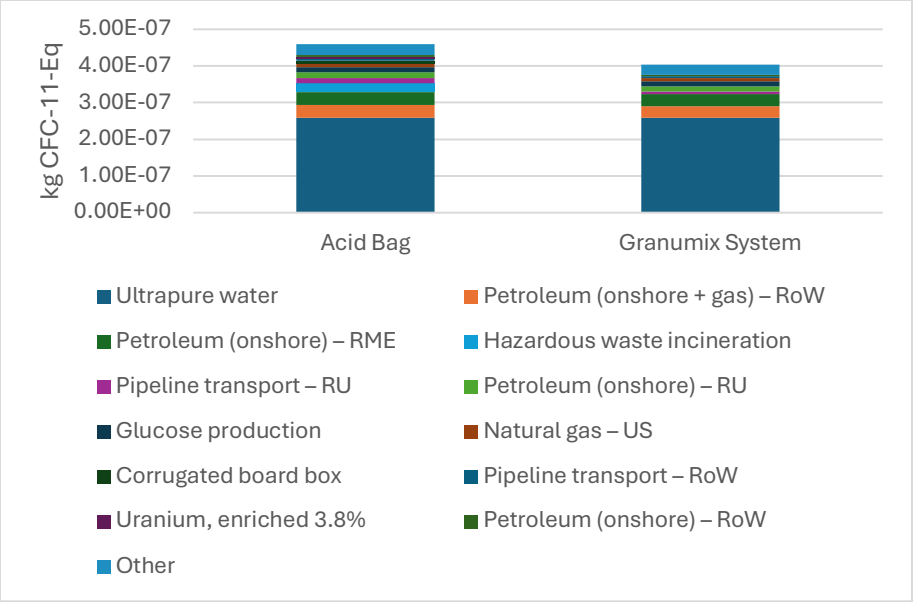

Figure 3. 58 Contribution Analysis, Ozone Depletion (Larkin et al. 2025a)

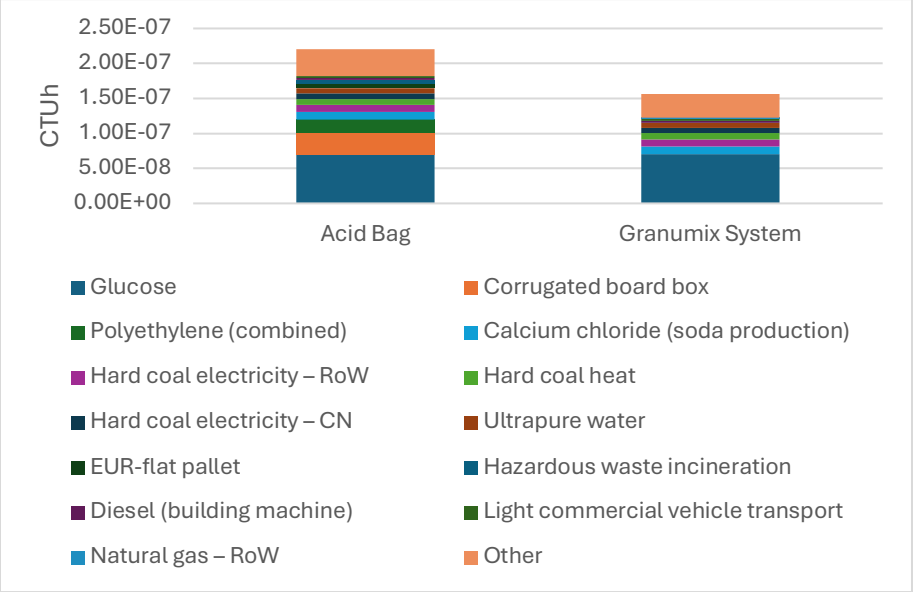

Figure 3. 59 Contribution Analysis, Particulate Matter Formation (Larkin et al. 2025a)

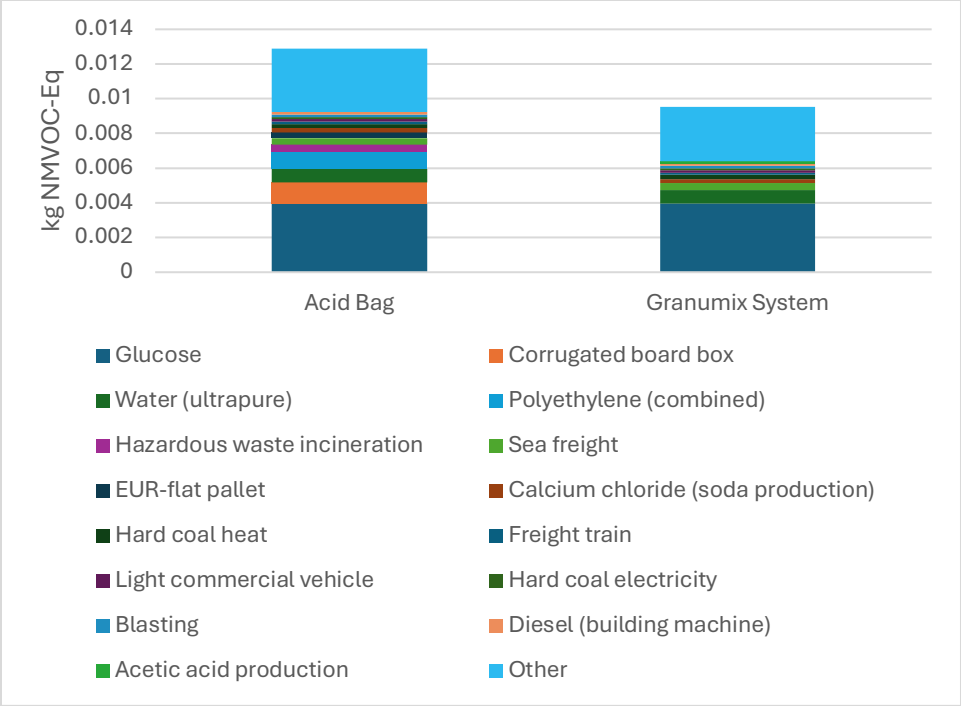

Figure 3. 60 Contribution Analysis, Photochemical Ozone Formation (Larkin et al. 2025a)

When scaled to service level, the per treatment reduction corresponded to an annual saving of approximately 43.5 tonnes CO_2 eq for the Modena unit, assuming 156 treatments per patient and 251 patients. This magnitude is consistent with reductions reported in external dialysis units that transitioned to central acid delivery systems (Murcutt et al., 2024).

Operational data indicated that the central system functioned within established quality and safety frameworks. Routine sanitation, monitoring of acid composition and preventive maintenance were implemented. Filters and system components were replaced infrequently and contributed minimally on a per treatment basis. The system complied with ISO standards governing dialysis fluids and water quality (13959, 2014; ISO23500, 2019).

Overall, the Granumix case study demonstrates that central acid preparation reduces environmental burdens across multiple categories compared with single use liquid acid bags. The largest reductions were associated with elimination of single use packaging, reduced freight of water based products and avoidance of hazardous waste incineration. These findings confirm that infrastructure level procurement decisions can materially alter the environmental profile of HD without modifying the clinical treatment itself.

3.4.5 Opportunities for optimisation

Although OLHDF provides clinical benefit, the pathway analysis shows limited environmental separation between modalities. The difference between HD and OLHDF was 2.7% per patient year. This indicates optimisation efforts should focus on system level issues rather than modality choice alone. The Modena analysis identified three areas with the greatest potential for improvement. These include travel, procurement and supporting infrastructure such as electricity, water and waste.

Travel as the main impact:

71% of pathway CO_2-eq comes from patient and staff travel, a structural property of three times a week in centre regimes (Larkin et al., 2026a). This aligns with cost and operational evidence: dialysis transportation is a major budget line and service bottleneck (Stephens et al., 2013). The implication is understood as: transport decarbonisation minimises modality changes. High leverage differences include:

- Care model shifts: scale home HD and shared care closer to home, where appropriate (Kennedy et al., 2018).
- Fleet/route optimisation: pooled transport, demand responsive shuttles, full EV minibuses.
- Incentives: parking policies and travel stipends aligned to low carbon modes.
- Scheduling: reduce missed/duplicative trips via better appointment clustering.

Procurement and material intensity:

21% of CO_2-eq is from consumables including dialysers, bloodlines, needles, concentrates and packaging (Larkin et al., 2026a). OLHDF's specific substitution line set explains most of the 2.7% difference. Cross study, single use kits are consistent hotspots (Rizan et al., 2021; Sherman et al., 2018).

Service ready actions:

- Product redesign: lighter sets, alternative polymers where clinically acceptable (Agar, 2015a; Barraclough et al., 2020).

- Packaging minimisation: right sized cartons, recycled content, supplier take back (Baxter, 2024).
- Centralised fluids: where compatible with clinical pathways, central acid systems reduce packaging/transport (Bendine et al., 2020; Larkin et al., 2025a).
- Evidence transparency: tender ask for LCAs/ Environmental Protection Declarations (EPD)s.

Electricity and water use:

Metering shows OLHDF 5.7% electricity (21.5 MJ/session) and 27 L product water/session relative to HD (Larkin et al., 2026a). While small in pathway share, they matter for local utilities, operational costs and water scarcity policy.

- Electricity: standby optimisation, session clustering and on site solar/ Power Purchase Agreements (PPAs) reduce the carbon intensity (NHS, 2020).
- Water: drive RO recovery upwards, reuse reject water for grey uses, consider reduced flow OLHDF where adequacy permits (Bendine et al., 2020; Canaud et al., 2024; Tattersall et al., 2013).

Waste management:

Waste is a smaller share (3% total), yet avoidable waste persists. Over classification as hazardous, suboptimal separation, or excess packaging (McGain et al., 2014; Rizan et al., 2021). Options:

- Waste separation training with spot audits, distinct bins/labels.
- Treatment innovation: evaluate pyrolysis for plastic products/parts where regulations/quality allow.
- Supplier redesign to cut pack in cardboard/films.

Drawing on the Modena pathway analysis, international dialysis LCAs and wider green nephrology literature, five priority action areas can be identified for dialysis services. These are framed as practical, service level recommendations that target the largest and most

achievable sources of carbon and resource savings while maintaining high standards of patient care and safety (Agar, 2015; Kennedy et al., 2018; NHS, 2020). Together, they provide a systems level roadmap that links transport, water and energy systems, procurement and waste management to the environmental hotspots identified in this chapter (Barraclough et al., 2020; McGain et al., 2014; Rizan et al., 2021).

Choose OLHDF or HD on clinical grounds (adequacy, haemodynamic, access, patient preference). environmental consistency within 3% means care quality remains decisive (Blankestijn et al., 2023; Maduell et al., 2013; Peters et al., 2016) (Larkin et al., 2026a).

If OLHDF extends survival, lifetime cumulative emissions will be higher simply due to more years of care, reinforcing the need to decarbonise the delivery context, not restrict effective therapy (Schouten et al., 2025).

3.5 Discussion and interpretation

3.5.1 What the hotspots tell us about procurement

This discussion integrates PD and HD pathway and procurement LCAs to interpret system level hotspots. This section expands on those findings from Sections 3.3 and 3.4, presenting an in depth discussion of five principal environmental hotspots. This includes dialysate production and freight, secondary packaging, the use of PVC in tubing and drainage systems, incineration based waste management and home based waste collection practices.

Dialysate production and its associated freight emerged as the single largest hotspot, responsible for more than half of the annual emissions for one APD patient. The 5 L dialysate bag alone accounted for 1,515 kg CO_2-eq annually, with transport responsible for approximately 764 kg CO_2-eq. This reflects the heavy weight and bulk of dialysate, which consists primarily of sterile water and solutes, making it logistically inefficient to ship over long distances. The findings align with research from in China, which also highlighted transport of dialysate fluid as a major environmental burden (Chen et a., 2017: Larkin et al., 2025b). HD shows a similar pattern through acid concentrate bags and bicarbonate cartridges, where transport of liquid or chemically dense products drives a large share of procurement emissions.

Transport emissions are increased by the globalised supply chains that support PD. Most dialysate bags used in Europe are manufactured in specialist production hubs and distributed internationally. Local or regional production would reduce transport distances and associated emissions. In this study, international freight of dialysate bags was one of the largest contributors to the carbon footprint of APD consumables, often exceeding the manufacturing emissions of the bags themselves (Larkin et al., 2025a). For example, McAlister et al (2024) reported that centralised dialysate production in Australia created disproportionately high freight emissions and that moving toward regional production facilities could reduce emissions significantly (McAlister et al., 2024b). A similar pattern was observed in HD procurement, where acid concentrate bags and bicarbonate cartridges showed raised transport related emissions due to their mass, liquid content and centralised production.

Optimising pallet density is another opportunity. Current packaging formats prioritise sterility and ease of handling, but the arrangement of bags within cartons and on pallets often leaves unused space. By improving pallet layout, using lighter secondary packaging and reducing empty headspace in cartons and containers, freight emissions per litre of dialysate delivered could be reduced (Larkin et al., 2026c).

Long haul transport modes are also critical. Dialysate bags are commonly shipped by road freight across Europe, which has higher emissions intensity than rail. Modal shifts toward lower carbon emitting freight, such as electrified rail networks or hybrid/electric trucks, could reduce emissions further. These findings indicate that logistics efficiency represents a shared optimisation opportunity across both PD and HD procurement systems.

Figure 3. 31 and Figure 3. 32 confirm that transport of high volume fluids is one of the root causes of procurement related emissions in both PD and HD (Larkin et al., 2025b).

The analysis also revealed that secondary packaging, primarily corrugated cardboard, contributed over 300 kg CO_2-eq annually for one APD patient. While packaging is rarely prioritised in clinical sustainability discussions, this result demonstrates its importance as a hidden hotspot. Figure 3. 32 shows the contribution of other materials, which includes cardboard packaging, across multiple products but particularly for the 5 L dialysate bag.

Cardboard is widely perceived as a sustainable material due to its recyclability, but its production is water and energy intensive, especially when derived from virgin pulp. In dialysis pathways, outer packaging is frequently incinerated with clinical waste, which removes the environmental benefit normally associated with paper based materials.

Any move toward bulk or reduced packaging must address risks of product damage and failure. Dialysate bags and associated components need sufficient protection to withstand handling and transport, so packaging changes should be co-designed with manufacturers and logistics providers and tested to ensure that breakage rates do not increase to the point where wasted product offsets environmental gains (Al-Hadithy et al., 2024).

Figure 3. 33 and Figure 3. 35 illustrate the energy and water impacts of packaging, with secondary materials accounting for a large share of burdens in the 5 L dialysate bag. These findings highlights that packaging should not be overlooked in procurement reform, as it represents a material hotspot with opportunities for reduction (Larkin et al., 2025b).

PVC is an impactful material in dialysis consumables, particularly in tubing, connectors and drainage systems. The LCA confirmed that PVC contributes disproportionately to toxicity related categories, including human toxicity and freshwater ecotoxicity, due to emissions of dioxins and heavy metals during incineration (Frischknecht, 2000; Lithner et al., 2011).

Figure 3. 33 and Figure 3. 35 show that plastics were a major contributor to both primary energy demand and water use in the automated drainage system and PD sets, both of which contain substantial amounts of PVC. The reliance on PVC reflects its clinical advantages, flexibility, transparency and durability, but its environmental and health risks are well documented (Larkin et al., 2025b). A similar material profile was observed in HD, where PVC based bloodlines and dialyser components contributed strongly to toxicity related impact categories.

Alternative materials such as thermoplastic elastomers (TPEs) and silicone have been proposed (Hosseini et al., 2021). These materials offer reduced toxicity risks and improved recyclability, though their adoption in clinical practice is limited. Barriers include regulatory approval, cost and performance validation in sterile environments. These barriers mirror those identified in HD procurement, indicating that material substitution challenges are shared across dialysis modalities.

International experience highlights the case for reducing PVC use in dialysis. In Australia, McAlister et al., (2024) found that PVC recycling could reduce emissions by up to 30%, though uptake remains limited (McAlister et al., 2024b). In Europe, pilot PVC collection schemes in hospitals have shown promise but are not yet standard practice. Without wider reform of product design, waste policy and recycling infrastructure, the toxicity impacts of PVC will remain a persistent challenge in dialysis sustainability (Larkin et al., 2025b).

Waste management was another major hotspot in the LCA, particularly for climate change and toxicity related impacts due to the incineration of clinical waste. In Italy, where this study was conducted, clinical waste is primarily treated through incineration. While incineration is effective at sterilising hazardous materials, it is energy intensive and contributes substantially to both carbon emissions and toxicity burdens (Larkin et al., 2025b).

Figure 3. 33 and Figure 3. 35 highlight waste related contributions across multiple product groups, with particularly high impacts in the automated PD set and drainage system. These products, composed of multi material plastics, are incinerated entirely, releasing harmful compounds into the environment (Larkin et al., 2025b). Waste related emissions influence by incineration of multi material plastics impact both PD and HD pathways.

Alternative waste treatment technologies are available. Autoclaving, microwave sterilisation and mechanical shredding have been widely adopted in some healthcare systems to reduce reliance on incineration (Lee et al., 2022). These methods consume less energy and avoid the release of persistent pollutants. Reclassification of certain PD waste streams could further reduce reliance on incineration. While these alternatives show potential, their feasibility depends on local regulation, infection prevention requirements and the ability to separate low risk waste streams.

Emerging thermal treatments such as plastic pyrolysis offer another potential pathway, converting mixed dialysis plastics into secondary fuels or chemical materials rather than ash and flue gases. Optimisation scenarios from Duane et al., (2025) suggest that, when powered by low carbon energy and applied to suitable dialysis waste types, pyrolysis can reduce toxicity indicators and divert a proportion of PVC containing waste away from conventional incineration (Duane et al., 2025a). However, these technologies remain at pilot stage in healthcare and require careful assessment of emissions control, regulatory acceptance and overall life cycle performance before large scale adoption.

International comparisons reinforce the importance of waste management reform. In China, Chen et al., (2017) identified waste incineration as a major contributor to PD's carbon footprint, while in Australia, McAlister et al., (2024) highlighted the role of PVC incineration

in toxicity impacts (Chen et al, 2017; McAlister et al., 2024). These findings suggest that reducing reliance on incineration is a priority across global contexts.

Home based dialysis shifts waste generation from hospitals to households. In the Italian context, patient generated PD waste is collected by third party contractors and classified as clinical waste. This limits separate opportunities and results in recyclable packaging being incinerated alongside clinical materials.

Figure 3. 34 and Figure 3. 36 show that even small consumables, such as disinfectants and medical kits, contribute to emissions largely through packaging that ends up incinerated. Improved logistics and patient education could increase recycling rates. For example, non-contaminated outer cardboard boxes could be separated and recycled at the household level if clear protocols and collection methods were provided (Larkin et al., 2025b).

International evidence suggests that home based waste separation is feasible. In some UK pilot programmes, patients were provided with separate bins for recyclable and non-recyclable materials, supported by clear guidance and periodic collection. Such systems require alignment with infection control policies but have the potential to reduce both carbon and toxicity impacts.

In addition, innovations in circular supply chains, such as take back schemes for packaging or reusable transport crates, could be integrated into home based dialysis logistics. These models have already been trialled in other areas of healthcare procurement, demonstrating their feasibility and scalability.

The five hotspots identified here demonstrate that environmental burdens in PD are concentrated in a small number of products and lifecycle stages. Dialysate bags, packaging, transport, PVC based products, incineration and household waste collection systems consistently emerged as priority areas. Figure 3. 34 and Figure 3. 36 collectively illustrate this concentration of impacts, reinforcing the need for targeted interventions rather than scattered or generic strategies.

The concentration of impacts within a limited number of products and lifecycle stages has clear implications for procurement and service level decision making. Addressing these hotspots requires a combination of technological innovation (e.g. alternative materials, local dialysate mixing), systemic reform (e.g. waste reclassification, packaging rationalisation) and patient engagement (e.g. recycling protocols for home based waste). Such interventions align with broader healthcare sustainability goals, including those in the NHS Net Zero strategy and the EU Green Deal (Commission, 2019; NHS, 2020).

By identifying these hotspots, this study highlights where changes in dialysate formats, packaging design, transport logistics and waste treatment would have the greatest effect on the environmental footprint of PD (Larkin et al., 2025b). The main contributions from dialysate production, plastics and waste incineration is consistent with international PD LCAs, supporting the relevance of these findings beyond the Italian setting (Chen et al., 2017; McAlister et al., 2024b).

The HD procurement analysis reinforces the same structural pattern observed in PD, where a small number of consumables accounts for the majority of environmental impacts due to material intensity, transport requirements and incineration based waste management. This strengthens the interpretation that procurement impacts in dialysis are driven by system design rather than modality specific practice. This mirrors the PD procurement findings, where a limited number of high volume consumables similarly contributed to the overall footprint.

The procurement level analysis of HD consumables shows that targeted interventions on a handful of products can drive substantial reductions in environmental impact. Dialysers and bicarbonate cartridges together accounted for nearly 70% of procurement related carbon emissions in the Modena case (Larkin et al., 2026b). Acid concentrate bags and bloodline sets further contributed significant burdens. Addressing these products through redesign, alternative delivery models and improved material choices therefore represents a clear priority.

Dialyser optimisation remains one of the most challenging areas. The single use hollow fibre dialyser has been the subject of repeated debate concerning the balance between infection control, patient outcomes and sustainability. Historically, dialyser reuse was widespread in the

United States, with patients reusing dialysers for up to 20-30 sessions (Feldman et al., 1999a; Feldman et al., 1999b). While reuse reduced procurement volumes, it introduced new risks including infection, loss of membrane performance and exposure to sterilant chemicals (Lacson et al., 2011; Matos et al., 2000). By the early 2000s, most high income countries, including Italy, banned reuse due to concerns about patient safety. From an environmental perspective, reuse reduces material use but introduces additional chemical, energy and infection control burdens, limiting its suitability as a contemporary sustainability strategy (Agar, 2015a). Current consensus favours focusing on product redesign rather than reintroducing reuse (Arias-Guillen et al., 2024).

Recent improvements in polymer science offer some pathways forward. High performance dialyser housings manufactured with polycarbonate and polyurethane have been optimised for biocompatibility but remain complex multi material products (Covestro, 2024; Moshkbid et al., 2024). Transitioning to mono material designs could simplify recycling, while substituting PVC in headers and connectors with thermoplastic elastomers or polyolefins could reduce toxicity impacts at end of life (Moshkbid et al., 2024). Early stage studies into biodegradable membranes remain exploratory but indicate future potential (Ali et al., 2021; Haider et al., 2019). Similar material innovation challenges were identified in PD sets and drainage systems, indicating that polymer redesign represents a shared research priority across dialysis modalities.

Bicarbonate cartridges represent another high impact product. In Modena, each cartridge contributed 198 kg CO_2-eq annually, primarily from sodium bicarbonate production, plastic housings and transport (Larkin et al., 2026b). A key inefficiency lies in residual bicarbonate left unused at the end of sessions. Tailoring cartridge size or adjusting prescriptions to reduce waste could deliver immediate savings. More transformative would be a shift to central bicarbonate supply systems (CSS), which mix bicarbonate on site from bulk powders. CSS eliminates single use cartridges entirely, reducing both material and packaging burdens. However, risks of bacterial contamination remain a barrier (Reddy et al., 2020). Implementation would require strict monitoring, but where feasible CSS aligns strongly with circular economy principles. This pattern is similar to PD dialysate bags, where residual unused fluid and packaging inefficiencies contribute substantially to avoidable waste.

Acid concentrate delivery also presents optimisation opportunities. Traditional 4.7 L acid bags are heavy and transport intensive, contributing disproportionately to freight emissions. Centralised acid distribution systems, such as those piloted in Modena, allow bulk preparation of acid concentrates on site, removing the need for single use bags (Di Chiaro et al., 2024; Larkin et al., 2025a; Tsai et al., 2025). This reduces plastic waste, packaging and transport weight, with life cycle benefits confirmed in comparative studies. Wider adoption of central acid systems could therefore represent one of the most effective strategies for reducing HD procurement footprints. The environmental impact is directly comparable to PD dialysate delivery, where transporting water based solutions rather than concentrates drives a large share of emissions.

Bloodline sets are particularly problematic due to their exclusive reliance on PVC tubing. Incineration of bloodlines accounts for both GHG and toxicity burdens (Lithner et al., 2011; Ljunggren, 1984; Nässberger et al., 1987). Substitution with PVC free alternatives has been slow, but manufacturers are beginning to trial TPE based bloodlines (Vinyl-Plus, 2021). Regulatory approval and clinical validation remain essential. Hospitals could accelerate adoption by introducing green procurement criteria that prioritise PVC free options once clinically available. This reinforces the wider finding across PD and HD that PVC is an impactful impact of toxicity related impacts due to its behaviour during incineration.

While dialysers, cartridges and acid bags account for the majority of impacts, smaller consumables should not be overlooked. Syringes, drapes, gauze and infusion sets contributed between 19 and 24 kg CO_2-eq annually each (Larkin et al., 2026b; Cheetham et al., 2013; Rizan et al., 2023). Though individually minor, their cumulative effect across thousands of sessions is substantial. In addition, items such as gauze demonstrated high water footprints due to cotton growing (over 320 m^3 per patient annually)(Leal Filho et al., 2024; McGain et al., 2010; Pollice et al., 2022). This shows the importance of examining agricultural supply chains alongside plastics. Sustainable cotton initiatives, recycled fibre alternatives, or reductions in single use textiles could all contribute to lowering impacts (Abtew et al., 2025; Neto et al., 2021). A similar effect was observed in PD, where small disposables and packaging items became significant when scaled across long term therapy.

Waste treatment is a defining factor in the environmental performance of HD procurement. In Italy, nearly all dialysis consumables are classified as hazardous clinical waste and sent to incineration (ARPAE, 2023; Zikhathile et al., 2022). This practice maximises infection control but eliminates opportunities for separation or recycling. As a result, outer packaging, cardboard boxes and protective films are destroyed alongside clinical items, despite negligible infection risk (EcoEridania, 2023). This pattern is summarised in Figure 3. 61, which contrasts the current all hazardous waste incineration pathway, with a reformed and very practical model based on at source separation and alternative treatment routes for sustainable materials. This waste profile closely reflects PD pathways, where incineration similarly increases both carbon and toxicity indicators.

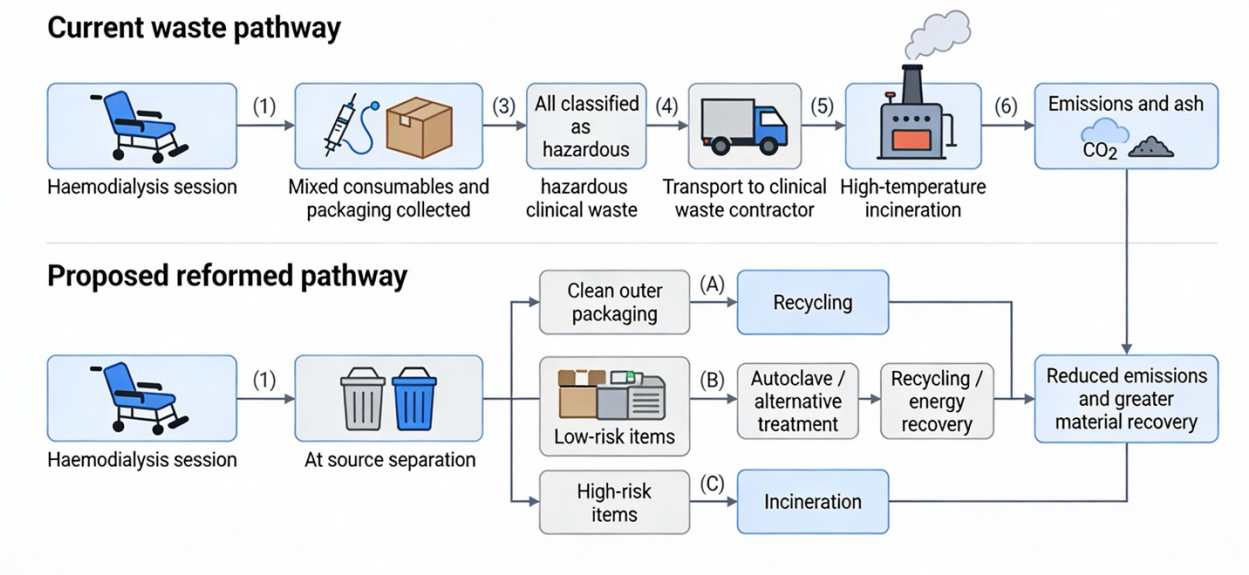

Figure 3. 61 Process flow for HD consumables under current and proposed waste pathways (Larkin et al., 2026b)

Within PD and HD several reforms could be considered. First, introducing separation at source to separate clean outer packaging from contaminated materials could allow recycling of large volumes of cardboard and plastic films (Goh et al.). Baxter pilot in PD recycling demonstrates that patients and staff are capable of separating waste streams with appropriate training and infrastructure (Baxter, 2024). Second, non-incineration treatment methods such as autoclaving, microwave sterilisation, or chemical disinfection could be applied to low risk consumables. Lee et al., (2022) reported that autoclaving reduced GHG emissions compared to incineration in hospital waste streams while maintaining safety standards (Lee et al., 2022).

Third, reclassification of certain consumables as non-clinical waste after appropriate treatment could open new recovery pathways. Pilot projects in Spain and Australia have explored recycling treated dialysis plastics into construction materials such as concrete (Create-Digital, 2018; Rahimireskati et al., 2021). Although small scale, these initiatives highlight the potential of waste improvement to turn an environmental liability into a resource stream. These approaches are similar to PD household waste pilots, supporting the feasibility of modality neutral waste reform.

The procurement and waste hotspots identified in Modena have system-wide implications for how healthcare organisations govern sustainability. The NHS Net Zero strategy recognises procurement as the single largest source of healthcare emissions, accounting for around 62% of the total footprint. Dialysis consumables provide a clear example of how a small number of products account for most impacts (NHS, 2020; Larkin et al., 2026b). Integrating LCA evidence into procurement contracts can encourage suppliers to reduce footprints through product design, packaging and logistics innovations (Keil et al., 2023; Lavoie et al., 2024; Sherman et al., 2018).

At the European level, policy frameworks such as the European Green Deal and the Circular Economy Action Plan set overarching goals for decarbonisation and resource efficiency in healthcare, including medical products and waste management (Commission, 2019). These sit alongside regulatory and technical standards. These include the EU Medical Device Regulation (2017/745) and ISO standards 14040, 14044, 13959 and 23500, which ensure safety, performance and robust environmental assessment (14040, 2006; 14044, 2006; 13959, 2014; ISO23500, 2019). Regulators are increasingly recognising the need to align these frameworks so that environmental criteria, such as carbon and toxicity, are incorporated alongside patient safety and device efficacy (Lokanathan, 2023). These frameworks provide a common policy context for both HD and PD procurement reform.

Within this policy context, healthcare providers and procurement agencies act as key operational areas. Embedding explicit sustainability criteria into dialysis tenders, supported by LCA or environmental product declarations, can shift demand towards lower impact consumables while maintaining compliance with safety and performance standards (NHS,

2020; Lavoie et al., 2024). Complementary actions include training staff in at source waste separation, implementing monitoring systems for water, energy and waste and engaging patients in home-based recycling where appropriate (De Simone et al., 2025; Duane et al., 2025). Multilevel collaboration between clinicians, procurement officers, waste managers and policymakers is therefore essential if the interventions proposed in this chapter are to move from isolated pilots to routine practice in sustainable nephrology (Mortimer et al., 2018). This role is particularly important in dialysis, where procurement decisions directly shape the majority of life cycle impacts.

Figure 3. 40, Figure 3. 41 and Figure 3. 42 collectively illustrate that the environmental burden of HD procurement is concentrated in a small set of consumables and life cycle stages. Dialysers and bicarbonate cartridges account for the majority of carbon and energy impacts, while gauze and cartridges drive water use. Bloodlines and acid bags add further burdens, particularly through PVC toxicity and transport emissions. Packaging and incineration offset these hotspots by preventing recycling and increase emissions (Larkin et al., 2026b; Hemberg et al., 2025; Piccoli et al. 2020; Tsai et al., 2025). This concentration of impacts mirrors the PD findings presented earlier, confirming consistency across modalities.

The evidence points towards a targeted strategy. Priority actions include redesigning dialysers and bloodlines to eliminate PVC, implementing centralised acid and bicarbonate systems where feasible, reducing packaging volumes, optimising transport logistics and reforming waste classification. These interventions align with broader healthcare sustainability strategies, including the NHS Net Zero target and the European Green Deal (Jiménez et al., 2024).

Comparing across categories, several consistent themes emerge. First, dialysate bags accounted for the majority of emissions in every way, carbon, energy, water and toxicity, due to their volume, packaging and transport requirements. Second, smaller consumables and multi material devices, while less significant in absolute terms, show disproportionate inefficiencies, especially when impacts are normalised by weight or functional output. Third, packaging emerges as a hidden impact across both energy and water categories, demonstrating the importance of rethinking not only core products but also their associated logistics systems

(Larkin et al., 2025b). When PD and HD results are considered together, several consistent themes emerge.

Together, the PD and HD analyses provide a clear map of procurement and waste hotspots that recur across dialysis systems.

Ultimately, procurement and waste optimisation in dialysis is not solely a technical challenge but a systemic one. Achieving meaningful reductions will require coordinated efforts across the supply chain, regulatory reform and cultural shifts in clinical practice. By embedding environmental impact assessments into procurement decisions, healthcare systems can move towards climate resilient nephrology that protects both patient outcomes and planetary health (Lavoie et al., 2024; Mortimer et al., 2018).

Alternatives exist. TPEs and silicones provide similar flexibility and mechanical performance without chlorine based degradation products. Hosseini et al., (2021) review a wide range of biodegradable and biocompatible elastomers suitable for healthcare (Hosseini et al., 2021). Biodegradable polymers are another area of exploration, although many remain limited by regulatory barriers and sterilisation performance (Haider et al., 2019). Substitution is not straightforward, but case studies in intravenous fluid bags and catheter devices have shown that PVC free designs can meet safety standards (Testai et al., 2016). These material pathways are equally relevant to PD tubing, drainage systems and connection sets.

The redesign study found mono material substitutions reduced incineration burdens by 25-35% relative to baseline designs. Incorporating pyrolysis as a waste strategy further improved outcomes by creating usable fuel and chemical feedstocks from post-consumer plastic waste (Duane et al., 2025a; Uzochukwu, 2021; Larkin et al., 2026d). These findings reinforce the importance of product redesign as a cross modality strategy rather than a technology specific solution.

Transitioning from PVC to alternative polymers requires compliance with the EU Medical Device Regulation (2017/745) and ISO 10993 biocompatibility standards (Council, 2017; ISO10993, 2018). Lokanathan (2023) emphasises that regulatory approval remains a barrier to rapid adoption of sustainable materials (Lokanathan, 2023). Nonetheless, pilot projects in

nephrology and other specialties indicate that co design with regulators is feasible, for example, reusable anaesthetic equipment and revised surgical kit layouts (McGain et al., 2014; Sherman et al., 2012). Incremental adoption, starting with low risk components such as connectors and tubing, may provide a pathway forward.

Packaging reform represents a relatively low risk intervention. Substituting recycled corrugated cardboard for virgin board reduces emissions by up to 40% (Ali et al., 2021). Lightweighting board grades without compromising structural integrity could achieve additional savings. Clearer labelling and improved waste separation would enable higher recycling rates, aligning with (EcoEridania, 2023) environmental declarations (Larkin et al., 2026d). This conclusion applies consistently to both home based PD supply chains and in centre HD logistics.

Localisation is not without challenges. Establishing regional manufacturing plants requires upfront capital and smaller production runs may reduce economies of scale. However, resilience and carbon savings may outweigh these costs over time, particularly as healthcare procurement agencies increasingly incorporate environmental criteria (Mortimer et al., 2018). Localisation therefore represents a shared opportunity across dialysis modalities where fluid volumes accounted for the majority of supply chains.

Dialysate accounts for more than half of PD's total emissions, with transport of prefilled 5 L and 2 L bags being a main impact. Each litre of dialysate is essentially water with added glucose and electrolytes, yet transporting such large liquid volumes results in both high carbon intensity and logistical inefficiencies. The contrast with HD, where concentrate mixing is routine, highlights the scale of avoidable emissions embedded in current PD fluid delivery models. This issue has long been recognised in HD, where local acid concentrate production and bicarbonate mixing are routine practices (Canaud et al., 2024; Larkin et al., 2025a). Extending this model to PD offers a promising intervention to eliminate the need for freight intensive prefilled bags (Larkin et al., 2026d).

Two approaches to onsite PD dialysate mixing are theoretically feasible:

- Hospital based compounding units: Dialysate would be prepared in centralised sterile facilities at hospitals and delivered to patients in refillable, reusable containers. This model mirrors practices in intravenous nutrition compounding and leverages existing pharmacy cleanroom capacity.
- Home based cartridge mixing systems: Compact devices could enable patients to generate dialysate from concentrated cartridges and tap water, provided appropriate purification (RO and sterilisation) is assured. describe technological options, including more flexible and locally prepared dialysis fluid systems, that could enable modular approaches to dialysate management in HD (Tsai et al., 2025; Zawierucha et al., 2023).

Both approaches would dramatically reduce transport emissions and packaging waste, since only concentrates and cartridges would need to be shipped, not full liquid volumes.

Despite these advantages, barriers remain. Ensuring sterility and consistency of dialysate solutions is critical for patient safety. The regulatory framework under ISO 23500 requires validated water quality and sterility assurance, which may be harder to maintain in decentralised home based systems (ISO23500, 2019). Moreover, patient acceptance, training and monitoring would need to be carefully considered (Connor et al., 2010a). Costs for equipment development and validation are also likely to be significant.

Nevertheless, experience from iPD prescriptions, where fluid volumes are gradually increased, suggests that flexible systems can be clinically feasible (Reddy et al., 2020). Onsite dialysate mixing represents one of the most transformative opportunities for PD sustainability if technical and regulatory hurdles can be overcome.

The procurement LCA Larkin et al., (2025) also demonstrated that Italy's reliance on incineration increases both carbon and toxicity burdens, particularly for PVC containing products (Larkin et al., 2026b). Clinical waste incinerators in Emilia Romagna typically operate at 850-1200 °C, consuming large amounts of fossil fuels and releasing hazardous byproducts (ARPAE, 2023). This reinforces the consistent role of incineration as a main hotspot across both PD and HD pathways.

Under current protocols, most PD related waste, including packaging, tubing and drainage sets, is classified as hazardous and incinerated regardless of infection risk. Evidence suggests that much of this waste is low risk. Used dialysate bags, for example, contain no blood and minimal pathogenic load compared with HD bloodlines. (Lee et al., 2022) argue that effective reclassification of such low risk items could enable diversion to less carbon intensive pathways, including autoclaving, microwave disinfection, or even municipal recycling home recycling initiative, which allows patients to separate plastic and cardboard for collection, provides proof of concept (Hassan et al., 2022; Baxter, 2024). The contrast between PD drainage waste and HD blood contaminated waste highlights the importance of risk based classification.

Beyond reclassification, pyrolysis offers a pathway to recover energy and chemical feedstocks from mixed plastic waste. Uzochukwu reviewed pyrolysis technologies, noting potential yields of 40-60% fuel oil equivalent from healthcare plastics (Wilson Uzochukwu, 2021). Larkin et al (2026) incorporated pyrolysis into redesigned scenarios, finding reductions of 10-15% relative to incineration, alongside improved circularity outcomes (Larkin et al., 2026d).

While still at pilot scale in the context of mixed plastic and medical waste treatment, pyrolysis has been trialled in several European and North American facilities as a route to convert plastic waste into secondary fuels or feedstocks (Brown et al., 2023). This approach is consistent with the EU Circular Economy Action Plan, which promotes higher value recovery of materials and reduced reliance on incineration and may offer a medium term option for dialysis plastics until dedicated closed loop medical recycling systems are developed (Commission, 2019).

Waste reclassification will only succeed with improved separation practices at both hospital and home levels. Patient education and provision of dedicated waste streams are essential and sustainability focused quality improvement projects have shown that behavioural interventions can substantially improve waste separation accuracy (Mortimer et al., 2018). Logistics systems must also adapt to collect waste separation materials cost effectively, a challenge that Baxter’s pilot programme attempts to address.

The procurement redesign analysis also showed that the APD machine contributed 151.7 kg CO_2-eq annually, with more than 130 kg attributable to electricity consumption. Although this represents a smaller share of the total than dialysate bags, it shows the importance of decarbonising the energy supply (Larkin et al., 2026d). This finding align with HD machine analyses, where electricity use accounted for the majority of machine level impacts.

Healthcare facilities in Europe are increasingly contracting renewable electricity, supported by solar, wind and hydro generation. Rayzon Solar (2024) report that onsite solar installations in hospitals can reduce grid dependence and contribute to energy resilience (RayzonSolar, 2024). If APD machines were operated under 100% renewable energy contracts, emissions from electricity use could be virtually eliminated.

The PD redesign study demonstrated this effect, emissions from the APD machine fell by 87% in redesigned scenarios, driven largely by renewable energy substitution and removal of unnecessary printed packaging (Larkin et al., 2026d). This finding aligns with global calls for hospitals to adopt green energy contracts as part of decarbonisation pathways (Karliner, 2020; McGain et al., 2014).

Beyond energy sourcing, there is scope to improve machine design itself. Lighter casings, modular components for refurbishment and reduced use of virgin plastics could all contribute to footprint reductions. Digitalisation could also reduce reliance on paper based manuals (Singh et al., 2025). These approaches would align with broader circular economy principles in medical device design (Sherman et al., 2018). Design for durability and refurbishment is relevant to both APD and HD machines.

While each intervention including product redesign, packaging reform, localisation, dialysate mixing, waste reclassification and renewable energy offers measurable savings individually, their combined effect is substantially larger. Scenario modelling undertaken by Larkin et al (2026) suggests that implementing all interventions simultaneously could reduce procurement related emissions by 20-40% per patient year (Larkin et al., 2026d). In high ambition scenarios including onsite dialysate mixing, reductions exceeded 50%.

These findings align with studies of PD in Australia and China, which also highlight material production, freight and waste as key hotspots (McAlister et al., 2024b; Chen et al., 2017). Arias-Guillen et al., (2024) similarly emphasise that addressing packaging, PVC and energy sources is essential for sustainable nephrology (Arias-Guillen et al., 2024). The evidence across different contexts suggests that these optimisation strategies are broadly applicable internationally. This comparison across countries and modalities strengthens confidence in the generalisability of the conclusions.

The proposed interventions support existing policy frameworks. The NHS Net Zero strategy (2020) prioritises sustainable procurement, while the European Green Deal emphasises circular economy measures (Commission, 2019; NHS, 2020). Mortimer et al argue that sustainability must be integrated into quality improvement, reframing value to include environmental outcomes (Mortimer et al., 2018). PD provides a clear test case where environmental optimisation aligns with patient centred care and system level policy objectives.

Clinicians are increasingly aware of the need for sustainable practices (Barraclough et al., 2020; Connor et al., 2010b). However, any redesign or reclassification must maintain safety and effectiveness. Concerns about infection risk from reclassified waste, or performance of alternative materials, must be addressed with strong evidence. Pilot trials of PVC free PD sets and autoclaved packaging are therefore essential. This reinforces the importance of integrating sustainability within existing clinical governance rather than treating it as a separate agenda.

Patients value home based treatment for independence and quality of life, but they are also exposed to large volumes of waste and packaging. Baxter's (2024) recycling initiative suggests that patients are willing to engage in separation if supported with convenient logistics (Baxter, 2024). Patient education programmes, combined with digital tools such as QR code based instructions, could further increase acceptability (Singh et al., 2025).

Manufacturers face both opportunities and risks. Transitioning to recyclable materials and renewable energy can include upfront costs but aligns with growing procurement requirements. Sherman et al demonstrated that life cycle costing can show long term savings when reusables

and recycling are adopted (Sherman et al., 2018). Early adoption could provide competitive advantage in tender processes.

Several areas require further research before interventions can be widely implemented:

- Material innovation: Bioplastics remain constrained by regulatory hurdles (Ali et al., 2021; Haider et al., 2019). Research into second generation feedstocks, such as lignocellulosic residues, could yield safe, durable and low carbon alternatives for PD products (Hassan et al., 2019; Yu et al., 2024).
- Circular economy pilots: Pyrolysis of PD plastics should be tested at scale in collaboration with waste companies. Eco Eridania (2023) has shown that regional waste processors in Italy are exploring advanced treatment methods, integrating healthcare plastics into these systems is a logical next step (Su et al., 2021).
- Dialysate mixing devices: Prototype home based systems must undergo clinical trials to confirm sterility and usability. Lessons from HD concentrate systems should inform PD adaptation (Canaud et al., 2024; Murcutt et al., 2024; Tsai et al., 2025).
- Digitalisation: Replacement of printed manuals with QR codes and digital training platforms could save tonnes of paper annually (Singh et al., 2025). The environmental trade-offs of electronic devices versus print materials need quantification (Joshi et al., 2024).
- Economic analyses: Cost effectiveness studies are needed to reassure procurement agencies. Mortimer et al., (2018) argues that sustainability must be integrated into value based care, which requires linking environmental savings with financial outcomes (Mortimer et al., 2018).
- Behavioural interventions: Trials of patient and staff education programmes should assess effects on waste separation accuracy and acceptance of redesigned products (Ashtari et al., 2020; Cayo-Rojas et al., 2023).

Clinical outcome evidence provides essential context for interpreting environmental findings. The CONVINCE trial reported lower mortality and higher Quality adjusted Life Years (QALYs) for high dose OLHDF vs high flux HD across diverse European centres (Blankestijn et al., 2023). This aligns with prior pooled individual patient data from four Randomised

Control Trails (RCTs) and earlier single trial evidence (Peters et al., 2016; Maduell et al., 2013; Schouten et al.,2025; Larkin et al., 2026a).

Table 3.12 analyses the shared procurement and waste interventions emerging from both the HD and PD analyses, linking environmental hotspots with policy and infection control considerations.

Table 3. 12 Alignment of dialysis procurement and waste interventions with policy and decontamination frameworks

Dialysis intervention	**Policy / strategy alignment**	**Decontamination / infection control link**	**Expected impact on hotspots**
PVC free bloodlines and dialysers	Supports NHS Net Zero supply-chain targets (NHS, 2020), consistent with EU Green Deal and Circular Economy Action Plan priorities for safer materials (Commission, 2019).	Must comply with existing biocompatibility, sterility and device regulations, no change to reprocessing workflows in most HD settings (Arias-Guillén et al., 2024).	Reduces toxicity and incineration burdens from PVC, while maintaining clinical performance (Agar, 2015) (Larkin et al., 2026a).
Central acid / bicarbonate preparation systems	Aligns with EU Circular Economy Action Plan by reducing single use packaging and freight, supports national and local decarbonisation plans (Commission,	Requires robust disinfection protocols, monitoring for contamination and clear decontamination policies for tanks and lines (Reddy et al., 2020).	Cuts plastic packaging and transport emissions from acid and bicarbonate concentrates (Larkin et al., 2025a; Tsai et al., 2025).

	2019; Di Chiaro et al., 2024).		
At-source separation of outer packaging and low-risk waste	Compatible with NHS and EU sustainability strategies that emphasise waste prevention and recycling (NHS, 2020; Commission, 2019).	Needs local infection control approval to define what can be declassified and sent to recycling after minimal handling or decontamination (ARPAE, 2023; McGain et al., 2014).	Diverts cardboard and plastic films from incineration, reducing waste related carbon and enabling material recovery (Baxter, 2024; Rahimireskati et al., 2021).
LCA informed tender criteria and environmental product declarations	Directly operationalises NHS Net Zero Supplier Roadmap and EU sustainable procurement guidance in kidney care (NHS, 2020; Rizan et al., 2021).	No direct change in decontamination practice, infection control remains a non-negotiable criterion alongside environmental performance (Sherman et al., 2018).	Shifts market towards lower impact products, addressing procurement and manufacturing hotspots (Sherman et al., 2018; Larkin et al., 2026a).
Local or regional manufacture of dialysate / concentrates	Consistent with circular economy goals and resilience agendas, reducing transport distances and packaging	Facilities must meet GMP, sterilisation and decontamination standards, may require updated local policies and	Decreases freight emissions and allows more efficient bulk packaging solutions (Larkin et al., 2025a).

	(Commission, 2019; Agar, 2015).	validation (Di Chiaro et al., 2024).	

Taken together, the PD and HD results show that dialysis impacts are concentrated in procurement and at end of life in waste treatment, with smaller contributions from modality specific operational differences. In PD, dialysate volume, freight and secondary packaging accounted for the majority of impacts, while PVC sets and incineration drive toxicity and additional carbon burdens. In HD, a small group of consumables, dialysers, bloodlines, bicarbonate cartridges and acid delivery formats, similarly account for the majority of procurement impacts, with packaging and hazardous waste incineration increase emissions and toxicity. The consistent pattern across modalities supports a targeted improvement agenda. Priority actions include redesigning high volume consumables for lower material intensity and reduced PVC, shifting from shipping water based fluids to concentrate or central mixing models where clinically feasible, reducing packaging mass and improving separation so that low risk materials avoid hazardous incineration. Embedding LCA evidence within procurement specifications and aligning waste pathways with infection control governance are therefore key areas for delivering meaningful reductions in environmental burden while maintaining patient safety and clinical outcomes.

3.5.2 Comparison with published life cycle assessments

These findings are consistent with published HD LCAs from Australia and the UK and with clinical evidence on OLHDF (Agar, 2015; Barraclough et al., 2024; Lim et al., 2013; Bendine et al., 2020; Tattersall et al., 2013; Blankestijn et al., 2023; Maduell et al., 2013; Peters et al., 2016; Larkin et al., 2025; McAlister et al., 2024; Rizan et al., 2021; Sherman et al., 2018). Table 3. 13 summarises how the Modena results compare with similar studies in terms of footprint magnitude, hotspot composition, water use and clinical implications.

Table 3. 13 Comparison of Modena HD/OLHDF findings with similar studies

Aspect	**Modena HD/OLHDF findings (this thesis)**	**Similar studies and evidence**	**Alignment/implication**
Magnitude (CO_2 eq)	Annual HD pathway 4.4-4.5 t CO_2 eq per patient-year (centre mix) (Larkin et al., 2026a).	Australian and UK HD footprints typically 4-6 t CO_2 eq per patient-year (Agar, 2015; Barraclough et al., 2024; Lim et al., 2013).	Modena totals sit within the same range, supporting external validity of the pathway model.
Composition (hotspots)	Procurement and travel account for the majority of hotspots. Electricity, water and waste are smaller shares (Larkin et al., 2026a).	Device/pathway LCAs repeatedly identify consumables and travel as key hotspots (Larkin et al., 2025b; McAlister et al., 2024; Rizan et al., 2021; Sherman et al., 2018).	Confirms that focusing on consumables, logistics and transport is a generalisable strategy, not site specific.
Water use	OLHDF uses more product water per session than HD, but pathway level CO_2 eq difference is small (Larkin et al., 2026a).	European working group reports and practice note higher substitution volumes and water demand for OLHDF (Bendine et al., 2020; Tattersall et al., 2013).	Modena metering is consistent with clinical definitions. Water optimisation should accompany OLHDF roll out.

Clinical considerations	Environmental results show consistency between HD and OLHDF (<3% CO_2 eq difference), so modality choice can remain clinically led (Larkin et al., 2026a).	Trials and guidelines favour OLHDF on clinical outcomes in suitable patients (Blankestijn et al., 2023; Maduell et al., 2013; Peters et al., 2016).	Environmental data support continued clinical preference for OLHDF, provided system level decarbonisation proceeds in parallel.

In regards to HD Procurement, the findings from Modena (Larkin et al., 2026b) align closely with international evidence but also reveal regional characteristics. In the UK, (Connor et al., 2011) reported that consumables, particularly dialysers and dialysate, contributed nearly half of HD related emissions. Barraclough et al., (2020) found a similar pattern in Australia, with single use plastics dominating procurement related impacts (Barraclough et al., 2020). In Spain, Arias-Guillen et al., (2024) identified dialysis consumables and medical waste incineration as the two largest environmental hotspots in nephrology services (Arias-Guillen et al., 2024).

While the high impact products are consistent across contexts, the magnitude of impacts varies according to waste management systems, electricity mixes and procurement models (Table 3. 14). For example, Australia's coal heavy electricity mix increases emissions from machine operation (Malik et al., 2018). Whereas in Italy a strong reliance on clinical waste incineration increases toxicity related impacts (ARPAE, 2023; EcoEridania, 2023). In Scandinavian countries, higher rates of district heating and recycling reduce the proportional burden of consumable incineration (Blankestijn et al., 2018). These regional variations highlight the importance of conducting site specific LCAs rather than assuming generalisability across health systems.

Table 3. 14 Regional Causes of HD Consumable Impacts

Setting	Key driver of impacts from HD consumables	Illustrative effect	Source
Australia	Coal heavy electricity mix for dialysis centres	Higher emissions from machine operation and water treatment per session	(Malik et al., 2018)
Italy (Modena)	High reliance on clinical waste incineration	Greater toxicity related impacts from PVC and mixed plastic waste	(ARPAE, 2023; EcoEridania, 2023)
Scandinavia	Greater use of district heating and higher recycling rates	Lower proportional burden from consumable incineration and more energy recovery	(Blankestijn et al., 2018)

The Modena case demonstrates how procurement decisions and waste management protocols interact to determine total impacts. Despite having relatively low carbon electricity compared to Australia, the Italian system's strict hazardous waste classification results in nearly universal incineration of dialysis waste, thereby elevating the contribution of PVC related toxicity (Larkin et al., 2026b).

PD findings similarly require validation via pilot studies on PVC free PD sets, trials of home based dialysate mixing devices and expansion of recycling initiatives. Economic analyses are also needed to determine cost effectiveness and to support procurement agencies in integrating environmental criteria into tenders (Sherman et al., 2018).

Sustainability challenges in PD are not unique to Italy. Evidence from other regions confirms that procurement, transport and waste are universal hotspots.

Australia: McAlister et al (2024) measured the carbon footprint of PD and found that dialysate production and packaging were main contributors (McAlister et al., 2024b). Their modelling

suggested that recycling and PVC substitution could reduce emissions by up to 30%. This echoes the Italian results, where dialysate bags alone represented more than 50% of annual emissions (Larkin et al., 2026d).

China: Chen et al., (2017) compared home based and incentre PD, finding that home treatment had higher packaging and transport burdens but avoided staff travel and building energy use (Chen et al., 2017). They concluded that optimising packaging and reducing long haul freight could substantially cut emissions. This supports interventions such as localisation and onsite mixing.

United Kingdom: NHS analyses estimate that procurement represents 62-72% of total healthcare emissions, with medical consumables being a critical impact (NHS, 2020). Dialysis is consistently flagged as a high intensity area. The NHS has already introduced environmental criteria into tenders, requiring suppliers to report product carbon footprints. PD manufacturers will therefore face increasing pressure to adopt the kinds of redesign strategies outlined in the Modena studies.

Spain: Arias-Guillen et al., (2024) highlight HD waste as a major sustainability challenge. They argue for the integration of circular economy approaches, particularly recycling of plastics and packaging. These findings mirror Italian results and underline that Mediterranean healthcare systems share similar waste related burdens (Arias-Guillen et al., 2024).

The merging of international evidence shows that targeted interventions, particularly addressing dialysate bags, packaging, transport and PVC, are transferable across different health systems.

The European Green Deal emphasises decarbonisation, circular economy and reduction of single use plastics (Commission, 2019). The redesign of PD products using recyclable materials, mono material formats and renewable energy directly supports these goals. Incorporating pyrolysis or advanced recycling technologies also aligns with EU waste directives promoting recovery over incineration.

The NHS strategy (2020) explicitly states that procurement must achieve net zero supply chains by 2045 (NHS, 2020). PD products, which account for a disproportionate share of dialysis emissions, will be early targets for reform. Manufacturers who invest in redesign strategies now will be better positioned to meet these procurement requirements.

Countries such as Australia and Spain have integrated sustainability into nephrology quality frameworks (Arias-Guillen et al., 2024; Barraclough et al., 2020). Italy has yet to implement such explicit policies, but regional waste regulations already constrain disposal practices (ARPAE, 2023). By aligning PD optimisation strategies with these frameworks, Italy could take a leadership role in European green nephrology.

Table 3. 15 outlines how proposed optimisation strategies for PD align with existing European and national policy. The table links each intervention with its regulatory or policy framework, describes its contribution to sustainability goals and provides measurable indicators to track progress. Suggested benchmarks and timelines are included to highlight realistic targets for implementation, offering a practical roadmap for integrating environmental optimisation into PD procurement and care delivery. However, the implementation of these strategies must also be considered alongside patient safety and clinical risk, which are identified in later chapters as key constraints on adoption.

Table 3. 15 Alignment of PD optimisation strategies with policy instruments, measurable indicators and roadmap benchmarks

Optimisation Strategy	**Relevant Policy Instrument(s)**	**Alignment/Contribution**	**Measurable Indicators**	**Suggested Benchmarks**
Product redesign (PVC elimination, mono	EU Medical Device Regulation (2017/745), ISO 10993 biocompatibilit	Encourages substitution of PVC with safer alternatives, simplifies recycling and supports compliance with	% reduction in PVC use, % increase in recyclable components, number of	Reduce PVC use in PD products by 50% by 2030, achieve 80%

materials, recyclability)	y, EU Circular Economy Action Plan	biocompatibility standards.	mono material certified products.	recyclability of product components by 2035.
Packaging reform (lighter, recycled materials, optimised palletisation)	EU Packaging and Packaging Waste Directive (94/62/EC, amended 2018/852), European Green Deal	Reduces waste through recycled content and weight optimisation.	g CO_2-eq saved per kg packaging, % recycled content, % reduction in packaging weight per unit.	Use 70% recycled cardboard in packaging by 2028, reduce packaging weight per bag by 30% by 2030.
Localisation of production (regional manufacturing)	European Green Deal, EU Industrial Strategy	Cuts freight emissions, improves resilience of supply chains.	Reduction in freight distance (km), CO_2-eq saved per product, % of production within EU/region.	Relocate 40% of dialysate production to within 800 km of use by 2030, reduce air freight to <5% of PD logistics by 2028.
Onsite dialysate mixing	NHS Net Zero Plan (2020), EU Green Deal	Eliminates transport of large liquid volumes, reduces packaging.	Litres of dialysate mixed onsite, CO_2-eq saved compared with shipped	Pilot onsite mixing in 10% of European PD centres

			liquid, % packaging reduction per patient year.	by 2030, scale to 50% by 2040.
Waste reclassification (autoclaving, recycling of low risk waste)	National waste regulations (e.g. ARPAE), EU Waste Framework Directive (2008/98/EC)	Diverts low risk products from incineration, allowing recycling.	% of waste reclassified as non-hazardous, % increase in recycled waste streams, CO_2-eq saved per tonne diverted.	Reclassify 25% of PD consumable waste as non-hazardous by 2028, increase recycling of PD packaging to 70% by 2035.
Renewable electricity for APD operation and production	EU Renewable Energy Directive (2018/2001/EU), hospital decarbonisation policies	Supports decarbonisation of dialysis operations and supply chains.	% renewable electricity, CO_2-eq avoided per APD machine per year.	Achieve 100% renewable electricity for APD machines by 2030, ensure all PD suppliers use >80% renewables in manufacturing by 2035.

Circular waste treatment (pyrolysis, advanced recycling schemes)	EU Circular Economy Action Plan (2019), EcoEridania (2023)	Diverts plastics from landfill/incineration, recovers feedstocks.	Tonnes of PD plastics processed, % diverted from incineration, CO_2-eq saved vs baseline.	Divert 50% of PD plastics to pyrolysis or advanced recycling by 2032, scale to 90% by 2040.
Digitalisation (QR code instructions, reduced printing)	EU Digital Strategy, Sustainable Products Initiative	Cuts paper use, reduces packaging bulk, supports digital healthcare goals.	% reduction in printed leaflets, kg paper saved annually, adoption rate of digital resources.	Replace 75% of printed PD instruction leaflets with digital versions by 2028, achieve full digitalisation by 2035.
Home recycling schemes (e.g. Baxter pilot)	NHS Greener Delivery, Extended Producer Responsibility (EPR)	Expands recycling access to patients' homes, engages suppliers in circular systems.	% patients enrolled, tonnes of cardboard/plastics collected, recycling rate per household.	Roll out home recycling schemes to 50% of PD patients in EU by 2030, target 90% participation by 2040.

3.5.3 Limitations

The HD/OLHDF comparison has several strengths. It uses an ISO aligned LCA framework with clearly defined functional units and system boundaries, consistent with international standards (14040, 2006; 14044, 2006). Primary measurements were collected on site for machine electricity and RO water, bills of materials were constructed from actual consumable inventories, waste pathways were verified with the local contractor and modelling was performed consistently using Ecoinvent background datasets, with both LCIA water and operational litres reported (Wernet et al., 2016; Larkin et al., 2026a). The study also quantifies observed modality differences in electricity use (approximately 5.7%) and water use (around 27 L per session) rather than assuming equivalence between HD and OLHDF.

There are, however, important limitations. The analysis is based on single centre inputs for grid factor, practice patterns and logistics and travel distances are derived from proxy datasets rather than patient level Modena data (McGain et al., 2014; Larkin et al., 2026a). Vascular access and capital equipment are excluded, in line with convention for these therapies where they typically contribute less than 5% of total impacts, but this means the absolute totals are conservative estimates (McGain et al., 2014; Sherman et al., 2018). These constraints do not alter the central pattern that travel and procurement account for the majority of the pathway footprint and that modality choice is a relatively minor determinant compared with system level factors.

To support reproducibility and secondary use, the underlying life cycle datasets and product images for the HD/OLHDF study are available in an open repository (Zenodo), as cited in the paper's Supplementary Material (Larkin et al., 2026a). This data transparency allows other researchers and service planners to inspect assumptions, adapt parameters to their own settings and extend the analysis to additional scenarios or impact categories.

The PD pathway assessment shares the single centre constraint, capturing Modena's specific home based APD practices rather than a representative Italian or European patient population (Larkin et al., 2026c). Unlike hospital HD, PD lacks direct onsite metering for home electricity/water, relying on manufacturer specifications and patient diaries, introducing higher

uncertainty around real world appliance efficiency and drainage losses. Consumables bills of materials depend heavily on supplier provided compositional data, carrying risks of over optimistic recycling credits or misclassification of plastic grades, as noted in recent Italian PD procurement LCAs (Larkin et al., 2025b). The analysis excludes CAPD/APD technique mix effects and peritonitis related drop-out rates (typically 20% within 2 years) (Li et al., 2022) underestimating lifetime environmental burdens compared to incremental PD pathways that extend therapy duration (Nardelli et al., 2025). Ecoinvent regionalisation proves particularly weak for Italian plastics production and hazardous waste incineration pathways, where site specific dioxin emissions and energy recovery rates diverge significantly from global averages (Ecoinvent, 2024).

Neither PD nor HD analyses conducted formal sensitivity testing around multi-functional process allocation (e.g., shared hospital electricity, waste co-incineration), representing a standard limitation of attributional LCAs where practitioner choices influence results by up to 30% (Decerna, 2025).

3.6 Summary and recommendations

3.6.1 Key implications and research priorities across peritoneal dialysis and haemodialysis

The Modena HD/OLHDF pathway analysis has revealed several priority areas where further research and development are needed to turn environmental insights into practice. These research directions span methodological improvements, procurement and supply chain innovation and health system implementation.

Research methodology and generalisation

Repeating the Modena LCA in dialysis units across different European countries, electricity grids, waste treatment systems and geographic contexts will establish whether the relative importance of travel, procurement and water is consistent or region specific. This is important for claiming generalisability and for tailoring recommendations to local conditions (Larkin et al., 2026a).

The current analysis focuses on climate change, water use and energy use. Complementary LCA studies should quantify particulate matter, toxicity, land use and other categories relevant to nephrology supply chains and waste incineration, to identify potential trade-offs or co benefits (Rizan et al., 2021; Sherman et al., 2018; Larkin et al., 2026a).

Procurement and product innovation

Pilots of key interventions, such as RO efficiency upgrades, reject water reuse systems, EV minibus fleet deployment and reduced flow OLHDF protocols, should be evaluated using the same LCA methodology, with repeat measurements before and after implementation. This will confirm whether modelled reductions are reflected in real world practice and will generate site specific data to refine the Modena pathway model (Larkin et al., 2026a).

Dedicated studies are needed to assess the viability and environmental benefit of lighter dialyser and bloodline sets, alternative polymers (TPE, silicone), centralised fluid preparation systems and waste to value options such as pyrolysis or advanced recycling (Agar, 2015; Bendine et al., 2020; Larkin et al., 2026a). These should include cost benefit analysis and clinical safety validation to support regulatory and procurement decisions.

Health system integration and clinical outcomes

Future work should link environmental footprint data to clinical outcomes, using metrics such as carbon per quality adjusted life year (QALY) saved for different modality and delivery system options. This will enable procurement and policy makers to balance environmental and clinical priorities transparently (Blankestijn et al., 2023; Schouten et al., 2025; Larkin et al., 2026a).

PD pathways present distinct environmental findings compared to centre-based HD OLHDF. These findings from Modena are consistent with international evidence. In China, bag manufacture and transport have been identified as impactful PD hotspots (Chen et al., 2017). PVC recycling in Australia has been estimated to reduce PD related emissions by around 30% (McAlister et al., 2024b). In the UK NHS analyses, they indicate that procurement of consumables accounts for most dialysis related emissions (Al-Hadithy et al., 2024). Taken together, these cross setting studies suggest that PD environmental hotspots are broadly similar worldwide, supporting the case for shared procurement and design guidelines for greener dialysis.

Reduction strategies include the use of lighter cardboard grades, which reduce both material intensity and transport emissions and the incorporation of higher recycled content. Closed loop recycling systems, where uncontaminated outer packaging is separated at the point of use and returned to the supply chain, would further reduce impacts. For example, the UK NHS has implemented packaging take back schemes in some medical device and pharmaceutical supply chains, such as returning outer cartons and delivery crates to suppliers for reuse demonstrating that such models are feasible when logistics and infection control protocols are carefully aligned (Al-Hadithy et al., 2024). An additional strategy is packaging rationalisation. Rather

than shipping dialysate bags individually boxed, bulk packaging could be used, reducing the ratio of packaging to product. This approach has been trialled in HD supply chains with success, lowering both carbon and cost impacts (Larkin et al., 2025a).

Focusing on product redesign, packaging optimisation, waste reclassification and localisation of production provides the clearest pathway towards sustainability. These results not only advance nephrology specific strategies but also illustrate how LCA can highlight cross cutting issues of single use plastics, packaging and incineration that affect healthcare systems more broadly.

3.6.2 Product level and system level recommendations

PD offers clinical and social advantages as a home based therapy but with a significant environmental footprint. Both pathway level and product level LCAs show that a small set of consumables, particularly dialysate bags and PVC based drainage systems, influence impacts across multiple environmental categories.

Bringing together the procurement LCA, the product redesign study and international evidence point to a staged set of opportunities for more sustainable PD.

Immediate opportunities (0-3 years):

- Switch to recycled and lighter secondary packaging materials.
- Replace printed manuals with digital information accessed via QR codes.
- Power APD machines with renewable electricity where available.
- Expand patient recycling schemes for cardboard and suitable plastics.

Medium term opportunities (3-7 years):

- Transition from PVC toward thermoplastic elastomers and silicone in tubing and drainage systems.
- Pilot pyrolysis of selected PD plastics with regional waste companies.

- Establish hospital-based dialysate compounding units to shorten supply chains.

Long term opportunities (7-15 years):

- Use home-based cartridge mixing systems for dialysate.
- Scale up bio-based plastics from second generation materials.
- Implement closed loop recycling supported by producer responsibility schemes.

In HD, major consumables such as dialysers, bloodlines and bicarbonate or acid concentrates account for most carbon, energy and water impacts, with machine electricity and water treatment contributing substantially at the unit level (Larkin et al., 2026b). Vascular access devices and minor disposables are comparatively small contributors in absolute terms but can show high impacts per unit mass or procedure because of complex materials and strict waste handling. These patterns suggest that procurement efforts should prioritise optimisation of fluids and core consumables, alongside efficiency gains in water treatment and machine operation, rather than focusing primarily on low-volume items (Larkin et al., 2026b).

To guide practice and connect this chapter with subsequent work in the thesis, the following HD specific recommendations are proposed:

- Replace bagged acid concentrates with on site preparation systems, where possible, to reduce plastic waste and freight emissions (Di Chiaro et al., 2024; Larkin et al., 2025a).
- Prioritise PVC free designs for dialysers and bloodlines as they become clinically available, supported by LCA and toxicity evidence (Agar, 2015; Arias-Guillén et al., 2024).
- Implement at source waste separation and alternative treatment pathways for suitable waste streams to divert packaging and low risk plastics from incineration (Lee et al., 2022; Rahimireskati et al., 2021).
- Embed LCA based criteria and environmental product declarations into dialysis tenders and governance processes to shift supplier incentives towards lower impact products (Sherman et al., 2018; Lavoie et al., 2024).

The Modena Granumix analysis shows that replacing single use liquid acid bags with the Fresenius Granumix central delivery system reduces environmental burdens across a wide set of indicators. Climate change falls by about 30% per treatment. Acidification and freshwater ecotoxicity decrease. Particulate matter and photochemical oxidant formation fall. Land use drops because corrugated board and pallets are no longer required at large scale. Hazardous plastic waste is reduced by more than 80%. The per treatment differences scale to tens of tonnes CO_2 eq avoided each year in a medium sized European unit. These improvements come without compromising fluid quality or the clinical workflow when appropriate quality management is in place. The intervention aligns with health system decarbonisation plans and with European policy priorities for waste prevention and reuse. It addresses a procurement hotspot identified in the HD consumables profile and provides a clear, implementable pathway for measurable improvement (Larkin et al., 2025a).

3.6.3 From evidence to implementation: Why chapter 4 matters

The LCA results presented in this chapter identify where environmental burdens arise across dialysis pathways. Across both PD and HD systems, impacts are concentrated in procurement activities, high volume single use consumables, transport logistics and end of life waste treatment. Quantitatively, these categories account for approximately 70 to 72% of total pathway emissions. The findings provide a robust evidence base for identifying priority hotspots and comparing relative contributions across modalities and products.

While these results clearly demonstrate where emissions occur, they do not explain why current practices persist across kidney services despite increasing awareness of sustainability goals. LCA provides structured quantification of material and energy flows but does not capture the institutional processes through which procurement decisions are made, waste streams are classified or clinical risk is interpreted. As a result, environmental modelling alone is insufficient to explain the persistence of carbon intensive systems within routine care delivery.

Many of the main hotspots identified in Chapter 3 reflect organisational and governance structures rather than technical inefficiency. Procurement emissions are shaped by tender

frameworks, supplier contracts and regulatory compliance requirements. Waste related impacts are driven by infection prevention policies and conservative risk classification that favour incineration. Transport emissions reflect commissioning arrangements, service configuration and scheduling practices. These are not failures of technology but outcomes of decision making processes embedded within healthcare systems.

The Modena findings therefore raise questions that cannot be answered through further LCA refinement. Why are lower impact alternatives rarely prioritised? How do infection control requirements influence material choice? What limits experimentation with reusable systems or alternative waste pathways? Where responsibility for environmental performance is located within renal services? Addressing these questions requires investigation beyond quantitative modelling.

Chapter 4 responds to this gap through qualitative research with 25 European kidney care stakeholders. These include clinicians, nurses, procurement professionals, industry representatives and policy actors. The interviews explore how sustainability is understood in practice, how environmental responsibility is distributed and how trade-offs between safety, cost and carbon are negotiated within real service contexts.

The qualitative findings provide interpretive depth for the LCA results. They explain why procurement account for the majority of emissions despite the availability of alternative products. They clarify how infection prevention priorities shape material use and waste handling. They reveal how financial structures and performance metrics marginalise environmental considerations within routine decision making. In this way, Chapter 4 provides the social and organisational context required to interpret the environmental hotspots identified in Chapter 3.

This integration of quantitative and qualitative evidence is essential for moving from measurement to intervention. Without understanding behavioural, institutional and regulatory constraints, proposed sustainability solutions risk remaining theoretical or non-implementable. The stakeholder perspectives presented in Chapter 4 therefore form the foundation for the design principles and system level interventions developed in Chapter 5.

Together, Chapters 3 and 4 establish both the environmental problem and the conditions that shape possible responses. The LCA identifies what must change. The qualitative analysis explains why change has been limited to date. This combined evidence base enables Chapter 5 to propose solutions that are grounded in clinical reality, procurement practice and governance structures rather than abstract optimisation alone.

Chapter 4: Stakeholder perspectives and implementation barriers

4.1 Introduction

4.1.1 Rationale for a qualitative approach

The environmental impact of healthcare is increasingly well described through quantitative methods such as LCA, material flow analysis and carbon footprinting. Studies applying these approaches to KRTs, including HD and PD, have demonstrated the high levels of resource use and GHG emissions associated with consumables, water, energy and waste treatment (Agar, 2015a; Connor et al., 2011; Larkin et al., 2025b; Piccoli et al., 2015). These assessments quantify the impact of environmental burdens and allow comparison between products or processes under standardised conditions. For example, Chapter 3 of this thesis showed that procurement contributes a significant amount of the carbon footprint for HD, with dialysers, bloodline sets and dialysate delivery formats identified as main contributors. Such findings are essential for identifying hotspots and guiding prioritisation, yet they are not sufficient for explaining why these burdens persist, why alternatives are difficult to implement, or how clinical, organisational and policy contexts shape the feasibility of change.

Qualitative approaches are one method used to complement quantitative models by uncovering the social, organisational and political areas of sustainability in healthcare (Pope C, 2020). While an LCA can demonstrate that dialyser plastic contributes several hundred kilograms of carbon dioxide equivalents per patient per year, it cannot explain why hospitals continue to purchase devices that are difficult to recycle, why procurement frameworks fail to reward lower impact alternatives, or how clinicians perceive the risks and benefits of product reuse. Semi structured interviews with expert stakeholders have the potential to bring out such insights, providing a better understanding of the system and supporting implementation strategies that address both technical and human factors (Green J, 2018).

The integration of LCA and qualitative research reflects the principle of mixed methods. Quantitative methods provide numerical precision, standardisation and comparability across sites, while qualitative approaches provide depth, context and explanation of behaviour (Creswell JW, 2018). Mixed method designs are increasingly promoted in health services research for addressing complex, multi layered problems where neither numbers nor narratives

alone are sufficient (O'Cathain et al., 2010). In the case of sustainable kidney care, quantitative evidence identifies the what of environmental impact, while qualitative evidence demonstrates the why and how.

This mixed methods approach has been applied in other areas of health and environment. For instance, McGain et al (2014) argued that hospital sustainability requires both quantitative evidence of environmental burden and qualitative understanding of organisational culture and clinical practice (McGain et al., 2014). Without attention to the latter, even technically optimal solutions fail to be used.

The argument for a mixed methods approach is particularly strong in kidney care because treatment pathways are highly resource intensive, tightly regulated and embedded in clinical routines. Small changes, such as reducing dialysate flow rates or separating low risk plastic waste, may have large impacts but face cultural, organisational and regulatory barriers. These barriers cannot be identified or addressed by LCA alone.

For this reason, Chapter 4 adopts a qualitative design to examine how environmental sustainability is explained and acted upon by key stakeholders within kidney care systems. By engaging clinicians, procurement professionals, industry representatives and policymakers, the study explores how decisions are shaped by institutional responsibility, perceived clinical risk, financial constraints and regulatory accountability. This approach allows examination of the gap between environmental evidence and real world practice, providing insight into why known hotspots persist despite available data and established sustainability targets.

This qualitative focus recognises that dialysis sustainability is not determined solely by technology or product design, but by how responsibility for environmental action is distributed across organisations and professional roles. Understanding these perspectives is necessary for turning LCA findings into implementable strategies. The qualitative analysis presented in this chapter complements the quantitative evidence in Chapter 3 by addressing the social and organisational conditions that influence whether environmental improvements are adopted, delayed or resisted in practice.

4.1.2 Understanding barriers to sustainable practice

A further rationale for qualitative inquiry is the need to capture how different people working in and affected by kidney care experience it. Clinicians, patients, procurement officers and waste managers all experience sustainability interventions differently. Their perspectives shape acceptance, resistance and adaptation, which in turn determine whether innovations succeed. For example, a centralised acid delivery system may reduce packaging waste and transport burdens, but if nurses perceive it as adding workload or infection risk, it may not be adopted regardless of LCA results (Murcutt et al., 2024). These differences often relate to perceived workload, clinical risk, accountability structures and uncertainty around regulatory responsibility.

Qualitative interviews allow these perspectives to be documented systematically. Semi structured formats encourage participants to describe not only what they do but why, including tacit knowledge and values that often remain unspoken in quantitative surveys (Patton, 2015). In sustainability research, this helps reveal trade-offs between clinical safety and environmental goals, perceptions of responsibility across professional groups and experiences of working under regulatory uncertainty (Rizan et al., 2021). Such insights are essential for designing feasible interventions that are aligned with professional cultures and patient safety instructions. The interviews in this thesis therefore purposively sampled clinicians, managers and procurement leads to capture these different experiences of sustainability interventions in kidney care.

Healthcare sustainability is a classic example of a complex system problem. It involves multiple processes, feedback loops, regulatory frameworks and interdependencies across scales. Systems thinking literature emphasises that complex problems cannot be solved by reduction metrics alone, they require exploration of stakeholder perspectives, emergent patterns and leverage points (De Savigny et al., 2009; Meadows, 2008). Qualitative methods are particularly suited to this because they allow exploration of context specific dynamics and capture how different parts of the system interact.

In kidney care, for example, procurement rules are influenced by EU directives, national health service policies, hospital budgets and supplier lobbying. Waste treatment is shaped by infection control law, municipal contracts and local infrastructure. Energy use depends not only on machine efficiency but also on building services and national electricity mixes. Interviews with stakeholders across these areas provide a systems level picture that complements the product level focus of LCA. By linking narratives to quantitative hotspots, it becomes possible to identify change points that are both technically impactful and institutionally feasible.

Another rationale is that qualitative research generates actionable knowledge for policy and practice. Implementation science emphasises that evidence based interventions require adaptation to local context and that barriers and facilitators must be understood before scaling (Damschroder et al., 2009). In the case of sustainable kidney care, qualitative interviews identify where guidelines conflict with practice, where staff lack training or time and where leadership or policy support is missing. Such knowledge supports design of interventions that are more likely to be adopted and sustained.

For example, if interviews reveal that waste separation bins are poorly placed relative to workflow, redesigning bin layouts may bring larger benefits than introducing new technologies. If procurement officers describe lack of expertise in interpreting environmental claims, then capacity building becomes a priority. These insights ensure that the recommendations from LCA do not remain abstract but are turned into feasible actions. These considerations informed the design of the interview topic guide and the focus on practical implementation questions in this study.

The NCSH audits done at KitNewCare sites (Utrecht, Warsaw, Madrid, Modena) complement this approach. They looked at actual energy use, waste sorting and procurement gaps on site. This matches up the numbers from LCA with what's really happening in clinics day to day. Audits found things like too much infectious waste being incinerated and RO systems wasting water which are similar hotspots the LCA showed. So together, the LCA displays the bigger picture. interviews revealing behavioural barriers and audits highlighting site specific priorities for action.

Together, these considerations support the use of qualitative interviews to examine sustainability as a lived and negotiated practice within kidney care systems. Understanding how barriers operate across professional roles and organisational levels provides the necessary foundation for the methodological approach outlined in the following section.

4.1.3 Research questions for stakeholder engagement

This study uses focused research questions to turn environmental evidence into implementable system level insight.

This qualitative study addresses three core questions:

- What are the primary barriers and enablers to implementing sustainable kidney care practices?
- How do clinical priorities, procurement constraints and policy frameworks interact to shape sustainability outcomes?
- Which sustainability interventions are viewed by stakeholders as feasible within current clinical, procurement and regulatory constraints?

These questions informed the interview topic guide, directing attention toward operational barriers, decision making constraints and areas where environmental evidence fails to turn into routine practice.

Sustainability transitions in healthcare require legitimacy across professional groups and sectors. Engaging stakeholders through qualitative interviews not only generates data but also encourages dialogue, awareness and ownership of the problem. Stakeholder engagement supports the legitimacy of sustainability research by recognising professional experience as a form of evidence and by situating proposed interventions within existing clinical and organisational structures. This participatory aspect improves the legitimacy of subsequent recommendations and aligns with the principle of coproduction in health research (Rycroft-Malone et al., 2016).

In the KitNewCare project, stakeholders from across Europe were recruited, including clinicians, sustainability experts, procurement officers and policy advisors. Their voices provide credibility and diversity, ensuring that the analysis is not seen as externally imposed but grounded in professional and organisational challenges (Larkin et al., 2026e). This approach is consistent with EU commitments to participatory policymaking and stakeholder driven sustainability transitions (Commission, 2019).

Together, these research questions define the focus of Chapter 4 by linking environmental hotspots identified in Chapter 3 with the organisational and behavioural conditions required for implementation.

4.2 Methods

4.2.1 Semi structured interview design

This qualitative study used semi structured interviews with 25 expert stakeholders from seven European countries, including nephrologists, dialysis nurses, hospital managers, procurement specialists and sustainability leads. Participants were recruited via professional networks and the KitNewCare consortium, with invitations sent by email and follow up snowball sampling to capture additional perspectives. Interviews were conducted online using secure videoconferencing platforms, lasted between 30 and 75 minutes and were audio recorded and transcribed verbatim with consent.

Semi structured interviewing is widely regarded as a flexible yet thorough qualitative method, providing a balance between consistency across interviews and freedom for participants to elaborate on themes that they perceive as important (Patton, 2015; Pope C, 2020). The interview structure ensured consistent coverage of predefined areas including procurement, waste, water, energy and policy, while allowing participants to introduce issues emerging from their own professional experience.

Interviews were structured around a 30 question guide that was piloted with nephrology clinicians to ensure clarity and relevance. The interview guide was designed as a flexible framework rather than a fixed script. A core subset of questions was asked across all participants to ensure comparability, while additional questions and emphasis were adapted depending on stakeholder role. For example, clinicians were asked in more detail about clinical workflows and patient safety considerations, procurement specialists about tendering processes and supplier constraints and engineers and sustainability leads about infrastructure and resource management. This approach ensured both consistency across interviews and depth within specific areas. While all participants were asked a core set of questions, additional prompts were selectively emphasised depending on stakeholder role, for example procurement specific questions for purchasing staff and clinical workflow questions for nephrologists and nurses.

Development of the interview guide followed an iterative process linking LCA findings with established sustainability and health services research frameworks. The guide was informed by three sources:

- Findings from preceding LCAs (Larkin et al., 2025b; Larkin et al., 2026e).
- Key sustainability frameworks in healthcare, including the NHS Net Zero plan (NHS, 2020) and the EU Green Deal (Commission, 2019).
- Qualitative best practices for healthcare sustainability research (Green J, 2018).

The guide was divided into thematic clusters, such as waste management, procurement practices, barriers to innovation and policy root causes. This role-specific tailoring supported the thematic analysis by enabling comparison across shared themes while capturing differences in how sustainability challenges are experienced across stakeholder groups. Within each cluster, open ended prompts were used, for example: "Can you describe how local policies have either supported or minimised sustainability efforts in your experience?" or "What are some unexpected outcomes, both positive and negative, that you've encountered while pursuing sustainability?".

Table 4. 1 presents the structured interview guide used in this study. While all questions were available within the guide, they were applied selectively and adapted in emphasis depending on stakeholder group and interview context.

Table 4. 1 Semi Structured Interview Guide Used in Qualitative Stakeholder Interviews on Healthcare Sustainability (Larkin et al. 2026e)

General Sustainability Issues	**Primary Stakeholder Relevance**
1. Thinking about the whole of healthcare, what do you consider the most pressing issues in sustainability?	All Stakeholders

2. Can you describe how local policies have either supported or minimised sustainability efforts in your experience?	All Stakeholders
3. What actions at the national or EU level do you think could significantly impact sustainability improvements in healthcare?	Policy, Management
4. In your view, what educational investments are crucial for advancing sustainability in healthcare?	All Stakeholders
5. How can workforce development be aligned with sustainability goals?	Policy, Management
Waste & Procurement	
6. From your perspective, what are the biggest challenges related to waste management in healthcare settings?	Clinicians, Waste, Sustainability
7. Could you share some of the best practices you've observed or implemented for reducing healthcare waste?	Clinicians, Sustainability
8. What role does procurement play in your sustainability strategy?	Procurement, Management
9. How do you assess the environmental impact of the products you procure?	Procurement
10. What changes would you suggest to improve procurement processes to support sustainability?	Procurement, Management
Barriers & Facilitators	
11. What are the major barriers you face when trying to implement sustainable practices in your facility?	All Stakeholders
12. Can you discuss any policies or incentives that have effectively facilitated sustainability initiatives where you work?	All Stakeholders
13. How significant is the impact of travel related emissions in your overall sustainability plan for healthcare?	Management, Sustainability
14. What prevents you from making more sustainable travel choices in your personal or professional life?	All Stakeholders
Legislation & Policy	

15. What are the key regulations affecting sustainability in healthcare that you currently adhere to?	Policy, Management
16. Are there any legislative differences that impact sustainability practices across different regions or countries you are aware of?	Policy
17. How has legislation supported or hindered progress in sustainable healthcare practices in your experience?	Policy, Management
Knowledge & Transferability	
18. How well do you think healthcare stakeholders are informed about sustainability efforts?	All Stakeholders
19. Are there specific sustainability practices from kidney care that you believe could be successfully applied to other medical disciplines?	All Stakeholders
20. What do you identify as the key knowledge gaps in sustainability within the field of healthcare?	All Stakeholders
Future Vision	
21. If you had unlimited resources, what one thing would you change to make healthcare more sustainable?	All Stakeholders
22. Looking forward, what needs to change in healthcare across Europe to improve its sustainability?	All Stakeholders
23. How do you envision the future of sustainability in healthcare over the next decade?	All Stakeholders
24. What role do you see technology playing in advancing sustainability in healthcare?	All Stakeholders
Additional Questions for Depth	
25. How do you measure the success of sustainability initiatives in your organisation?	Management, Sustainability
26. Can you describe a project you led or participated in that significantly improved sustainability?	All Stakeholders
27. What are some unexpected outcomes, both positive and negative, that you've encountered while pursuing sustainability?	All Stakeholders

28. How do you engage with other healthcare professionals to promote sustainability practices?	All Stakeholders
29. What advice would you give to a healthcare facility just starting to explore sustainability?	All Stakeholders
30. How do you think patient care can benefit from improved sustainability practices?	Clinicians, Management

By using this design, the study was able to generate data that was both comparable across participants and sensitive to the specific contexts in which they worked. This was critical given the international scope of the project, which spanned seven EU member states, each with different health system structures, regulatory frameworks and cultural attitudes to environmental sustainability (Larkin et al., 2026e)

Semi structured interviews were selected to examine how sustainability knowledge is interpreted, prioritised and acted upon within real clinical and organisational settings. Sustainability in kidney care is not reducible to objective technical measures alone but is shaped by professional values, organisational routines and perceptions of risk. Interviews allow access to these areas, making visible how decision makers interpret their responsibilities and constraints (Ginn et al., 2019; Larkin et al., 2026e).

This approach generated rich qualitative data suitable for thematic analysis, allowing identification of recurring barriers, enablers and decision making logics that explain the persistence of environmental hotspots identified in Chapter 3.

4.2.2 Participant recruitment and ethics

Participants were purposively sampled to ensure breadth across roles and national contexts. This strategy ensured inclusion of stakeholders involved at different stages of dialysis delivery, from clinical decision making to procurement and waste handling. Recruitment targeted six main groups. These include nephrologists, dialysis nurses, hospital sustainability officers, procurement managers, waste management specialists and policy advisors. This multi stakeholder approach reflects the complexity of dialysis pathway, where environmental

impacts arise around clinical practice, procurement decisions and waste handling (Larkin et al., 2026e).

Initial contacts were established through professional networks associated with the KitNewCare project and the European Renal Association. Snowball sampling was then used, with participants recommending colleagues with relevant expertise. Recruitment continued until sufficient depth and repetition across themes was observed, consistent with established guidance on qualitative sample fairness (Guest, 2006; Larkin et al., 2026e).

In total, 25 participants were interviewed, representing seven countries. These include Ireland, the United Kingdom, Italy, Sweden, the Netherlands, Poland and Spain. Each participant had a minimum of five years of professional experience in their field and many were directly responsible for environmental or operational decision making within their institutions. This ensured that the perspectives captured were grounded in practical expertise rather than hypothetical reflection (Larkin et al., 2026e).

Ethical approval was obtained from Trinity College Dublin, School of Dental Science Research Ethics Committee (Ref: 2024-057). All participants were provided with information sheets detailing the study aims, data use and their rights. Written informed consent was obtained prior to participation. Participants were assured of anonymity, with transcripts labelled using numerical interview identifiers only, for example Interview 4. Interviews were conducted via Zoom and recorded with permission (Larkin et al., 2026e)

Data protection was ensured in line with the EU GDPR. Audio files were stored on encrypted institutional drives and transcribed word for word. Transcripts were anonymised before analysis and participants retained the right to withdraw their data until the point of analysis (Larkin et al., 2026e).

Researcher reflexivity was addressed by maintaining a field journal after each interview, noting impressions, contextual factors and potential biases. As the interviewer had a background in LCA and product design, this reflexive practice was important to minimise the risk of framing discussions too narrowly around technical solutions and to remain open to broader social and organisational insights (Larkin et al., 2026e). This reflexive approach supported precision by

ensuring that interpretations were grounded in participant accounts rather than prior assumptions from the quantitative modelling.

4.2.3 Thematic analysis process

Analysis followed the six step framework for reflexive thematic analysis described by Braun et al. (2021), which is widely used in health research. Transcripts were imported into NVivo 14 for coding, supplemented by Excel for cross case comparisons (Nowell et al., 2017; Larkin et al., 2026e).

Step one involved familiarisation with the data through repeated reading of transcripts and listening to audio files. Step two generated initial codes, both inductive (emerging directly from the data) and deductive (informed by prior literature on green nephrology and healthcare sustainability). Examples of inductive codes included “lack of recycling infrastructure” and resistance from clinical staff, while deductive codes included procurement regulations and circular economy potential (Larkin et al., 2026e).

Step three involved searching for themes, grouping codes into broader categories such as barriers to procurement reform, innovation enablers, and policy leadership gaps. Step four refined these themes by checking coherence against the dataset. Step five involved defining and naming the final themes, ensuring they captured both semantic content and underlying patterns. Step six produced the analytic narrative, linking themes to the study aims and existing literature (Larkin et al., 2026e).

Reliability was improved by double coding 20% of transcripts with a second researcher. Discrepancies were discussed and resolved, ensuring consistency of interpretation. Validity was strengthened through cross checking with grey literature, such as sustainability strategies from hospital trusts and policy documents from the European Commission (Larkin et al., 2026e).

By the 22nd interview, no substantively new themes were emerging and three additional interviews were conducted to confirm thematic stability. This aligns with methodological

guidance that saturation typically occurs between 20-30 interviews for diverse groups (Guest et al., 2006).

The use of NVivo facilitated systematic organisation of data, but Excel spreadsheets were also used to link themes with quantitative LCA findings from earlier chapters. For example, codes related to plastic waste burden were cross referenced with procurement hotspot data from the PD/HD LCA (Larkin et al., 2025b; Larkin et al., 2026b). This integration ensured that qualitative insights were grounded in the material reality of dialysis pathways and could inform actionable recommendations. This analytic approach enabled identification of barriers and enablers that directly informed the design principles and intervention pathways developed in subsequent chapters.

4.2.4 Integration with quantitative life cycle assessment

A key methodological innovation of this thesis was the integration of qualitative insights with quantitative LCA. This integration was not limited to validation. It followed an iterative sequence in which LCA findings informed interview design and interview findings were then used to interpret and contextualise quantitative hotspots. The LCA results identified single use consumables, transport and incineration as hotspots. The interviews explained why these persist, highlighting issues such as procurement frameworks that prioritise lowest cost, clinician concerns about infection risk and lack of investment in waste infrastructure.

This integrative approach aligns with mixed method models in sustainability research, where environmental metrics are complemented by organisational and behavioural insights (Creswell JW, 2018). It also responds to calls from nephrology societies to address not only the technical but also the cultural and policy areas of green dialysis (Piccoli et al., 2020).

Qualitative precision was addressed using Lincoln and Guba's (1985) criteria of credibility, transferability, dependability and confirmability (Lincoln, 1985). In this study, trustworthiness was supported through double coding of a sample of transcripts, maintenance of an audit trail of coding decisions, regular peer debriefing with supervisors and cross checking of interview findings with quantitative LCA results. Credibility was supported through prolonged

engagement with participants, iterative analysis and discussion of preliminary interpretations within the research team (Larkin et al., 2026e)

Transferability was improved by providing thick descriptions of context, allowing readers to assess applicability to their settings. Dependability was supported by maintaining a detailed audit trail of coding decisions and confirmability was strengthened through reflexivity and independent review of transcripts (Larkin et al., 2026e)

Peer debriefing with supervisors and coauthors provided additional assurance of reliability. Thematic outputs were cross referenced with LCA results to make sure that findings aligned with quantitative evidence while adding new explanatory depth.

Together, this integrated approach allowed the thesis to move beyond identification of environmental hotspots toward explanation of underlying decision structures. By linking quantified impacts with stakeholder accounts of constraints and priorities, the analysis provides a stronger basis for the intervention concepts and design responses developed in subsequent chapters.

4.3 Results: Key themes and stakeholder concerns

4.3.1 Participant characteristics and roles

To reiterate, this study included 25 expert participants from seven European countries: Ireland, the UK, Sweden, the Netherlands, Poland, Italy and Spain. The sample consisted of clinicians, policy advisors, procurement leads, waste management experts, sustainability managers and additional stakeholders with backgrounds in various healthcare disciplines. Five interviews focused specifically on the transferability of sustainability strategies from kidney care to other resource intensive healthcare areas (Larkin et al., 2026e).

Interview analysis identified seven overarching themes and 32 subthemes related to sustainability in healthcare, centred on kidney care. These themes included policies, key challenges, waste and circularity, travel and access, measurement, education and workforce development and visions for the future. Figure 4. 1 illustrates the thematic map, showing the relationships between themes and subthemes, which informed the reporting of results below (Larkin et al., 2026e).

This section presents the key findings from stakeholder interviews, organised by theme. Interpretation of these findings is developed in Section 4.4.

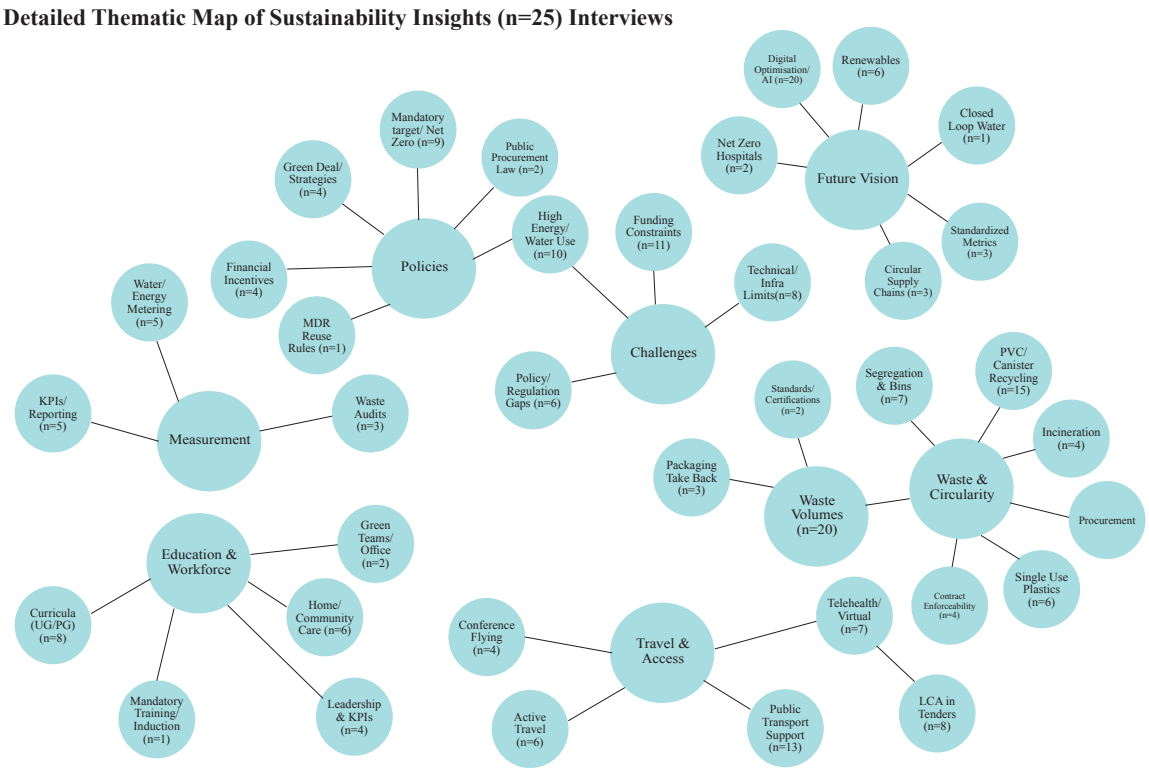

Figure 4. 1 Thematic map of sustainability insights from 25 expert interviews, showing seven overarching themes and their subthemes (Larkin et al.2026e)

4.3.2 Theme 1: Clinical vs environmental priorities

Participants consistently identified carbon emissions, waste generation and the high resource intensity of dialysis as central sustainability concerns. Water consumption and electricity demand were raised repeatedly, alongside the visibility of single use plastics within routine clinical practice (Larkin et al., 2026e).

“Plastic waste is everywhere in healthcare, not just dialysis, but it is most visible there” [Interview 6].

“Dialysis consumes huge amounts of water and energy, it is a glaring issue” [Interview 8].

“The pressure comes from both sides, more patients needing treatment and more scrutiny on environmental performance” [Interview 5].

“We know the impact is big, but in some areas there is still very little measurement or awareness” [Interview 2].

National and EU level policy frameworks were frequently described as important areas for sustainability action. Participants referred to instruments such as the EU Green Deal, waste directives and national climate strategies as providing legitimacy and external pressure (Larkin et al., 2026e).

“The EU Single Use Plastics Directive has forced suppliers to rethink packaging” [Interview 10].

“In Sweden, national waste segregation targets have really driven change, whereas in other countries it is left to individual hospitals” [Interview 3].

“Without clear enforcement, policies become nice words” [Interview 18].

“Our national health plan now has environmental Key Performance Indicators (KPIs), but there is no budget or training to deliver them” [Interview 21].

While sustainability goals were often articulated at policy or executive level, responsibility for implementation wasn’t clear. Alongside these challenges, participants expressed strong future oriented visions. These included net zero hospitals, circular procurement models and integrated water and energy systems (Larkin et al., 2026e).

“We need to measure success, otherwise it is just good intentions” [Interview 14].

“I see a future where every hospital has a sustainability dashboard, just like they have for finance” [Interview 6].

“A net zero hospital is possible, but it needs investment and political commitment” [Interview 22].

“If we design systems for circularity from the start, we save resources and reduce waste” [Interview 17].

4.3.3 Theme 2: Procurement constraints and cost driven decisions

“Without leadership commitment, sustainability projects just fizzle out” [Interview 12].

“We have passionate staff, but they do it in their own time because it is not recognised as part of the job” [Interview 7].

“If you put sustainability into performance reviews, it suddenly becomes a priority” [Interview 16].

“Involving staff in finding solutions makes them much more likely to follow new practices” [Interview 13].

Several sustainability practices developed in kidney care, such as reusable textiles, telemedicine to reduce travel emissions and packaging take back (Larkin et al., 2026e).

“The PVC take back model from dialysis could be used for other high volume plastics” [Interview 20].

“Telemedicine worked really well for kidney patients and could reduce travel for other outpatient care” [Interview 5].

“Reusable surgical gowns are standard in our dialysis units, but in other areas there is resistance” [Interview 3].

“To transfer ideas, you need champions in the new area who can adapt them to their workflow” [Interview 8].

4.3.4 Theme 3: Knowledge gaps and training needs

Waste separation, strict infection control requirements and insufficient recycling infrastructure were prominent barriers described by participants. Some shared examples of progress, such as

PVC take back schemes and heat recovery. However, implementation remains varied (Larkin et al., 2026e).

“We could recycle more if regulations were interpreted less rigidly” [Interview 15].

“In Italy, we have a PVC take back for dialysis tubing, but it only covers a few hospitals” [Interview 20].

“Segregation is still poor because the bins are not where they are needed” [Interview 11].

“Staff are worried about infection control if we start reusing certain items, even if there is evidence it is safe” [Interview 4].

“If sustainability is not in the tender, suppliers will not make it a priority” [Interview 9].

“In the Netherlands, we now ask for LCA data in tenders and that has shifted supplier behaviour” [Interview 1].

“Procurement teams need more training in what to look for when assessing environmental claims” [Interview 19].

“Suppliers can be slow to adapt unless there is a clear commercial reason” [Interview 14].

4.3.5 Theme 4: Systemic and governance barriers

Several participants highlighted that sustainability objectives are frequently articulated in national or EU level strategies but are weakly turned into operational requirements within hospitals.

“The EU Green Deal gives direction, but at hospital level nobody is clearly responsible for turning that into action.” [Interview 7]

“There are targets and ambitions, but no one owns them locally.” [Interview 12]

“Environmental goals are nice to have, but they are not treated like infection control or safety targets.” [Interview 4]

“If sustainability is optional, it will always lose when budgets are tight.” [Interview 19]

Many participants noted that sustainability investments require upfront capital, while savings often result elsewhere in the system or over longer timeframes.

“We are asked to reduce emissions, but there is no budget attached to that expectation.” [Interview 9]

“The problem is that sustainability savings do not come back to the department that makes the effort.” [Interview 15]

“Procurement law pushes you toward the cheapest compliant product, not the most sustainable one.” [Interview 11]

“Even when greener products exist, it is very difficult to justify them if they cost more.” [Interview 21]

Several respondents noted that environmental data supplied by manufacturers is inconsistent, difficult to interpret or not trusted, further limiting procurement teams’ ability to make informed decisions.

“We receive environmental claims, but no one is trained to assess them.” [Interview 6]

“There is a lack of standardisation in sustainability reporting from suppliers.” [Interview 18]

“Everything becomes infectious by default because nobody wants to take responsibility.” [Interview 2]

“Waste rules are written for safety, not sustainability and they have not kept pace with new evidence.” [Interview 14]

Procurement, infection control, facilities and clinical teams operate under separate governance structures, making coordinated change difficult.

“Sustainability sits between departments, so it falls between responsibilities.” [Interview 10]

“You need procurement, nursing, waste and management aligned, otherwise nothing moves.” [Interview 22]

“If sustainability was built into KPIs, behaviour would change quickly.” [Interview 5]

“We need the same seriousness for environmental metrics as we have for finance.” [Interview 16]

4.3.6 Summary of thematic findings

Across the interviews, a clear pattern emerged regarding how sustainability is currently understood and prioritised within kidney care and wider healthcare systems.

To support interpretation of the qualitative coding, term frequency analysis was undertaken. These topics were repeatedly raised across professional groups, suggesting shared recognition of their relevance and visibility in day to day practice. Figure 4. 2 presents these as a word cloud, visually contextualising their prominence.

Figure 4. 2 Most frequently mentioned best practices in healthcare sustainability (frequency weighted word cloud (Larkin et al. 2026e)

Participants repeatedly described waste as substantial, measurable and immediately observable, unlike carbon or supply chain emissions which remain unrealistic for many staff. Beyond overall frequency, differences emerged in how themes were discussed. Figure 4. 3 presents the distribution of references across three categories, challenges, existing best practices and future oriented aspirations. Examples included waste separation, reduction of over classification and improved staff awareness.

Participants often described structural limitations, strict regulations and lack of expertise as barriers preventing meaningful procurement reform. Education and workforce development were commonly framed as necessary foundations for future change rather than established systems.

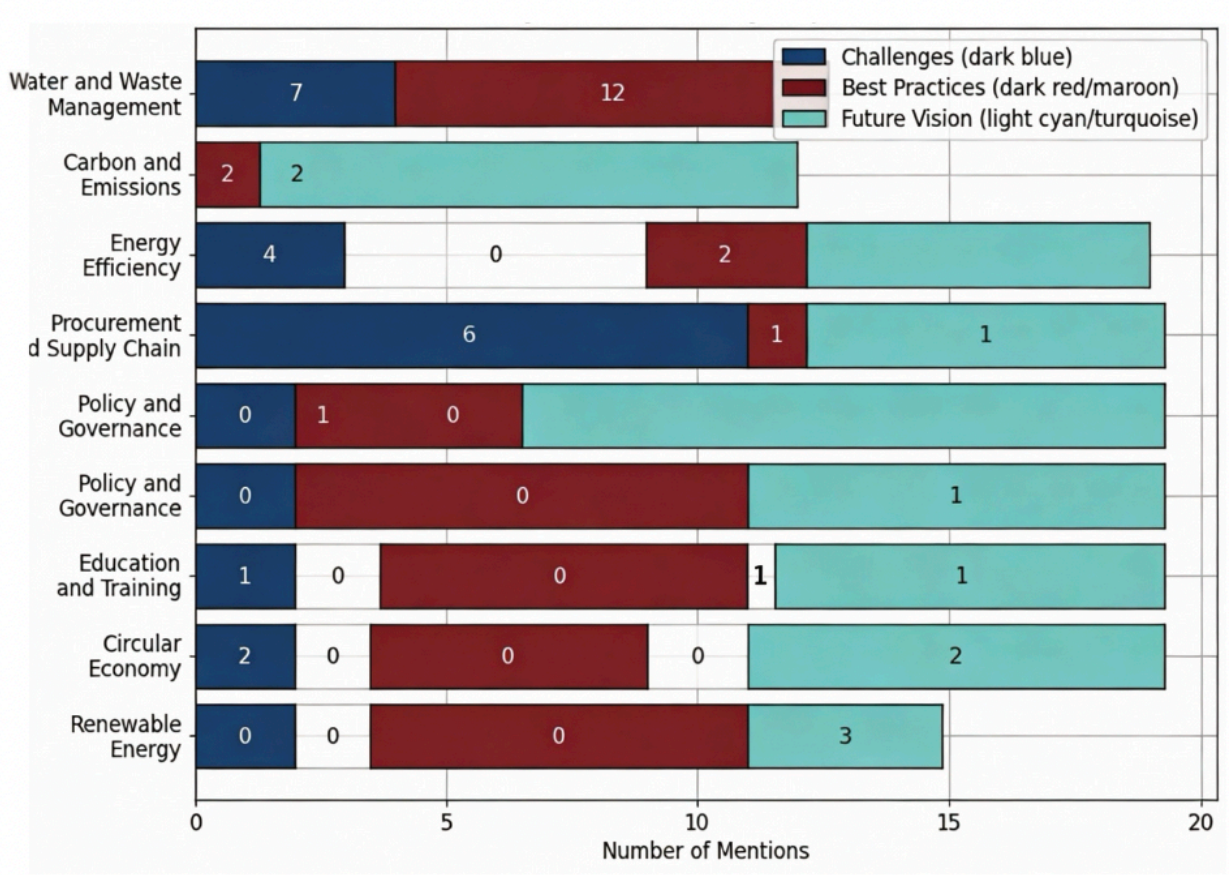

Figure 4. 3 Frequency of mentions for principal sustainability topics, grouped by challenge, best practice, or aspirational vision (n = 25 interviews) (Larkin et al. 2026e)

Topics such as waste separation and water efficiency were viewed as achievable within existing structures. Procurement reform, circular supply chains and system level redesign were recognised as higher impact but constrained by governance, funding and policy alignment. Quantitative analysis identifies procurement and transport as impactful root causes of environmental burden. Qualitative evidence shows that these same areas are viewed by stakeholders as the hardest to influence due to institutional and regulatory constraints. Waste emerges as a visible and actionable focus, procurement as a critical but constrained area and education as a necessary enabler for long term change.

4.4 Analysis: Integrating qualitative evidence

This section interprets the stakeholder findings presented in Section 4.3, focusing on how these perspectives explain the environmental hotspots identified in Chapter 3. While quantitative analysis highlights procurement, waste and resource use as the main contributors to environmental impact, stakeholder perspectives reveal the organisational and systemic factors that limit change in these areas.

Participants consistently described procurement systems, governance structures and funding mechanisms as key constraints. Procurement processes were characterised as cost driven and compliance focused, limiting the integration of environmental criteria even when lower impact alternatives exist. Similarly, waste management practices were shaped by infection control requirements and risk averse policies, often resulting in default classification of waste as hazardous.

These findings indicate that environmental hotspots persist not due to lack of awareness, but due to structural conditions within healthcare systems. Responsibility, limited measurement and weak accountability mechanisms reduce the capacity of organisations to act on sustainability evidence. This highlights the need for integrated approaches that align clinical, procurement and policy frameworks.

4.4.1 Stakeholder perspectives on environmental hotspots

The qualitative findings in this chapter provide an interpretive layer for the LCA results presented in Chapter 3. The qualitative analysis of stakeholder interviews, when considered alongside the quantitative findings from LCAs of PD and HD, provides a comprehensive picture of the environmental challenges facing kidney care. Stakeholders across clinical, managerial, technical and policy areas highlighted recurring themes of procurement, waste, energy and systemic barriers that collectively hinder progress towards sustainable dialysis. This analysis brings together the trends observed across interviews, analysing them with the quantitative hotspots identified in earlier chapters and with broader literature on healthcare sustainability (Larkin et al., 2026e).

A central theme across interviews was the main contribution of consumable procurement to dialysis related environmental impacts. Participants repeatedly identified the prevalence of single use plastics as a pressing issue, not only because of their volume but also because of the toxicity risks associated with PVC. These concerns resonate with the quantitative results of procurement focused LCAs, which showed that plastics account for a disproportionate share of climate change, human toxicity and ecotoxicity impacts (Larkin et al., 2025b; Larkin et al., 2026b). Several stakeholders observed that while water and electricity consumption in dialysis are visible and often discussed, the environmental burden of consumables remains largely hidden from patients and many staff. As one respondent summarised, “we recycle paper cups but we incinerate tonnes of plastic each year without question” (Larkin et al., 2026e).

Another consistent concern was waste management, particularly the reliance on incineration. In Italy, where the AOU Policlinico di Modena is located, medical plastics are typically classified as hazardous waste, limiting opportunities for recycling. Multiple respondents criticised this classification system, noting that much of the dialysis related plastic waste is chemically clean once rinsed but is still forced into high impact incineration pathways. The interviews highlighted the frustrations of frontline staff, who recognise the wastefulness but lack authority to deviate from strict waste protocols.

Stakeholders also raised persistent concerns about energy and water use, though the emphasis varied by role and context. Engineers and sustainability officers were more likely to highlight opportunities for technical optimisation, such as integrating solar energy into dialysis facilities or reusing RO reject water for non-clinical purposes. Clinicians, by contrast, often framed energy and water issues in terms of clinical feasibility and safety, noting that innovations must not compromise patient care. The LCA findings show that while procurement accounts for the majority of impacts, energy and water remain significant contributors, particularly in HD setting (Agar, 2015a; Arias-Guillen et al., 2024). This tension reflects a broader theme in sustainable healthcare, that technical opportunities exist, but they must be carefully balanced against operational challenges (Larkin et al., 2026e).

Many participants argued that current procurement standards are driven almost entirely by cost and safety, with little or no weighting for environmental performance. Several explicitly called

for environmental criteria to be embedded in tendering processes, citing examples from Nordic health systems where life cycle impacts are increasingly considered. Yet others warned that without agreement at EU level, hospitals risk being constrained by national regulations that prevent deviation from established specifications. This relates to the argument of, Mortimer et al., (2018) who emphasised that sustainability in healthcare requires redefining value to integrate environmental outcomes alongside clinical and financial metrics (Mortimer et al., 2018). Interviews confirmed that without systemic change, local champions for sustainability often find their efforts blocked by strict procurement rules (Larkin et al., 2026e).

Interestingly, stakeholders displayed different perspectives on innovation readiness. Industry representatives tended to be optimistic about emerging material alternatives, such as thermoplastic elastomers or biodegradable polymers, though they acknowledged challenges in regulatory approval and cost competitiveness. Clinicians, however, were more cautious, noting that the dialysis community has historically been risk averse due to patient safety concerns. This aligns with the literature on medical device innovation, where strict regulatory requirements can delay the adoption of more sustainable alternatives (Lokanathan, 2023). The interviews suggest that bridging this gap will require deliberate collaboration between regulators, manufacturers and clinicians, ensuring that innovations are tested but also prioritised for sustainability benefits (Larkin et al., 2026e).

Several respondents highlighted logistical and behavioural barriers. For example, centralised acid delivery systems such as Granumix were recognised as environmentally superior, but their adoption was often limited by infrastructure constraints or resistance to change in clinical routines. Similarly, waste separation at the patient's home in PD was seen as theoretically valuable but practically difficult without investment in collection systems and patient education. Behavioural studies in healthcare have shown that staff buy-in and workflow integration are critical determinants of whether sustainability initiatives succeed (Lennox et al., 2020; Larkin et al., 2026e).

Another trend evident across the interviews was the ethical aspect of sustainability in kidney care. Some participants emphasised the moral obligation of high income countries to reduce the environmental footprint of dialysis, particularly given the global bias in access to treatment.

Stakeholders framed dialysis sustainability not only as a technical challenge but also as a matter of justice, raising questions about the long term viability of resource intensive models in a warming world (Larkin et al., 2026e).

The integration of qualitative and quantitative findings strengthens the overall analysis. LCAs demonstrated that procurement, particularly acid concentrate bags, dialysate solutions and tubing, influences environmental impacts (Larkin et al., 2025b; Larkin et al., 2026b). Interviews corroborated this, with stakeholders repeatedly naming these products as wasteful and unsustainable. Similarly, LCAs highlighted the impact of incineration based waste management in Italy, which was discussed by staff who described incineration as a "necessary evil" but also as an area ready for reform. Where LCAs showed energy and water as secondary contributors, interviews revealed how these categories remain important to staff as visible indicators of environmental burden. This analysis confirms the robustness of the hotspot analysis and provides a richer understanding of why certain issues persist despite being well recognised (Larkin et al., 2026e).

The key stakeholder concerns can be grouped into five areas:

- Procurement impacts, especially plastics and packaging, seen as the largest and main issue.
- Waste management challenges, with frustration at strict incineration policies and lack of recycling.
- Energy and water use, acknowledged as significant but perceived through different lenses by engineers and clinicians.
- Policy and regulatory gaps, limiting the ability of hospitals to prioritise sustainability in procurement and waste.
- Innovation and ethics, with different views on readiness for change but shared recognition of the moral obligation to act.

These concerns align with and expand upon, the LCA findings, offering both validation of quantitative data and new insights into barriers and opportunities. They also reflect broader patterns observed in the sustainability literature, suggesting that the challenges in kidney care represent those facing healthcare systems more generally.

4.4.2 Policy and system level implications

Building on the stakeholder findings, this section considers how these challenges relate to policy and system-level frameworks at EU level. The findings from this study, when considered alongside the quantitative LCA evidence generated in preceding chapters, directly inform healthcare transformation at the EU level. The EU has committed to ambitious climate and health goals through frameworks such as the European Green Deal, the Circular Economy Action Plan and the EU Chemicals Strategy for Sustainability (Commission, 2019). Yet, as the interviews in this project reveal, the implementation of sustainable kidney care at the service delivery level is restricted by systemic barriers in procurement, waste regulation and clinical practice. This section explores how EU level instruments, funding mechanisms and policy coordination could address these barriers and accelerate the transition toward sustainable kidney care (Larkin et al., 2026e).

A recurring theme across interviews was the separated approach to procurement within EU healthcare systems. Hospitals often purchase dialysis consumables through regional or national frameworks, but suppliers remain global and environmental performance criteria are inconsistently applied. This aligns with prior critiques of medical procurement processes, which have historically prioritised cost and clinical reliability over environmental outcomes (Larkin et al., 2025b; Sherman et al., 2018). At the EU level, initiatives such as the Green Public Procurement (GPP) criteria offer a foundation for adjustment. However, interviewees noted that without binding requirements, uptake remains uneven (Larkin et al., 2026e).

One potential pathway is to expand the scope of the EU Medical Device Regulation (2017/745) to explicitly require manufacturers to disclose environmental performance data, including life cycle carbon footprints and material toxicity. Interviewees supported this direction, emphasising that dialysis products such as PVC based tubing, dialysers and acid concentrate bags represent large volumes of single use plastic and yet clinicians have no access to environmental product declarations when making procurement decisions. If mandatory eco design and disclosure criteria were applied EU wide, hospitals could leverage comparative data to favour lower impact products, incentivising manufacturers to innovate (Hoveling et al., 2024; Duane et al., 2025a; McDermott et al., 2024; Larkin et al., 2026e).

The EU has already introduced similar requirements in other sectors, such as electronics through the Ecodesign Directive (2009/125/EC), which sets performance standards on energy use and recyclability. Extending this model to medical consumables would align with both the EU Circular Economy Action Plan and the broader ambition of climate neutral healthcare. Such an approach could also build on the European Health Data Space, enabling integration of sustainability metrics into procurement datasets, thereby supporting transparency and benchmarking across member states (Bundgaard et al., 2023; Hoveling et al., 2024; Lenarczyk et al., 2025).

Interviewees repeatedly highlighted the rigid classification of dialysis waste as hazardous, disregarding of actual contamination risks. In Italy, for example, used acid bags and packaging are automatically categorised as hazardous healthcare waste and sent for incineration, despite evidence that cardboard and residual plastics pose minimal risk once separated (EcoEridania, 2023). Similar concerns have been raised in other EU countries, where over classification inflates costs, undermines recycling potential and increases carbon and toxicity impacts (Nozharov, 2018).

At EU level, this suggests a need for reform of the Waste Framework Directive (2008/98/EC) and its application to healthcare waste. Specifically, the development of risk based reclassification protocols could allow certain dialysis waste (e.g., outer cardboard, unused but uncontaminated plastics) to be diverted into conventional recycling streams. This would require EU guidance, validated by infection control agencies such as the European Centre for Disease Prevention and Control (ECDC), to ensure safety is not compromised (Larkin et al., 2026e).

The Circular Economy Action Plan already commits the EU to reducing single use plastics and improving recycling rates across sectors. Extending this ambition into healthcare would require strict provisions for hospitals to pilot and scale alternative waste treatments such as autoclaving, microwave sterilisation, or advanced pyrolysis (Wilson Uzochukwu, 2021). EU research programmes, including Horizon Europe, could fund demonstration projects to evaluate these technologies in real world hospital contexts, providing the evidence base for wider adoption (Hoveling et al., 2024).

The HD pathway has a dual reliance on energy and water. Interviews highlighted frequent frustrations among clinical staff at the lack of integration between hospital energy management teams and dialysis services. This disconnect reflects a wider division within European hospitals, where sustainability initiatives are often kept separate from clinical operations. Yet, the EU's Energy Efficiency Directive (2012/27/EU, revised 2023) and Water Framework Directive (2000/60/EC) both provide levers for change (Larkin et al., 2026e).

In energy terms, hospitals are identified as priority sites for efficiency upgrades under the EU's Renovation Wave strategy (Commission, 2019). Dialysis units, with their predictable and high energy loads, represent ideal candidates for targeted renewable energy integration. Some interviewees referenced pilot projects where solar PV was directly linked with dialysis facilities, demonstrating feasibility (RayzonSolar, 2024). EU level funding streams, such as the Cohesion Fund and InvestEU, could explicitly prioritise clinical areas with high environmental footprints, including dialysis, when allocating resources for renewable integration (Larkin et al., 2026e). Water conservation also emerged as a recurrent theme. RO systems used in dialysis reject large volumes of water, often discharged directly to drain. Interviewees described hospital attempts to repurpose RO reject water for cleaning or irrigation, but these usually lacked regulatory clarity. EU level guidance under the Water Framework Directive could support safe reuse pathways for non-clinical applications, standardising practices across member states. Furthermore, linking hospital water audits to EU reporting systems would allow benchmarking and create incentives for efficiency (Larkin et al., 2026e).

A consistent barrier identified in interviews was the limited integration of sustainability into clinical guidelines and training. Nurses and physicians expressed uncertainty about whether, for example, reducing dialysate flow from 500 mL/min to 400 mL/min would be clinically acceptable and environmentally beneficial. While emerging evidence suggests such prescriptions are safe for selected patients (Canaud et al., 2024). The absence of formal endorsement in clinical guidelines deters implementation (Larkin et al., 2026e).

The European renal best practice guidelines, issued by the European renal association, could play an important role in normalising environmentally conscious practices. If sustainability

metrics were explicitly included in European renal best practice recommendations, such as minimising residual acid waste, adopting centralised fluid delivery systems, or preferring products with verified environmental declarations, clinicians would have greater confidence to adopt these practices (Duane et al., 2025a).

Similarly, the European Credit Transfer and Accumulation System for health professional education could incorporate sustainability competencies into training curricula. Interviewees often described sustainability as "no one's responsibility," falling outside traditional medical or nursing roles. EU level frameworks for continuing professional development could address this gap, ensuring all healthcare staff are exposed to environmental sustainability principles as part of core training (Luque-Alcaraz et al., 2024).

Finally, interviewees highlighted a pervasive lack of policy coherence. Hospitals often operate under parallel pressures: national procurement rules, EU waste directives and global supply chain dependencies. Participants described feeling constrained by a lack of clear leadership on how sustainability should be operationalised in dialysis care (Larkin et al., 2026e). This resonates with broader analyses of EU health policy, which frequently note division across directorates and agencies (Greer, 2019).

Addressing this gap may require the establishment of an EU Taskforce on Sustainable Healthcare, bringing together DG SANTE, DG ENV and DG GROW with clinical societies and patient organisations. Such a taskforce could ensure alignment between environmental policies and health system challenges, preventing the kinds of regulatory contradictions repeatedly cited in interviews (Larkin et al., 2026e).

The NHS Net Zero model provides a relevant precedent (NHS, 2020). By setting a clear national target, backed by detailed implementation pathways, the NHS created a framework within which hospitals and suppliers were expected to align. An EU level equivalent, adapted to the subsidiarity principle but supported by common metrics and funding incentives, could offer similar coherence for member states (Mirow et al., 2024).

The qualitative insights reveal that while frontline staff and procurement managers recognise the urgency of sustainability in dialysis, structural barriers rooted in procurement frameworks,

waste classification, energy management and broken leadership limit progress. At EU level, several policy levers already exist, Green Public Procurement, the Waste Framework Directive, the Energy Efficiency Directive and the Water Framework Directive, but they require targeted application to healthcare. Embedding sustainability into clinical guidelines, training programmes and regulatory standards would help bridge the current implementation gap (Hoveling et al., 2024).

The implications are clear. Without EU level leadership joining together, sustainable kidney care will remain reliant on isolated local initiatives, unable to achieve the scale of transformation demanded by the Green Deal and net zero ambitions. Contrastingly, with strategic alignment, dialysis could become a model of how highly resource intensive treatments can be delivered within planetary boundaries.

4.4.3 How qualitative findings explain life cycle assessment hotspots

The interview data address this gap by revealing organisational, behavioural and governance factors that reinforce existing systems, even when lower impact alternatives are known.

Procurement emerged as the most impactful hotspot, accounting for approximately 70 to 72% of total PD related emissions. Interview participants repeatedly confirmed that procurement structures strongly determine environmental outcomes. One procurement lead stated, “If sustainability is not in the tender, suppliers will not make it a priority” [Interview 9]. This insight explains why high volume consumables such as dialysate bags, bloodlines and PVC tubing remain unchanged, despite LCA evidence showing that these products alone account for more than three quarters of procurement related emissions (Larkin et al., 2025b). Stakeholders described tenders as rigid, cost focused and clinically conservative, leaving limited scope for innovation unless environmental requirements are explicitly mandated.

Waste management practices, particularly the impact of incineration, were also strongly reinforced by interview data. Participants consistently cited infection prevention as the primary reason for strict disposal pathways. One clinician noted, “Staff are worried about infection control if we start reusing certain items” [Interview 4]. This concern persists even in cases where LCA results show that large volumes of PD waste have no blood contact and present

minimal biological risk. The interviews clarify how risk perception, rather than evidence of actual contamination, drives waste classification decisions. This explains the continued reliance on incineration despite its strong contribution to carbon and toxicity indicators in Chapter 3.

Water and energy inefficiency was similarly explained through qualitative findings. Although HD pathways consume approximately 430 to 510 litres of water per session, interviewees described limited monitoring and weak ownership of resource use. As one participant stated, “We know the impact is big, but in some areas there is still very little measurement or awareness” [Interview 2]. Engineers and sustainability officers often understood the scale of resource loss, particularly from RO reject water, but clinicians rarely had access to real time data. This disconnect helps explain why technical optimisation opportunities identified in the LCA have not been widely implemented.

These findings further support the quantitative hotspot analysis by explaining why high-impact processes persist in practice. The interviews demonstrate that high impact processes continue not due to lack of alternatives, but due to procurement rules, risk governance, limited measurement and unclear responsibility. Importantly, they also point toward realistic implementation pathways. Embedding LCA criteria within tenders, developing evidence based waste reclassification protocols and improving training on water and energy monitoring directly target the most actionable hotspots identified in Chapter 3. In this way, the qualitative evidence changes numerical results into practical guidance for system level change.

4.5 Discussion: Implications for practice

4.5.1 Methodological lessons from interdisciplinary collaboration

Interdisciplinary collaboration within KitNewCare fundamentally improved this study's methodological approach. It demonstrated how integrating clinician, engineer, procurement and sustainability expert perspectives can transform technical LCA findings into clinically feasible interventions (Larkin et al., 2026e). This approach addresses a persistent challenge in healthcare sustainability research, the disconnect between technically optimal solutions and operational realities.

Iterative feedback loops between LCA analysts and clinical teams proved particularly valuable. Regular conversations and discussion enabled clinicians to validate quantitative hotspot analysis against daily workflow constraints, ensuring recommendations like waste separation protocols were practical before formalisation. For example, nephrologists identified that proposed bin layouts conflicted with infection control pathways, prompting redesign that maintained both environmental and safety priorities, a refinement impossible through LCA modelling alone.

The mixed methods approach strengthened the analysis by linking quantitative hotspots to stakeholder explanations. Procurement impacts reflected tender structures lacking environmental criteria, while infection control concerns explained reliance on incineration. Measurement gaps contributed to persistent inefficiencies in water and energy use.

These lessons highlight a broader principle for healthcare sustainability research. Quantitative environmental modelling must be embedded within iterative, stakeholder-driven processes to achieve change in practice. The KitNewCare model, feedback loops, co-design and methodological pluralism, offers a replicable framework for future studies seeking to bridge the knowing doing gap in sustainable healthcare transformation (Greenhalgh et al., 2018).

This has practical implications for how sustainability programmes in kidney care are designed and governed. Interventions are more likely to be adopted when environmental evidence is

introduced through existing clinical and quality improvement structures rather than as a separate agenda. Embedding sustainability expertise within renal governance, procurement groups and service redesign teams would support earlier alignment between environmental goals and clinical priorities. This approach reduces resistance, improves feasibility and increases the likelihood that environmental improvements become routine practice rather than isolated projects.

4.5.2 Researcher standpoint and reflexivity

The researcher's standpoint inevitably shapes the questions asked, the interpretations made and the recommendations proposed. In sustainability research, where values and trade-offs are explicit, reflexivity is particularly important (Finlay, 2002). A qualitative design makes this visible by foregrounding the interpretive process and by allowing diverse voices to challenge researcher assumptions. This transparency improves the credibility and trustworthiness of the study (Nowell et al., 2017).

As a researcher trained in product design and LCA, the author's primary area of expertise is quantitative and technical analysis. Engaging in qualitative inquiry therefore broadens the lens, ensuring that social and organisational dimensions are not overlooked. Reflexive thematic analysis, used in this study, acknowledges the active role of the researcher in constructing themes rather than pretending that findings emerge objectively from the data (Braun et al., 2021). This honesty about standpoint strengthens the overall accuracy of the thesis.

This reflexive position influenced how findings were interpreted and how recommendations were framed. Rather than presenting sustainability as a purely technical optimisation problem, the analysis deliberately prioritised feasibility within real clinical systems. This positioning supports the broader aim of the thesis, which is to move from measurement of environmental impact toward interventions that are acceptable, implementable and durable within kidney care practice.

4.5.3 Limitations and trustworthiness

While this qualitative study provides detailed insights into stakeholder perspectives, several limitations must be acknowledged to assess its trustworthiness and scope (Larkin et al., 2026e).

The 25 European participants, though diverse across clinical, procurement and policy roles, were mostly from KitNewCare partner institutions or linked through them. This may over represent sustainability committed organisations, potentially under capturing resistance from less engaged settings. Geographic focus on EU countries limits generalisability to global contexts with different regulatory and cultural dynamics.

Semi structured interviews captured rich narratives but lacked follow up to track attitude or practice changes post intervention. Self-reported behaviours risk social desirability bias, though separated with LCA hotspots (Chapter 3) and S-LCA findings (Chapter 5) reduces this by validating reported barriers against quantified impacts.

As a product design and LCA researcher conducting interviews, the interviewees technical framing may have directed discussions toward measurable interventions over experiential areas. Reflexive thematic analysis addressed this through explicit audit trails and member checking, where participants reviewed theme summaries for accuracy (Braun & Clarke, 2021).

Trustworthiness measures included:

- Credibility through prolonged engagement and differentiation across methods.
- Transferability through detailed description of clinical and policy contexts.
- Dependability through documentation of the full analytic process.
- Confirmability through independent coding by co-researchers on 20% of transcripts.

Confirmability via independent coding by co-researchers on 20% of transcripts. These align with COREQ-32 qualitative reporting standards (Tong et al., 2007).

Despite limitations, the study's strength lies in its integration with quantitative LCA, where stakeholder explanations consistently identified impactful environmental hotspots, improving

overall thesis reliability. Future studies could expand to non-EU settings and incorporate observational methods to complement self-reported data.

Taken together, these limitations do not undermine the central findings but define the boundaries within which they should be interpreted. The consistency between qualitative explanations and quantitative environmental hotspots strengthens confidence in the conclusions and supports the use of mixed methods for analysing sustainability challenges in kidney care.

4.5.4 From barriers to solutions: Setting the stage for design innovation

Chapter 4 demonstrates that environmental impacts identified in earlier LCA chapters are shaped by organisational and system-level conditions within kidney care. These findings highlight that effective sustainability interventions must address how products are specified, how workflows are organised and how responsibility for environmental performance is distributed.

Chapter 5 builds directly on these insights. It uses the environmental hotspots identified through LCA in Chapter 3 together with the organisational barriers identified in Chapter 4 to inform targeted design interventions. Rather than proposing idealised solutions detached from practice, the next chapter adopts a design led approach grounded in real world constraints. This includes rethinking product design to reduce material intensity, developing service models that shorten supply chains and creating tools that support sustainability informed decision making within procurement and clinical workflows.

The transition from analysis to intervention is central to the structure of this thesis. Chapters 3 and 4 establish where environmental harm occurs and why it persists. Chapter 5 addresses how change might realistically occur within existing regulatory, clinical and organisational boundaries. By framing sustainability barriers as design problems rather than failures of compliance or motivation, the thesis positions innovation as a practical pathway toward lower impact kidney care.

This approach also reflects a broader shift within healthcare sustainability research. Moving beyond measurement toward implementation requires turning evidence into forms that are usable by clinicians, managers and suppliers. Design innovation offers a method for this by embedding environmental goals into products, services and decision systems rather than relying on behavioural change alone.

Together, Chapters 3 to 5 form an integrated progression. Quantitative modelling identifies priority hotspots. Qualitative inquiry explains the institutional and cultural conditions that sustain them. Design innovation then provides a structured means of responding to these challenges. This sequence enables the thesis to move from diagnosis toward actionable solutions, supporting the development of kidney care systems that protect both patient outcomes and environmental integrity.

Chapter 5 : Design innovation for sustainable kidney care

5.1 Introduction

5.1.1 From evidence (Chapters 3-4) to action

Sustainability challenges in healthcare are varied, not only including the technical design of products and processes, but also clinical workflows, organisational behaviour, policy frameworks and wider social engagement. Healthcare is both resource intensive and highly regulated, which means that no single intervention or discipline can provide the complete solution. Addressing these challenges requires an integrated approach that brings together engineers, clinicians, social scientists, policy experts and designers. Collaborative work of this kind has been described as essential to tackling sustainability problems that are simultaneously scientific, social and political in nature (DeFries et al., 2017; Galozzi et al., 2024). Within kidney care, which is among the most resource demanding areas of medicine, collaboration has proven especially important, since environmental impacts arise at multiple levels, from product design and procurement to waste disposal and clinical practice.

Chapter 5 turns the quantitative evidence from Chapter 3 and the organisational insights from Chapter 4 into applied responses. Rather than identifying additional problems, the focus shifts toward intervention design. The aim is to show how environmental hotspots and stakeholder barriers may be addressed through practical changes to products, services and decision tools. Design is used here as an approach that connects life cycle evidence with real clinical constraints, enabling sustainability strategies that fit within existing regulatory, safety and workflow structures. The chapter therefore moves from diagnosis toward implementation, demonstrating how evidence informed design may support delivery of lower impact kidney care.

Chapter 5 builds on Chapters 3 and 4 through the following key collaborative studies:

- Toolbox Paper: Duane, et al., (2026c) - 12 step LCA/education toolkit.
- Dental Sustainability: Duane et al., (2026a) - AI calculator/dashboard prototype.
- Social Optimisation: Duane, Larkin et al., (2026b) - S-LCA labour risks.
- Scoping Review: Yasar et al., (2025) - 95 interventions identified.
- Environmental Optimisation: Duane et al., (2025) - Procurement redesign quantifications.

Together, these studies provide the applied foundation for this chapter. Each addresses a different aspect of sustainability implementation, ranging from decision support tools and product redesign to social risk assessment and education. In the sections that follow, these contributions are examined in turn, showing how design led approaches turn environmental evidence and stakeholder insights into practical interventions for kidney care.

5.1.2 Role of design and innovation

Research into environmental optimisation of kidney care has grown rapidly over the past decade, but the literature remains uneven across modalities and inconsistent in its methodological approaches (Yeo et al., 2022). HD is by far the most studied modality, with many interventions reported in areas such as water conservation, dialysate flow optimisation and transport reduction. PD and transplantation have received far less attention and conservative management is almost absent from the sustainability discussion. In addition, existing studies differ widely in their use of metrics, reporting frameworks and methodological precision, which makes direct comparison challenging. These gaps highlight the importance of collaborative research that draws on diverse expertise, applies consistent methods such as LCA and builds a better evidence base for sustainable kidney care. Design and innovation play a central role in this process by turning evidence into tools, systems and interventions that can operate within clinical, organisational and regulatory constraints. This chapter organises the design and innovation work into three themes that address environmental optimisation, social sustainability and practical implementation through education and decision support in kidney care.

5.1.3 Research questions

This chapter addresses the following research questions, which build on the environmental and qualitative findings presented in Chapters 3 and 4:

- How can LCA be applied to identify and quantify practical environmental optimisation opportunities in kidney care delivery and procurement?

- How can social value and labour risk considerations be integrated alongside environmental metrics within healthcare sustainability assessments?
- What tools, educational approaches and design interventions support the translation of sustainability evidence into routine clinical and organisational practice?

The chapter presents contributions to collaborative research that has aimed to address these challenges. It is organised around three linked themes. An environmental optimisation theme focused on travel, energy, procurement, water and waste. The social value theme examines labour risk and equity in healthcare supply chains. The educational and implementation theme addresses workforce capability, LCA literacy and organisational readiness.

These themes represent substantial contributions to the field and directly align with the themes of this thesis, including the environmental optimisation of HD, systematic evidence analysed across interventions, the revaluation of healthcare waste management and the integration of social value perspectives alongside environmental outcomes. They highlight how collaboration not only supported the technical execution of complex studies but also shaped the framing of sustainability as a complicated challenge for kidney care.

Taken together, these collaborative contributions demonstrate the value of transdisciplinary team science in addressing the sustainability of kidney care. They show how working across institutions and disciplines can generate more robust evidence, enable validation of methods across different settings and create opportunities for comparative analysis between countries and modalities. Collaboration also allowed for a deeper integration of clinical knowledge with technical modelling, ensuring that proposed interventions were not only environmentally beneficial but also feasible in practice. Importantly, these projects provided the opportunity to test the adaptability of LCA methodologies in real world clinical contexts and to extend their application beyond environmental metrics to include social and organisational aspects, which are taken up explicitly in the social value and educational implementation themes later in the chapter.

The structure of this chapter reflects this balance of depth and breadth. Each theme draws on multiple collaborative studies, including environmental and social LCAs, a scoping review and

design led initiatives, but the focus here is on how these strands of evidence collectively inform practice, policy and education. A final reflective section analyses cross cutting lessons from this collaborative work, with particular attention to how design and LCA can support future innovation, implementation and governance in sustainable healthcare.

5.2 Methods and literature Review

5.2.1 Scoping review of sustainability interventions in haemodialysis and peritoneal dialysis

Sustainability has emerged as a critical consideration in kidney care because dialysis, transplantation and long term chronic disease management are highly resource intensive. Dialysis in particular relies on large volumes of water, single use plastics, energy and transportation, making it one of the most environmentally demanding treatments delivered in healthcare systems. Despite this, the nephrology literature has historically prioritised clinical effectiveness and patient outcomes, with limited attention given to environmental consequences. The scoping review Advancing Green Nephrology: A Scoping Review of Sustainability Interventions in Kidney Care was developed to address this gap by systematically mapping published sustainability interventions and identifying patterns, strengths and limitations across the evidence base (Yasar et al., 2025).

This study provides a structured overview of sustainability interventions in nephrology and informs the subsequent analyses presented in this chapter. This study is an important collaborative contribution because it provides a comprehensive overview of the state of knowledge in sustainable nephrology and acts as a bridge between smaller case studies and the more systematic LCAs described elsewhere in this thesis. The review was designed to map the existing evidence base and identify intervention patterns across kidney care. By gathering diverse interventions into a structured framework, the review laid the foundation for a common understanding of where the most progress has been made and where future attention should focus (Yasar et al., 2025). This scoping review therefore functions as a methodological foundation for the design and optimisation studies presented later in this chapter.

The review followed PRISMA-ScR guidance, which is the gold standard for scoping reviews in health research. Multiple databases were searched for studies published between 2005 and 2024 that described or evaluated an intervention explicitly aiming to reduce the environmental footprint of kidney care. Grey literature was also included, reflecting the fact that many

sustainability innovations emerge from practice based initiatives that do not appear in peer reviewed journals (Yasar et al., 2025).

Eligibility criteria required that studies describe a defined intervention relevant to nephrology. Interventions could be technical, organisational, or behavioural. Outcomes of interest were any reported measure of environmental or resource impact, ranging from carbon footprint and water use to waste reduction or proxy indicators such as reduced energy bills. Studies that only described general principles without reporting an intervention were excluded (Yasar et al., 2025).

Screening was conducted independently by two reviewers with disagreements resolved by consensus. Data extraction captured details of study design, setting, modality, intervention category and reported outcomes. Interventions were grouped into broad categories. Procurement and resource use, energy, water, waste, transport and service design. The review also examined geographical distribution and reporting quality (Yasar et al., 2025).

The PRISMA flow diagram (Figure 5. 1) summarises the search and screening process. Out of several hundred records identified, 95 studies were included in the final analysis. Figure 5. 2 shows the spread of interventions across modalities and categories, revealing where evidence is concentrated and where gaps remain (Yasar et al., 2025).

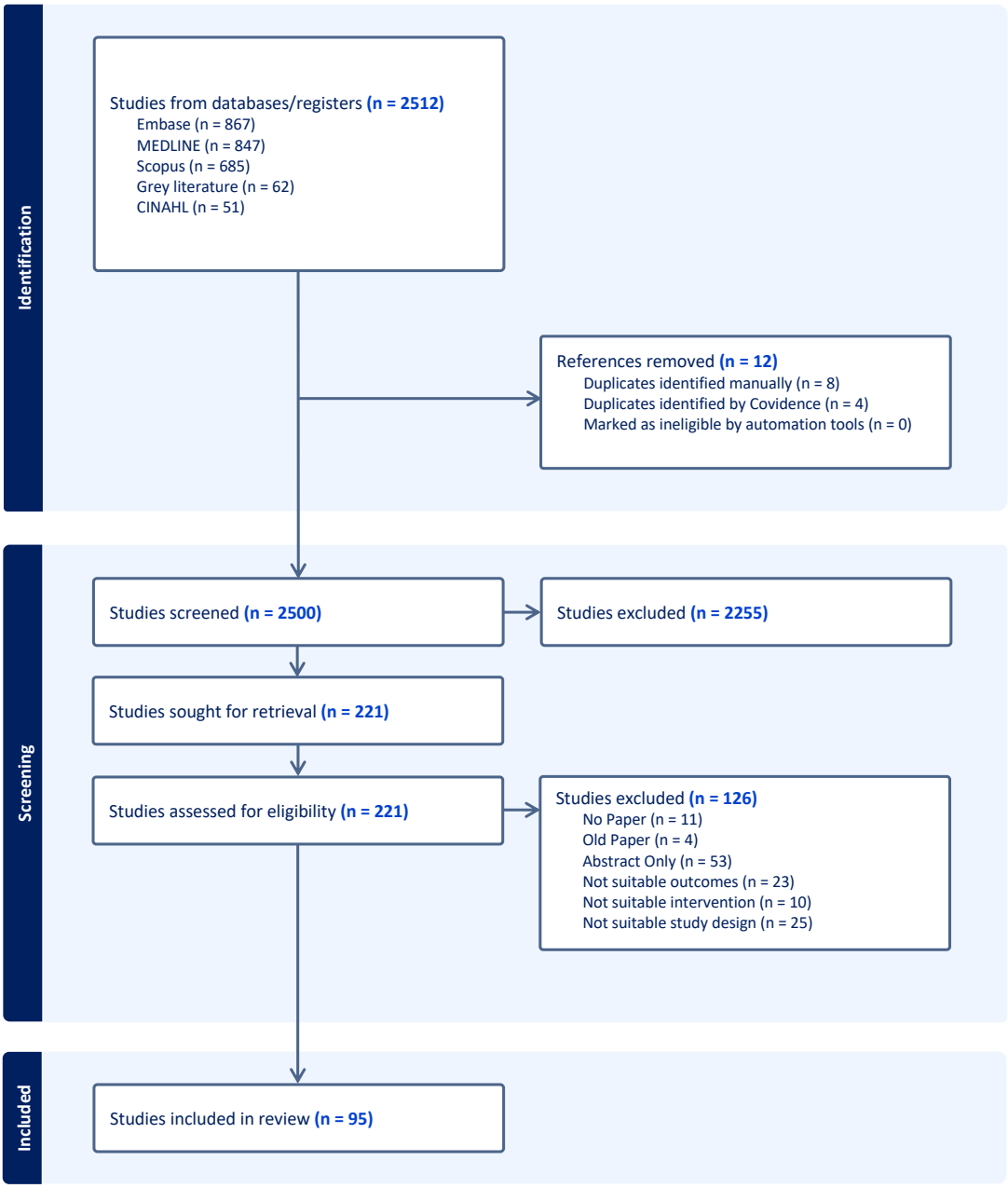

Figure 5. 1 PRISMA flow diagram for scoping review (Yasar et al. 2025)

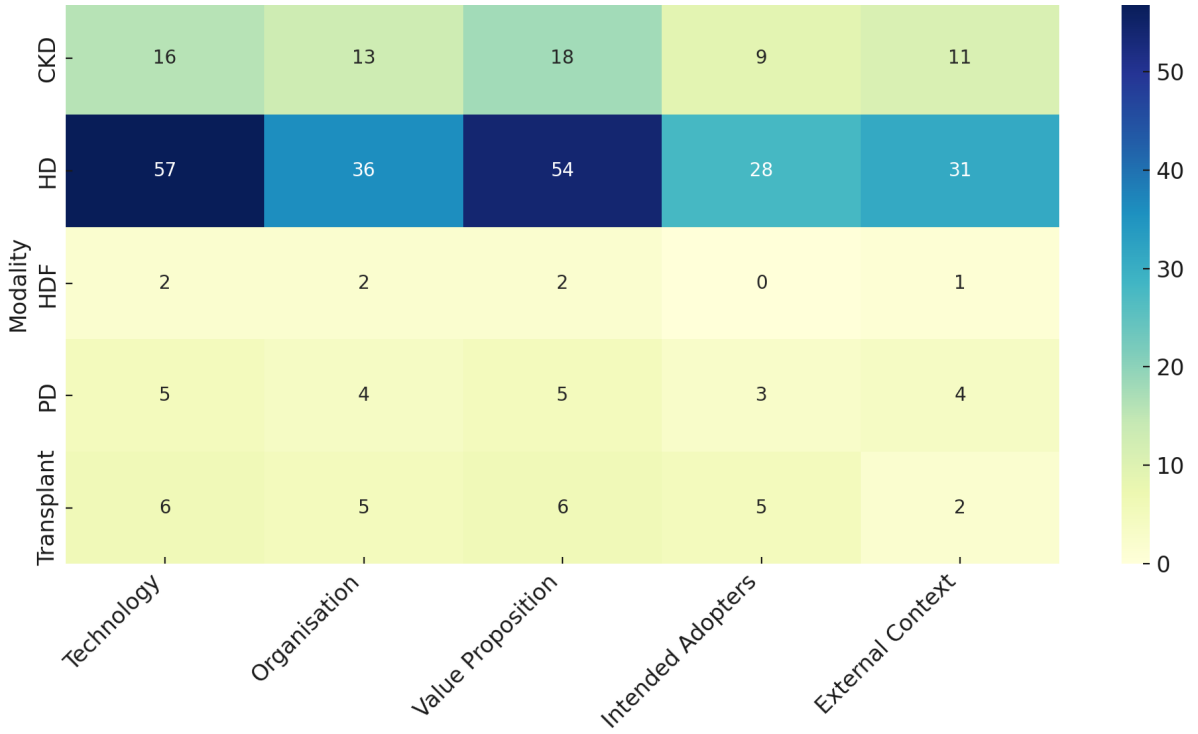

Figure 5. 2 Heatmap of 'Yes' counts by kidney care modality and the review questions based on the NASSS and CSH's Green Team Competition Success Factors (Categorised by: Technology, Organisation, Value Proposition, Intended Adopters, External Context) (Yasar et al. 2025)

5.2.2 Social life cycle assessment framework for supply chain risk

The pursuit of sustainability in healthcare has often emphasised environmental impacts, yet the social aspect of sustainability remains underrepresented in research and policy. Social sustainability includes labour rights, equity, inclusion, well-being and community welfare. In kidney care, these factors intersect with the globalised supply chains that support dialysis equipment, pharmaceuticals and consumables. This section outlines the S-LCA approach used to assess the social implications of procurement, energy, travel, waste and water related interventions. Using forced labour risk as a primary indicator, the analysis provides insights into how clinical and operational changes can reduce social harm embedded in medical supply chains. Detailed analysis of the social implications of these interventions is presented in Section 5.4.2 (Duane, et al 2026b).

The concept of sustainable value in healthcare links health outcomes with economic, environmental and social impacts to capture long term societal benefit. The Sustainable Value Equation positions social value alongside environmental performance as an essential component of healthcare system transformation (Mortimer et al., 2018). Within this framework, social value includes a broad spectrum of outcomes, including fair wages, labour conditions, local employment, gender equity and human rights (Hussain et al., 2018). In dialysis care, these areas extend across every life cycle stage, from raw material extraction to product use and waste treatment (Duane et al., 2026b).

CKD affects approximately 10% of the global population, with kidney failure treatment consuming a disproportionate share of healthcare resources (Agar, 2015a). As dialysis access expands, the environmental and social consequences of medical supply chains increase accordingly. Studies have documented the resource intensity of dialysis, yet few have explored the human labour implications of these same systems (Conner et al., 2010b; McGain et al., 2014; Barraclough et al., 2020). Addressing these issues requires integrating social impact assessment with environmental LCA (Duane et al., 2026b).

S-LCA builds upon ISO 14040 and ISO 14044 methodologies by incorporating social and socioeconomic indicators into traditional LCA (Benoît Norris et al., 2020). The product social impact life cycle assessment (PSILCA) database and its derivative, Soca v2, operationalise these indicators by quantifying social risks in medium risk hours, a measure representing the estimated hours of labour performed under medium or high risk conditions within a given supply chain (Hamed et al., 2025). This method allows for the integration of labour rights, occupational safety and human development metrics into healthcare LCA models. Forced labour risk, as defined by the International Labour Organisation, was selected as the focal indicator due to its global relevance and its role as a proxy for wider human rights concerns in manufacturing and logistics (Alsamawi et al., 2019). Forced labour risk was prioritised because it is strongly associated with global manufacturing of plastics, electronics and transport services, all of which impact dialysis supply chains.

This study followed an attributional LCA framework, applying social LCA principles to assess the risk of forced labour associated with kidney care interventions. The modelling was

performed using OpenLCA version 3.10, with environmental background data from Ecoinvent v3.1 and social impact data from Soca v2 (Ecoinvent, 2024). The system boundary was cradle to grave, including material extraction, manufacturing, packaging, transport, use and end of life stages for each intervention. The functional unit was defined as one year of HD for a single patient, assuming three sessions per week and a four hour treatment duration per session. HD was selected as the reference pathway due to its standardised treatment schedule and its central role in comparative modelling across the KitNewCare studies (Duane et al., 2026b).

The interventions assessed corresponded to those evaluated in the environmental optimisation paper, allowing for direct comparison of environmental and social results (Duane et al., 2025a). Seventeen interventions were modelled, grouped under procurement, energy, travel, waste and water categories. Data sources included hospital procurement records, published LCA data and KitNewCare inventory models. When country specific datasets were unavailable, Spanish input datasets were applied to maintain internal consistency with the EU funded modelling framework and to avoid mixing national risk profiles across scenarios. Irish data were used only for travel related scenarios (Duane et al., 2026b).

The key indicator, forced labour risk, was expressed in medium risk hours per functional unit. Reductions in medium risk hours indicate a lower probability of exploitative labour within the supply chain, reflecting improved social sustainability. This does not represent observed labour violations but indicates relative exposure to social risk across alternative care delivery models (Duane et al., 2026b).

The cradle to grave boundary captured activities, including energy production, material refinement, packaging manufacture, global logistics, hospital level use and waste disposal. For energy related interventions, electricity generation and infrastructure were included. For procurement interventions, the entire product manufacturing chain was modelled, including plastics, electronics and packaging materials. Patient travel included both vehicle production and fuel cycles. End of life treatment covered incineration, pyrolysis, recycling and landfill scenarios (Duane et al., 2026b).

Key assumptions included:

- iHD involved two sessions per week for the first six months, increasing to three thereafter.
- Solar energy replaced 100% of grid electricity, assuming an average Spanish solar capacity factor of 18%.
- Waste treatment via pyrolysis was modelled with a 90% diversion rate from incineration.
- Travel optimisation assumed 10% and 50% reductions in private car travel, based on shared transport initiatives.
- Water savings reflected reuse of RO reject water for grey water applications.

All inputs and assumptions were validated with clinicians and sustainability leads within KitNewCare. Ethical approval was not required because the analysis relied exclusively on secondary datasets and did not involve patient level, staff level or identifiable human data (Duane et al., 2026b).

5.2.3 Design led innovation approach

HD places a high burden on energy, water, consumables and waste management. As access to KRT increases, the associated environmental footprint will grow unless services adopt higher impact interventions guided by robust comparative evidence. The Clinical Kidney Journal study, “But how green is it actually? Calculating the environmental footprint of kidney care environmental optimisations within haemodialysis,” quantified a wide range of interventions using attributional LCA within the EU funded KitNewCare programme (Duane et al., 2025a). The analysis used OpenLCA with Ecoinvent, aligned with ISO 14040 and EU Product Environmental Footprint guidance and reported results in CO_2 eq and water deprivation. The study provides a comparative basis for prioritising interventions in clinical practice while maintaining safety and success. From a design perspective, this approach reframes sustainability not as a single solution but as a portfolio of comparable design choices, allowing clinicians and health systems to select interventions based on quantified impact rather than assumption.

The study grouped interventions into five areas, procurement and resource optimisation, energy, travel, water and waste. Standard care was compared against defined functional units for each intervention, using a one patient, three sessions per week, one year reference frame.

All modelling used Spanish foreground data where available for consistency with project funding constraints. Travel distances used Irish data due to lack of Spanish figures (Duane et al., 2025a). Functional units, assumptions and inputs are detailed in Table 5.1 and Table 5.2 with additional data on flow diagrams and inventory inputs in the supplementary materials (Duane et al., 2025a). These structured assumptions ensure transparency and allow results to be interpreted as design options that could be adopted, combined or scaled within routine HD services. By structuring interventions into comparable areas using a consistent functional unit, the study operationalises design thinking principles, enabling trade off analysis between alternative service configurations rather than evaluation of isolated technologies.

Table 5. 1 Study Functional units, assumptions and inputs (Duane et al. 2025a)

Table 5. 2 Continued (Duane et al. 2025a)

Innovation	Functional unit	Comparative unit/standard care	Summary and assumptions
Procurement optimizations			
Using a 3 mL syringe	A 3 mL Luer lock syringe	A 10 mL Luer lock syringe	The LCA of a Luer lock syringe was assessed—70% of the syringe was estimated to calculate environment savings
Going paperless	The use of electronic resources equivalent to paper used for patient records	Six pieces of paper per patient per hospital visit used for patient records	We assumed one piece of paper was the same as 1 min use of (i) a computer and (ii) the internet. In addition, a Carnegie Mellon University study concluded that the (iii) energy cost of data transfer and storage is about 7 kWh per gigabyte One page is 5 kbyte, which works out at 0.00024 kWh for each piece of paper [41] We subtracted the environmental cost of the data storage and electronic appliance from the saved paper costs
Pre-ordering sandwiches	Providing sandwiches during patient care using an ordering process to reduce waste	Providing sandwiches during patient care without ordering	
Food choices: using vegetarian vs beef lasagne	Providing vegetarian lasagne for each patient visit	Providing beef lasagne for each patient visit	
Incremental HD	Patients start with fewer dialysis sessions per week and increase as needed, to conserve resources and reduce patient burden	Patients have usual standard of care	See Appendix 3 for more details. Only the use of the machine was measured not the build of the machine
Not using the saline bag	Not using a 1-L saline bag for every dialysis session	The use of a 1-L saline bag for every dialysis session	
Not offering blankets	The use of a 100% cotton blanket weighing 2 kg for 30% of visits	The use of a 100% cotton blanket weighing 2 kg for 100% of visits	The seed, cotton, yarn processes all taken from Ecoinvent 3.7.1. It was assumed based on Vozzola like a gown the cotton blanket would be used 60 times before discarded [42]. Calculations were made using laundry processes (transport, washing, drying) as per 3.7.1. In order to calculate the environmental impact, 70% of a blanket was calculated. The blanket was assumed to weigh 2.2 kg based on products online [43]
Energy optimizations			
Automatic IT shutdown	The use of a laptop for one patient for 1 year of HD which is always shut down when not in use	The use of a laptop for one patient for 1 year of HD which is never shut down	It was assumed that one laptop would be used for four patients. The study was based on a CSH case study [44] with 16× laptops running for 24 h and 7 days a week would (consume 3916 kWh annually); we then compared 16× laptops running 14 h a day for seven days (consume 2563 kWh annually)
Heat exchange	The use of a standard dialyser with a heat exchanger for one patient for 1 year of HD	The use of a standard dialyser without a heat exchanger for one patient for 1 year of HD	Energy savings were estimated by comparing a standard cycle on a machine with heat exchanger to one without. Results in the dialysis unit showed 5.2 kWh vs 4.7 kWh (with heat exchanger), a saving of 0.5 kWh per treatment, or approx. 10%. This was mapped for the year
Changing lightbulb	The use of a T8 lighting for one patient for 1 year of HD.	The use of a T5 lighting for one patient for 1 year of HD	Assume lighting was needed for each patient for 3 half days a week, and machine savings were calculated at 12 sessions a week (not working Sunday) Assume T5 are 9% more efficient [45]

Innovation	Functional unit	Comparative unit/standard care	Summary and assumptions
Using solar energy	The energy use for one patient for 1 year of HD using roof mounted solar energy	The energy use for one patient for 1 year of HD using standard Spanish grid electricity	The energy used was derived from Arias-Guillén [46]
Lowering the dialysis fluid temperature	The energy use setting standard dialysate temperature at 36.5°C	Personalised cooler dialysate: 0.5–0.9°C below each patient's measured pre-dialysis body temperature, with a lowest recommended dialysate temperature of 35.5°C (ref)	To decrease from 36.5°C to 35.5°C save 80 Wh in a 4 h dialysis treatment, representing 2% of the total energy expenditure of the dialysis monitor [47]
Travel optimizations			
Travel optimizations	The mode of transport for a patient for 1 year of HD consists of 10% of patients using a minibus and 90% using a car	The distance a patient travels for 1 year of HD using a car	We know that patients travel far for their HD. We used the Irish figure of 29 km [48] one way and calculated a 10% reduction
	The mode of transport for a patient for 1 year of HD consists of 50% of patients using a minibus and 50% using a car		An average of four patients sharing a minibus when going to a HD centre
Waste optimizations			
Optimizing waste	The amount of waste for a HD patient for 1 year of HD using sophisticated pyrolysis treatment for 90% of clinical waste/10% incineration	The amount of waste for a HD patient for 1 year of HD using incineration only	Used 2.9 kg of waste per dialysis session (three times a week for 1 year of HD)
Saving water	The amount of water for a HD patient for 1 year of HD when this water is diverted for grey water uses, e.g. toilet use throughout the hospital	The amount of water for a HD patient for 1 year of HD	This does not include the environmental footprint or energy used in reprocessing the water for other uses

HD, haemodialysis.

5.2.4 Educational and implementation methods

The collaborative paper Twelve Components for a Toolkit on Teaching Carbon Footprinting to Healthcare Students Using LCA was conceived as a practical framework for embedding environmental literacy into healthcare education (Duane et al., 2026c). Healthcare is one of the most resource intensive sectors globally, responsible for approximately 4.4% of global GHG emissions and significant contributions to waste and pollution (Karliner, 2020). While healthcare professionals are increasingly aware of the environmental consequences of their work, structured education in carbon accounting and life cycle thinking remains limited (Mortimer et al., 2018). This section outlines the educational and digital methods used to support implementation and sustainability capability.

The rationale for developing this toolkit emerged from the European Horizon funded KitNewCare project, after investigating environmental and social impacts across kidney care pathways. Through multidisciplinary collaboration, the project identified an educational gap. Students and professionals lacked a common methodological and conceptual framework for performing LCAs in healthcare. Many participants could not define system boundaries, identify functional units, or perform sense checks on results. Inconsistent data interpretation led to widely varying conclusions about sustainability interventions (Duane et al., 2026c). The educational rationale for the toolkit is analysed further in Sections 5.3.3 and 5.4.3.

Previous studies have identified similar challenges in healthcare sustainability education. Sherman et al., (2018) noted that the absence of standardised environmental literacy training in clinical curricula limits the sector's ability to meet decarbonisation goals (Sherman et al., 2018). Likewise, the "Delivering a Net Zero Health Service" report emphasised workforce education as a central strategy for achieving carbon neutrality (NHS, 2020). Duane et al., (2026) directly addresses this need by proposing a structured educational model that integrates technical LCA methods with experiential, reflective and interdisciplinary learning approaches (Duane et al., 2026c). The toolkit was designed to support consistent interpretation of environmental data across clinical, managerial and procurement roles.

The toolkit provides a structured approach for teaching LCA within healthcare education. It provides healthcare learners with the ability to quantify, interpret and act upon the environmental impacts of clinical processes, aligning with frameworks such as the WHO's Health and Climate Change Global Strategy and the EU Green Deal's emphasis on environmentally sustainable public services (Commission, 2019).

Duane et al., (2026) draws on the methodological structure of ISO 14040 and ISO 14044 for LCA, combined with educational theories that promote experiential and reflective learning (Duane et al., 2026c). The toolkit emerged through iterative development within the KitNewCare doctoral training network, where PhD students from engineering backgrounds conducted LCAs on dialysis systems and healthcare processes (Kolb, 2014; Lave et al., 1991).

Through workshops, peer discussions and repeated modelling exercises using OpenLCA and the Ecoinvent v3.10 database, educators observed recurring conceptual challenges. Students frequently struggled with defining system boundaries, interpreting allocation procedures and contextualising emissions results. To address this, the research team designed a structured, twelve component pedagogical model that builds methodological understanding step by step (Duane et al., 2026c). The twelve-component structure was developed iteratively to support progression from conceptual understanding to applied use of clinical datasets.

Each component was tested through application to real life datasets from dialysis procurement and pathway LCAs (Larkin et al., 2025b). Feedback from clinical mentors and sustainability professionals refined the approach. The result was a reproducible framework for integrating carbon footprinting into healthcare education (Duane et al., 2026c).

Figure 5. 3 illustrates the typical structure used in training, showing material and energy flows from raw material extraction through production, transport, use and disposal (Duane et al., 2026c). The exercise of defining this boundary helps students understand the interconnectivity of clinical and nonclinical systems, a foundational skill in systems thinking (Meadows, 2008).

Figure 5. 3 System Boundary Diagram (Duane et al. 2026a)

The healthcare sector has been identified as a significant contributor to global GHG emissions, with estimates suggesting that healthcare activities account for approximately 4-5% of total global emissions (Lenzen et al., 2020; Romanello et al., 2023). Although developed outside nephrology, this work is included here because it demonstrates transferable implementation tools relevant to kidney care sustainability. Within this total, dentistry represents a small but measurable share, driven by energy use, material consumption, single use plastics and patient and staff travel (Duane et al., 2024). Despite increasing awareness of healthcare's environmental footprint, the accessibility of carbon accounting tools for clinical users remains limited. LCA is widely recognised as the gold standard for quantifying environmental impacts, yet the method's complexity, data intensity and software requirements often restrict its application to specialised researchers (Duane et al., 2026a).

While the toolkit provides structured LCA education, the AI carbon calculator (Duane et al., 2026a) complements it by normalising carbon accounting for clinical practice, validated in dentistry but adaptable to nephrology workflows.

This collaborative study, Prompt Driven ChatGPT Carbon Calculator for Dental Practices, aimed to address that gap by developing and validating an artificial intelligence (AI) assisted carbon calculator tailored for dental care. The tool was designed to use conversational AI, specifically ChatGPT, to interpret user prompts, quantify emissions associated with dental practice activities and present structured carbon estimates comparable to those produced by standard manual LCA methods. By leveraging large language models (LLMs) for environmental analysis, the project explored how generative AI could support sustainability transitions in clinical disciplines lacking dedicated environmental data expertise (Duane et al., 2026a).

Although this study focused on dentistry, its relevance extends beyond oral healthcare. The framework offers a transferable proof of concept for other resource intensive clinical pathways, including dialysis, surgery and imaging. Within the context of kidney care, similar tools could support unit level carbon tracking, procurement discussions and staff engagement without requiring specialist LCA expertise. Within this thesis, it illustrates how methodological and digital tools developed outside nephrology can support the educational and implementation

theme, providing accessible ways to extend carbon literacy and LCA-informed decision making to clinical teams (Duane et al., 2026a).

There was two reasons behind the rationale for selecting dental care as the testbed. First, dental practices present a well-defined, discrete service model with relatively standardised processes including energy consumption, sterilisation, travel, procurement and waste generation that mirror hospital based care on a smaller scale (Duane et al., 2024). Second, dentistry has a mature body of environmental LCA research providing a solid reference base for validation (Duane et al., 2019). The study therefore sought to evaluate whether:

- ChatGPT could generate reliable carbon estimates from prompt driven inputs.
- Whether its outputs aligned with peer reviewed LCA data.
- How its potential could be extended as an educational and operational sustainability tool for healthcare practitioners (Duane et al., 2026a).

These frameworks all emphasise the need for accessible tools that empower clinicians to measure and reduce emissions at the point of care. By bridging AI and environmental science, this work contributes to a growing movement towards digitally enabled, data driven carbon literacy in healthcare (Duane et al., 2026a; Floridi et al., 2020; Topol, 2019).

The objectives of the study were to:

- Develop a prompt based methodology using ChatGPT to estimate the carbon footprint of dental procedures, materials and activities.
- Validate the AI generated results against published LCA data and national benchmarks for healthcare emissions.
- Evaluate the tool's interpretability, reproducibility and potential application in clinical education and sustainability governance.
- Identify limitations and opportunities for integrating generative AI into environmental impact assessment frameworks.

Three structured prompt formats were created to evaluate the consistency and accuracy of ChatGPT (https://chatgpt.com) in estimating carbon emissions and providing sustainability

recommendations for dental practice activities. These prompt variants (1, 2 and 3) differed in their level of detail and the extent to which quantitative information was embedded in the input. Model outputs were assessed for completeness, contextual accuracy and the inclusion of credible supporting references. To benchmark performance, results were compared against those generated using a previously validated Excel based dental carbon calculator developed by the National Clinical Environmental Sustainability network (NCES, 2025). The comparison examined alignment in emission estimates, the appropriateness of the sustainability guidance provided and the use of verifiable evidence sources (Duane et al., 2026a).

Variant 1

In the first variant, ChatGPT was prompted to generate a comprehensive sustainability assessment for a hypothetical dental practice without receiving any prior context or parameters. The instruction provided was open ended: "Please calculate the carbon footprint of my dental practice and suggest evidence based strategies to reduce it " (Duane et al., 2026a).

In the second variant, ChatGPT was guided using a structured input framework that requested specific operational data from the user. This approach enabled the model to generate more tailored estimates and recommendations while still operating without explicit direction on which scientific sources to reference. The structure of this data driven prompt is summarised in Table 5. 3 (Duane et al., 2026a).

Table 5. 3 Variant 2. A prompt to calculate an appropriate dental footprint (Duane et al. 2026a)

You are a carbon footprint calculator specifically trained for dental clinics. I will answer a few simple questions about my dental practice and you will estimate our carbon footprint in kg or tonnes of CO_2 equivalent (CO_2e), based on reasonable emission factors. Then, give me a breakdown of emissions by category (e.g., travel, energy, waste, procurement) and offer 3–5 tailored recommendations to help us reduce emissions. Please do this in three steps: ###A. Ask me these questions:

Practice Information (Annual figures)

1. How many days is the practice open on an average year?

2. How many full-time staff are in the practice?

3. How many patient visits does the practice see every year?

Staff Travel (in miles)

4. How far do all staff travel (return trip) to work or for work by car per day?

Patient Travel (in miles)

5. What is the total distance travelled by 30 patients using:

- Petrol/Diesel Car?
- Electric Car?
- Bus?
- Train?
- Motorbike?
- Bike/Walk?

Waste (Number of bags disposed per day)

6. How many bags of plastic waste for recycling?

7. How many bags of cardboard waste for recycling?

8. How many bags of infectious waste for incineration?

9. How many bags of domestic waste for disposal?

Energy Use (in kilowatt-hours - kWh)

(This year – make sure it's a normal year)

10. How much standard electricity did the practice use?

11. How much green electricity did the practice use?

12. How much electricity did you generate from solar panels on your roof?

13. How much gas did the practice use?

Water

14. What was the total water usage annually in cubic metres?

Procurement

15. How much did you spend annually on other things, equipment and materials in pounds sterling (£)?

(Do not include rent or interest)

B. Use these emission factors:

Travel

- Staff car travel per mile: **0.5300 kg CO_2e**
- Patient travel per mile:
  - Petrol/Diesel Car: 0.5300
  - Electric Car: 0.1830
  - Bus: 0.1500
  - Train: 0.1900
  - Motorbike: 0.1600
  - Bike/Walk: 0.0000

Waste per bag

- Plastic recycling: 0.0000
- Cardboard recycling: 0.0000
- Infectious waste (incineration): **7.5869 kg CO_2e**
- Domestic waste (disposal): **1.1558 kg CO_2e**

Energy per kWh

- Standard electricity: 0.2749
- Green electricity: 0.0110
- Solar on roof: 0.0410
- Gas: 0.2100

Water

- Per m^3: **0.3378**

Procurement

- Per £ spent: **0.1315**

C. After I provide the answers, calculate and present:

1. **Total CO_2e per year for my practice**
2. **Which category is the highest emitter**

3. **Recommendations to reduce emissions**, draw on own data

In the third variant, ChatGPT was instructed to gather detailed operational data using the structured prompt framework but, unlike the previous version, to explicitly reference and

incorporate content from the Centre for Sustainable Healthcare (CSH) Sustainability Assessment Tool, an open access resource available online. This approach was designed to evaluate whether directing the model toward an established sustainability framework would enhance the accuracy, consistency and evidence base of its recommendations. The structure of this adapted prompt is presented in Table 5. 4 (Duane et al., 2026a).

Table 5. 4 A prompt to calculate an appropriate dental footprint with tailored recommendations (Duane et al. 2026a)

C. After I provide the answers, calculate and present: 1. **Total CO_2e per year for my practice** 2. **Which category is the highest emitter** 3. **Recommendations to reduce emissions**, focussed and based on my answers, but solely using information from *https://sustainablehealthcare.org.uk/wp-content/uploads/2024/09/how_to_guide_sustainable_dentistry.pdf*

Table 5. 5 Summary of sustainability related inputs for the general practice (mock data) (Duane et al. 2026a)

Category	**Answer to question**	**Value (mock data)**	**Unit / Notes**
Practice Activity	Practice open days (annual)	220	Days
	Full time staff	2.5	Full Time Equivalent (FTE)
	Annual patient visits	2,654	Visits
Staff Travel	Total weekly travel (car)	587.5	Miles (return journeys)
Patient Travel	Petrol/Diesel car	174.3	Miles (30 patients sampled)
	Electric car	0.0	Miles
	Bus	7.6	Miles
	Train	37.2	Miles

	Motorbike	10.0	Miles
	Bike/Walk	6.0	Miles
Waste (weekly)	Plastic (recycling)	0.5	Number of bags
	Cardboard (recycling)	0.4	Number of bags
	Infectious waste (incineration)	0.6	Number of bags
	Domestic waste (general disposal)	0.9	Number of bags
Energy Use (annual)	Electricity (standard)	5,387	kWh
	Electricity (green)	0.0	kWh
	Solar power	0.0	kWh
	Gas	11,457	kWh
Water Use (annual)	Total water usage	41.5	Cubic metres (m^3)
Procurement	Equipment, materials, consumables	£45,454.80	GBP, excludes rent and interest

5.3 Key findings: Interventions across three levels

5.3.1 Evidence from intervention mapping and optimisation

The review revealed several important patterns. First, HD accounted for the majority of the evidence base, consuming more than half of all interventions identified. This is unsurprising given its high environmental footprint and the relative ease of implementing technical modifications in dialysis units compared with transplant or community care. Within HD, common interventions included RO water reuse, reduction of dialysate flow, installation of heat exchangers and improved waste separation (Yasar et al., 2025).

Second, interventions targeting PD were limited and primarily focused on waste reduction, especially packaging and plastic disposal. This is noteworthy because PD is often considered less resource intensive than HD, yet the environmental literature addressing it is minimal (Yasar et al., 2025).

Third, transplant related interventions were scarce, although some studies described telemedicine approaches for post-transplant follow up, reducing the need for patient travel. CKD management studies, though fewer, often focused on challenging prevention strategies such as optimising medication use and introducing digital consultations. These interventions are indirectly sustainable by reducing progression to dialysis, which carries the largest footprint (Yasar et al., 2025).

A fourth finding was the impact of high income countries, particularly in Europe, Australia and North America. Low and middle income countries were largely absent, despite carrying much of the global burden of kidney disease (Yasar et al., 2025).

Finally, the review highlighted major methodological variability. Some studies used full LCA, reporting standardised impact categories, while others relied on simple measures such as electricity use or waste weight. A number of papers reported only qualitative impressions or theoretical proposals (Yasar et al., 2025).

The scoping review Yasar et al., (2025) informs the environmental optimisation LCA (Duane et al., 2025; Yasar et al., 2025).

Travel reduction delivered the largest CO_2 eq savings among all areas. Modelling a 10% shift from private car to shared minibus saved 175 kg CO_2 eq and 32 m3 of water per patient per year. A 50% shift saved 710 kg CO_2 eq and 129 m3 as shown in Table 5. 6. Energy interventions showed a mixed pattern. Solar energy integration had the strongest effect, 646 kg CO_2 eq and 52 m3 water saved per patient per year. Heat exchange provided moderate benefits, 31 kg CO_2 eq and 9 m3. Automatic IT shutdown gave smaller savings, 8 kg CO_2 eq and 2 m3, while lightbulb changes were negligible as shown in Table 5. 7 (Duane et al., 2025a).

Table 5. 6 The environmental and water footprint of saving in patient travel (Duane et al. 2025a)

Travel Item	CO2e (kg)	Water use (m^3)
Travel optimizations 10%	175	32
Travel optimizations 50%	710	129

Table 5. 7 The carbon and water footprint of saving in energy (Duane et al. 2025a)

Energy Item	CO2e (kg)	Water deprivation (m^3)
Automatic IT shutdown	8	2
Heat exchange	31	9
Changing lightbulbs	Neg	Neg
Using solar energy	646	52

Procurement and resource changes ranged from marginal to substantial. Eliminating cotton blankets saved 116 kg CO_2 eq and 899 m^3 water per patient per year. Incremental Haemodialysis (iHD) saved 316 kg CO_2 eq and 137 m^3. Preordering sandwiches saved 53 kg CO_2 eq and 90 m^3. Going paperless and avoiding a saline bag per session produced minimal

savings in this model, 1 kg CO_2 eq and 0 m^3 and 3 kg CO_2 eq and 2 m^3 respectively. A 3 mL syringe in place of a 10 mL syringe was modelled at 4 kg CO_2 eq and 2 m^3 saved (Duane et al., 2025a).

Waste optimisation through pyrolysis outperformed incineration, with savings of 735 kg CO_2 eq and 71 m^3 water per patient per year. Direct water conservation measures produced modest benefits in the model, 16 kg CO_2 eq and 19 m^3 saved per patient per year (Duane et al., 2025a).

5.3.2 Service pathway redesign

S-LCA results for pathway redesign are presented here, with detailed analysis provided in Section 5.4.2 (Duane et al., 2026b).

The analysis demonstrated significant variation in forced labour risk across interventions. iHD had the largest reduction, saving an estimated 712 medium risk hours annually, primarily due to lower consumption of medical consumables, electricity and water. The solar energy intervention achieved 611 hours of savings, reflecting the displacement of fossil fuel supply chains associated with high labour exploitation risks. Eliminating cotton blankets saved 395 hours, attributed to reduced demand for textiles sourced from high risk cotton producing regions such as Uzbekistan and Xinjiang (International, 2022). Preordering sandwiches reduced risk by 317 hours and water reuse saved 279 hours. In contrast, administrative changes such as paperless systems and smaller syringe volumes produced marginal savings under 50 hours (Duane et al., 2026b).

Table 5. 8 to

Table 5. 12 detail specific results by intervention type (Duane et al., 2026b).

Table 5. 8 Forced labour risk savings by procurement intervention (Duane et al. 2026b)

Item	**Forced Labour risk savings (medium risk hours)**
Using a 3 ml syringe	27

Going paperless	2
Pre-ordering sandwiches	317
Using beef versus vegetarian lasagne	63
Incremental haemodialysis	712
Not using the saline bag	28
Not offering cotton blankets	395

*A negative score implies a worsening rather than an improvement

Table 5. 9 Forced labour risk savings by energy intervention (Duane et al. 2026b)

Item	**Forced Labour risk savings (medium risk hours)**
Automatic IT shutdown	44
Heat exchange	173
Changing lightbulbs	0
Using Solar energy	611

Table 5. 10 Forced labour risk savings by travel intervention (Duane et al. 2026b)

Item	**Forced Labour risk savings (medium risk hours)**
Travel Optimisations 10%	39
Travel Optimisations 50%	167

Table 5. 11 Forced labour risk savings by waste intervention (Duane et al. 2026b)

Item	Forced Labour risk savings (medium risk hours)
Optimising waste (Optimal e.g. pyrolysis of medical waste)	11

Table 5. 12 Forced labour risk savings by water intervention (Duane et al. 2026b)

Water deprivation	Forced Labour savings (medium risk hours)
Saving water	279

These results are analysed further in Section 5.4.2.

5.3.3 Educational toolkits

This section describes how educational design functions as a practical implementation method for sustainability, turning LCA evidence into workforce capability. Duane et al (2026) identifies twelve components that collectively form a coherent educational system for teaching carbon footprinting through LCA (Duane et al., 2026c). Each component builds upon the previous to develop both technical and reflective competencies:

- Alignment with International Standards: Students learn ISO compliant LCA methodology to ensure consistency and global comparability. This establishes credibility and prepares learners for professional sustainability roles.
- Experiential Learning: Real world data collection and modelling exercises engage learners in active discovery, reflecting (Kolb, 2014) experiential learning cycle.
- Sense Checking as Core Competency: Students are trained to critically evaluate the likelihood of their results, avoiding over reliance on automated outputs.
- Benchmarking and Literature Comparison: Learners compare their results with published LCAs in healthcare (Connor et al., 2010a; Sherman et al., 2018) to contextualise outcomes and identify methodological differences.

- Internal Consistency Checking: Exercises in internal validation ensure that assumptions about materials, mass balance and process emissions align logically.
- Structured Peer Review: Modelled on scientific publication, peer feedback sessions simulate professional scrutiny, improving both accuracy and communication skills.
- Cognitive Apprenticeship: Expert mentors demonstrate reasoning processes, guiding students through complex problem solving while gradually reducing support as competence increases (Collins et al., 2018).
- Collaborative Learning: Group projects encourage multidisciplinary collaboration and shared responsibility for results, reflecting real world LCA workflows.
- Documentation of Assumptions: Transparent recordkeeping builds reproducibility and academic integrity.
- Sensitivity Analysis: Learners explore how parameter changes affect results, developing critical understanding of uncertainty and variability (Finnveden et al., 2009).
- Treating Variation as Learning: Differences between student outcomes are reframed as opportunities to explore methodological influence rather than errors.
- Reflection and Dialogue: Structured reflection connects technical modelling to ethical, clinical and social dimensions of sustainability (Mortimer et al., 2018).

Figure 5. 4 illustrates how teaching visual data breakdowns by lifecycle stage improves comprehension and communication of environmental hotspots (Duane et al., 2026c).

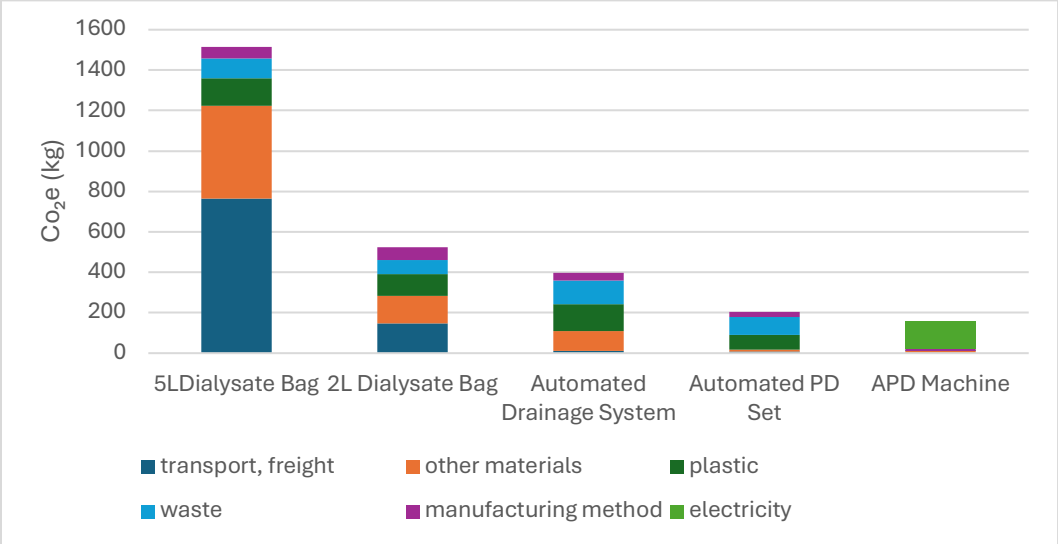

Figure 5. 4 Contribution Analysis (Duane et al. 2026c)

Although the educational toolkit was developed and tested within dental care, its underlying structure is transferable to nephrology and other resource intensive clinical pathways. Both dental and dialysis services involve complex combinations of procurement, energy use, consumables and patient activity, making them suitable for life cycle thinking approaches. However, important differences remain. Dialysis operates within more tightly regulated, high risk clinical environments with greater dependency on large scale infrastructure and continuous treatment delivery. As a result, implementation in nephrology requires adaptation to reflect clinical governance structures, infection control requirements and multidisciplinary decision making. Despite these differences, the core educational components, including system boundary definition, hotspot identification and scenario comparison, remain directly applicable. This supports the use of the toolkit as a transferable framework rather than a discipline specific model.

The educational rationale and implementation implications of this framework are analysed in Section 5.4.3.

5.3.4 Carbon dashboards

Carbon dashboards represent a practical mechanism for turning sustainability evidence into everyday clinical decision making. While LCAs provide detailed retrospective analysis, dashboards and digital tools offer prospective, near real time feedback that can support behavioural change, control and quality improvement. This study evaluated generative AI as a potential carbon dashboard capable of approximating formal LCA outputs and supporting sustainability implementation in clinical settings (Duane et al., 2026a). To evaluate the impact of prompt structure on performance, the outputs generated by ChatGPT across the three variants were compared with those from the validated Excel based dental carbon calculator, which served as the benchmark.

Each output was assessed for the precision of its carbon footprint estimates, the scope and relevance of its sustainability recommendations and the inclusion of credible, verifiable references. Although this evaluation involved some degree of subjectivity, it provided valuable insight into the relative strengths and weaknesses of different prompting strategies. To

minimise potential bias from the model's memory and adaptive learning, all three prompt types were tested independently on two separate ChatGPT accounts (Duane's and Larkin's), ensuring that prior interactions did not influence subsequent responses (Duane et al., 2026a).

Although the prototype was validated in dental practice, the methodological objective was transferable. The study functioned as a proof of concept for AI supported carbon dashboards applicable to other resource intensive services, including dialysis units, outpatient clinics and community care pathways.

Three prompt structures were tested to assess how levels of contextual detail and external guidance influenced accuracy, transparency and usefulness of outputs.

Variant 1:

Variant 1 did not generate a site specific carbon footprint, as ChatGPT did not prompt the user to supply any contextual or operational data. Instead, the model produced a generalised estimate based solely on information drawn from existing literature. The output included an extensive list of sustainability recommendations supported by references from multiple recognised sources. Among these were two familiar tools:

- The Green Impact for Health Toolkit.
- The CSH sustainability framework (Healthcare., 2024)

Additional references from the Eco Dentistry Association and the American Dental Association. The full interaction for this variant is illustrated in Figure 5. 5 (Duane et al., 2026a).

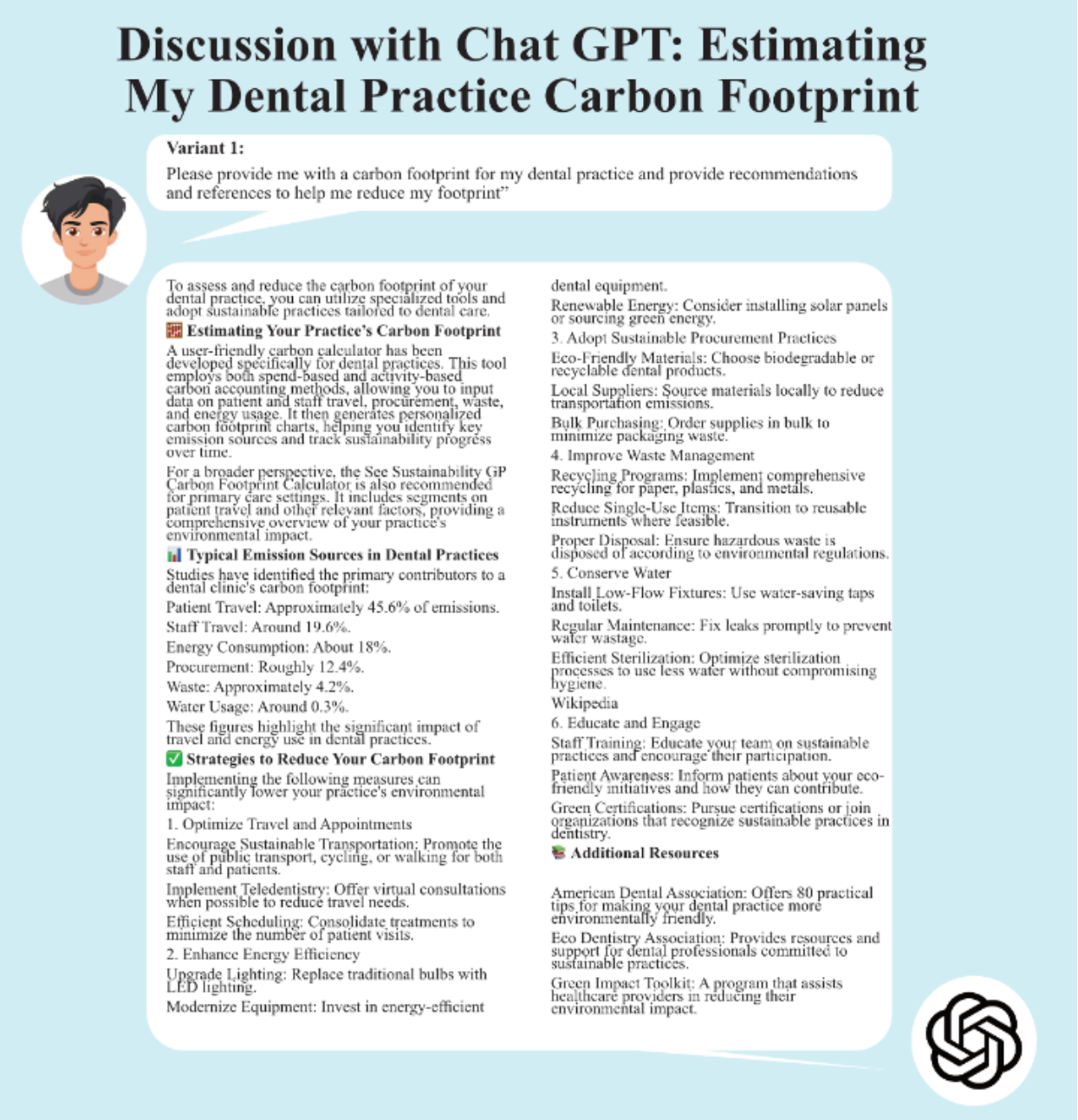

Figure 5. 5 Discussion with ChatGPT using variant 1 (Duane et al. 2026a)

Variant 2:

As intended, Variant 2 generated a more detailed and practice specific carbon footprint for the dental clinic. In this case, ChatGPT actively requested additional operational details when initial responses were incomplete, demonstrating an adaptive questioning approach. The resulting output included twelve targeted recommendations aimed at reducing the clinic's

overall environmental impact. However, while the advice was contextually relevant and well structured, none of the recommendations were supported by formal references or external data sources. The full dialogue illustrating this process is shown in Figure 5. 6 (Discussion with ChatGPT using Variant 2) (Duane et al., 2026a).

Discussion with Chat GPT: Estimating My Dental Practice Carbon Footprint

Variant 2:

Was told to collect specific data based on the attached prompt (without specifying specific literature to draw down personalised recommendations)

You are a carbon footprint calculator specifically trained for dental clinics. I will answer a few simple questions about my dental practice, and you will estimate our carbon footprint in kg or tonnes of CO_2 equivalent (CO_2e), based on reasonable emission factors.

Then, give me a breakdown of emissions by category (e.g., travel, energy, waste, procurement), and offer 3–5 tailored recommendations to help us reduce emissions.

Please do this in three steps:

A. Ask me these questions:

Practice Information (Annual figures)

1. How many days is the practice open on an average year?
2. How many full-time staff are in the practice?
3. How many patient visits does the practice see every year?

Staff Travel (in miles)

4. How far do all staff travel (return trip) to work or for work by car per day?

Patient Travel (in miles)

(Use a survey of 30 patients to estimate total distances per transport type)

5. What is the total distance travelled by 30 patients using:
   - Petrol/Diesel Car?
   - Electric Car?
   - Bus?
   - Train?
   - Motorbike?
   - Bike/Walk?

Waste (Number of bags disposed per day)

6. How many bags of plastic waste for recycling?
7. How many bags of cardboard waste for recycling?
8. How many bags of infectious waste for incineration?
9. How many bags of domestic waste for disposal?

Energy Use (in kilowatt-hours - kWh)

(This year – make sure it's a normal year)

10. How much standard electricity did the practice use?
11. How much green electricity did the practice use?
12. How much electricity did you generate from solar panels on your roof?
13. How much gas did the practice use?

Water

14. What was the total water usage in cubic metres?

Procurement

15. How much did you spend on other things, equipment, and materials in pounds sterling (£)?

(Do not include rent or interest)

B. Use these emission factors:

Travel

- Staff car travel per mile: **0.5300 kg CO_2e**
- Patient travel per mile:
  - Petrol/Diesel Car: 0.5300
  - Electric Car: 0.1830
  - Bus: 0.1500
  - Train: 0.1900
  - Motorbike: 0.1600
  - Bike/Walk: 0.0000

Waste per bag

- Plastic recycling: 0.0000
- Cardboard recycling: 0.0000
- Infectious waste (incineration): **7.5869 kg CO_2e**
- Domestic waste (disposal): **1.1558 kg CO_2e**

Energy per kWh

- Standard electricity: 0.2749
- Green electricity: 0.0110
- Solar on roof: 0.0410
- Gas: 0.2100

Water

- Per m^3: **0.3378**

Procurement

- Per £ spent: **0.1315**

C. After I provide the answers, calculate and present:

1. **Total CO_2e per year for my practice**
2. **Which category is the highest emitter**
3. **Recommendations to reduce emissions**, draw on own data

Excellent — I'm ready to calculate your dental practice's carbon footprint using the method you've outlined.

Let's begin with Step A: Questions. Please answer the following:

Practice Information (Annual figures)

How many days is the practice open in an average year?

How many full-time staff are in the practice?

How many patient visits does the practice see every year?

Staff Travel (in miles)

How far do all staff travel (return trip) to work or for work by car per day?

(Total return mileage for all staff combined per day, not per person)

Patient Travel (in miles)

(Based on a survey of 30 patients, estimate the total distance travelled per day by mode of transport)

5. What is the total distance per day travelled by patients using:

Petrol/Diesel Car?

Electric Car?

Bus?

Train?

Motorbike?

Bike/Walk?

Waste (Number of bags disposed per day)

How many bags of plastic waste for recycling?

How many bags of cardboard waste for recycling?

How many bags of infectious waste for incineration?

How many bags of domestic waste for disposal?

Energy Use (in kilowatt-hours - kWh)

(For the past year – assuming it's a typical year)

10. How much standard electricity did the practice use?

11. How much green electricity did the practice use?

12. How much electricity did you generate from solar panels on your roof?

13. How much gas did the practice use?

Water

What was the total water usage annually in cubic metres (m^3)?

Procurement

How much did you spend annually on other things, equipment, and materials in pounds sterling (£)?

(Exclude rent, salaries, or interest)

Please respond with your answers, and I'll move to Step B (calculations) and Step C (results + recommendations).

Figure 5. 6 Discussion with ChatGPT using variant 2 (Duane et al. 2026a)

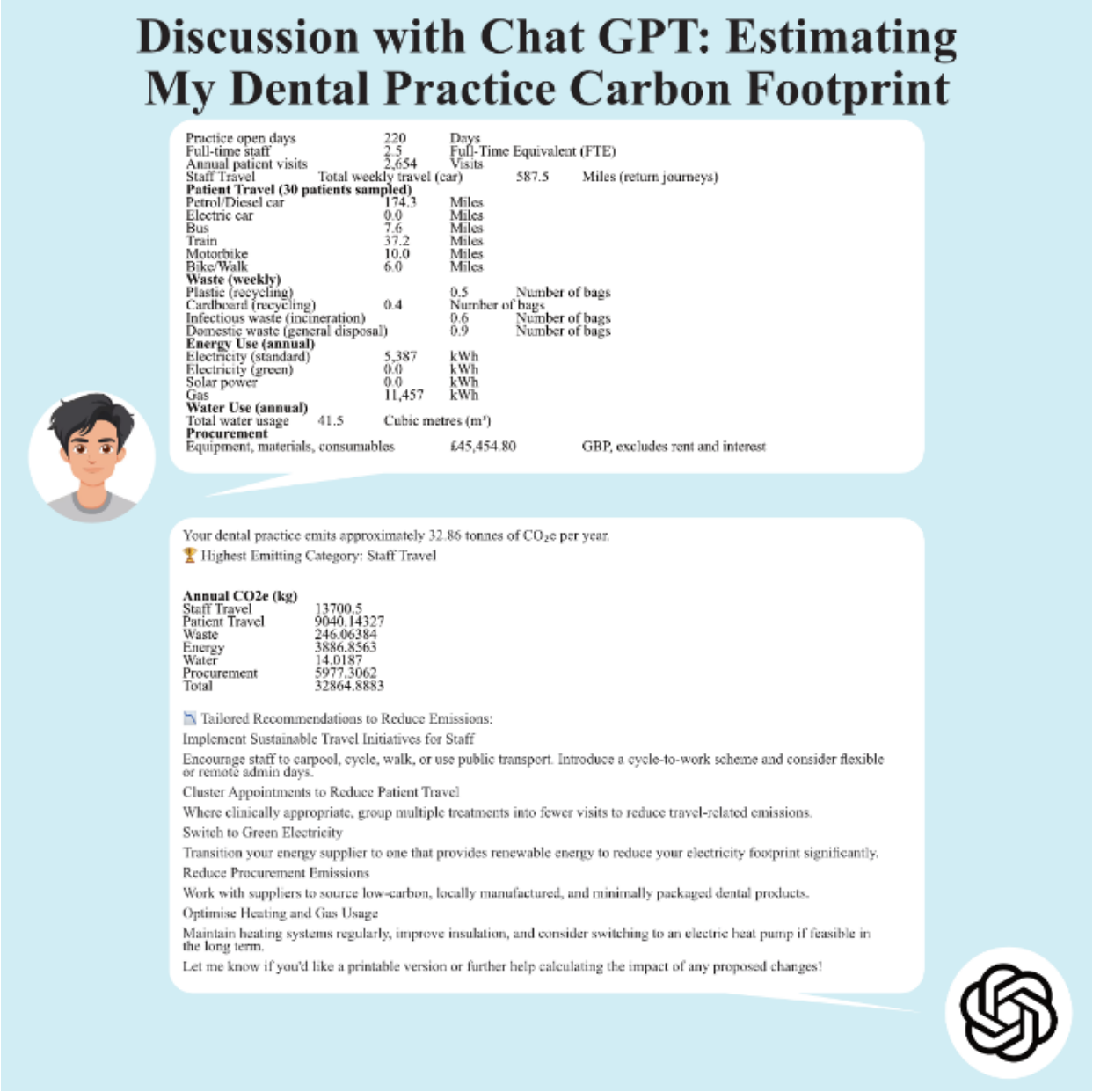

Figure 5. 7 Discussion with ChatGPT using variant 2 (Duane et al. 2026a)

Variant 3:

Variant 3 produced seventeen customised recommendations, reflecting a broader and more comprehensive response than the previous variants. In this iteration, ChatGPT successfully incorporated information from the CSH sustainability tool, demonstrating its ability to integrate recognised frameworks when explicitly directed. However, some references included

less reliable sources, such as Wikipedia, indicating occasional inconsistencies in source credibility. The full exchange for this variant is presented in Figure 5. 8 (Discussion with ChatGPT using Variant 3) (Duane et al., 2026a).

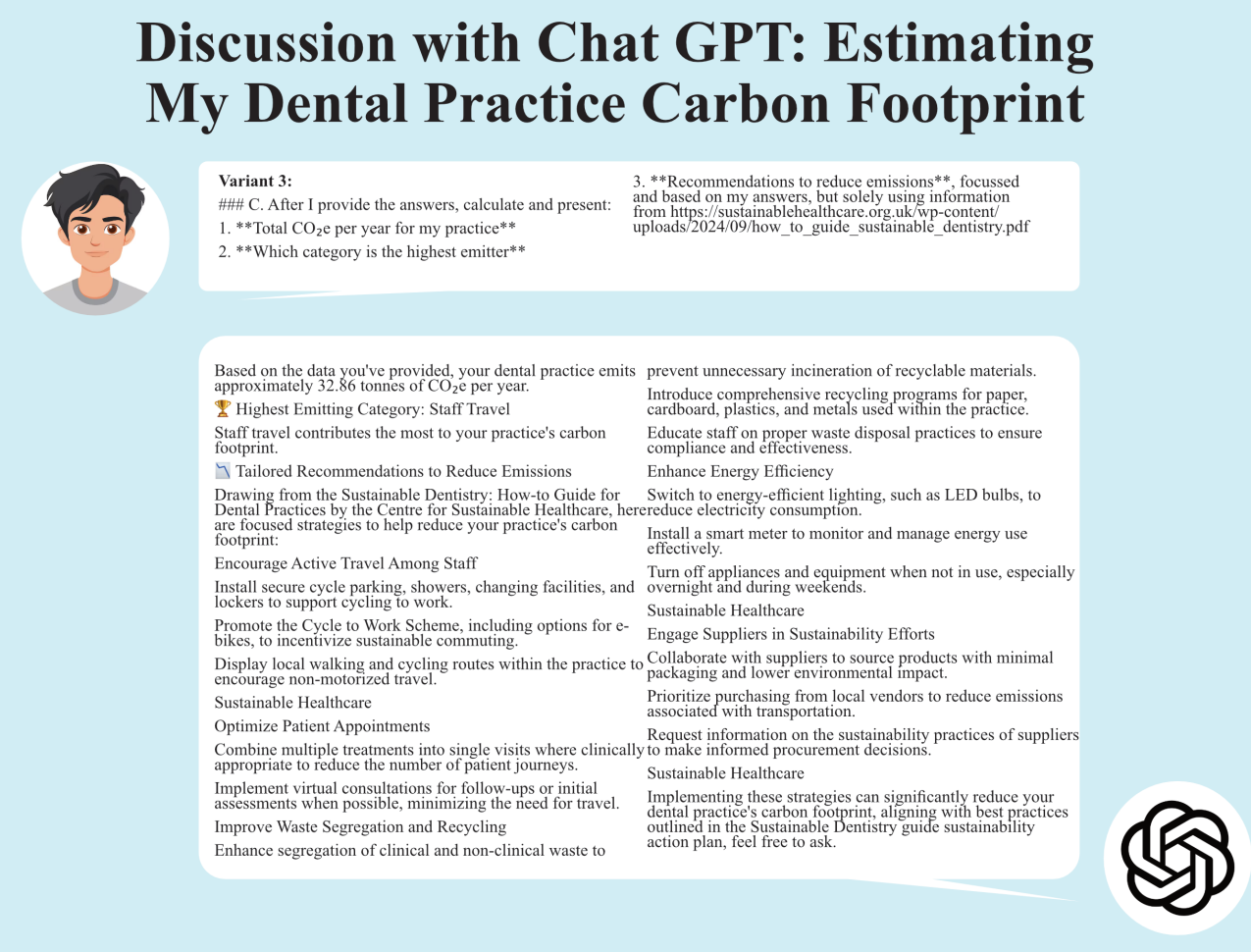

Figure 5. 8 Discussion with ChatGPT using variant 3 (Duane et al. 2026a)

Table 5.13 compares annual carbon estimates generated by the Excel benchmark tool with those produced by ChatGPT across the three prompt variants, illustrating similarities and differences in total emissions and category attribution.

Table 5. 13 Comparison of V1,V2 and V3 (Duane et al. 2026a)

Inserted Mock Data	**Practice information**	**CO_2 eq Annual from Excel in kg**	**CO_2 eq Annual from Chat**	**CO_2 eq Annual from Chat (v2)**	**CO_2 eq Annual from Chat (v3)**
220.0 days	How many days is the practice open on an average year?				
2.5 people	How many full time staff in the practice?				
2654 visits	How many patients visits does the practice see every year?				
587.5 miles	This week (make sure it's a normal week) how far do all staff travel return to work or for work by car.	**13701.6**	Advised 45.6% CO_2 eq comes from patient travel	Identical to Excel	
Do the simple patient survey for 30 patients (see notes) and total the distance of all patients travel by each method					
174.3 miles	Petrol/Diesel Car	92.4	Didn't ask	No breakdown given	
0.0	Electric Car	0.0			
7.6 miles	Bus	1.1			
37.2 miles	Train	7.1			
10.0 miles	Motorbike	1.6			
6.0 miles	Bike/Walk	0.0			
		9040.1	Advised 19.6% CO_2	Identical to Excel	

			eq comes from staff travel	
	Waste		No breakdown given	
	Total number of bags of			
0.5 bags	Plastic waste for recycling	0.0		
0.4 bags	Cardboard waste for recycling	0.0		
0.6 bags	Infectious waste for incineration	4.3		
0.9 bags	Domestic waste for disposal	1.0		
		232.2	Advised 4.2 % CO_2 eq comes from waste	Minor difference 246.1
5387.0 Kwh	Standard electricity	1480.7	Didn't ask	No breakdown given
0.0	Green electricity	0.0		
0.0	Solar power on your roof	0.0		
11457.0Kwhr	Gas	2406.0		
		3886.6	Advised 15.3 % CO_2 eq comes from energy	Identical to Excel
41.5m3	**Water usage in Metres cubed**	**14.0**	Advised 0.3% CO_2 eq comes from water	Identical to Excel

£45454.8	**Procurement: The things you buy: How much did you spend on other things, equipment, materials in pounds Stirling £ (don't include rent, interest)**	**5975.8**	**Advised 12.4% CO_2 eq comes from procurement**	Identical to Excel
	Your results for your practice	32850.4	675 tonnes	32.86 tonnes
Recommendations V 1. Non tailored. Optimise travel and appointments. Enhance energy efficiency. Adopt sustainable procurement practices. Improve waste management. Conserve water- educate and engage V2. Tailored (with no reference to literature) Implementing sustainable travel initiatives for staff, cluster appointments, optimise energy use, reduce procurement emissions, nothing on waste V3. Tailored (referenced to the CSH guide) Implementing travel (detailed), waste segregation (detailed) energy efficiency (detailed for elect, nothing on gas), procurement (detailed)				

In Figure 5. 8 Discussion with ChatGPT using variant 3, the carbon footprint results generated by ChatGPT closely matched those produced by the Excel based calculator, with only minor variations observed across categories. The largest difference occurred in waste related emissions, where ChatGPT estimated 232.2 kg CO_2-eq compared with 246.1 kg CO_2-eq from the Excel tool. Estimates for energy, water and procurement were identical across both methods, indicating a strong alignment in overall model outputs. However, the ChatGPT generated assessment lacked detail, as it did not breakdown emissions by patient transport mode or waste stream type, reducing transparency and traceability within the results (Duane et al., 2026a).

The practical implications of digital dashboards and AI supported tools are discussed in Sections 5.4.3 and 5.5.3.

5.4 Analysis: Feasibility, impact and social considerations

5.4.1 Environmental & literature analysis

The optimisation LCA highlights that impacts vary substantially across intervention types (Duane et al., 2025a). The largest benefits arise where emissions are driven by structural factors, for example transport modes, energy sources and session frequency. Travel optimisation, iHD, solar integration and pyrolysis are consistently high impact in the model. Cotton textiles also carry high water burdens, which explains the large water deprivation savings from removing cotton blankets in dialysis units (Duane et al., 2025a).

Findings depend on context. Energy savings vary with the electricity mix. Regions with coal heavy grids gain more from electrification and on site renewables, whereas highly renewable grids yield smaller marginal gains for the same intervention. Travel patterns vary by geography and transport policy, which changes the achievable savings. The model used Spanish foreground energy data for consistency, with Irish patient travel distances for lack of published Spanish figures, which should be considered when generalising (Duane et al., 2025a). This reinforces the importance of using LCA not as a universal tool but as a decision support framework that must be interpreted within local infrastructural and policy conditions.

The scoping review provides a map of the wider field against which the empirical studies of the thesis can be positioned. While the modelling studies focus on specific interventions in HD and PD, the review captures the breadth of approaches globally, showing the hotspots identified (procurement, transport, waste and energy) are consistently reported by other groups. This link across independent studies strengthens confidence in the identification of procurement, transport and waste as priority areas for improvement, rather than parts of a single modelling approach.

The review highlights where current efforts are concentrated and where evidence gaps remain.

The review also sharpened the recognition that while technical solutions such as water reuse or solar integration are important, social and organisational aspects are less well represented. Very few studies reported patient engagement, staff behaviour change, or organisational

readiness, despite evidence from other areas of healthcare that these are critical for sustainability. This insight links back to broader thesis focus on integrating design and life cycle thinking with behavioural and organisational perspectives (Yasar et al., 2025).

5.4.2 Social life cycle assessment: Labour, equity and supply chain risks

The Social LCA shows a direct relationship between material and energy intensity in healthcare processes and exposure to labour related supply chain risks (Duane et al., 2026b). Interventions that reduce overall resource use, such as iHD, therefore achieve the greatest relative social benefit. This supports previous research showing that procurement and supply chain processes account for most healthcare related social risks (Eckelman et al., 2016; García-Sánchez et al., 2020). These findings reinforce the argument that sustainability strategies focused solely on operational efficiency fail to address the social consequences embedded within global production systems (Duane et al., 2026b). The high forced labour risk associated with textiles and food reflects the structural vulnerability of agricultural and manufacturing sectors within globalised supply chains, where labour protections are often weak and price pressure is intense (Alsamawi et al., 2019; Theron, 2024).

Solar energy adoption reduced labour risk through the displacement of coal and oil industries, which have documented histories of forced labour in extraction and refining (Free, 2022). However, solar energy technologies themselves are not free from social risks. The mining of cobalt and polysilicon has been associated with human rights violations in the Democratic Republic of Congo and western China (Ayuk, 2023). This demonstrates the need for traceable, ethically sourced renewable energy components within hospital sustainability programmes. Without such safeguards, environmental optimisation risks shifting harm rather than reducing it, transferring burden from climate impacts to labour exploitation (Duane et al., 2026b).

The Social-LCA therefore extends traditional environmental assessment by revealing that high impact clinical decisions also carry ethical consequences beyond the healthcare system itself.

5.4.3 Educational necessity

Building on the toolkit described in Section 5.3.3, this section analyses the role of education in supporting implementation. Researchers applied it across multiple studies, including the environmental LCA of PD pathways (Larkin et al., 2025b) and the HD procurement study (Larkin et al., 2026b).

The framework also bridged technical and social areas of sustainability. For instance, integrating S-LCA into student projects demonstrated how environmental and human rights indicators can be combined in healthcare evaluations (Ekener et al., 2018). This interdisciplinary approach supports the growing literature advocating for triple bottom line sustainability in healthcare (Duane et al., 2026c). By training researchers and clinicians to evaluate environmental and social outcomes together, the toolkit supports decision making that reflects real system trade-offs rather than isolated metrics (Barraclough et al., 2020; McGain et al., 2014).

Educational infrastructure therefore plays a direct role in shaping research quality and policy relevance (Duane et al., 2026c).

These findings indicate that building sustainability capacity requires more than technological solutions. It demands educational transformation. Without shared methodological literacy, sustainability evidence remains misunderstood and difficult to turn into coordinated clinical or procurement action. The toolkit provides a scalable framework for embedding sustainability science into professional curricula, aligning with national strategies such as the Net Zero Plan and the European Green Deal (Commission, 2019; NHS, 2020).

Embedding LCA knowledge into hospital training equips future clinicians to participate in sustainable procurement decisions and design greener clinical pathways (Connor et al., 2010b). In doing so, it contributes to the professionalisation of sustainability as a healthcare competency, paralleling infection control or patient safety training (Duane et al., 2026c).

The intended audience for this educational framework spans multiple levels of the healthcare system. For students and trainees, it provides foundational skills in environmental assessment

and systems thinking. For clinicians, it supports interpretation of sustainability evidence in relation to clinical workflows and patient care. For sustainability leads and managers, it offers a structured method for evaluating interventions and supporting procurement and service redesign decisions. For multidisciplinary teams, it creates a shared language through which environmental, clinical and operational priorities can be discussed and aligned. In practical terms, the toolkit can be implemented through integration into undergraduate and postgraduate curricula, continuing professional development programmes and hospital based quality improvement initiatives. Embedding the framework within existing training and governance structures increases the likelihood that sustainability becomes part of routine decision making rather than a separate activity.

These findings position education as a central component of sustainable kidney care.

5.5 Discussion and implications for practice

5.5.1 Design principles for sustainable kidney care products

The findings indicate that sustainable healthcare innovation requires interdisciplinary design, clinical and sustainability input. Clinicians grounded each project in patient safety, workflow and regulatory reality, while engineers and designers focused on how systems and products might be changed in practice. Sustainability specialists pushed the teams to look beyond single measures such as carbon, asking what different choices meant for water, materials and labour conditions in supply chains (Duane et al., 2026a; Duane et al., 2025; Yasar et al., 2025; Duane et al., 2026b; Duane et al., 2026c).

Clinical services run under constant time pressure and risk awareness, whereas design and LCA require slower, iterative work and a willingness to revisit assumptions. In both the dental and renal case studies, simple changes from sustainability tools, such as switching products or adjusting flushing regimes, were experienced as disruptive when they cut across infection control routines or added steps to already busy sessions. These findings indicate that sustainable kidney care interventions should be co-designed with frontline staff and integrated into existing quality and safety structures (Duane et al., 2026a; Duane et al., 2025; Yasar et al., 2025; Duane et al., 2026b; Duane et al., 2026c).

Design and LCA should be integrated early in healthcare innovation rather than applied retrospectively. Evidence across case studies shows that early design decisions can produce substantial environmental gains when scaled across services. This reinforces the importance of early stage design decisions, where small modifications accumulate into large system effects over time (Duane et al., 2026a; Duane et al., 2026b; Duane et al., 2026c; Duane et al., 2025a; Yasar et al., 2025).

In kidney care, KitNewCare's multi centre LCAs demonstrated that design decisions about dialyser construction, dialysate delivery formats, transport logistics and building systems determine most of the life cycle footprint long before clinicians encounter the product at the bedside. This shifts responsibility toward manufacturers, procurement frameworks and

infrastructure planning rather than individual clinical behaviour alone (Duane et al., 2026a; Duane et al., 2026b; Duane et al., 2026c; Duane et al., 2025a).

Decision support tools that combine LCA evidence with clinical and operational criteria can support more sustainable product and service choices. By linking inventory data, scenario modelling and clinical performance into accessible formats, these tools allow frontline teams to compare options (e.g. central acid vs. bags, different transport models, alternative consumables) in terms of both clinical suitability and environmental impact. Design principles should also account for equity, ensuring that lower impact pathways do not worsen access or outcomes (Duane et al., 2026a; Duane et al., 2026b; Duane et al., 2026c; Duane et al., 2025a; Yasar et al., 2025).

Taken together, these findings suggest a pathway for future work, embedding design thinking and LCA into routine service development, using mixed method tools to translate evidence into actionable guidance and maintaining interdisciplinary partnerships so that innovations remain clinically safe, technically robust and socially acceptable (Duane et al., 2026a; Duane et al., 2026b; Duane et al., 2026c; Duane et al., 2025a; Yasar et al., 2025).

A critical consideration emerging across Chapters 1 and 4 is the role of real and perceived risks to patient safety in shaping the adoption of sustainability interventions. While many proposed strategies demonstrate clear environmental benefits, their implementation is often constrained by concerns related to infection control, treatment reliability and clinical responsibility. For example, changes to consumables, reuse practices or waste handling are frequently evaluated through a precautionary lens, where even low probability risks are treated as unacceptable within clinical environments. These concerns are not solely technical but are embedded within professional norms, regulatory requirements and institutional governance structures. As a result, sustainability interventions must be designed and evaluated not only in terms of environmental impact but also in terms of their compatibility with existing safety standards and risk management processes. Addressing this requires early engagement with clinical stakeholders, clear evidence of equivalence or safety and alignment with infection prevention and control protocols.

These findings position design not as an aesthetic or optional layer, but as a core aspect through which sustainability becomes operational within kidney care systems.

5.5.2 Procurement strategy and supplier engagement

Procurement emerged as a key determinant of both environmental and social impact. Procurement decisions shape the materials, manufacturing pathways and end-of-life outcomes of dialysis products (Larkin et al., 2025b). Embedding social criteria into procurement, such as supplier transparency and labour standards, offers a pathway to reducing social harm. The integration of social indicators, including forced labour risk, into EU Green Public Procurement frameworks could align medical purchasing with broader human rights goals (Commission, 2019). This positions procurement as a primary change point where environmental and social sustainability join (Duane et al., 2026b).

Chapter 4 showed that procurement teams often lack the authority to apply sustainability criteria in practice (Larkin et al., 2026e). Participants described a gatekeeping effect in which centralised purchasing policies constrain supplier diversity and innovation. Similar findings were reported in the literature on medical device regulation, where compliance requirements slow the adoption of alternative materials and sustainable manufacturing processes (Lokanathan, 2023). Overcoming these barriers will require collaboration between regulators, clinicians and suppliers to align sustainability objectives with patient safety and quality standards (Duane et al., 2026b).

The findings encourage hospitals to integrate social indicators into procurement scoring systems, supplier audits and sustainability reporting (Duane et al., 2026b). In practical terms, S-LCA findings can be operationalised within procurement through the development of multi-criteria tender frameworks that combine environmental, social and clinical requirements. For example, procurement scoring systems could assign explicit weighting to social risk indicators alongside cost and performance, such as requiring suppliers to disclose manufacturing locations, labour standards compliance and traceability of high-risk materials. Forced labour risk data derived from S-LCA can be translated into comparative scoring criteria, where products associated with lower risk supply chains are prioritised where clinically equivalent.

In addition, contract clauses can be used to require ongoing reporting on supply chain transparency and continuous improvement in labour conditions. By embedding these criteria into existing procurement structures rather than treating them as optional add ons, S-LCA insights can directly influence purchasing decisions in a manner consistent with current governance and regulatory frameworks.

Policymakers could support this shift through binding social criteria in medical device tenders, similar to existing environmental directives under the EU Green Deal (Commission, 2019).

Material selection remains a practical procurement issue. In PD systems, PVC and multilayer packaging contribute to environmental burden and are difficult to recover within existing waste systems. Procurement specifications that favour lower-toxicity materials, design for recyclability and reduced packaging could therefore support both environmental and operational improvements. Together, these findings show that procurement strategy is not a technical function alone but a central method for delivering environmental and social sustainability in kidney care.

5.5.3 Digital tools and standardised life cycle assessment methods

Structured sustainability tools informed by LCA can support operationally feasible reductions in environmental impact. This demonstrates how standardised LCA methods supported by digital tools create transferable pathways for sustainability across clinical disciplines (Duane et al., 2026a; Duane et al., 2026b; Duane et al., 2026c; Yasar et al., 2025).

Combining LCA, quality improvement and education can create a shared language for prioritising high impact interventions (Duane et al., 2026a; Duane et al., 2026b; Duane et al., 2026c; Yasar et al., 2025).

Digital tools should support not only environmental assessment but also broader considerations of equity, access and implementation across patient groups.

Across these studies, methodological consistency emerged as a central enabler of implementation. Together, the toolkit paper, dental LCA, optimisation studies and scoping

review illustrate that shared methods, particularly LCA paired with structured improvement tools, can be used in different areas and create a coherent evidence base for greener practice (Duane et al., 2026a; Duane et al., 2026b; Duane et al., 2026c; Yasar et al., 2025).

Digital tools, including AI-supported interfaces, have potential as low-barrier entry points for sustainability assessment when grounded in validated datasets and standardised methods. Their value lies in screening, engagement and routine monitoring rather than formal reporting or procurement approval. To be useful in practice, such tools require transparent assumptions, clear scope limitations and appropriate staff training.

Taken together, these findings show that digital tools, when grounded in standardised LCA methods and supported by training, can extend sustainability practice beyond specialist analysts and into routine clinical decision making.

5.5.4 Limitations and future research directions

The analysis focuses on CO_2 eq and water deprivation rather than a full multi category impact set. This choice was made to support clarity and comparability for decision makers and aligns with the KitNewCare approach. Model assumptions use Spanish electricity and wastewater data and Irish travel distances. The relative rankings remain informative, but local services should update the model with local data before investment decisions (Duane et al., 2025a).

The review has several limitations. The diverseness of study designs and outcomes made quantitative analysis impossible. Many interventions lacked detailed environmental metrics, relying instead on assumptions or qualitative accounts. Geographic concentration in high income countries limits generalisability. Moreover, publication bias may have skewed the sample towards successful or innovative interventions, leaving unsuccessful attempts undocumented. Despite these limitations, the review provides the most comprehensive overview to date of sustainability efforts in nephrology and offers a foundation for future comparative research (Yasar et al., 2025).

This study relied on secondary data from the Soca v2 and PSILCA databases. While these sources provide valuable insights into global supply chains, they cannot fully capture regional

variations or company specific practices. Results should be interpreted as indicative of relative differences rather than absolute quantifications. Furthermore, only one social indicator forced labour risk was assessed. Expanding the scope to include gender equity, occupational health and fair wage indicators would yield a more comprehensive understanding of social sustainability (Duane et al., 2026b).

One limitation of the method lies in its reliance on static, UK specific emission factors. These values provide a reasonable baseline for comparison but may not accurately capture emissions in regions with differing energy systems, waste management practices, or transportation habits (IEA, 2024). Local adaptation of emission factors is therefore recommended for improved accuracy. A centralised, peer reviewed database of international emission factors, accessible to both human and AI users, would improve reproducibility, reduce misinformation and strengthen the reliability of AI assisted carbon footprinting (Deloitte, 2025; Roumeliotis et al., 2023). Developing such a resource would also reduce "hallucination" risks, where the AI generates plausible but incorrect data, a known issue in current LLMs (Alkaissi et al., 2023; Duane et al., 2026a).

It is equally important to acknowledge the environmental footprint of the AI itself. A typical ChatGPT session of about fifty prompts consumes roughly 50 watt hours of electricity, corresponding to approximately 24 grams of CO_2 equivalent emissions, assuming an average grid intensity of 0.475 kg CO_2e/kWh (IEA, 2024). While this contribution is negligible compared with the emissions from clinical activity, it excludes the embodied carbon associated with data centre infrastructure and model training. As AI becomes more embedded in sustainability practice, transparency regarding its operational footprint will be essential (Duane et al., 2026a; Hoque et al., 2023; Roumeliotis et al., 2023).

These considerations indicate that digital sustainability tools must be used with the same transparency and accountability expected of clinical decision support systems.

5.6 Conclusion

5.6.1 Key interventions validated

For clinical services, the model supports a hierarchy of action. First, reduce patient travel through service configuration, shared transport, telehealth and suitable home modalities. Second, decarbonise energy supply or add on site solar where practical. Third, adopt iHD where clinically appropriate and supported by guidelines. Fourth, address high burden materials and textiles through procurement policies and adopt advanced waste treatment where regulation and safety permit. These priorities align with broader EU climate targets and health system decarbonisation programmes. These actions are directly supported by the combined environmental LCA, social LCA and stakeholder evidence presented across Chapters 3 to 5 (Duane et al., 2025a).

Duane et al (2026) represents an important part in the integration of environmental literacy and life cycle thinking into healthcare education (Duane et al., 2026c). Its twelve components combine technical thoroughness, experiential pedagogy and reflective learning to produce professionals capable of quantifying and reducing the environmental footprint of clinical care.

By aligning educational design with ISO standards, OpenLCA methodology and sustainability policy frameworks, the toolkit creates a bridge between environmental science and clinical practice. It ensures that the next generation of healthcare workers are equipped not only to understand but also to act upon sustainability data. This educational contribution strengthens the long term implementation potential of the technical and system level interventions identified in this thesis (Duane et al., 2026c).

In summary, this study demonstrates that ChatGPT can provide reliable and user friendly sustainability assessments when properly guided through structured prompts linked to verified resources. While spreadsheet based tools remain more transparent, the conversational AI approach offers a practical and scalable alternative that lowers technical barriers to engagement. The findings indicate that structured AI supported carbon accounting has potential as a low barrier entry point for sustainability engagement across clinical disciplines when grounded in verified open access resources. Continued refinement of AI prompt design,

together with global access to open sustainability data, will further improve the quality, transparency and accessibility of environmental assessments across the healthcare sector (Duane et al., 2026a; Duane et al., 2024; Federation, 2025).

Together, these findings reinforce the central conclusion of this thesis, sustainable kidney care requires coordinated action across service design, procurement, education and governance rather than isolated technical optimisation.

5.6.2 From individual interventions to system change

The authors role included life cycle modelling and data analysis for selected interventions, cross checking foreground assumptions and manuscript contributions to the methods and interpretation. This work supports the thesis aim of using LCA as a decision framework for prioritising environmental improvements in kidney care. It also demonstrates how comparative modelling can direct attention to the largest changes, travel, energy sourcing, session frequency, high burden materials and waste treatment choices forming a core part of the environmental optimisation theme. Taken together, this modelling work shows how LCA supports a shift from isolated efficiency actions toward structured system level decision making in kidney care (Duane et al., 2025a).

This review complements the LCAs reported in other chapters by providing a higher level analysis. Together, they demonstrate that advancing green nephrology requires both detailed quantification of interventions and broad evidence mapping. The scoping review situates the thesis within a global research landscape, showing how the authors contributions both align with and extend beyond existing efforts. This highlights the importance of collaborative research structures that integrate technical analysis with organisational and social understanding. In Chapter 5, these insights feed directly into the environmental optimisation, social value and educational implementation themes, ensuring that the thesis recommendations rest on both detailed LCAs and a broad evidence map. This positioning reinforces the role of Chapter 5 as a bridge between measurement based evidence and future implementation (Yasar et al., 2025).

This study provides evidence that social and environmental optimisation can be achieved simultaneously in kidney care. Interventions targeting procurement, energy and resource efficiency not only reduce emissions but also reduce forced labour risks fixed in global supply chains. The results highlight the value of integrating S-LCA into clinical decision making, procurement policy and product design. Embedding social value into healthcare sustainability frameworks will be essential for achieving ethically responsible, low carbon kidney care across Europe. These findings directly extend the procurement and waste related hotspots identified in Chapter 3 and the stakeholder barriers explored in Chapter 4.

In the context of this thesis, the paper provides the educational infrastructure that demonstrates the methodological consistency of the environmental, social and system level LCAs presented across earlier chapters. It transforms LCA from a research technique into a transferable educational model that can inform training, policy and practice across the European healthcare landscape, forming a key component of the educational and implementation theme in this chapter. In doing so, the chapter demonstrates how methodological consistency enables environmental and social evidence to inform policy aligned action rather than remaining academic output (Duane et al., 2026c).

5.6.3 Link to chapter 6

Chapters 3 to 5 establish a structured foundation for understanding sustainability in kidney care. Chapter 3 quantified environmental pressures across HD and PD pathways and identified clear hotspots linked to travel, procurement, water systems and waste treatment. Chapter 4 added a human and organisational layer by identifying how clinicians, managers and procurement teams experience sustainability efforts in practice. Chapter 5 then examined this combined evidence into evaluated interventions, design principles and educational tools that demonstrate how environmental and social optimisation can occur within real clinical settings.

Together, these chapters move beyond descriptive assessment. They show where impacts arise, why existing practices persist and which interventions deliver meaningful benefit across environmental and social areas. Yet this body of work also reveals a central challenge. Individual interventions, even when supported by strong evidence, are insufficient when

implemented in isolation. Sustainable kidney care depends on coordinated change across multiple parts of the health system, including procurement governance, workforce capability, infrastructure planning, supplier engagement and policy alignment.

The findings demonstrate recurring patterns across chapters. Procurement decisions shape both carbon intensity and labour risk long before products reach clinical settings. Waste outcomes depend on regulatory interpretation rather than technical contamination alone. Energy and water optimisation rely on institutional coordination rather than equipment performance in isolation. Education determines whether sustainability knowledge becomes embedded in routine practice or remains peripheral. These interdependencies highlight the need for a system level framework that connects evidence to action in a structured and scalable manner.

Chapter 6 responds to this need. Drawing directly on the environmental modelling, stakeholder insights and intervention analyses presented earlier, the final chapter analyses findings into an integrated implementation roadmap. This roadmap focuses on alignment rather than invention. It identifies priority action areas, clarifies roles across clinical and non-clinical areas and outlines pathways for embedding sustainability into routine decision making. The chapter also examines how hospitals, manufacturers and policymakers can act in parallel rather than continuously, reducing separation and improving feasibility.

By combining the thesis findings into a coherent strategy, Chapter 6 moves the work from analysis toward application. The emphasis shifts from identifying what should change to explaining how change can occur within existing healthcare structures. In doing so, the chapter positions kidney care as a leading example of how resource intensive medical services can progress toward net zero delivery through coordinated systems design rather than isolated innovation.

Chapter 6: Systems analysis and implementation roadmap

6.1 Introduction

6.1.1 Thematic analysis across chapters

This chapter brings together the findings developed across Chapters 3 to 5 and reframes them at system level. Rather than treating PD and HD as separate technical pathways, the analysis here examines how patterns repeat across modalities, institutions and intervention types when environmental modelling, stakeholder evidence and collaborative studies are considered together. Reading these chapters in combination allows underlying aspects to become visible, particularly those rooted in infrastructure, procurement governance and organisational practice rather than in individual clinical choices.

The thematic approach in this chapter differs from earlier analyses. Chapters 3 and 5 quantify impacts and intervention effects, while Chapter 4 explains how these impacts are experienced and managed within real services. When integrated, these areas reveal that sustainability performance in kidney care is shaped less by modality selection and more by system design decisions that operate in healthcare settings. The Modena case studies provide a consistent important aspect across this analysis, linking pathway LCAs, procurement redesign and stakeholder accounts within a single operational context.

Three main themes emerge across the thesis.

The first concerns transport and procurement as main impacts. Across both PD and HD pathways, material movement and product choice account for the majority of environmental burden. In PD, fluid bags, plastics and associated packaging exceed one tonne of CO_2 eq per patient year (Larkin et al., 2025b). In HD, patient and staff travel contributes between 50 and 71% of total pathway emissions. These patterns are reproduced across studies and reinforced through collaborative modelling (Larkin et al., 2026a). The Granumix case study demonstrates that delivering acid concentrate through centralised fluid preparation reduces emissions by approximately 40% without altering clinical delivery (Larkin et al., 2025a). Together, these findings show that procurement format and logistics design give greater influence on sustainability outcomes than marginal efficiency changes within treatment sessions.

The second theme relates to energy and water systems as secondary but highly responsive areas. Electricity use and RO water treatment represent a smaller proportion of total impacts, typically under 20% of pathway footprints. Yet modelling shows that these components remain highly reducible through infrastructure redesign. Solar integration, reject water reuse and system level efficiency measures achieve reductions ranging from 30 to more than 80% within these categories. The comparison between HD and OLHDF further illustrates this point. While OLHDF shows higher impacts in most midpoint categories, these differences remain structurally small relative to transport and procurement root causes (Larkin et al., 2026a). This reinforces the interpretation that infrastructure investment offers meaningful improvement potential but does not substitute for addressing material flows.

The third theme concerns socio organisational constraints that shape what change is possible. Qualitative interviews across seven European countries show strong motivation among clinicians and managers to reduce environmental harm (Larkin et al., 2026e). Yet this is frequently constrained by regulatory interpretation, limited data access and separated responsibility across departments. Procurement staff report restricted authority to specify environmental criteria. Clinical teams express uncertainty when sustainability actions intersect with infection control or guidelines. These barriers explain why known hotspots persist despite available technical alternatives. The Social LCA results add an additional aspect by demonstrating that procurement choices also embed labour risks within global supply chains, extending the consequences of system design beyond environmental outcomes alone.

The Modena pathway analyses provide a point of merging across these themes. The same procurement structures that drive carbon intensity also shape waste classification, supplier behaviour and labour exposure. This alignment across Chapters 3 and 4 confirms procurement as a central point for system change. Environmental modelling identifies where impacts arise. Stakeholder evidence explains why current practices continue. Collaborative redesign studies demonstrate which modifications are feasible within existing services. Together, they support a shift in focus away from isolated behavioural interventions toward coordinated governance and infrastructure reform.

This thematic analysis forms the basis for the remainder of Chapter 6. The sections that follow look at these recurring patterns into an implementation roadmap that prioritises high impact actions, clarifies responsibility across system stakeholders and proposes mechanisms for embedding sustainability into routine kidney care delivery.

6.1.2 Quantitative trends and validation

Rather than restating individual pathway results, this section analyses quantitative patterns across chapters to validate system level trends. When the data from Chapters 3 and 5 are outlined together, a clear picture emerges of dialysis as one of healthcare's most environmentally burdensome services. Total carbon footprints range from 1.5 tonnes CO_2e per patient-year for incremental PD to 4.7 tonnes for facility-based HD, placing these figures within international benchmarks reported for Australia and the UK (Barraclough et al., 2020; Lim et al., 2013). These figures provide a quantitative baseline for the system level analysis developed in this chapter, allowing intervention priorities to be evaluated against scale of impact rather than just isolated improvements.

This cross-chapter consistency in carbon impacts, procurement and transport accounting for over 60% of impacts in every model speaks to the reliability of LCA as a diagnostic tool for healthcare systems. In PD, dialysate bags contribute 54% of procurement emissions and tubing 23% (Chapter 3), in HD, dialysers and bicarbonate cartridges alone make up 66% of product-related carbon (200.7 and 198.2 kg CO_2e per patient-year). The Granumix case study in Chapter 3 provides concrete validation of intervention potential, demonstrating a 70% reduction in acid concentrate emissions through on-site powder preparation rather than single-use bags. Similarly, the redesign products in Chapter 3 achieve cuts ranging from 54% (dialysate bags) to 87% (APD machines), confirming that these hotspots are not inevitable but addressable through design choices. The analysis across independent models, products and settings functions as internal validation of both the modelling approach and the framework used throughout the thesis.

Comparative modality analysis further reinforces this systems perspective. OLHDF despite clinical survival advantages, carries a modest environmental premium over HD: +2.7% CO_2e,

+5.7% energy and worse performance across 12 of 16 impact categories (Chapter 3) (Blankestijn et al., 2023). Yet at the unit level, shifting from 0-100% OLHDF alters the total footprint by less than 3%, highlighting that modality choice is secondary to structural factors like travel patterns and procurement specifications. When viewed through a systems lens, these findings turn attention away from clinical modality debates toward infrastructure and procurement decisions that shape all treatments. Sensitivity analyses increase this insight. A 10% improvement in RO recovery halves water consumption, while sourcing manufacturing electricity from renewables delivers 20-30% energy-related savings (Chapter 3).

Scaled to hospital level, interventions like Granumix could save several tonnes of CO_2 annually per centre, while electric vehicles or home PD could halve the main transport source (Chapter 3). These quantitative trends gain deeper validity when linked with the qualitative evidence from Chapter 4. All 25 interviewees independently identified the same hotspots, procurement, logistics and waste incineration highlighting the LCAs precisely, yet consistently attributed their persistence to regulatory mandates (e.g., hazardous waste rules) and data gaps rather than technological limits. This alignment across methods establishes a robust evidence base: dialysis emissions are systemic, predictable and ready for targeted reduction without compromising care standards (Duane et al., 2025).

This quantitative and qualitative method provides the foundation for the implementation roadmap developed in the following sections, which turns these validated patterns into a coordinated framework.

6.1.3 Implications for systems change

The thematic patterns identified above do not just describe problems. They point explicitly to areas where interventions can give disproportionate returns. Procurement emerges as the single greatest opportunity. It is responsible for 60% of emissions across both home and facility-based modalities. The Modena cases illustrate this. PD pathway mapping in Chapter 3 highlights gaps in the scope of work that lock in high plastic kits, while Granumix in Chapter 3 proved that switching to centralised powder preparation delivers 40-70% savings without disrupting clinical workflows.

Interviews in Chapter 4 reveal why such shifts remain important. Procurement teams lack EPDs and face rigid tender frameworks prioritising cost over life cycle performance (NHS, 2020). The clear implication calls for embedding LCA evidence directly into tender criteria, mandatory EPDs, circularity requirements (take back schemes, modular designs, Chapter 5) and supplier accountability for end-of-life treatment. Scaled across a nephrology unit, per product reductions of 40-87% reflect hospital wide decarbonisation, positioning procurement as the point for systemic change (Larkin et al., 2025b).

Transport, the other main contributor (50-71% in HD), demands similar redesign. Three times weekly patient travel creates not just environmental costs but equity burdens. This also creates financial strain and access barriers for rural or low-income patients. This dual benefit strengthens the case for transport redesign as a health intervention as well as a climate action. Chapter 3 quantify the solutions. Satellite units, home PD expansion, electric vehicle fleets, or telemedicine could halve emissions while improving outcomes (Stephens et al., 2013). Equity gains confirm the case, as reduced travel reduces both carbon and patient hardship.

Energy and water, though secondary (10-20% of impacts), offer low regret optimisations with immediate payback. High recovery RO systems and renewable electricity sourcing deliver 30% gains with existing infrastructure (Chapter 3). Here a refined ethical tension arises. OLHDF's survival benefits extend treatment duration and therefore lifetime environmental burden (Blankestijn et al., 2023). This planetary health dilemma, clinical success increases resource use and demands a framework that balances individual benefit against system sustainability, prioritising low carbon infrastructure over modality changes. This reinforces the need for decision frameworks that compare interventions at system scale rather than evaluating modalities in isolation.

Overcoming socio-organisational barriers, highlighted in Chapter 4, requires cultural and structural collaboration. Stakeholders across different countries expressed motivation to act but cited regulation, data scarcity and identified governance gaps across procurement, infection control and sustainability leadership. Sustainability leads who succeeded embedded green KPIs into performance reviews, allocated staff time for pilots (e.g., PVC take back) and built

cross departmental coalitions. The AI assisted tools in Chapter 5 point to scalable solutions, including real time carbon dashboards, while S-LCA findings (Chapter 5) expose medium high labour risks in global supply chains, demanding ethical procurement beyond carbon alone.

Research and policy gaps remain, but KitNewCare provides a blueprint. Iterative LCAs feed procurement pilots, which inform EU Green Deal aligned frameworks (Commission, 2019). Multi-centre studies and clinical environmental outcome models are needed next, but kidney care's intensity positions it perfectly as healthcare's sustainability testbed (Rizan et al., 2021). These implications highlight the thesis' importance. Sustainable dialysis demands coordinated redesign of products, pathways and power structures which are achievable through evidence-based governance and clinician leadership.

The following sections turn these implications into a structured implementation roadmap that defines roles, timelines and responsibilities across clinical, organisational and policy levels.

6.2 Cross cutting themes and lessons learned

6.2.1 What was learned

The comparative studies across PD and HD pathways revealed a series of recurring patterns that extend beyond individual technologies or hospital contexts. These cross cutting themes describe not only the shared environmental hotspots across modalities, they also describe the structural, behavioural and institutional behaviour that sustain high emissions in kidney care. Environmental sustainability is now a stated priority in healthcare, most day to day practice still follows older, resource intensive patterns. Clinical workflows, procurement systems and transport pathways remain largely unchanged, linking kidney care to high energy use, material consumption and repeated travel. This mismatch between aims and what works in reality explains why dialysis emissions remain stable despite growing policy attention.

This section discusses five main cross cutting themes identified across the thesis:

- Shared environmental hotspots.
- Intervention points for emission reduction.
- The trade-off between clinical feasibility and environmental necessity.
- The systemic role of procurement and waste management.
- The emerging role of design and innovation in bridging environmental and clinical priorities.

Together, these themes explain why isolated technical improvements fail without system alignment and why coordinated action across practice, procurement and governance is required.

The following subsections discuss these themes in turn, drawing directly on evidence from the LCAs, interviews and collaborative studies presented across the thesis.

6.2.2 Shared hotspots across modalities

Despite differences in modality, geography and operational setting, dialysis systems display a striking consistency in their environmental dependencies. Each treatment pathway relies on large quantities of water, electricity and disposable plastics, all of which contribute to cumulative environmental impacts. Across studies, electricity and water use combined accounted for roughly 10% of the total dialysis carbon footprint, procurement for 20 to 25% and travel for 50 to 70% (Larkin et al., 2026a; Larkin et al., 2026b). This repetition across modalities indicates that dialysis sustainability is driven more by system design than by clinical modality choice.

In PD, material intensity was the defining characteristic. Each patient produced between 300 and 400 kilograms of plastic waste annually, driven by the single use nature of dialysate bags and tubing (Larkin et al., 2026c). Procurement accounted for over two thirds of total impacts because PD consumables are imported, used once and disposed through high temperature incineration.

In HD, operational energy and water consumption were proportionally higher due to the need for continuous machine function and RO water treatment (Barraclough et al., 2020; Bendine et al., 2020). Each HD session required approximately 382 litres of treated water and 5.2 kWh of electricity, while OLHDF used an additional 27 litres of ultrapure water and 5.7% more electricity (Larkin et al., 2026a). These operational requirements represent fixed baseline impacts that are difficult to reduce without systemic technological redesign. These requirements are set within current dialysis infrastructure and therefore cannot be addressed through behavioural change alone.

Across all in centre modalities, patient and staff transport emerged as the main emission source. In the Modena case study, travel accounted for 71% of total emissions, minimising contributions from energy, water and procurement (Larkin et al., 2026a). Similar findings were observed in prior analyses of dialysis systems in Australia and the UK, where travel accounted for 50 to 75% of total emissions (Lim et al., 2013; Stephens et al., 2013).

This recurring contribution of transport reflects both logistical and infrastructural challenges. Most dialysis centres operate in urban hospitals, requiring three times a week travel by patients. Many of these patients rely on dedicated transport services or private vehicles. Each journey contributes directly to Scope 3 emissions and indirectly to healthcare costs. The dependence on fossil fuel based mobility reveals the need for integrating decarbonised transport systems, telemedicine supported home therapies and shared care community models as primary sustainability interventions (Sehgal et al., 2022; Yusuf et al., 2024; Zurl et al., 2025). This makes transport reduction one of the few interventions capable of delivering rapid system wide emission reductions without altering clinical care.

6.2.3 Intervention points for emission reduction

Reducing patient and staff travel represents the single most effective emission reduction opportunity in dialysis care. Travel reduction also lowers service costs and improves fairness for patients who attend dialysis three times weekly.

Home based PD, shared care satellite units and low emission patient transport have all demonstrated potential to halve total pathway emissions (Agar, 2015a; Kennedy et al., 2018). The shift to home therapy decentralises care. This reduces logistical burdens while empowering patients. However, it also shifts responsibility for procurement and waste management from the hospital to the household, meaning environmental improvements depend on supply chain and waste reforms. This shift highlights the need for coordinated supply chain design so that home care does not put environmental impacts on patients.

Adopting hybrid transport models, including electric ambulances and community based vehicles, would further reduce emissions. In regions with renewable grid electricity, transitioning hospital vehicle fleets to electric could achieve significant reductions in operational Scope 1 emissions (Duane et al., 2025a; NHS, 2020). Implementation requires coordination between renal units and regional transport authorities

Dialysis is one of the most water intensive hospital processes. In HD and OLHDF, RO systems typically reject 30 to 40% of feed water. Improving RO recovery rates from 50 to 70% reduces total water use by around 30%, saving roughly 40,000 litres per patient per year. This directly

addresses the main water hotspot identified across all HD and OLHDF LCAs (Larkin et al., 2026a).

Water reuse represents a promising strategy. RO reject water can be safely repurposed for cleaning, sterilisation pre washes, or irrigation, provided local regulations permit. Interviews showed that uncertainty around infection control guidance remains the primary barrier rather than technical feasibility. Such measures align with circular economy principles and have been successfully demonstrated in Australian and French dialysis units (Bendine et al., 2020).

Electricity use, while modest compared to transport, is still substantial given the scale of dialysis delivery. Across a full unit these small per session demands accumulate into a substantial annual energy load. The environmental impact of this consumption is determined by the carbon intensity of the regional grid (Romanello et al., 2023).

Switching to renewable electricity or integrating on site solar power reduces operational emissions immediately without requiring clinical or behavioural change. The KitNewCare findings support prioritising energy procurement reform at hospital level as a high return intervention for decarbonisation (Duane et al., 2025a). This makes energy decarbonisation one of the few interventions that delivers reductions without altering clinical practice.

Procurement remains a high yield area for improvement. Across PD and HD, a small subset of consumables including dialysate bags, bloodlines and acid concentrate accounted for most procurement emissions (Larkin et al., 2025b; Larkin et al., 2026c). This concentration of impact makes procurement an efficient area for system wide reduction.

The introduction of the Granumix central acid delivery system reduced procurement related impacts by up to 70% by eliminating disposable packaging (Larkin et al., 2025a). Expanding this principle across other consumables such as adopting refillable dialysate systems or multi use transport containers could allow for further savings (Martínez-Cadenas et al., 2025; Tsai et al., 2025). This demonstrates how redesign at the supply stage achieves larger reductions than at hospital level.

Design level innovations, including alternative polymers, reduced packaging mass and standardised recyclability, are necessary for structural reduction. Previous LCAs of surgical devices have shown that reusables, when properly sterilised using renewable energy, outperform disposables on nearly all environmental metrics (Leiden et al., 2020; Sherman et al., 2018). These interventions require early engagement with manufacturers rather than relying on hospitals to implement sustainability.

Waste management contributes 2-5% of dialysis emissions but remains significant for healthcare sustainability (Rizan et al., 2021). Autoclaving and incineration are the main disposal routes, both energy intensive and emission generating. Improved separating between hazardous and non-hazardous waste streams can substantially reduce volume requiring high temperature treatment. Although numerically smaller these emissions remain visible and important within hospital sustainability strategies.

Emerging technologies such as pyrolysis of clinical plastics offer potential emission reductions compared with incineration (Duane et al., 2025a). Integrating circular waste treatment systems within hospital campuses could reduce transport distances and energy use, complementing procurement and operational reforms. Together these intervention show that meaningful reduction depends on coordinated action across products pathways and governance rather than isolated local initiatives.

6.2.4 Clinical feasibility versus environmental necessity

A recurring theme across the thesis is the tension between clinical feasibility and environmental necessity. This tension shapes which interventions are prioritised and which remain politically or professionally difficult to implement. Dialysis, as a life sustaining therapy, cannot be easily reduced or compromised for environmental reasons. Many environmental interventions such as switching from single use to reusable items are constrained by sterility requirements, liability concerns and regulatory standards (Duane et al., 2025a; Rizan et al., 2024).

However, the LCA studies in Chapters 3 and 5 demonstrate that many impactful changes lie outside the direct clinical boundary. Energy sourcing, transport logistics and procurement

design can all be modified without affecting patient safety. These interventions represent the most practical short term strategies (Arias-Guillén et al., 2024; Larkin et al., 2025b).

The comparison of HD and OLHDF demonstrates another form of this trade off. While OLHDF provides improved survival, its environmental footprint is slightly higher due to additional water and energy requirements (Blankestijn et al., 2023; Maduell et al., 2013). Over a patient's lifetime, longer survival implies greater cumulative environmental impact. This reflects a wider challenge across healthcare where improved outcomes increase resource demand. This raises ethical questions regarding the definition of sustainable care. If environmental and clinical goals separate, health systems must determine whether extended survival at marginally higher environmental cost constitutes acceptable sustainability. Long term solutions will depend on reducing baseline emissions per session through renewable energy, efficient water systems and sustainable procurement so that clinical improvements no longer increase total ecological burden (Jameton et al., 2001; MacNeill et al., 2021). From this perspective sustainability depends less on restricting treatment and more on redesigning the infrastructure that delivers it.

The studies also revealed institutional and behavioural barriers to implementing sustainability interventions. Hospitals often rely on strict procurement frameworks, slow approval processes and vendor contracts that prioritise cost and compliance over environmental performance. Clinical staff may lack training in environmental awareness and sustainability metrics are rarely embedded in performance indicators (Duane et al., 2025b).

Addressing these barriers requires institutional leadership and policy alignment. Embedding environmental indicators into audit evaluations and service planning would shift sustainability from optional activity to routine clinical governance (Dolcini et al., 2025; Mortimer et al., 2018).

6.2.5 The systemic role of procurement and waste

Procurement represents a critical but non transparent element of healthcare sustainability. The PD and HD procurement studies demonstrated that processes including material sourcing, manufacturing and distribution account for most of the embodied carbon of dialysis care

(Larkin et al., 2025a; Larkin et al., 2025b). Yet hospitals typically have limited visibility over these supply chains. This disconnect means environmental impacts are largely determined before products reach the clinic.

Improving transparency requires collaboration with suppliers, inclusion of environmental criteria in tenders and adoption of standardised product environmental declarations. The EU's forthcoming Sustainable Product Regulation and Green Claims Directive will make such reporting mandatory across medical supply chains, creating new opportunities for data driven procurement (Romanello et al., 2023). These policies have the potential to shift procurement from voluntary sustainability reporting to enforceable performance standards.

The findings support the adoption of centralised, standardised procurement frameworks based on environmental performance. For instance, switching to concentrated powder delivery systems for acid solutions demonstrates how structural change in supply logistics can produce large scale emission reductions (Tsai et al., 2025). This approach also reduces packaging waste storage demands and transport frequency.

Circular procurement models where waste materials are reprocessed into new medical or industrial products are emerging as a feasible long term approach (Agar et al., 2018; Berman-Parks et al., 2024). This requires separation at source, traceable material streams and contractual agreements with manufacturers. Pilot studies in the UK have shown that single use plastics from dialysis can be mechanically recycled when properly separated (Rizan et al., 2021). Together, these findings show that procurement and waste management function as areas for improvement through which dialysis can transition from a linear take, make and dispose model toward a more circular and accountable material system (Hoveling et al., 2024).

6.2.6 Integrating design and systems thinking

A distinctive contribution of this research lies in integrating design thinking within environmental analysis. The product teardowns, pathway mapping and flow diagrams developed for each study illustrate how environmental impact can be understood as a design framework rather than an outcome (Barros et al., 2024; Duane et al., 2025b; Johannson et al.,

2023; Larkin et al., 2026c). This shifts environmental assessment from a retrospective evaluation tool toward a method for shaping clinical systems.

For this thesis, design led analysis provides a framework for reimagining dialysis systems beyond incremental technical fixes. It encourages multidisciplinary collaboration between clinicians, engineers, designers and policy makers to create products and services that are both clinically effective and resource efficient (Altman et al., 2018; Mc Laughlin et al., 2022).

The PD procurement analysis demonstrated how disassembly and material characterisation can identify priority components for redesign. Similar approaches could be applied to HD consumables, identifying substitution opportunities for polymers or reconfiguration of packaging volumes (Cano et al., 2025; Larkin et al., 2025b).

At the service level, system design offers opportunities to restructure care delivery. For example, decentralising water treatment, integrating solar powered micro grids, or modularising equipment to extend lifetime could all reduce environmental intensity while maintaining quality of care (Agar et al., 2012; Tarrass et al., 2024; Yeo et al., 2022).

The design framework developed through KitNewCare aligns with the broader model of planetary health, which recognises human health as inseparable from ecological stability (Rockström et al., 2009). Within this framework, sustainable dialysis design becomes not only a technical challenge but an ethical obligation (MacNeill et al., 2021).

Embedding LCA into the design phase allows early identification of environmental trade-offs and prevents downstream inefficiencies. This positioning supports the transition toward system level planning explored in the following section, where design and governance are combined into an implementation roadmap for sustainable kidney care (Dalla Valle, 2022; Duane et al., 2025b).

6.2.7 Lessons for health systems and policy

The main findings from the thesis directly support European and global health system decarbonisation policies. The EU Green Deal and the WHO's call for climate resilient health

systems emphasise the importance of reducing healthcare's environmental footprint (Lakatos et al., 2023; Sherman et al., 2021). This thesis provides quantitative evidence suitable for translation into regulatory targets rather than remaining at the base level.

By quantifying the impacts of dialysis, the KitNewCare studies provide a data driven foundation for policy integration. Emission data at modality and pathway levels can inform carbon accounting frameworks, procurement standards and national sustainability metrics (Duane et al., 2025a). These outputs support decision making by hospital managers, procurement authorities and national health agencies responsible for infrastructure planning

The evidence also shows the need for mixed methodologies for healthcare LCA, enabling comparability across hospitals and countries. Without shared definitions of functional units and boundaries, sustainability data cannot be standardised across centres or used for national reporting (Hauschild, 2024; Lee et al., 2022).

To operationalise sustainability, health systems must introduce incentives for environmental performance alongside clinical and financial indicators. Examples include carbon linked reimbursement models, green procurement criteria and sustainability audits (Hider et al., 2025; Keil et al., 2023). Without formal incentives, sustainability actions remain optional and uneven across regions

The NHS Net Zero strategy provides a model for embedding environmental metrics into procurement, requiring suppliers to publish carbon reduction plans as a precondition for tendering (NHS, 2020). Similar frameworks could be adopted within the EU and national healthcare systems, supported by transparent environmental product declarations and digital LCA databases (Commission, 2019; Ecoinvent, 2024). This approach demonstrates how procurement regulation can shift sustainability from voluntary activity to routine system requirement.

6.2.8 Key lessons learned

Together, the analyses presented across Chapters 3 to 6 generate a set of core lessons that extend beyond individual case studies or interventions. These lessons emerge from the

combined interpretation of life cycle modelling, stakeholder perspectives and collaborative implementation work. They reflect recurring patterns observed across modalities, institutions and scales of analysis. Rather than representing isolated findings, the points below summarise the structural insights required to guide sustainable transformation in kidney care, highlighting where change delivers the greatest benefit and where future efforts should be concentrated.

- Sustainability in dialysis is a systems issue. Isolated product level changes display limited benefit unless integrated into broader infrastructure and transport systems (Barraclough et al., 2020; Larkin et al., 2025b; Larkin et al., 2026b).
- Transport accounts for the majority of total emissions**.** Decarbonising travel and expanding home therapies offer the highest potential for carbon reduction (Lim et al., 2013; Larkin et al., 2026a).
- Procurement and design reform are essential. Material substitution, reusable systems and centralised supply solutions provide measurable benefits (Larkin et al., 2025a; Larkin et al., 2025b).
- Water and energy efficiency are achievable with existing technology. Improving RO recovery and adopting renewable electricity can reduce environmental impacts substantially (Bendine et al., 2020, Larkin et al., 2026a).
- Clinical feasibility must coexist with environmental necessity. Sustainable design requires ensuring that environmental improvements do not compromise patient care (Arias-Guillen et al., 2024; Feldman et al., 1999b; Lacson et al., 2011; Matos et al., 2000).
- Data transparency is critical. Reliable, open access LCA data are essential for evidence based decision making and policy alignment (Ecoinvent, 2024; Rizan et al., 2021; Romanello et al., 2023).
- Design plays a transformative role. Integrating design thinking into LCA shifts sustainability from assessment to innovation (Duane et al., 2025a; Larkin et al., 2025b; Larkin et al., 2026d).

6.3 Design, policy and systems level implications

6.3.1 Introduction

The transition toward environmentally sustainable kidney care requires coordinated action across design, clinical practice, procurement and policy (Duane et al., 2025a; Larkin et al., 2025a; Larkin et al., 2025b; Larkin et al., 2026a; Larkin et al., 2026c; Larkin et al., 2026e). Identifying environmental hotspots alone does not produce change unless the organisational structures responsible for design, purchasing and service delivery are also addressed. While the LCAs presented in this thesis identified specific environmental hotspots in dialysis, addressing them effectively requires changes to how decisions are made, funded and governed within healthcare systems.

This is particularly true in dialysis, where the largest sources of impact sit in procurement contracts, infrastructure design and transport systems rather than individual clinical actions. Single solutions such as minor product substitutions or energy saving behaviours are insufficient to align dialysis services with the EU's net zero goals (Commission, 2019; NHS, 2020).

This chapter outlines design driven and systems level implications from the collective evidence across the PD and HD studies. The recommendations are structured to correspond with three interacting levels:

- Design and technology innovation.
- Institutional and clinical implementation.
- Policy and governance frameworks.

Together, these layers form a logical strategy for decarbonising kidney care while maintaining safety, effectiveness and equity (Duane et al., 2025b). Design innovation defines what solutions are technically possible, institutional implementation determines whether they are adopted in practice and policy frameworks establish the conditions under which they can be scaled and sustained.

6.3.2 Design implications for products and technologies

The findings highlight the environmental impact of consumable plastics across both PD and HD modalities (Larkin et al., 2025b; Larkin et al., 2026b). Across both modalities, product design decisions made during manufacture and material choices determine the majority of waste environmental burden before clinical use begins. Redesigning products for material efficiency and reusability is therefore one of the most direct strategies for reducing environmental impact (Larkin et al., 2025a). This places responsibility for impact reduction primarily at the manufacturing and specification stage rather than within frontline clinical behaviour.

Product teardowns conducted for the PD procurement study demonstrated that dialysate bags, tubing and connectors collectively accounted for over 80% of total material mass and embodied carbon (Larkin et al., 2025b). Substituting fossil derived polymers such as PP and PVC with biopolymers or recycled polymers could reduce emissions substantially (Jiang et al., 2022; Rizan et al., 2024). However, substitution must be validated against biocompatibility, sterilisation tolerance and shelf life requirements. This reinforces the need for regulatory engagement so that sustainability driven material changes are evaluated through structured equivalence and safety testing pathways.

Material selection alone will not achieve full sustainability. Design for disassembly and recycling where components are marked, separated and recovered post use is essential to create circular product lifecycles (Al-Hadithy et al., 2024; Joseph et al., 2021). In hospital settings, such design principles could enable onsite mechanical recycling or supplier take back systems, reducing waste and procurement costs. Without compatible waste separation infrastructure and contractual take back arrangements, recyclable design features risk remaining unused in practice.

Modularity offers another promising approach. The Fresenius HD system, used in the Modena study, demonstrated high energy and water efficiency but remains dependent on disposable tubing and dialysers (Larkin et al., 2026a). Reconfiguring machines to allow reprocessed or multiuse circuits could extend device lifetimes while maintaining sterility through validated

reconditioning cycles (Duane et al., 2025a; Larkin et al., 2026b). Such approaches are already established in other high risk medical device categories and demonstrate that reusability and safety are not exclusive when supported by robust validation.

Hybrid systems such as centralised dialysate preparation linked to distributed treatment modules may also enable significant water and energy savings (Larkin et al., 2025a; Tsai et al., 2025). These configurations also reduce transport volumes and packaging intensity, further lowering procurement related emissions. Integrating low energy heat recovery from RO reject water and machine cooling circuits could further reduce environmental intensity without affecting patient outcomes (Bendine et al., 2020).

The lack of embedded environmental data in medical devices limits accountability across supply chains. Integrating digital LCA reporting within product design such as QR linked environmental product declarations would allow hospitals to make procurement choices based on verified carbon and water data. This approach aligns with the EU's Digital Product Passport initiative under the Circular Economy Action Plan (Ecoinvent, 2024; Vikingsson et al., 2025).

By including transparency at the design stage, manufacturers can differentiate products by sustainability performance and healthcare organisations can incorporate environmental data into tender evaluation criteria. Embedding environmental transparency into product design therefore shifts sustainability from a post purchase evaluation to a core design requirement.

6.3.3 Service and pathway design in hospitals

Hospital based dialysis services are complex sociotechnical systems involving clinicians, engineers, patients and logistical support. Embedding environmental performance within these systems requires design thinking that treats sustainability as a clinical quality parameter rather than an administrative target (Duane et al., 2025b; Mortimer et al., 2018). Viewing dialysis units as sociotechnical systems clarifies that environmental outcomes emerge from interactions between infrastructure, routines and decision making rather than from isolated actions.

Pathway mapping in both PD and HD LCAs showed that the majority of emissions occur outside the treatment room specifically in procurement, waste transport and patient travel

(Larkin et al., 2026a; Larkin et al., 2026c). This insight demonstrates the importance of designing service pathways that minimise unnecessary movement and material use. It also shows that meaningful reductions depend on service configuration choices made at managerial level rather than on individual clinician behaviour.

Implementing sustainability checkpoints within the dialysis workflow for example, during prescription planning, equipment setup and waste handling can embed environmental awareness at the operational level. Formalising these checkpoints within existing quality improvement structures increases uptake by aligning sustainability with familiar governance processes. Training modules on sustainable clinical practice should be incorporated into continuous professional development programmes, as recommended by the CSH (Yau et al., 2021).

Retrofitting existing infrastructure offers immediate environmental and financial benefits. These interventions are particularly relevant for older hospital buildings where full replacement is not feasible in the short term.

Water reuse systems that capture RO reject water for cleaning or landscaping can save up to 40,000 litres per patient annually (Larkin et al., 2026a). Hospitals can also adopt closed loop water recirculation systems with variable recovery rates to optimise efficiency without compromising water purity standards (Barraclough et al., 2024; Bendine et al., 2020). Clear internal guidance and infection control approval are required to ensure staff confidence in reuse systems and to prevent informal workarounds.

Energy audits of dialysis units frequently reveal inefficiencies related to lighting, ventilation and standby energy consumption. Upgrading to automated energy management systems and LED lighting, alongside renewable energy procurement, can reduce electricity related emissions by up to 20% without operational disruption (Bendine et al., 2020; Brighton et al., 2023). Embedding energy performance indicators into estates reporting allows dialysis units to be prioritised alongside other high demand clinical areas.

Redesigning waste management practices within dialysis units can reduce both emissions and costs. The HD procurement and waste study demonstrated that 20-30% of materials classified

as hazardous waste could safely be reclassified as non-hazardous with proper separation training (Lee et al., 2022; Larkin et al., 2026b). This finding indicates that misclassification represents an organisational issue rather than a technical limitation.

Introducing colour coded waste stations, onsite autoclaving and sealed transport containers minimises cross contamination and transport needs. Partnerships with recycling contractors for plastics such as PP and PET can further close the material loop (Lee et al., 2022; NHS, 2020; Rizan et al., 2020). Emerging pyrolysis technologies can process mixed plastic waste into feedstock oils, as demonstrated in comparative analyses of incineration and pyrolysis pathways (Blumenthal et al., 2025; Duane et al., 2025a; Yaqoob et al., 2025).

Together, these measures show that pathway redesign within hospitals offers cumulative gains when waste, energy and water strategies are coordinated rather than implemented independently.

6.3.4 Procurement and supply chain reform

Traditional procurement models in healthcare prioritise unit cost and regulatory compliance, rarely accounting for environmental externalities. The PD and HD procurement studies revealed that focusing solely on upfront cost hides significant embodied emissions (Larkin et al., 2025b; Larkin et al., 2026b). Environmental externalities transferred to manufacturers and to waste systems remain invisible within current structures.

Transitioning to sustainability based procurement requires explicit integration of environmental metrics into tendering criteria. Without formal weighting in tenders, sustainability data remains advisory rather than decision shaping.

Procurement policies should mandate suppliers to provide verified LCA data, ideally through third party EPDs. Incorporating carbon intensity into purchasing decisions can drive market transformation by rewarding manufacturers with lower impact production methods. The NHS has already implemented similar frameworks through its Net Zero Supplier Roadmap (Ecoinvent, 2024; NHS, 2020; Larkin et al., 2026c). Standardised reporting formats are

essential to allow meaningful comparison between suppliers and to prevent selective disclosure.

Localising production and assembly of dialysis consumables can reduce emissions from international freight transport. Shorter supply chains also reduce dependency on volatile global logistics networks. The reliance on long distance importation of PD fluids and HD tubing adds substantial transport related carbon burdens (Larkin et al., 2025b; Larkin et al 2026b). Establishing regional supply hubs within Europe would reduce transport distances, create employment and improve resilience against global supply disruptions (Malik et al., 2018).

Collaborative procurement models between hospitals could further increase bargaining power, allowing environmental performance to influence supplier behaviour more effectively than individual tenders. Circular procurement involves retaining ownership of materials through reuse, remanufacture, or recycling agreements. Manufacturers could reclaim used consumables for mechanical recycling, closing the material loop. Clear responsibility allocation between hospitals and suppliers is required to ensure traceability and compliance. This model is already being trialled for surgical instruments and single use plastics in the UK (Matschewsky et al., 2024; Rizan et al., 2021). Shared procurement platforms also reduce duplication of assessment effort across institutions.

In dialysis, suppliers could be contracted to collect and process used dialysers and tubing, ensuring recovery within controlled systems. Such circularity aligns with extended producer responsibility (EPR) frameworks under EU legislation (Dalhammar et al., 2025). Embedding environmental responsibility within supplier contracts shifts sustainability from voluntary commitment to structural obligation.

6.3.5 Policy and governance implications

The findings across this thesis provide an evidence base for integrating kidney care into national climate and health strategies. The EU Green Deal and the European Climate Law (2021) set the overarching target of net zero emissions by 2050, while healthcare is increasingly recognised as a critical sector within this transition (Commission, 2019; Karliner, 2020; Larkin et al., 2025a; Larkin et al., 2025b; Tennison et al., 2021). Dialysis represents a

suitable entry point for policy action due to its high per patient footprint and predictable service structure.

At national level, health systems such as the NHS have already established decarbonisation roadmaps (NHS, 2020). Italy and Ireland have begun aligning their healthcare climate policies with EU objectives but lack sector specific implementation frameworks for high emission clinical services like dialysis. This gap limits accountability and delays translation of national climate targets into operational practice. The data presented in this research can inform such sectoral plans, enabling targeted emission reduction goals (Campbell-Lendrum et al., 2023; HSE, 2025).

Current healthcare governance frameworks focus on clinical quality, safety and cost efficiency, but rarely include environmental metrics. As a result, sustainability remains optional rather than embedded within routine performance management. Introducing carbon and resource indicators into quality assurance processes would institutionalise sustainability. For example, dialysis centres could be required to report annual carbon intensity per patient year, similar to existing infection rate reporting (Duane et al., 2025a; Rizan et al., 2021). Standardised indicators would enable comparison across centres and support benchmarking over time.

Accreditation bodies could include sustainability compliance as part of hospital performance evaluations. This would embed environmental responsibility into clinical leadership and encourage staff engagement across departments (Tennison et al., 2021; Yau et al., 2021). Linking sustainability indicators to leadership accountability would strengthen organisational ownership.

Innovation in medical device design is often hindered by regulations. Lengthy approval timelines discourage manufacturers from investing in alternative materials and circular designs. Governments should introduce incentives such as tax credits, grant funding and fast track approvals for verified low impact technologies. Programmes like Horizon Europe already support sustainability oriented innovation and expanding these to include healthcare device design would accelerate change (Cemal, 2021; Duane et al., 2025b; Europe, 2024). Dedicated

sustainability criteria within funding calls would further align research investment with climate objectives.

In addition, establishing national healthcare LCA databases would provide transparent baselines for innovation benchmarking, helping both industry and regulators evaluate product performance objectively (Eckelman et al., 2016). Such infrastructure would reduce duplication of modelling effort and improve consistency across studies.

6.3.6 Integration with the European union green deal and net zero health systems

Dialysis is among the most resource intensive clinical services in hospitals, yet remains largely absent from decarbonisation plans (Barraclough et al., 2025; Choo et al., 2025; Commission, 2019; Larkin et al., 2025b). Dialysis therefore represents a priority service for early inclusion within EU climate action due to scale, predictability and concentration of impacts.

Integrating dialysis specific targets into EU and national frameworks would align healthcare practice with the European Green Deal's circular economy and energy efficiency pillars (Barraclough et al., 2025; Commission, 2019; Duane et al., 2025a). Explicit targets would turn high level climate ambition into measurable clinical action.

At a systems level, this integration requires cross sector coordination between healthcare providers, energy utilities and waste authorities. Shared infrastructure such as district renewable grids and water reuse systems can support hospitals in achieving decarbonisation without compromising operational reliability (Choo et al., 2025). Formal coordination mechanisms between health ministries and environmental authorities are required to support this integration.

Establishing mixed environmental reporting standards for healthcare will enable comparability across countries. Without common criteria, variation between national systems limits progress and shared learning. Benchmarking dialysis carbon intensity across European centres could facilitate the identification of best practices and drive regional collaboration (Barraclough et al., 2025; Duane et al., 2025a). Such benchmarking would also support performance improvement through peer comparison.

Projects like KitNewCare demonstrate the feasibility of multinational data collection and LCA standardisation. These collaborative models support consistency in methods while allowing adaptation to national health system structures. Expanding such organisations would contribute to the European Research Area's objective of integrating environmental performance data across public institutions (Duane et al., 2025b). Together, these measures position dialysis as an important pathway for net zero healthcare delivery across Europe.

6.3.7 The role of education and cultural change

Sustainable transformation requires more than technological substitution, it demands cultural change within the healthcare workforce. Cultural norms strongly influence which practices are perceived as acceptable within clinical environments. Surveys have shown that while clinicians support sustainability in principle, few feel confident applying it in practice (Armand et al., 2024; Hagan, 2023). This gap between awareness and action limits the uptake of sustainability interventions even when evidence is available.

Educational initiatives such as those led by the CSH and the Students Organising for Sustainability UK provide models for integrating environmental literacy into medical and nursing curricula. Embedding LCA concepts, resource awareness and practical sustainability skills into professional education ensures that future clinicians view environmental stewardship as normal to patient care. Early exposure during training is particularly important because professional habits formed during education often persist throughout clinical careers.

The environmental complexity of healthcare systems requires collaboration between designers, clinicians, engineers and policymakers. Codesign methods, where clinicians and designers work jointly to optimise functionality and sustainability should be standard practice in device and service innovation (Larkin et al., 2026d). This approach helps ensure that sustainability measures align with real workflow constraints rather than being perceived as external demands.

Interdisciplinary research centres, such as the partnership between Trinity College Dublin and the University of Modena within the KitNewCare project, represent this integrated approach. These collaborations enable translation of scientific findings into implementable design and policy interventions (Duane et al., 2025a; Duane et al., 2025b). Such environments also support

mutual learning, allowing technical experts to understand clinical risk while clinicians engage with environmental evidence.

Without sustained education and cultural reinforcement, technical solutions alone are unlikely to deliver lasting change.

6.3.8 Product redesign and circular innovation in peritoneal dialysis

The PD product redesign study put LCA findings into practical design proposals aimed at reducing environmental burden without compromising clinical function (Larkin et al., 2026d). By dismantling and weighing PD consumables, the study identified PP and PVC components as key contributors to emissions and waste. These materials accounts for the majority of both the production and disposal phases, confirming trends observed in broader healthcare LCA literature (Larkin et al., 2025b; Sherman et al., 2018). This confirms that PD sustainability is primarily determined at the product design stage rather than during clinical use.

Three redesign pathways were proposed:

- Material substitution using recyclable polymers and biobased plastics.
- Reduction in packaging and over specification of sterile barriers.
- Modular system design enabling separation and recycling of clean components.

The analysis demonstrated that switching to biobased PP or closed loop PVC recovery could reduce procurement related emissions by up to 30% per patient year (Cano et al., 2025; Sherman et al., 2018). Although these reductions appear moderate at patient level, they scale substantially when applied across national PD populations.

The redesign approach applied principles of user centred and circular design. Interviews with PD clinicians informed ergonomic adjustments to connectors and bag handling, ensuring safety was maintained while reducing material use. These codesign processes parallel the interdisciplinary collaboration emphasised in the qualitative interviews and support the concept of design as a clinical sustainability tool (Duane et al., 2025b; Larkin et al., 2026d;

Larkin et al., 2026e). This process also improved clinician acceptance of redesign concepts by grounding sustainability changes in everyday handling routines.

A notable finding was the disconnect between recyclability and real world recovery. Although several proposed materials are technically recyclable, the absence of dedicated healthcare recycling streams limits actual circularity. This reinforces the argument for EPR, requiring manufacturers to retrieve used devices for controlled reprocessing (Garcia et al., 2025; Larkin et al., 2025b). Without investment in collection infrastructure, recyclable design alone does not deliver environmental benefit.

Beyond material substitution, the PD redesign study argued for digital integration. Embedding product data into QR coded identifiers, aligned with the EU Digital Product Passport initiative, would allow traceability across the supply chain. This concept directly supports the wider systems level recommendations of this thesis to align device innovation with circular economy governance and transparent data frameworks (Buzeti, 2025). Such traceability would also support hospital level reporting and enable procurement teams to compare products using consistent environmental data.

The PD redesign study also shows the value of design methodology within sustainability research. Whereas LCAs quantify impacts retrospectively, design tools generate solutions prospectively. Embedding both within the same framework, as demonstrated across the KitNewCare project, enables a continuous feedback loop between evidence and innovation. This reinforces the emerging idea of environmental design, where environmental insights are immediately channelled into product and process improvement (Duane et al., 2025a; Larkin et al., 2026d). Together, these findings position PD as a strong candidate for circular redesign within kidney care due to its high material intensity and standardised consumable systems.

6.3.9 Summary of systems level recommendations

This section draws together the evidence generated across the thesis into a set of systems level recommendations. The LCAs in Chapters 3 and 5 identify where environmental impacts are concentrated, while the qualitative findings in Chapter 4 explain why these impacts persist in practice. When considered together, they point toward a small number of points where

coordinated action can deliver meaningful change. The recommendations below turn these findings into practical priorities for product design, service configuration, procurement, governance and workforce development, providing a structured foundation for implementing sustainable kidney care at scale.

- Product design: Prioritise modularity, material substitution and circular lifecycle planning in all dialysis consumables and equipment (Larkin et al., 2025b; Sherman et al., 2018; Larkin et al., 2026d).
- Infrastructure: Retrofit dialysis facilities with efficient RO systems, renewable energy integration and waste separation systems (Bendine et al., 2020; CSH, 2023).
- Procurement: Transition to sustainability based purchasing that mandates supplier LCA transparency and environmental product declarations (Larkin et al., 2025b; NHS, 2020; Rizan et al., 2020).
- Policy: Embed environmental performance metrics in healthcare governance, accreditation and reimbursement systems (Duane et al., 2025a; Tennison et al., 2021).
- Education: Institutionalise environmental literacy in clinical and engineering training to embed sustainable practice from the outset (Yau et al., 2021).
- Governance: Develop national and EU level frameworks specifically targeting high impact services like dialysis within net zero strategies (Commission, 2019; Pruijm et al., 2024).
- Collaboration: Promote partnerships between academia, healthcare and industry to turn LCA data into practical design and operational innovations (Duane et al., 2025b).

6.4 Limitations and future research

6.4.1 Methodological limitations of the life cycle assessments

The LCAs conducted across PD and HD pathways represent some of the most comprehensive environmental evaluations undertaken for kidney care to date (Larkin at al., 2025a; Larkin et., 2025b; Larkin et al., 2026a; Larkin et al., 2026b; Larkin et al., 2026c; Larkin et al., 2026d). However, as with all LCA studies, methodological limitations affect the precision and transferability of the results. These limitations do not undermine the comparative findings, but they should be considered when interpreting absolute footprint values.

The first limitation concerns the reliance on process based system boundaries. While detailed, they cannot fully capture all impacts. Each analysis applied cradle to grave boundaries, including procurement, operation and waste management. Yet capital infrastructure, indirect services and secondary supply chain activities were excluded. Studies by Sherman et al., (2018) and McGain et al., (2014) have demonstrated that such exclusions typically underestimate total emissions by up to 10-15% in hospital contexts (Sherman et al., 2018; McGain et al., 2014). As a result, the LCAs are most robust for comparing relative intervention performance rather than estimating total system wide emissions.

The selection of impact categories was another constraint. While climate change, water use and energy resources were prioritised as the most policy relevant and material categories (Larkin et al., 2026a), others such as terrestrial ecotoxicity, land use and mineral depletion were not modelled. Although these categories tend to contribute marginally to the total environmental burden of dialysis, their omission limits the completeness of planetary boundary assessments (Rockström et al., 2009). Future work should consider using endpoint methods such as ReCiPe or IMPACT World+ to capture damage pathways extending to ecosystem and human health endpoints (Hauschild, 2024). This thesis therefore adopts a realistic focus on decision relevant categories most actionable within hospital settings, rather than attempting full environmental completeness.

Finally, data detail and variability pose challenges to comparability. The analyses presented rely on single year datasets collected in specific facilities, representing operations during 2024-

2025. Changes in supply chain composition, grid electricity intensity, or clinical practice over time will inevitably alter environmental profiles. Continuous updating of LCA inventories through digital monitoring could address this limitation (Drew et al., 2022; Duane et al., 2025b; McGain et al., 2014). This limits direct transfer of numeric results across countries, although the ranking of hotspots and intervention priorities is likely to remain stable across comparable European health systems.

6.4.2 Data availability and representativeness

Data access remains a major barrier to environmental quantification in healthcare. Most dialysis manufacturers treat product composition and supply chain data as private information. This lack of transparency restricted the ability to model production processes. Consequently, several inputs were derived from secondary data in the Ecoinvent 3.11 database rather than primary manufacturer disclosures (Ecoinvent, 2024). This constraint reinforces that the LCAs are most appropriate for identifying relative hotspots and intervention priorities rather than producing definitive product specific carbon claims.

While the dismantling and weighing of consumables improved accuracy, some product level assumptions remained particularly regarding polymer production routes and packaging materials. Differences in polymer formulation, sterilisation method and geographical sourcing could affect embodied carbon and water footprints by 10-30% (Rizan et al., 2024) (Duane et al., 2025a). Sensitivity testing across key parameters showed that although absolute values varied, the ranking of high impact contributors remained stable.

Representativeness also poses challenges across regions. Data was collected primarily at AOU Policlinico di Modena in Italy, which operates a large and technically advanced dialysis centre with efficient water recovery systems. Centres in low and middle income settings may have lower RO recovery rates, higher energy intensities, or more carbon intensive grid mixes (Bikbov et al., 2020). Therefore, while the Modena data provide a robust benchmark for European contexts, they may understate impacts elsewhere (Francis et al., 2024). This has important implications for global nephrology, where environmental and resource constraints may be more severe despite lower overall treatment access.

For PD, the dataset was specific to Italy, where delivery logistics and waste treatment differ from systems in Northern Europe or Asia (Larkin et al., 2026c). A multisite comparative approach across climatic and infrastructural contexts would improve representativeness and enable development of generalisable emission factors for kidney care. Future research should prioritise linking international datasets that allow comparison between high income and resource constrained dialysis systems.

6.4.3 Limitations in social and health impact integration

Although this thesis includes a social impact assessment for kidney care, the environmental LCAs were not explicitly paired with social or health outcome models (Duane et al., 2026b). This separation reflects a broader methodological gap in healthcare sustainability assessment, where environmental metrics are rarely linked to patient centred outcomes such as survival, quality of life, or equity of access (McAlister et al., 2024b). This limits the ability of decision makers to judge whether lower carbon pathways also deliver comparable clinical benefit.

For example, OLHDF has demonstrated superior survival rates and quality adjusted life years compared with conventional HD (Blankestijn et al., 2023; Maduell et al., 2013). From a purely annualised environmental perspective, OLHDF produced 2.7% higher emissions (Larkin et al., 2026a). However, over a patient's lifetime, the cumulative environmental burden may increase further due to extended treatment duration. Without integrating such health adjusted functional units, environmental efficiency cannot be interpreted in isolation from clinical effectiveness. This tension reflects the findings in Chapters 3 and 4, where clinicians prioritised survival and safety even when environmental differences were identified.

Moreover, environmental and social burdens are distributed unevenly. The majority of healthcare waste is exported to low income countries for processing or disposal (Rizan et al., 2021). LCAs typically account for emissions but not for these geographic inequities. The next generation of LCAs should integrate S-LCA and health adjusted environmental metrics such as Disability Adjusted Life Years (DALYs) (Alsamawi et al., 2019; Benoît Norris et al., 2020; Gao et al., 2015; Hauschild, 2024). As a result, environmental reductions achieved within European hospitals may shift burdens elsewhere rather than eliminating them.

Adopting a comprehensive triple bottom line framework including environmental, social and health would enable decision makers to evaluate trade-offs between clinical benefit, equity and environmental responsibility. This alignment with planetary health principles (van Daalen et al., 2024) is crucial to ensure that environmental sustainability complements, rather than competes with, patient care quality (Rockström et al., 2009). Future sustainability assessments in kidney care should therefore adopt integrated functional units that combine treatment outcomes with environmental and social performance.

6.4.4 Challenges of cross centre comparability

Another limitation relates to the difficulty of comparing environmental performance between dialysis centres. Variability in infrastructure, patient demographics and operational protocols strongly influences environmental outcomes. For example, patient travel distances depend on regional geography and public transport access, making travel related emissions site specific (Barraclough et al., 2025; Duane et al., 2025a; Kennedy et al., 2018; Sehgal et al., 2022). This variation reflects structural differences in service configuration rather than inconsistency in modelling quality.

Comparative results between Modena and other centres must therefore be interpreted cautiously. Although travel accounted for approximately 71% of total emissions in the Modena HD pathway (Larkin et al., 2026a), this proportion might differ substantially in urban centres with localised patient bases or integrated public transport systems. Despite this variation, the Modena case remains useful as a high resolution reference model for identifying the main emission root causes.

Cross centre benchmarking is further complicated by the absence of mixed reporting standards. While ISO 14040 and 14044 ensure methodological consistency, they do not specify healthcare specific functional units or emission boundaries. This often results in partial system boundaries across studies, reducing comparability (Rizan et al., 2024). This limits the ability of policymakers to compare performance or set shared reduction targets across regions.

To address this, developing standardised functional units such as “per patient year of treatment” or “per dialysis session” should become mandatory in healthcare LCAs. The

establishment of an EU wide healthcare LCA registry, similar to the Ecoinvent structure, could facilitate consistent data exchange and benchmarking between centres (Arta et al., 2021). Such standardisation would directly support the implementation roadmap developed in Chapter 6 by enabling consistent tracking of progress.

Additionally, coordinated life cycle inventory templates for medical devices would allow direct comparison of supplier impacts. Such correlation would benefit procurement teams seeking to apply environmental criteria in tenders while maintaining regulatory compliance (Rizan et al., 2023).

6.4.5 Opportunities for model refinement and digital integration

Emerging digital tools provide opportunities to refine and scale healthcare LCA. The growing availability of real time resource monitoring within dialysis machines and facility infrastructure could enable dynamic, data driven environmental reporting. Modern dialysis systems, such as the Fresenius 5008 and 6008 models, already record detailed energy and water consumption data per session. Linking these datasets to open source LCA models would allow automated calculation of per session footprints (Barraclough et al., 2024; Gauly et al., 2022). This shift from static annual averages to session level data would improve sensitivity to operational change and support continuous improvement.

AI systems also hold promise for rapid sustainability analysis. Early experiments using AI assisted LCA estimators, such as ChatGPT driven carbon calculators, have shown that LLMs can approximate emission values using known conversion factors and public databases (Duane et al., 2026a). However, these outputs remain limited by model transparency and access to paywalled data (OpenAI, 2023; Shojaei et al., 2024). In this context, AI functions best as a screening and prioritisation tool rather than a substitute for formal LCA.

Incorporating AI into hospital sustainability systems could accelerate preliminary assessments, freeing LCA specialists to focus on detailed modelling. The key challenge lies in ensuring data traceability and source verification. Hybrid systems combining AI generated estimates with verified datasets (DEFRA, Ecoinvent, or national carbon inventories) would provide both

scalability and reliability (Wernet et al., 2016). Such hybrid systems could support procurement decisions, service redesign and regulatory reporting using a shared evidence base.

Digitalisation also enables interactive environmental dashboards for clinical staff, displaying live energy and water metrics per treatment. Integrating these dashboards into hospital management systems would make sustainability performance visible and actionable, encouraging behaviour change at the point of care (Arias-Guillén et al., 2024). Future research should test these digital models in live dialysis settings to assess accuracy, staff usability and long term integration into clinical governance systems.

6.4.6 Expanding scope to circularity and planetary health metrics

The LCAs conducted in this thesis primarily focused on quantifying environmental burdens rather than evaluating circularity potential. Yet circular design principles including reuse, remanufacture and recycling represent one of the most promising strategies for systemic decarbonisation (Commission, 2019; Matschewsky et al., 2024). This is particularly relevant in dialysis, where high volume consumables create predictable material flows suitable for closed loop systems.

Future research should quantify not only emissions but also material circularity indicators and recycling potential ratios for key dialysis components. Such metrics can inform procurement strategies that prioritise recoverable materials and incentivise manufacturers to design for disassembly (Rockström et al., 2009). These measures directly build on the procurement hotspots identified in Chapters 3 and 6, turning impact diagnosis into material recovery strategies.

A related limitation is the narrow environmental focus of traditional LCA. Although climate change remains the most visible endpoint, healthcare contributes to multiple planetary boundary inconsistencies, including freshwater depletion, nitrogen cycle disruption and plastic pollution (Rockström et al., 2009). Expanding future LCAs to integrate planetary health metrics such as total material footprint and biodiversity loss potential would align assessment frameworks with global sustainability goals. Including these indicators would allow decision

makers to avoid carbon focused optimisation that unintentionally shifts burden to other ecological systems.

Finally, the role of healthcare in climate adaptation remains underexplored. Dialysis services are vulnerable to extreme weather events that disrupt water supply and electricity grids (Cole et al., 2025). Future environmental studies should assess the resilience of dialysis infrastructure under projected climate scenarios, linking reduction and adaptation within a unified systems framework. Integrating circularity, planetary boundaries and climate resilience would position kidney care sustainability within a long term systems perspective rather than short term emission reduction alone.

6.4.7 Generalisability of findings

While this thesis is grounded in the Modena case study, not all findings are context-specific. Several environmental hotspots identified across the LCAs are likely to be transferable to other dialysis systems. In particular, the main contribution of procurement, single-use consumables, transport logistics and waste treatment to overall environmental impact has been consistently reported across healthcare sustainability studies (Sherman et al., 2018; Eckelman et al., 2016; Karliner et al., 2020). These patterns suggest that the identification of procurement and waste as primary hotspots represents a robust finding rather than an artefact of a single case.

However, the magnitude of impacts and the feasibility of specific interventions remain highly context dependent. The Modena case reflects a particular combination of procurement structures, regulatory requirements, clinical workflows, infrastructure and energy supply. For example, the high impact of incineration is closely linked to Italian waste classification practices, while the feasibility of centralised fluid delivery systems depends on existing infrastructure and capital investment capacity (Larkin et al., 2026d; Duane et al., 2025a). These findings are therefore most directly transferable to comparable European hospital systems operating under similar regulatory and organisational conditions.

A distinction should therefore be made between transferable principles and context-specific results. Transferable principles include the central role of procurement in shaping environmental and social impacts, the importance of aligning sustainability with clinical

governance and safety and the value of integrating LCA into decision making processes. In contrast, intervention specific outcomes, such as the absolute carbon savings associated with travel optimisation, energy substitution or waste treatment pathways, require validation across additional settings before broader generalisation.

The qualitative findings in Chapter 4 reinforce this distinction. Structural barriers such as cost driven procurement, waste policies and lack of responsibility were consistently identified across stakeholder groups, suggesting that these organisational constraints are not unique to Modena but reflect wider patterns in healthcare systems (Larkin et al., 2026e; Mortimer et al., 2018). However, how these barriers manifest and how easily they can be addressed will vary across institutions and countries.

Future research should prioritise multi centre comparative studies to test the stability of these findings across different healthcare systems. In particular, further work is needed to evaluate procurement strategies, waste reclassification approaches and service redesign interventions in diverse organisational and regulatory contexts. This would strengthen the evidence base for scaling sustainable kidney care beyond individual case studies.

6.4.8 Non European contexts

The transferability of these findings beyond European healthcare systems requires careful consideration. Several assumptions used in this thesis reflect European conditions, including strict waste classification rules, regulatory constraints on reuse, centralised procurement systems and publicly funded hospital structures. These assumptions may not hold in non-European settings, particularly in low and middle income countries and in more market driven health systems such as the United States.

In many non-European contexts, reusable or semi reusable devices may be more feasible due to differences in labour costs, sterilisation infrastructure and regulatory frameworks. While such approaches are often constrained in EU settings due to infection control standards and liability concerns, they have been explored in other healthcare systems as a means of reducing both environmental impact and cost (McGain et al., 2014; Campion et al., 2015). This

highlights that assumptions about single use systems, which highlight much of the modelling in this thesis, are not universally applicable.

Similarly, waste management practices vary widely across regions. The reliance on incineration observed in the Modena case reflects European regulatory frameworks, whereas other regions may rely more heavily on landfill, informal recycling or alternative treatment methods (Lee et al., 2022). These differences may significantly alter both environmental and social impact profiles. For example, informal recycling sectors in some low and middle income countries introduce additional occupational health and labour risks not captured in European models.

Energy systems also differ substantially. The environmental benefits of electrification and renewable integration depend on the carbon intensity of the local electricity grid. Regions with coal based energy systems may experience greater relative benefits from renewable adoption, while those with already low carbon grids may see smaller marginal gains (International Energy Agency, 2024). This reinforces the need to interpret LCA results within local energy contexts.

Procurement structures represent another key area of variation. In European systems, procurement is often centralised and governed by strict regulatory frameworks, limiting flexibility. In contrast, more decentralised systems may allow greater variation in supplier choice, which could enable faster adoption of sustainable alternatives but may also reduce standardisation and oversight (Greer, 2019). These differences influence both the feasibility and the governance of sustainability interventions.

Taken together, these variations indicate that the findings of this thesis should not be interpreted as prescribing a single pathway for sustainable kidney care. Instead, they provide a structured framework for identifying hotspots, evaluating interventions and understanding trade-offs within specific contexts. The combination of LCA, S-LCA and qualitative analysis offers a transferable methodology, even where specific results differ.

Future research should extend this work to non-European case studies, including settings with different regulatory environments, resource constraints and care delivery models. Comparative

studies across European and non-European systems would help identify which interventions are robust across contexts and which require substantial local adaptation. In addition, further research should examine how sustainability strategies interact with equity, access and resource limitations in lower resource settings, ensuring that environmental improvements do not compromise the delivery of essential care.

6.4.9 Future research directions

Building on these limitations, several avenues for future investigation are proposed.

1. Development of standardised healthcare LCA frameworks

Future research should establish consensus system boundaries, functional units and impact categories for healthcare LCAs. Collaboration between ISO, the European Environment Agency and research consortia like KitNewCare could formalise such standards, enhancing comparability and policy integration (Drew et al., 2022; Duane et al., 2025b). Such standardisation would directly address the comparability challenges identified in Chapters 3 and 6.

2. Integration of environmental, social and clinical outcomes

Combining LCA with health economics and patient outcome data will allow decision makers to assess trade-offs between clinical benefit and environmental burden. Applying quality adjusted or DALYs as functional units would enable this integration (Alsamawi et al., 2019; Gao et al., 2015). This approach aligns with the planetary health perspective adopted in this thesis, where environmental performance must be interpreted alongside human outcomes.

3. Expansion of digital and AI driven LCA models

Future studies should explore machine learning techniques for rapid footprint estimation based on existing hospital data. Such systems could generate near real time emissions dashboards, helping operational decision making (Duane et al., 2026a; OpenAI, 2023; Shojaei et al., 2024). These tools should complement, rather than replace, transparent and peer reviewed LCA modelling.

4. Circularity focused LCAs of medical devices

Actual testing of material recovery systems for dialysis consumables, such as take back or pyrolysis schemes, should be conducted. Comparative LCAs of incineration, mechanical recycling and chemical recycling would identify optimal waste management pathways (Duane et al., 2025a; Matschewsky et al., 2024; Rizan et al., 2023). This is particularly relevant for PD consumables, where predictable material streams make circular recovery technically feasible.

5. Longitudinal and multicentre analyses

Expanding LCA data collection to multiple European centres and tracking changes over several years would improve representativeness and capture technological evolution. Integration with carbon accounting systems used by national health services could enable cross country benchmarking (Drew et al., 2022; Sehgal et al., 2022). Longitudinal datasets would strengthen the evidence base needed for national and EU level climate reporting.

6. Health system level modelling

Extending the analysis from individual treatment pathways to entire nephrology departments or health systems would quantify the total national burden of kidney care. This scaling up could inform climate action planning within ministries of health and European sustainability agencies. This shift would enable assessment of cumulative impacts rather than isolated intervention effects.

7. Policy translation and implementation research

Turning environmental evidence into practical policy remains a significant gap. Implementation studies examining the real world uptake of LCA informed procurement or energy optimisation in hospitals would bridge the divide between research and practice (Rizan et al., 2023). This responds directly to stakeholder concerns identified in Chapter 4 regarding implementation barriers.

8. Education and behavioural research

Future work should evaluate the effectiveness of educational interventions in shifting clinician behaviour. Controlled studies assessing the impact of sustainability training on energy use, waste separation and prescription practices would provide evidence for curriculum design (Hagan, 2023) (Centre for Sustainable, 2025). Together, these directions outline a research agenda that supports sustained, evidence based transformation of kidney care systems.

6.4.10 Summary

While the research presented in this thesis represents a substantial step forward in quantifying the environmental burden of dialysis care, it also makes clear where current approaches fall short. Limitations in data transparency, restricted access to manufacturer information and reliance on secondary datasets constrain precision and reduce comparability across centres. Methodological boundaries, including limited impact categories and the separation of environmental analysis from clinical and social outcomes, further restrict the ability to interpret sustainability performance in a comprehensive way. These constraints do not undermine the value of the findings. Instead, they clarify where future research effort must be directed.

The evidence assembled across this thesis shows that sustainable kidney care cannot be evaluated through carbon metrics alone. Environmental performance interacts with patient outcomes, equity of access, workforce practices and global supply chain conditions. Advancing the field therefore requires integrated analytical frameworks that connect LCA with health outcomes, social indicators and system resilience. Without this integration, sustainability risks remaining separate to clinical decision making rather than becoming embedded within it.

Future progress depends strongly on digital infrastructure and data availability. Real time monitoring of water, energy and material use offers a route toward more accurate and responsive environmental accounting. Open access databases, shared reporting standards and transparent emission factors are necessary to support both human analysts and emerging digital tools. When combined with structured governance, such systems could enable routine environmental reporting at service and hospital level rather than isolated research studies.

Circular design principles also emerge as central to long term transformation. Moving beyond linear models of production and disposal toward reuse, recovery and extended producer responsibility offers one of the most credible pathways for reducing material intensity in dialysis. Embedding circularity at the design stage links environmental evidence directly with innovation, ensuring that sustainability considerations inform products and pathways before they become locked into clinical practice.

Taken together, the limitations identified in this chapter do not represent barriers to progress but signposts for the next phase of research. With coordinated development across policy, design, education and data systems, environmental assessment can evolve from descriptive analysis into a practical decision framework. Such a shift is essential if kidney care is to operate within planetary limits while continuing to deliver safe, fair and effective treatment.

6.5 Conclusion and final recommendations

6.5.1 The evolving role of design in sustainable kidney care

Product and system design has traditionally been an outlier to clinical practice, often confined to product aesthetics or usability. Yet the research presented throughout this thesis positions design as one (of a number of) central mechanism for environmental transformation within healthcare. The integration of LCA, environmental data and systems thinking demonstrates that design is not simply a technical tool but a framework for decision making that influences every stage of the clinical pathway (Larkin et al., 2025b). This reframes design as a way of shaping choices about materials, infrastructure and service organisation rather than focusing only on form or usability.

Kidney care represents an ideal testbed for this integration. Dialysis therapies, both PD and HD, are highly material, energy and water intensive. Each session requires the joint thinking of industrial production, clinical procedures, patient interaction and waste management. This complexity aligns with design's capacity to connect technical, human and systemic areas of a problem (Duane et al., 2025b). It also exposes how small design decisions are multiplied across thousands of treatment episodes over a patient's lifetime. Through detailed mapping of treatment pathways, product teardowns and LCA analysis, the research highlights how design decisions at the product and system level influence long term environmental outcomes (Larkin et al., 2025b; Larkin et al., 2026b).

The redesign of dialysis systems requires moving beyond incremental product optimisation toward systemic design at every level. This involves understanding environmental hotspots not only as technical inefficiencies but as outcomes of historical, organisational and behavioural patterns within healthcare. The consistent impact of procurement and transport impacts across all studies reinforces this point. These impacts reflect structural design choices embedded within healthcare delivery models rather than individual clinical behaviour indicates that emissions are embedded in the structural design of healthcare delivery rather than isolated product choices (Larkin et al., 2026a; Larkin et al., 2026c). This finding highlights the shift in this chapter from intervention analysis toward system redesign and governance level change.

From a design research perspective, the thesis positions environmental assessment as a feedback mechanism for innovation. Quantitative results inform the direction of design interventions, identifying where material substitution, process redesign, or behavioural change would yield the most meaningful reductions. This feedback loop reflects of evidence informed design, where environmental data are treated as material for creative iteration rather than static measurement. Within this thesis, this approach enabled environmental modelling to directly shape product concepts, service pathways and procurement strategies rather than remaining a analytic evaluation tool.

The research therefore proposes sustainability as a continuous design process rather than a one-time optimisation exercise. This feedback loop is illustrated in Figure 6. 1, which illustrates the iterative cycle: LCA hotspots from Chapter 3 inform targeted design interventions (Chapter 5), driving procurement and tender reforms (Chapter 3), collecting 40-87% emissions reductions (Chapter 6) and generating refined data for the next cycle.

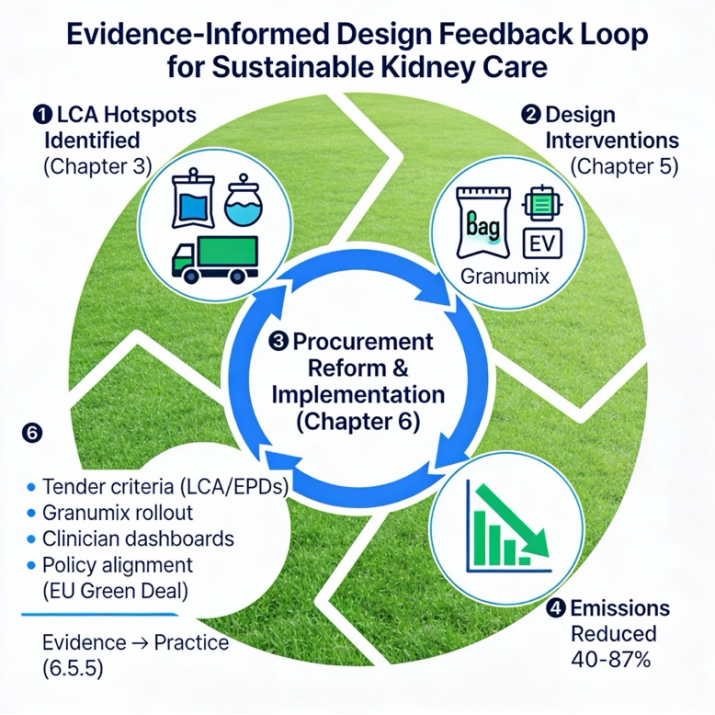

Figure 6. 1 Iterative design loop integrating LCA, redesign, procurement reform and measurable emissions cuts to decarbonise kidney care pathways

6.5.2 Integrating life cycle thinking into clinical contexts

Introducing life cycle thinking into clinical environments poses unique challenges. Healthcare systems rightfully prioritise patient safety and success and sustainability considerations are often secondary. Healthcare's ethical mandate 'first, do no harm' must expand beyond infection control to planetary health. Patient safety includes clean air (transport emissions), untainted water supplies (RO depletion) and food chains free from microplastics and dioxins released by

incinerating 1+ tonnes of PD plastics per patient year. Climate impacts increase kidney disease through heatwaves and water scarcity, while S-LCA reveals medium high labour risks embedded in global dialysis supply chains (Chapter 5). Sustainability protects this generation's patients and future ones (McMahon, 2025). This framing positions sustainability as part of clinical responsibility rather than an external policy concern.

Through the KitNewCare project, this research demonstrates that LCA can be turned into a practical tool for clinical decision making when presented through accessible frameworks (Duane et al., 2025b). This was essential for engagement within time pressured clinical settings.

The studies on PD and HD pathways achieved this translation by aligning functional units with clinical concepts, such as “one patient year of treatment” allowed clinicians to interpret environmental results in familiar units of care delivery (14040, 2006; Larkin et al., 2025b; Larkin et al., 2026a). This alignment reduced abstraction and supported meaningful comparison between treatment options. Similarly, visual process maps of dialysis workflows provided a physical representation of where materials, water and energy intersect with patient care. These diagrams served both as analytical and educational tools, bridging the gap between engineering data and clinical practice.

The findings also reveal how limited affect the adoption of life cycle thinking. Clinical teams depend on product suppliers for sustainability data, yet much of this information remains proprietary. The dismantling and weighing of products exposed major data gaps across supply chains. These gaps highlight the need for open access product databases within healthcare procurement systems. Transparency would enable clinicians and procurement officers to select lower impact products based on verified life cycle data rather than manufacturer claims. Such transparency would shift sustainability assessment from voluntary reporting toward accountable decision making.

Integrating life cycle thinking also requires institutional support. During fieldwork in Italy, staff engagement was strongest when environmental data were contextualised within patient outcomes, safety and efficiency. Clinicians were motivated not by abstract sustainability

targets but by clear evidence of resource waste, such as water losses from RO systems or excess plastic packaging. This finding indicates that sustainability gains change when environmental evidence is framed through safety, efficiency and quality of care. These insights reinforce the need for system level structures that normalise life cycle thinking within routine clinical governance.

6.5.3 Reflections on interdisciplinary collaboration

The interdisciplinary nature of this research was central to its success. This collaboration shaped both the research questions and the methods used to address them. The project brought together clinicians, engineers, environmental scientists and designers across multiple European institutions. Each discipline contributed distinct methods and perspectives, requiring ongoing translation between vocabularies and priorities. This process required time, negotiation and willingness to adapt disciplinary assumptions.

From a design perspective, this interdisciplinarity challenged conventional roles within healthcare research. Collaboration with nephrologists and biomedical engineers demanded that environmental modelling be both thorough and clinically interpretable. Engaging directly with dialysis staff also revealed the importance of contextual expertise, as much of the environmental burden in healthcare arises from routine operational practices rather than technological limitations (Agar, 2015a). This shifted attention toward workflow design, procurement routines and service organisation.

The process of conducting detailed LCAs in an active hospital setting highlighted the value of coproduction in sustainability research. Without this shared involvement, several datasets would not have been accessible. Data collection required cooperation from clinical and technical staff, waste managers and procurement officers. This participatory approach allowed for local ownership of the results, increasing the likelihood of practical implementation. This reinforced the view that sustainability responsibility is distributed across clinical, technical and managerial roles.

Cross national collaboration within KitNewCare further revealed how differences in healthcare infrastructure, regulation and energy systems shape environmental performance. These

differences influenced both baseline impacts and the feasibility of proposed interventions. For example, dialysis centres in Italy benefit from relatively low grid carbon intensity (Agency, 2021), while UK centres operate under strict waste separation policies (Rizan et al., 2021). Comparative analysis between these contexts highlighted the importance of tailoring sustainability strategies to local conditions rather than applying uniform global metrics. Effective implementation therefore depends on aligning environmental evidence with national regulation and infrastructure capacity.

6.5.4 Contribution of the researcher and Kitnewcare project

This thesis contributes to the emerging field of sustainable nephrology through methodological innovation and practical application. Its outputs include seven peer reviewed papers (Chapter 3 and 4), a scoping review (Chapter 5) and multiple methodological tools hosted on Zenodo, which together form an integrated body of evidence addressing the environmental, social and systemic aspects of kidney care. Together, these outputs were developed across a single analytical framework rather than as isolated studies.

Within the KitNewCare consortium, the candidate held primary responsibility for the conception, design and execution of the LCA research presented in this thesis. This included defining system boundaries and functional units, leading primary data collection through product teardown and resource measurement, developing LCI models and conducting quantitative environmental analyses across PD and HD pathways. The candidate led interpretation and analysis of results across chapters and was the primary author on the majority of dialysis related publications arising from this work. Collaborative contributions from clinical, engineering and policy partners supported data access and contextual interpretation, while all analytical decisions, integration of findings and conclusions presented in this thesis represent the independent work of the candidate.

The methodological contribution lies in operationalising the LCA framework for healthcare at multiple scales. From the product level (acid concentrate comparison) to full pathway analysis (PD and HD) and social impact mapping, the research demonstrates a scalable model of environmental quantification. This approach supports replication across centres and adaptation

to other high intensity clinical services. By maintaining a consistent functional unit and boundary definition across studies, the results allow meaningful comparison between modalities and sites. This consistency reduced interpretive doubts and strengthened cross chapter analysis.

The contribution is under the expression of "designing for sustainable kidney care" as a distinct standard. This reframes sustainability not as an addon but as a design constraint integrated into every aspect of care delivery. The thesis positions the designer as a mediator between evidence, clinical practice and system reform.

Within this broader conceptual framing, the KitNewCare project provided the institutional platform for this work, linking academic research with clinical implementation. This connection ensured that analytical outputs were tested against operational constraints rather than theoretical assumptions. Its interdisciplinary network enabled real world testing of sustainability interventions, from product teardown workshops to digital carbon calculators (Duane et al., 2025b). The project also established a model for transnational collaboration, demonstrating how EU funded research can align with broader policy frameworks such as the European Green Deal and the WHO's net zero healthcare initiative. This alignment improved relevance for regulators, healthcare managers and procurement authorities.

As a researcher trained in product design and sustainability, the role of the author evolved from analyst to facilitator. This transition occurred as the research moved from modelling toward implementation focused dialogue. Early work focused on technical modelling and data verification. Over time, the emphasis shifted toward communication, translation and system integration. Presenting results to clinicians required visualisation tools and clear narratives connecting environmental impact to patient care. This translational role reflects the function of design in supporting implementation through clarity, structure and shared understanding.

6.5.5 From evidence to implementation: Turning research into practice

The transition from research evidence to clinical implementation remains one of the central challenges in healthcare sustainability. Despite growing awareness, hospitals often lack structured mechanisms to act on environmental data. Interview findings in Chapter 4 showed

uncertainty around responsibility, authority and accountability as recurring barriers. This thesis demonstrates that design led approaches can bridge this gap by embedding environmental reasoning into decision making processes. This translation function is necessary because environmental evidence alone rarely changes behaviour without structured pathways for action.

For example, the procurement analyses of both PD and HD pathways identified specific consumables contributing most to emissions (Larkin et al., 2025b; Larkin et al., 2026b). Turning these findings into practice requires procurement redesign, such as integrating environmental scoring into tender evaluations or encouraging suppliers to disclose full life cycle data. Without such mechanisms, high impact products remain locked into contracts despite clear evidence of avoidable emissions. In the UK, NHS England's Net Zero Supplier Roadmap provides a model for such alignment (NHS, 2020). This approach mirrors the design logic applied throughout the thesis, where evidence informs structured choice rather than optional guidance.

At the operational level, environmental monitoring can inform quality improvement initiatives. The introduction of dashboards displaying water and energy metrics per dialysis session could transform sustainability from a management goal into a daily practice. Visible metrics support routine reflection and normalise environmental awareness within clinical workflows. Design principles such as feedback visibility, user engagement and iterative improvement can be directly applied to sustainability reporting systems (Arias-Guillen et al., 2024; Yeo et al., 2022). This shifts sustainability from retrospective reporting toward continuous improvement.

Implementation also requires attention to policy change. Life cycle evidence must be communicated in formats that align with regulatory and financial frameworks. Highly technical LCA outputs require interpretation layers that turn findings into thresholds, targets and procurement criteria.

This involves engaging policymakers early in the research process and framing sustainability not only as environmental responsibility but also as risk management and cost containment. This framing increases institutional uptake by aligning sustainability with existing governance

priorities rather than positioning it as an additional burden. The evidence generated in this thesis supports the argument that resource efficiency aligns with economic resilience, especially as energy and material costs rise globally (Rasmussen et al., 2025; Sharma et al., 2024).

6.5.6 Reflections on methodological evolution

The research journey involved continual methodological refinement. This evolution reflected growing alignment between analytical methods and real clinical decision needs. Early LCAs revealed the difficulty of accessing product data and the sensitivity of results to system boundaries. Small boundary changes produced large shifts in reported impacts, reinforcing the need for consistency across studies. Later studies incorporated direct measurement of energy and water use, improving accuracy and transparency. This shift marked a move from abstract modelling toward operational relevance. Having to dismantle products and measure flows ourselves highlights how healthcare LCA has moved from interesting theory into something busy procurement teams can use day to day (McGain et al., 2014; Rizan et al., 2024).

A key reflection is the importance of iteration. Environmental modelling in healthcare is not a one-time exercise but a continuous process of updating and validation. Without regular revision, environmental models risk becoming detached from current clinical reality. As clinical technologies evolve, so too must their environmental datasets. Establishing feedback loops between hospitals, suppliers and researchers will allow LCAs to become living documents that evolve alongside clinical practice. This includes routine data exchange on product composition, energy use and logistics changes.

The use of digital platforms such as OpenLCA and Zenodo repositories represents progress toward open science. Publishing datasets and system boundary diagrams improve transparency and reproducibility, enabling other researchers to replicate or adapt the models. This approach reduces duplication of effort and supports cumulative knowledge building across centres. This openness is critical for building trust and a collaborative culture of environmental accountability in healthcare. Methodological evolution therefore emerges not as a limitation of the work but as evidence of maturity within the field.

6.5.7 Personal and professional reflection

Conducting this research reinforced the interdependence between environmental science, design and clinical practice. This understanding developed gradually through practical engagement rather than theoretical framing. Working across disciplines and national contexts required adaptability, patience and communication skills. The process of collecting data in a live clinical environment highlighted the challenges of hospital operations, the time constraints, safety priorities and administrative layers that shape decision making. These constraints frequently determined what was feasible regardless of technical potential.

As a designer by training, engaging directly with clinicians reshaped the author's understanding of the profession's social responsibility. Sustainable design extends beyond materials and aesthetics; it encompasses systems that sustain human and planetary health. The iterative development of each paper reflected this shift from analysing impacts to proposing actionable redesigns. This shift marked a movement from observation toward responsibility.

The experience also highlighted the importance of collaboration and humility in interdisciplinary research. Sustainability challenges are too complex for any one discipline to solve. Attempts to work in isolation consistently proved insufficient. Progress depends on creating shared language and mutual respect between designers, clinicians and scientists. This principle guided the collaborative ethos of the KitNewCare consortium and will continue to inform future research. It also shapes how the author approaches practice beyond academia.

6.5.8 The future of design in sustainable healthcare

Looking forward, the role of design in sustainable healthcare will expand from project based interventions to systemic transformation. Designers will increasingly work within health policy, procurement and digital infrastructure, embedding sustainability into organisational DNA.

In kidney care, future opportunities include codesigning circular product systems, developing modular and reusable consumables and designing patient centred home dialysis solutions that reduce travel and facility demand. Integration of AI and sensor based monitoring will allow

continuous environmental feedback, transforming every dialysis session into a data point for improvement.

The broader implication is that healthcare design must embrace the principles of planetary health, recognising that patient wellbeing depends on ecological stability. This requires collaboration between designers, clinicians, policymakers and patients to create solutions that align human and environmental health.

6.5.9 Summary

The work presented in this thesis demonstrates that sustainable kidney care is not solely a technical problem to be solved through efficiency gains or new technologies. It is equally a cultural and organisational challenge that involves how healthcare systems define value, responsibility and success. Meaningful progress depends on reliable environmental data, transparent supply chains, supportive governance structures and a workforce equipped to interpret and act on sustainability evidence.

Across the studies presented, LCA provided a consistent method for identifying where environmental burdens arise and where interventions offer the greatest potential. Yet the findings also show that data alone is insufficient. Without ways for change in procurement decisions, service redesign and professional education, environmental evidence risks remaining disconnected from practice. This thesis therefore positions sustainability as an issue of integration rather than optimisation, requiring coordination across clinical care, design, management and policy.

Design emerges as a central framework for enabling this integration. Through pathway mapping, product teardown, visualisation and codesign, design methods turned complex environmental information into forms that clinicians and decision makers could engage with. In doing so, design functioned not as a supplementary activity but as a mediator between scientific analysis and real world healthcare delivery.

Interdisciplinary collaboration highlights this process. The work illustrates how environmental modelling gains relevance when shaped by clinical knowledge and how clinical practice

benefits when informed by systems thinking. These collaborations revealed that many of the most significant environmental impacts in kidney care are structurally embedded in procurement models, transport arrangements and regulatory assumptions rather than in individual clinical choices.

Taken together, the evidence and reflections presented in this thesis contribute to an emerging understanding of sustainable kidney care as a shared professional responsibility. Sustainability is reframed not as an optional improvement but as part of ethical clinical practice, organisational accountability and long term patient protection. By grounding sustainability in data, reflected through design and embedding it within collaborative practice, this research establishes a foundation for continued innovation in kidney care that respects both human health and environmental limits.

Bibliography

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ORIGINAL ARTICLE

A life cycle assessment of peritoneal dialysis procurement in Italy: environmental burden and opportunities for improvement

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Abstract

Background Procurement activities in healthcare, especially within nephrology, contribute significantly to the environmental footprint. In peritoneal dialysis (PD), procurement of consumables such as dialysis bags, tubing, and machines plays a critical role in driving environmental impacts. Previous studies, including those by the National Health Service (NHS), have shown that procurement can account for up to 72% of the healthcare sector's carbon emissions.

Methods A life cycle assessment (LCA) was conducted from April to July 2024 at the Nephrology Dialysis and Kidney Transplantation Unit of AOU Policlinico di Modena, Italy, in accordance with ISO 14040/14044 standards. The study focused on procurement-related environmental impacts in automated peritoneal dialysis (APD), based on a standard prescription of two 5L bags overnight and one 2L daytime dwell per day. Products were dismantled to assess materials and modelled using OpenLCA with the Ecoinvent v3.10 database. Transportation, manufacturing, and waste disposal were included within system boundaries.

Results The 5L Dialysate Bag (used twice daily) had the highest carbon footprint (1515 kg carbon dioxide equivalent [CO_2-eq/year]), followed by the 2L Bag (457 kg) and Automated Drainage System (286 kg). Primary drivers were long-distance transport, plastic production (especially polyethylene and PVC), and energy-intensive manufacturing. Although the 5L bags are used in greater quantities due to the APD prescription (typically two bags per night), it still showed a lower carbon footprint per litre of dialysate delivered (0.415 kg CO_2-eq/L) compared to the 2L bag (0.626 kg CO_2-eq/L). Smaller items like disinfectant sprays and medical kits contributed less individually but were used frequently. Across all categories, plastic production, packaging, electricity use, and incineration were key contributors.

Conclusion The environmental impact of PD procurement is concentrated in a few high-use, high-impact items. Reduction strategies should target material substitutions, modular product design, and lower-emission transport and energy use.

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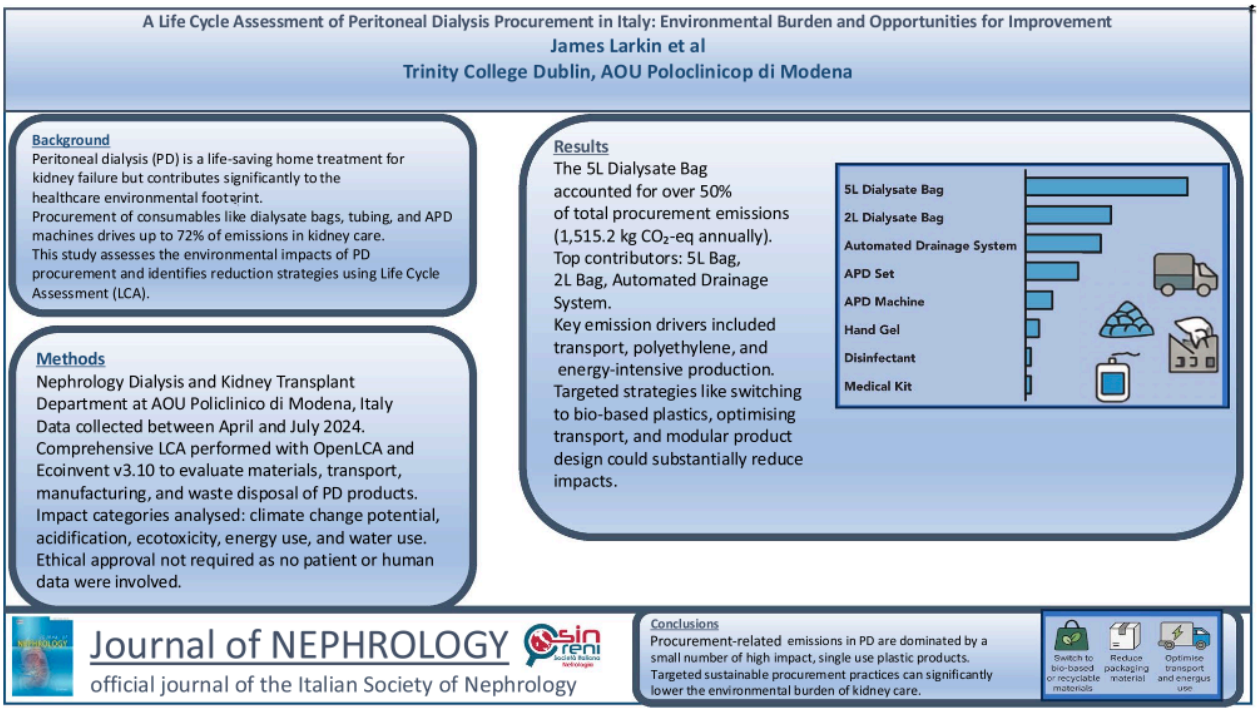
Innovations such as local dialysate mixing, improved waste segregation, and increased recyclability could substantially reduce the environmental burden of PD.

Graphical abstract



Keywords Procurement · Peritoneal dialysis · Life cycle assessment · Environmental impact · Plastics · Carbon footprint · Sustainability · Healthcare waste · PVC · LCA

Introduction

Healthcare is increasingly recognised as a significant contributor to climate change, with the procurement of medical devices and supplies playing a central role. Recent studies, including National Health Service (NHS) research, have shown that procurement can account for up to 72% of healthcare's total carbon footprint [1]. In nephrology, where treatments like dialysis are resource intensive, procurement emerges as a critical area for environmental improvement [2].

Kidney failure requires kidney replacement therapies like dialysis or kidney transplantation for survival [3]. Among dialysis options, Peritoneal Dialysis (PD) has emerged as the leading home-based treatment, offering patients more autonomy and convenience [4].

While PD offers many advantages, such as home-based treatment, its environmental impact, particularly from the procurement of materials and medical devices, has become a growing concern. PD requires large quantities of consumables, including dialysis bags, tubing, and connectors, most of which are single use plastics. The environmental burden of manufacturing, transporting, and disposing of these products is substantial [5].

The healthcare sector's contribution to global pollution has led to increasing calls for sustainable practices, especially in procurement, which is a major driver of environmental impact [6]. Life cycle assessment (LCA) offers a comprehensive method for evaluating the environmental footprint of each product and process involved in PD, from raw material extraction to production, distribution, use, and disposal [7]. By assessing procurement in detail, this study aims to identify specific products and processes with the highest environmental impact, enabling the development of targeted strategies to reduce the carbon footprint of PD.

This paper is part of the KitNewCare project, which seeks to reduce the environmental impact of kidney care through sustainable innovations [8].

Methods

This study was conducted between April and July 2024 at the Nephrology Dialysis and Kidney Transplantation Unit of AOU Policlinico di Modena, Italy, using Life Cycle Assessment based on ISO 14040/14044 [9]. The goal was to evaluate the environmental impacts of procurement activities in automated peritoneal dialysis (APD), covering the full lifecycle of products from raw material extraction to disposal.

Procurement data collection

A comprehensive inventory of all products used in PD was compiled, with a focus on items with high environmental impacts, such as dialysate bags, tubing, APD machines, and consumables like disinfection sprays and sorbent paper. Data were collected from the AOU Policlinico di Modena to obtain:

- Quantities of each product used annually per patient.
- Supplier and manufacturing details, including production locations and transportation logistics.
- Material composition and associated certifications or product data sheets.

Material and product analysis

To assess the environmental footprint of individual products:

- Products were disassembled (dismantled into their components, such as plastic bags, connectors, and tubing) to identify materials used.
- Each component was weighed using precision scales, and the material types (e.g., polyethylene, polypropylene, polyvinylchloride (PVC) were identified through safety data sheets and product specifications.
- Packaging materials were included in the analysis to account for their contribution to overall impacts.

Lifecycle assessment modelling

The environmental impacts of PD products were modelled using OpenLCA software [10]:

- Procurement-related processes, such as raw material extraction, manufacturing, transportation, and disposal, were created for each product.
- The EcoInvent database was used to evaluate environmental impacts across categories such as global warming potential, water use and energy use [11].

System boundary

Figure 1 illustrates the system boundaries defined for this study, encompassing all stages from raw material extraction through to end-of-life disposal. This cradle-to-grave approach captures the full environmental burden of each product used in peritoneal dialysis, including specific material types, manufacturing methods, transport distances, usage profiles, and waste treatment.

Transportation assessment

The transportation stage was assessed to capture the carbon footprint associated with the movement of PD products:

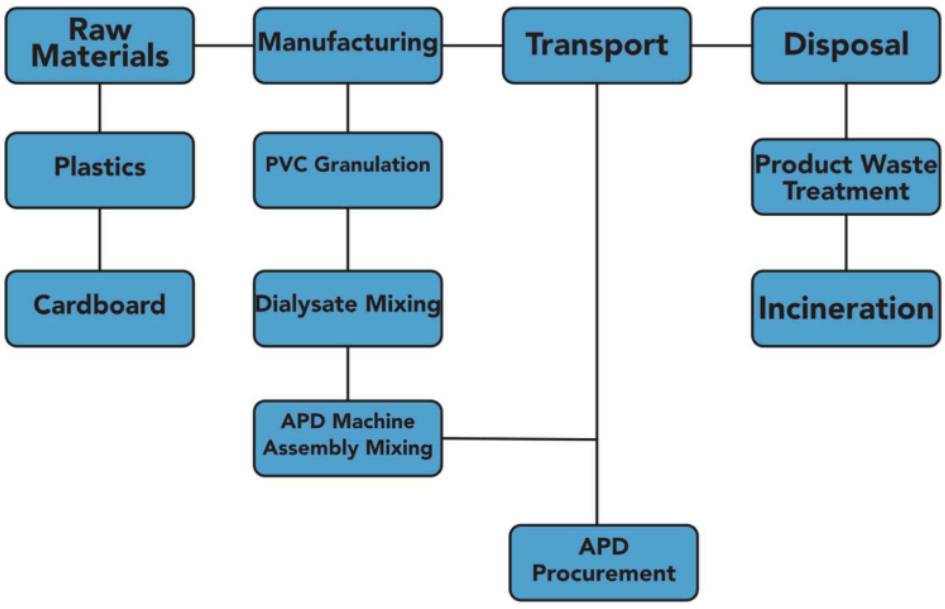


Fig. 1 System boundary. *PVC* Polyvinylchloride, *APD* Automated Peritoneal Dialysis

- Shipping distances from manufacturers to the hospital were calculated using online tools such as Google Maps and FluentCargo.com [12, 13].
- The modes of transportation and fuel types were identified through published literature [14].
- Transportation of waste from the hospital to disposal facilities was included in the analysis.

Disposal pathways

The study analysed waste disposal methods for PD consumables:

- Waste was modelled according to Modena's hospital protocols. Waste was classified into recyclable and non-recyclable streams based on Modena hospital waste management practices.
- The disposal impacts of incineration, recycling, and landfill were modelled, with data provided by waste management providers and literature sources.
- Home patient waste was collected by third-party contractors and incinerated. Where feasible, we explored potential alternative scenarios (e.g., autoclaving or non-clinical segregation) for discussion [15].

Stakeholder engagement

Key stakeholders, including clinical staff, admin staff and waste management teams, were asked to verify data accuracy and ensure comprehensive coverage of all procurement-related activities.

Impact categories

A range of midpoint categories were assessed in OpenLCA. This paper presents the categories with the greatest impact factors: global warming potential, primary energy demand, and water use. Toxicity-related categories were also assessed and are referenced in the Discussion [16]:

- Global warming potential (kg carbon dioxide equivalent [CO_2-eq]): Total greenhouse gas emissions.
- Primary energy demand (mega-joules [MJ]): Total energy consumed during product lifecycle.
- Water use (m^3): Water consumed during production and packaging.

Functional Unit

The functional unit was defined as the complete APD treatment for one patient over one year. The life cycle assessment was based on the most common APD prescription at the hospital: two 5L dialysate bags overnight and one 2L dialysate bag for a daytime dwell, used every day. Equipment quantities and usage patterns were averaged annually per patient based on hospital procurement records. The APD machine's emissions were annualised based on an assumed 5-year operational lifespan, in line with manufacturer specifications and hospital replacement cycles.

Ethics

Ethical approval was not required for the project detailed in the document because it involved the environmental assessment of procurement processes and medical devices, rather than research on human participants, patient data, or any other ethical domain requiring institutional review board (IRB) oversight. The focus was on analysing the lifecycle and environmental impacts of products, which does not typically intersect with areas necessitating formal ethical considerations.

Results

Product overview

To improve clarity and generalisability, product names have been anonymised into more generic categories. Table 1 describes the updated nomenclature used throughout this section.

Total Carbon Footprint (Fig. 2 in Appendix 1).

Figure 2 in Appendix 1 presents the total carbon footprint (kg CO_2-equivalent) associated with the procurement of PD-related products over one year for one patient.

The 5L Dialysate Bags (two per day as per APD prescription) contributes the largest share (1515.2 kg CO_2-eq), accounting for over 50% of total emissions. While the 5L dialysate bags had the highest overall primary energy demand and water use, they also showed slightly higher energy and water use per litre when compared to the 2L bags (2.92 MJ/L vs 2.90 MJ/L and 0.0655 m^3/L vs 0.0479 m^3/L, respectively). This is taking into account that this is two bags as per APD prescription. This is followed by the 2L Dialysate Bag (457.0 kg CO_2-eq), and the Automated Drainage System (285.9 kg CO_2-eq). The Automated PD Set (186.5 kg CO_2-eq) and APD Machine (151.7 kg CO_2-eq) also have notable impacts. Smaller but cumulatively important contributors include the Hand Washing Gel (29.9 kg CO_2-eq), Disinfectant (11.5 kg CO_2-eq), and Medical Kit (3.3 kg CO_2-eq).

Carbon emissions contribution analysis (Figs. 2, 3).

In this contribution analysis, "plastic" and "other materials" refer specifically to emissions arising from the production and end-of-life disposal of plastic and non-plastic materials. Plastic-related emissions are highest in the 5L

Table 1 Product descriptions and generic names

Generic name	Description
5L Dialysate Bag	A 5-L dialysate bag with 2.7% glucose concentration used daily in PD. Two bags are taken into account here as per APD prescription
2L Dialysate Bag	A 2-L dialysate bag with 2.7% glucose concentration
Automated Drainage System	PD system component for managing 15L drainage capacity with spike set
Automated PD Set	Cassette-based automated PD set with 8 prong connectors
APD Machine	Automated peritoneal dialysis machine for home use
3L Empty Bag	A 3-L empty drainage bag used in fluid collection
Drainage Set	Tubing and connectors for draining dialysate waste
Hand Washing Gel	Disinfection gel for hand hygiene prior to PD handling
Disinfectant	Surface disinfection spray used before PD exchanges
Medical Kit	Miscellaneous items including surgical masks, gloves, and dressings

Bag (135.3 kg CO_2-eq), followed by the Automated Drainage System (133.7 kg) and 2L Bag (107.1 kg). This results from the carbon intensity of producing and incinerating polyethylene and PVC components. The figures presented are ordered by total emissions per product, with each category (transport, plastic, other materials, manufacturing, waste) contributing proportionally to the product's total footprint. Waste refers to end-of-life emissions, including incineration or landfill. Manufacturing emissions reflect energy-intensive production processes.

Transport dominates for the 5L Dialysate Bags (763.6 kg CO_2-eq) and 2L Dialysate Bag (145.8 kg CO_2-eq), due to weight and volume during distribution. Emissions from other materials (e.g., additives, secondary packaging) are particularly high for the 5L Bag (461.4 kg CO_2-eq). Secondary packaging, particularly corrugated cardboard used for dialysate bag shipments, contributed significantly to emissions. Across one year of treatment, cardboard packaging alone accounted for over 300 kg CO_2-eq**.** Cardboard is one of the largest contributors to emissions after plastic and transport.

Plastic-related emissions were highest in the 5L Bag (135.3 kg CO_2-eq), followed by the Automated Drainage System (133.7 kg) and 2L Bag (107.1 kg). This reflects the carbon intensity of producing and incinerating materials such as polyethylene and PVC, rather than product weight alone. Although the 5L bags are used in greater quantities due to the APD prescription (typically two bags per

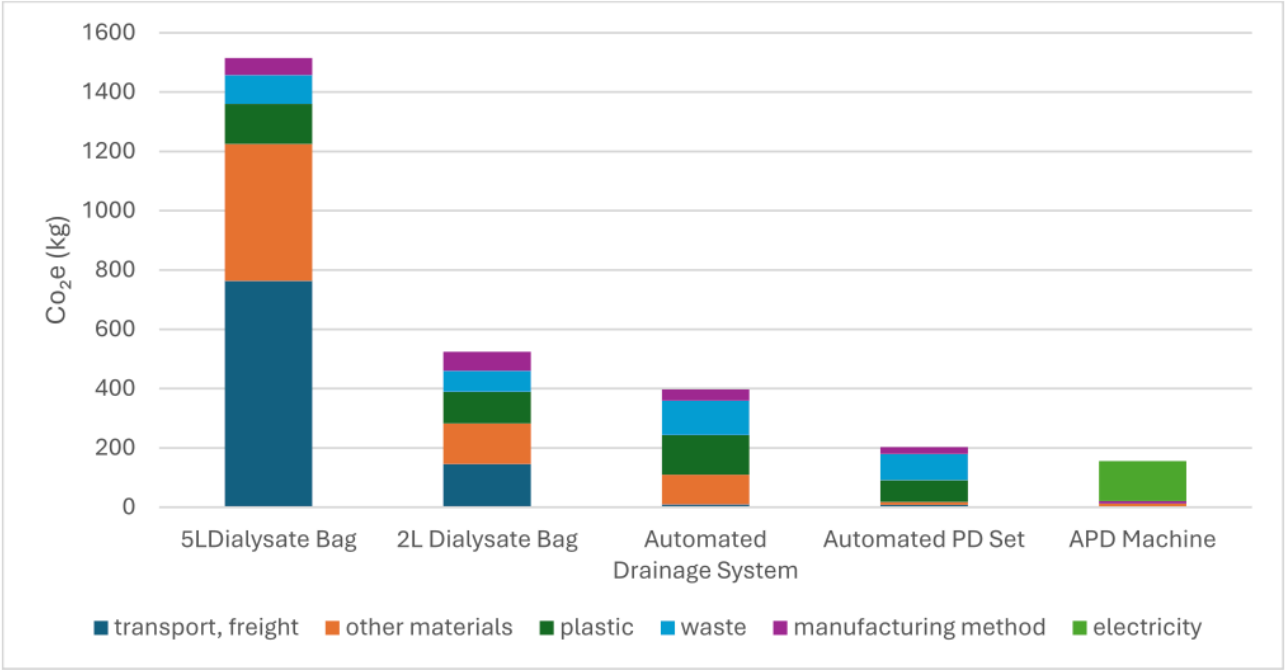


Fig. 2 Contribution analysis (carbon emissions)

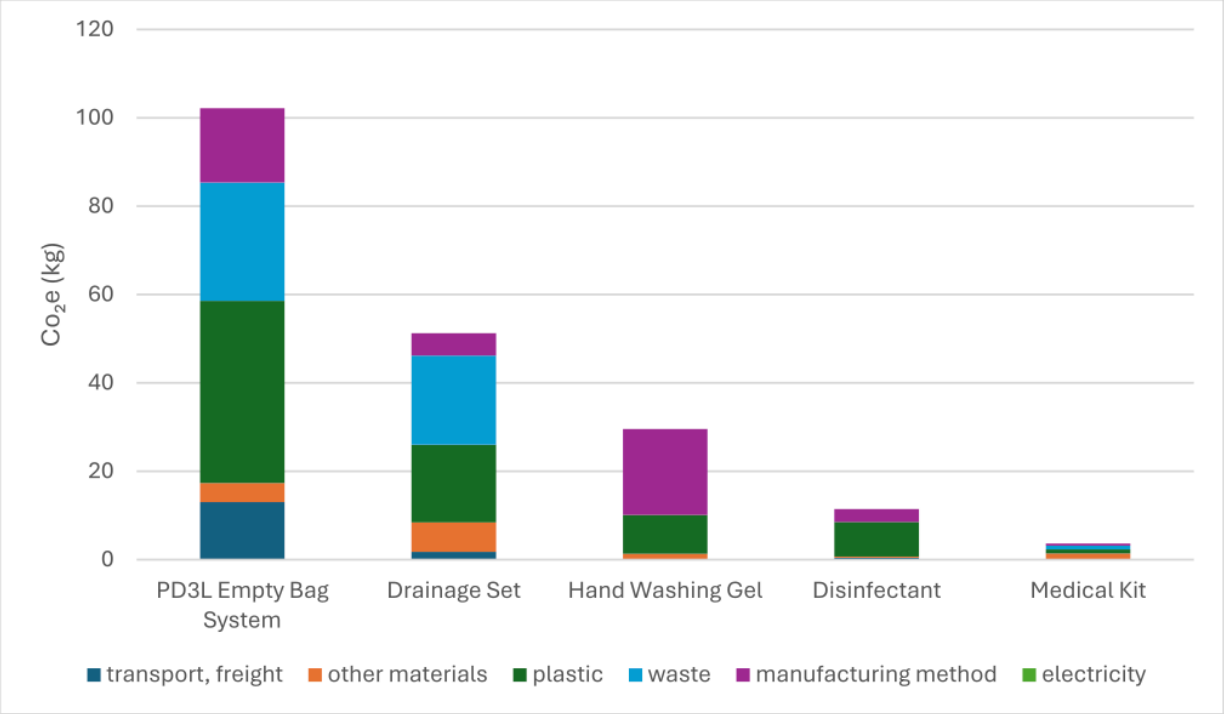


Fig. 3 Contribution analysis (carbon emissions)

night), it still showed a lower carbon footprint per litre of dialysate delivered (0.415 kg CO_2-eq/L) compared to the 2L bag (0.626 kg CO_2-eq/L). This suggests that while the 5L bag has a higher overall impact due to volume and frequency, it remains more efficient per unit of fluid, supporting its continued use under optimised transport and packaging conditions.

Manufacturing contributes substantially across products, with the APD Machine using 134.5 kg of electricity-driven emissions. Waste-related emissions are especially high in the Automated PD Set and Drainage Set, due to incineration of non-recyclable plastics.

Energy resource use (Figs. 5 and 6 in Appendix 1).

Primary energy demand (MJ):

The 5L Dialysate Bags consume 10,648 MJ, followed by 2L Bag (2,119 MJ). High energy demand is associated with both plastic production and long distance transport. Automated Drainage System and Automated PD Set each exceed 2,000 MJ due to multi material complexity.

Water use (Figs. 7 and 8 in Appendix 1).

Water consumption (m^3): 5L Dialysate Bags lead with 239.2 m^3 over one year, mostly due to material processing and packaging. Automated Drainage System follows with 26.2 m^3. Though Medical Kits and Hand Gel have low overall water use, their high water use per kg of product weight makes them inefficient from a water perspective.

Discussion

This study reinforces the growing body of evidence that procurement activities are a significant driver of environmental impact in healthcare, particularly within dialysis care. As previous research has shown, procurement may account for up to 72% of healthcare's total carbon footprint [1]. Our life cycle assessment of APD in Italy found that three products alone, the 5L dialysate bag, the 2L dialysate bag, and the automated drainage system, contributed over 75% of the total procurement-related emissions for one patient's annual treatment. This aligns with prior calls for urgent reform in dialysis-related procurement to enable climate-resilient nephrology care [2].

The 5L dialysate bags were the single largest contributor to emissions, primarily due to high transport emissions, polyethylene use, and energy-intensive manufacturing processes. Importantly, when comparing emissions per litre, the 2L bag is more carbon intensive than the 5L bag (0.626 kg CO_2-eq/L vs 0.415 kg CO_2-eq/L), indicating that the use of larger bags may help minimise impact through improved packaging and transportation efficiency when compared to utilising smaller bags of dialysate. However, the contribution from packaging, particularly corrugated cardboard, remained substantial, accounting for over 300 kg CO_2-eq annually.

Waste management was a key driver of toxicity-related impacts across all products. This was particularly true for PVC-containing products such as tubing and drainage systems, which release dioxins and other harmful compounds during incineration [22]. While some literature suggests PVC is recyclable under the right conditions [17], such systems are not widely implemented in clinical settings. Until they are, transitioning to safer alternatives such as thermoplastic elastomers or silicone, despite their own recycling limitations, may reduce environmental and human health risks [4, 22]. Reclassification of some PD-related waste as non-hazardous, where infection risk is low, could enable increased material recovery and lower the need for incineration [15, 20].

Internationally, alternative clinical waste treatment methods such as autoclaving, microwave disinfection, and mechanical shredding are increasingly adopted to reduce reliance on incineration, which is associated with high energy use [15, 20]. These technologies offer a lower-impact pathway for managing infectious and non-infectious medical waste and could be applied to certain peritoneal dialysis components. For example, the automated drainage system and used PD drain bags are currently treated as clinical waste and incinerated; however, it is unclear whether this classification is always necessary from an infection control perspective. Further research is needed to assess the actual microbiological risk associated with such components. If risks are minimal, reclassifying these items could allow for safer recycling and diversion from incineration, offering substantial environmental benefits.

The use of a broad range of impact categories, global warming potential, energy use, and water consumption allowed us to capture the full environmental burden of procurement activities. While carbon footprint is a dominant concern, a narrow focus on this metric alone would obscure critical trade-offs in energy use and water use [16]. The observed alignment of high-impact products across categories reinforces their environmental impact and highlights the value of full-spectrum life cycle assessments in guiding healthcare sustainability strategies.

In terms of practical reductions, our findings point to several clear opportunities:

- Product redesign: shifting from multi-material to mono-material formats and eliminating PVC where possible. Mono-material formats can improve recyclability by simplifying sorting and reducing contamination.
- Localisation: manufacturing closer to the point of care to reduce transport emissions [18].
- Modular system design: enabling disassembly and more efficient recycling [17].
- Procurement reform: offering dialysate in a wider range of volumes, may reduce unnecessary waste.
- Innovation: exploring on-site dialysate mixing, similar to what has proven effective in haemodialysis, could reduce both transport and packaging impacts [2, 18].
- Transitioning to renewable energy sources for dialysis equipment could further reduce emissions. As our data showed, the electricity required to run an APD machine contributed over 130 kg CO_2-eq annually. Decarbonising this electricity supply through institutional green energy contracts could substantially lower emissions without changes to the machine design itself.

Our findings align with those reported in a similar study, which assessed the carbon footprint of peritoneal dialysis in China [23]. While their study focused primarily on energy use and patient travel, our work offers a more granular product-level breakdown of emissions. Notably, the overall magnitude of emissions is comparable, but our inclusion of packaging, plastics, and waste management reveals additional hotspots for intervention.

Our results also echo those of another study which examined PD carbon emissions in Australia [17]. Their study emphasised the role of material choices, particularly PVC recycling, in reducing carbon impacts by up to 30%. While such strategies show promise, our study highlights the need for supportive infrastructure to enable recycling and waste reclassification in clinical contexts.

By identifying transport, waste management, and plastic production as the most impactful lifecycle stages, this study offers a roadmap for targeted intervention. These findings support the development of greener procurement strategies and more sustainable nephrology care models, both in Italy and internationally.

This study has several limitations that must be acknowledged. One being that the data collection was limited to a specific timeframe (April to July 2024) and location (Nephrology Dialysis and Kidney Transplantation Unit, AOU Policlinico di Modena, Italy). This does not fully represent the global practices and differences in PD procedures. The Kit New Care project will undertake recreating this study in three other clinical sites. This will eliminate this limitation as comparative studies will be carried out.

The life cycle assessment relied heavily on the accuracy and completeness of the input data. The weights and types of materials used in PD need to be accurate. However, these are subject to measurement and categorisation errors.

Additionally, the environmental impact assessment was constrained by the available impact categories and methodologies in OpenLCA.

Conclusion

Procurement plays a central role in shaping the environmental footprint of PD. By focusing on the materials, production, and transportation of PD consumables, this paper has identified the main contributors to procurement-related environmental impacts. The dialysis bags, APD machine and tubing products represent the largest sources of emissions and resource use, highlighting the need for focused efforts to reduce their environmental impact.

Sustainable procurement practices, including the adoption of greener materials, optimising production processes, and reducing transportation emissions, are essential to lowering the carbon footprint of PD treatments. As healthcare systems try to become more sustainable, procurement must be a priority area for innovation and improvement in reducing the overall environmental burden of kidney care.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40620-025-02409-z.

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Declarations

Competing interests The authors declare that they have no competing interests.

Ethical approval Ethical approval was not required for this study as it did not involve human participants or animal research. The study focused solely on environmental data collection and analysis related to peritoneal dialysis systems.

Informed consent to participate Not applicable. This research did not involve any individual participants, patients, or human data.

Data availability statement All data generated or analysed during this study are publicly available in the Zenodo repositories: Larkin, J. (2024) 'Life Cycle Assessment Dataset For Peritoneal Dialysis in Modena'. Brett Duane. https://doi.org/10.5281/zenodo.14258866. Larkin, J. (2024) 'Product Images for Life Cycle Assessment Dataset For Peritoneal Dialysis in Modena'. Brett Duane. https://doi.org/10.5281/zenodo.14258920.

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ORIGINAL ARTICLE

Green haemodialysis: comparison of dialysis bags versus fresenius granumix at the AOU Policlinico di Modena, Italy

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Abstract

Background Haemodialysis (HD) has a significant environmental footprint due to its high resource consumption and waste generation. A key component is dialysate production, which typically involves mixing water, bicarbonate, and a single-use acid concentrate bag for each session. An alternative method is the central delivery of acid concentrate, prepared on-site using dry powder formulations. This study compares the environmental impact of these two delivery systems, focusing on waste reduction, elimination of single-use plastic, and decreased transport-related emissions.

Methods A detailed life cycle assessment (LCA) was carried out using OpenLCA and the Ecoinvent v3.1 database to compare the traditional acid concentrate bag system with the central delivery system (Granumix, Fresenius, Germany). Data on material inputs, energy use, waste generation, and transportation were collected. Flow diagrams captured the full life cycle of each method, and various environmental indicators were analysed, including climate change, acidification, and ecotoxicity.

Results The Granumix system demonstrated considerably lower environmental impact than traditional bag use. It reduced climate change potential by 30% (CO_2-equivalent) and freshwater ecotoxicity by 15%. Additional benefits were observed in acidification, resource use, and overall emissions, indicating the system's broader environmental advantages.

Conclusions The central delivery of acid concentrate using the Granumix system is a more sustainable option for HD, significantly reducing environmental burdens across several categories. These findings underscore the value of adopting innovative delivery models to make essential healthcare treatments more environmentally sustainable.

James Larkin and Gaetano Alfano have contributed equally as first authors.

Extended author information available on the last page of the article

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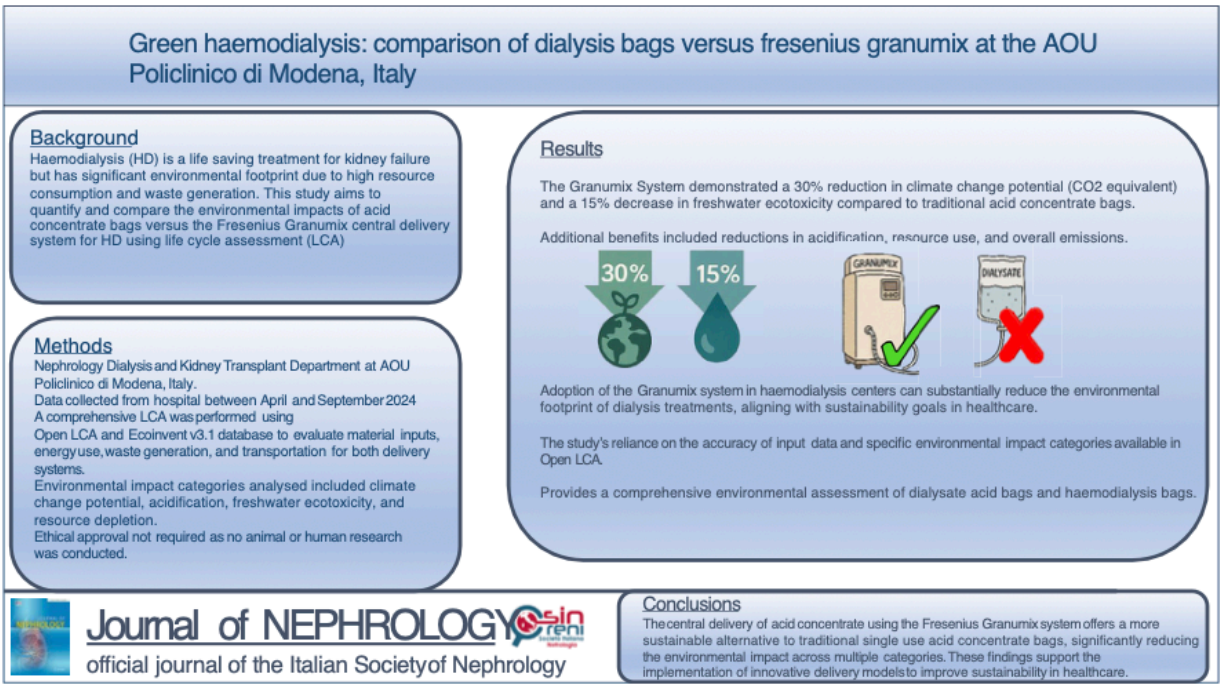
Graphical abstract



Keywords Haemodialysis · End stage kidney disease · Environment · Sustainability · Life cycle assessment · Acid concentrate bags · Fresenius granumix plus system · Dialysate · Resource consumption · Waste generation · Carbon footprint · Water use

Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AOU	Azienda Ospedaliero-Universitaria
CTUh	Comparative Toxic Units for humans
CTUe	Comparative Toxic Units for ecosystems
ESKD	End Stage Kidney Disease
HD	Haemodialysis
KRT	Kidney Replacement Therapy
LCA	Life Cycle Assessment
LDPE	Low Density Polyethylene
MJ	Megajoule
NH_3	Ammonia
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
PLA	Polylactic Acid
PM2.5	Particulate Matter smaller than 2.5 microns
Sb-eq	Antimony Equivalent
SO_2	Sulphur Dioxide
U235-eq	Uranium-235 Equivalent

Introduction

Haemodialysis (HD) is a lifesaving treatment for patients with kidney failure [1]. In 2017, estimates indicated that 3.9 million people with kidney failure were being treated with Kidney Replacement Therapy (KRT) globally[1].This prevalence is projected to increase year over year due to the ageing population, an increase in lifestyle diseases such as hypertension and diabetes, and greater access globally to health care treatment [2]. HD remains the commonest form of KRT, accounting for approximately 89% of all dialysis treatments [3].

The environmental impact of HD is significant; it is considered one of the most energy-intensive procedures in healthcare, particularly due to its high resource consumption and waste generation [2]. The substantial energy demands of HD arise from multiple aspects of the treatment process, including the production of dialysate, which involves mixing pure or ultrapure, deionised water with both an acid and a base concentrate. The HD machine

prepares dialysis fluid by mixing manufacturer-supplied concentrates with treated water in precise proportions to achieve the desired composition.

Currently, there are several methods for delivering acid concentrate to dialysis machines:

i. concentrated liquid in individual plastic containers (bags or canisters),
ii. individual cartridges of powder,
iii. semi-dry concentrates delivered in reusable barrels for bulk automated reconstitution [4],
iv. premixed acid pumped into large on-site storage tanks, and
v. bags of dry powder for bulk manual reconstitution.

Options (i) and (ii) allow for individualisation of prescriptions, making them suitable for patient-specific treatment adjustments. In contrast, options (iii), (iv), and (v) are used in central delivery systems and do not allow for easy prescription individualisation.

In this study, we focused only on the acid delivery systems available at the AOU Policlinico di Modena—specifically option (i), represented by single-use acid bags (Baxter Softpak 3.5 L), and option (iii), represented by the Granumix system. Other international configurations were not assessed due to lack of availability at the study site.

The primary advantage of (i) and (ii) is the ability to customise the dialysate to suit a patient's specific needs; but this advantage in clinical care is offset by its significant contribution to the environmental impact in terms of plastic waste and discharge of unused acid concentrate [3, 5].

In contrast, the use of centralised systems such as the B. Braun EcoMix or Fresenius Medical Care Granumix Plus represents a significant step towards reducing the environmental impact of haemodialysis. These systems automate the production and distribution of acid concentrate directly to HD machines within a facility, eliminating the need for individual single-use containers [6]. The Granumix system uses reusable Diamix powder containers, each of which can be reused up to ten times before being recycled, thereby significantly reducing plastic waste. Additionally, the system relies on pre-treatment filters and other minor consumables that are replaced periodically and have been included in our life cycle analysis. The filter (FX Cordiax 100) contributes minimally to material use and waste due to its long service life and infrequent replacement (3 used simultaneously, changed once a year). By reducing plastic use, minimising chemical waste, and lowering transport-related emissions, the Granumix system offers a more sustainable approach to dialysate preparation and delivery.

Life Cycle Assessment (LCA) is a method used to evaluate the environmental impacts associated with all stages of a product or process, from raw material extraction through manufacturing, usage, and disposal or recycling. Life cycle assessment generates results across various environmental categories, such as carbon footprint, water use, energy consumption, acidification, eutrophication, and toxicity. These results are typically complex and expressed in units specific to each impact category [7]. To facilitate interpretation, results are often normalised, converting them into dimensionless scores that allow straightforward comparisons across categories. Normalisation involves scaling results relative to average environmental impacts caused by a standard reference, often referred to as the "average person", enabling readers to easily understand whether a particular impact is higher or lower than average [8].

Aim of the study

This study aims to evaluate the environmental impact of acid concentrate delivery systems in haemodialysis by conducting a comprehensive life cycle assessment comparing traditional single use acid concentrate bags with the Fresenius Granumix system. By analysing key environmental impact categories, including climate change potential, acidification, freshwater ecotoxicity, and resource depletion, this research seeks to quantify the sustainability benefits of central acid concentrate preparation and distribution. The study further explores potential areas for improvement in dialysis sustainability, highlighting strategies to reduce emissions, waste generation, and resource consumption. The findings aim to provide healthcare providers, policymakers, and manufacturers with data-driven insights to promote greener dialysis practices and support the transition towards more sustainable kidney care solutions.

Methods

This study uses a comprehensive life cycle assessment to evaluate the environmental sustainability of two acid concentrate delivery methods used in haemodialysis: traditional single-use acid concentrate bags and the Fresenius Granumix central delivery system. Life cycle assessment is a widely adopted method for quantifying the environmental impacts associated with a product or process across its full life cycle—from raw material extraction to end-of-life disposal. Data collection and modelling were carried out between April and September 2024 at the AOU Policlinico di Modena in Italy. The study involved detailed process

mapping, material inventory, energy and water usage, and waste management assessment for both systems.

Creating flow diagrams

The first step involved developing a detailed flow diagram to visualise the entire life cycle of both dialysis methods. The flow diagram serves as a graphical representation of the processes and stages involved in the production, use and waste of the two dialysis methods. All processes involved in the life cycle of methods were identified, including materials, products and waste.

Each process was mapped out. Flow diagrams were created using a professional page layout software, Visio [9] – See Fig. 1

The flow diagrams were verified through discussion and consultation with clinical staff and dialysis experts to ensure accuracy.

Data collection

Data were collected from the Nephrology Dialysis and Kidney Transplant Department at the AOU Policlinico di Modena, Italy, and from a previous study on Acid concentrate by nephrologists and researchers at the same hospital [8].

Collected data included the number of acid concentrate bags used annually, the volume of dialysate produced by the Granumix machine, the amount of waste generated, including packaging waste, acid solution and other related items and materials. Resource consumption data, including energy and water usage were also collated.

Inputting data into OpenLCA.

The material weights and types alongside the process flow diagrams were input into OpenLCA [10]. This involved compiling all relevant data for both dialysis methods.

The data were used to model the life cycle of both dialysis methods.

Impact assessment was conducted using various environmental impacts such as climate change, ecotoxicity, resource use, water use in OpenLCA alongside the Eco Invent database [11]. This step involved calculating the environmental impacts across various impact categories, such as global warming potential, ecotoxicity and acidification.

Bicarbonate cartridges were excluded from this life cycle assessment as their use and environmental impact were identical across both systems and therefore would not affect the comparative results.

The full data set for this study can be found at Larkin, J. (2025). Green Haemodialysis: Comparison of Dialysis Bags Versus Fresenius Granumix Water Recycling System at the AOU Policlinico di Modena, Italy (Version v1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14610055.

Functional unit

The functional unit for this study is defined as the amount of dialysate required for one haemodialysis treatment for a single patient. Each session was assumed to last 4 h with a dialysate flow rate of 500 mL/min**,** resulting in a total of 120 L of dialysate per treatment. This standardised prescription allows for comparability across haemodialysis units and reflects common clinical practice.

Impact categories in life cycle assessment

This study used OpenLCA to analyse a range of environmental impact categories relevant to dialysis delivery systems. These included:

- Acidification potential, measured in mol H^+-eq, which reflects the emission of substances (e.g., SO_2, NO_x, NH_3) that increase the acidity of soil and water bodies, potentially harming ecosystems.
- Eutrophication, measured in kg P-eq or kg N-eq, refers to the nutrient enrichment of water bodies (freshwater, marine, or terrestrial) that can lead to excessive algal growth and oxygen depletion.
- Human toxicity (carcinogenic and non-carcinogenic), measured in comparative toxic units for humans, estimates the risk to human health from exposure to harmful substances over the product lifecycle.
- Freshwater ecotoxicity, measured in comparative toxic units for ecosystems, evaluates the potential of emissions to cause toxic effects in aquatic organisms.
- Other categories include climate change (kg CO_2-eq), ozone depletion (kg CFC-11-eq), particulate matter formation (disease incidence), water use (m^3 world eq. deprived), land use, and resource depletion (e.g., kg Sb-eq for metal use).

A full glossary of all impact categories, including definitions and units, is provided in the supplementary material (Supplementary Material S1: life cycle assessment Impact Categories).

System boundaries

Figure 2 outlines the system boundaries, covering the full life cycle of traditional acid concentrate bags and the Fresenius Granumix system, from raw material extraction to end-of-life waste. For acid bags, materials include plastics, acid solution chemicals, and packaging (3.8–4.5 L per bag).

Fig. 1 Flow Diagram of acid bags vs Acid Concentrate

Granumix materials include metals, plastics, and other system components. The filter, including its material composition, packaging, transport distances, and replacement frequency, was included in the life cycle inventory for the Granumix system to ensure a complete and representative environmental assessment.

Manufacturing includes plastic bag and acid solution production for the bags, and full system and component assembly for the Granumix. Transportation covers raw material delivery, product distribution, and maintenance-related transport for both systems. Waste transport is also included.

Both the use and waste phases are assessed, including disposal of used bags and solution, as well as waste from Granumix components.

Product manufacture

The product materials and weight information were retrieved from the previous study which investigated the difference between acid concentrate bags and the Granumix system with regard to the quantity of each material and the amount of waste generated [9]. The manufacturing processes that were used in the production of all the products were found through product safety data sheets and assumptions. These have all been referenced at Larkin, J. (2025). Green Haemodialysis: Comparison of Dialysis Bags Versus Fresenius Granumix Water Recycling System at the AOU Policlinico di Modena, Italy (Version v1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14610055. The energy usage of the machinery that was used to manufacture the products was provided by Eco Invent.

Transportation

Transportation distances were calculated from the manufacturing site to the AOU Policlinico di Modena using Google Maps for road transport and Fluentcargo.com for shipping distances. These tools provided the most geographically direct and commonly used routes for freight transport, based on available infrastructure. Actual routes may vary depending on specific logistics provider operations, but the shortest and fastest available routes were used as a conservative estimate for environmental modelling.

Information on modes of transport (e.g., truck, ship) was obtained from product manufacturers where possible. In instances where exact transport logistics were unavailable,

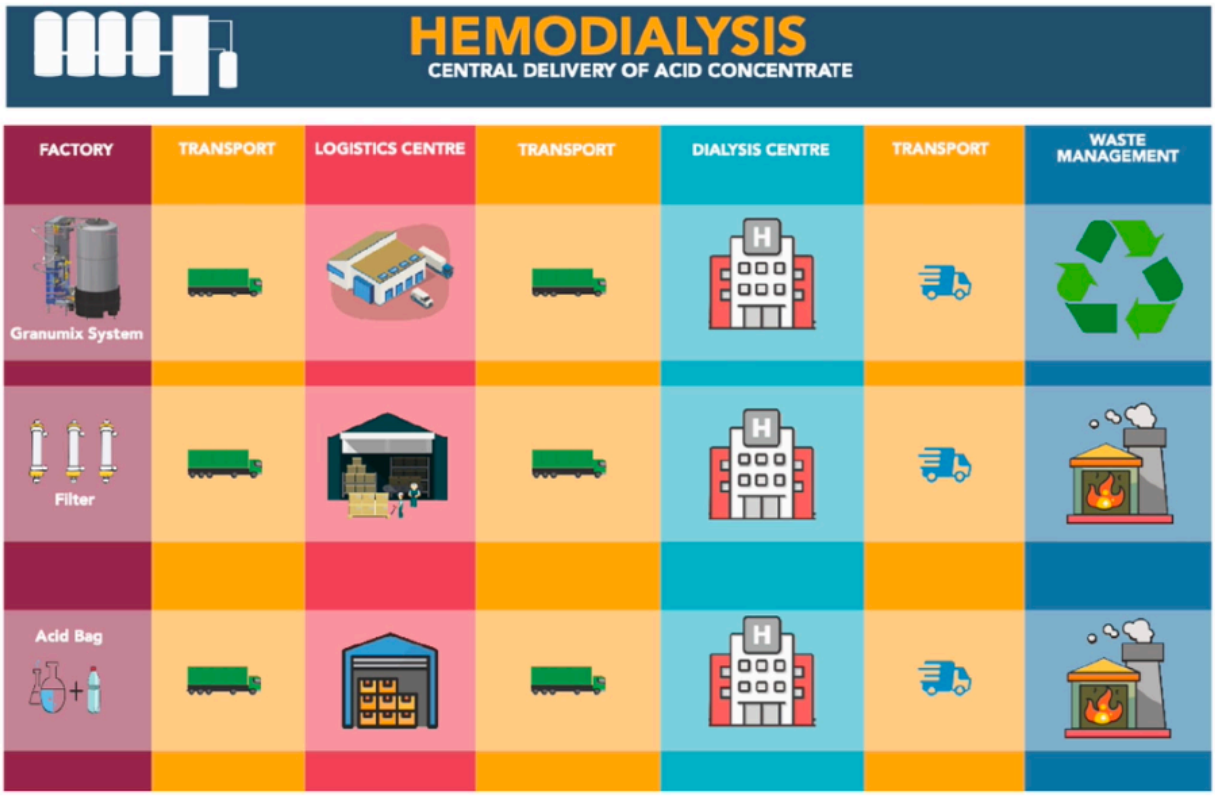


Fig. 2 System boundaries for Acid Concentrate Bags and the Fresenius Granumix System. The system boundary shows the "cradle to grave" analysis of the life cycle assessment

reasonable assumptions were made based on standard industry practices for medical device distribution, considering typical transport modes, packaging formats, and the origin–destination pairing.

Waste

To evaluate the environmental impact of waste, data were collected from hospital administrative staff on the hospital's waste management processes. Healthcare waste and recycled materials were the main focus. Hospital admin staff were able to identify waste management providers, and the waste processes for the acid concentrate bags as well as the recycling of the Granumix container. Waste was categorised into healthcare waste and recyclable materials to assess their environmental impacts. The quantity of unused acid solution was estimated based on observational data provided by the nursing staff at AOU Policlinico di Modena, with an average of 0.4 L discarded per bag.

In Italy, acid concentrate bags are classified as hazardous medical waste due to potential chemical contamination and are typically incinerated as part of national healthcare waste protocols. This may differ from practices in other countries, where such waste might be considered non-hazardous and treated via alternative methods such as autoclaving or landfill disposal. This has implications for the generalisability of toxicity and waste-related results in the life cycle assessment.

Data analytics

The process involved entering the collected data into the OpenLCA software that incorporated all aspects of the products with the cradle to grave approach [12]. A detailed life cycle model was created using various impact categories such as acidification, climate change, and ecotoxicity to calculate environmental impacts across multiple categories, including areas such as global warming potential, resource depletion, and human health impacts. The analysis identified and quantified the most significant environmental contributors between acid concentrate bags and the Fresenius Granumix system. Detailed assessments of each process and material involved were included.

Results

Life cycle assessment results across 15 impact categories

The life cycle assessment compared the environmental impacts of acid concentrate bags and the Fresenius Granumix central delivery system across 15 impact categories. The results are presented in Table 1. Across all categories, the Granumix system demonstrated reduced environmental impacts compared to traditional single-use acid concentrate bags.

The climate change impact, measured in kg CO2-equivalent, showed that the traditional acid concentrate bags contribute significantly more to global warming (3.74 kg CO2-eq) compared to the Granumix system (2.63 kg CO2-eq). A 29.83% reduction in greenhouse gas emissions was seen when using the Granumix system, primarily due to the elimination of the need for the production, transportation, and waste of large quantities of single-use acid concentrate bags.

Extrapolating these findings to the AOU Policlinico di Modena dialysis unit, which treats, on average, 251 patients three times per week, the total estimated CO_2-equivalent reduction from implementing the Granumix system is

Table 1 LCA Results Across 15 Impacts

Impact Categories	Unit	Acid Bag	Granumix system	% Reduction
Acidification	mol H+-Eq	2.36E-02	1.97E-02	17%
Climate change	kg CO2-Eq	3.74E+00	2.63E+00	30%
Ecotoxicity: freshwater	CTUe	5.70E+01	4.90E+01	14%
Eutrophication: freshwater	kg P-Eq	6.29E-03	6.12E-03	3%
Eutrophication: marine	kg N-Eq	8.29E-03	7.33E-03	12%
Eutrophication: terrestrial	mol N-Eq	5.68E-02	4.78E-02	16%
Human toxicity: carcinogenic	CTUh	2.35E-09	1.60E-09	32%
Human toxicity: non-carcinogenic	CTUh	5.42E-08	4.60E-08	15%
Ionising radiation: human health	kBq U235-Eq	2.75E-01	2.42E-01	12%
Land use—soil quality index	dimensionless	6.99E+01	2.73E+01	61%
Material resources: metals/minerals	kg Sb-Eq	7.87E-05	7.68E-05	3%
Ozone depletion	kg CFC-11-Eq	4.60E-07	4.04E-07	12%
Particulate matter formation	disease incidence	2.20E-07	1.56E-07	29%
Photochemical ozone formation	kg NMVOC-Eq	1.29E-02	9.55E-03	26%
Water use	m3 world eq. deprived	4.12E+00	3.97E+00	4%

approximately 43.5 tonnes per year. This cumulative impact highlights the substantial environmental benefit achievable at the facility level, reinforcing the value of transitioning to central acid delivery systems to reduce the carbon footprint of haemodialysis at scale.

In terms of acidification potential, the results reveal that the Granumix system also has a lower impact (0.0197 mol H^+-Eq) compared to acid concentrate bags (0.0236 mol H^+-Eq), with the reduction attributed to the minimised use of packaging materials and fewer emissions associated with transportation.

Concerning ecotoxicity, particularly in freshwater ecosystems, the Granumix system demonstrates a lower impact (49.03 comparative toxic units for ecosystems) compared to acid concentrate bags (57.03 comparative toxic units for ecosystems), i.e., a reduction of 14.02%. The reduced release of harmful substances during the production and waste stages of the Granumix system (compared to the production of single-use concentrate bags) likely contributes to this improvement., Both freshwater (0.00612 vs 0.00629 kg P-Eq) and marine (0.00733 vs 0.00829 kg N-Eq) eutrophication impacts are slightly lower for the Granumix system. The reduced nutrient release into aquatic systems highlights the environmental benefits of the Granumix system.

In terms of human toxicity, both carcinogenic (1.60E-9 vs 2.35E-9 comparative toxic units for humans) and non-carcinogenic (4.60E-8 vs 5.42E-8 comparative toxic units for humans) effects were lower for the Granumix system. These toxicity impacts arise primarily from the production of materials (e.g., plastics and chemicals) and end-of-life processes such as incineration, rather than the direct use of the systems during dialysis. The difference in toxicity scores reflects a lower release of harmful substances over the lifecycle of the Granumix system compared to single-use acid concentrate bags.

The analysis of resource use (7.68E-5 vs 7.87E-5 kg Sb-Eq) and ozone depletion potential (4.04E-7 vs 4.60E-7 kg CFC-11-Eq) also favours the Granumix system. Similarly, ozone depletion potential is lower for the Granumix system.

Water use, a critical environmental factor in dialysis, shows a notable reduction with the Granumix system, consuming 3.97 m^3 world eq. deprived compared to 4.12 m^3 for acid bags.

Normalised analysis

* Y-axis represents dimensionless normalised environmental impact scores, scaled relative to the average global person's annual contribution to each category (based on Ecoinvent v3.1 normalisation factors).

Figure 3 compares the normalised environmental impacts of the Acid Bag and Granumix systems across multiple categories. **Freshwater eutrophication** and **ecotoxicity** were the highest impacts for both, with the Acid

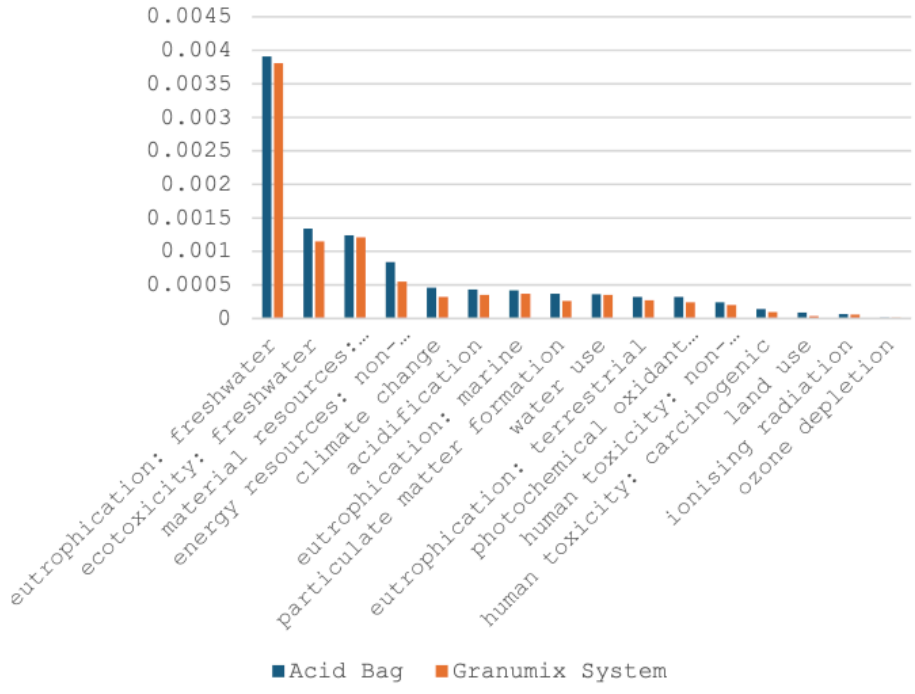


Fig. 3 Normalised Scores Across All Impacts

Bag showing consistently higher scores. This supports the environmental benefits of centralised systems like Granumix in dialysis care.

Contribution analysis

The life cycle assessment found that material production, transport, and waste management were the main impact drivers. The Acid Bag system had higher emissions due to single-use components, including polyethylene (0.285 kg CO_2-eq), packaging (0.240 kg CO_2-eq), and waste incineration (0.372 kg CO_2-eq). In contrast, Granumix uses reusable containers and local preparation, avoiding most single-use waste and reducing emissions across impact categories (Figs. 4–5, Appendix 3).

At AOU Policlinico di Modena, each Acid Bag generated 372 g CO_2-eq from waste incineration, plus 53.5 g from cleaning residues and 72.8 g from packaging—emissions that are avoided in Granumix. Recyclable Granumix containers produced just 0.020 kg CO_2-eq.

Energy use was dominated by glucose and ultrapure water production (11.21 MJ and 6.19 MJ). The Acid Bag system had added impacts from polyethylene (10.51 MJ), packaging (3.17 MJ), and hazardous waste (1.76 MJ)—again, avoided with Granumix. Small reductions were also seen in petroleum, gas, and uranium use, showing overall lower energy resource consumption for the Granumix system.

Contribution analysis figures for all environmental impact categories are provided in Appendix 3.

Discussion

This study demonstrates that the centralised acid delivery system using the Fresenius Granumix provides a more sustainable alternative to single-use acid concentrate bags for haemodialysis. Through life cycle assessment, we found that the Granumix system reduces environmental impacts across multiple categories, including climate change potential, resource consumption, waste generation, and ecotoxicity.

Our findings align with a growing body of evidence supporting the environmental advantages of central acid delivery systems in dialysis. The Bradford NHS study reported substantial carbon footprint reductions following a similar transition to central acid delivery [13]. Beyond greenhouse gas emissions, our study expands the analysis by considering additional environmental categories such as acidification, freshwater ecotoxicity, and human toxicity. These broader findings highlight the environmental trade-offs often overlooked when focusing solely on carbon emissions.

The results indicate that dialysis centres seeking to reduce their environmental footprint can benefit from implementing centralised acid delivery systems. Key advantages include reductions in single-use plastic waste, packaging, and transport-related emissions. Furthermore, decreased hazardous waste generation can ease the burden on hospital waste management systems. As healthcare providers work toward decarbonisation targets, such procurement decisions can make a meaningful contribution to greener dialysis care.

Despite its environmental advantages, the Granumix system's production process still contributes to resource use and emissions, primarily due to the use of metals and plastics. Opportunities for further environmental improvement include incorporating recycled materials into system components [14], utilising bioplastics [15], and integrating renewable energy sources into manufacturing processes [16]. In addition, adopting circular economy principles, such as closed-loop recycling for Granumix components, could further minimise environmental burdens [17, 18].

While this study focused on the comparison between single-use acid concentrate bags and a dry powder-based central acid delivery system (Granumix), it is important to acknowledge that liquid centralised acid delivery systems represent another alternative used in dialysis facilities. These systems store premixed acid solution in large on-site tanks, eliminating single-use containers and reducing packaging waste, similar to the Granumix approach [19]. However, compared to dry powder-based systems, liquid central delivery may involve higher transport-related emissions due to the weight of transporting large volumes of liquid. Existing studies suggest that while liquid central delivery reduces waste generation, the overall environmental advantage compared to dry powder systems depends on factors such as transport distances, facility size, and local infrastructure [4, 6]. Further research directly comparing dry powder and liquid central delivery would be valuable to inform optimal sustainable procurement choices for haemodialysis centres.

It is important to acknowledge the limitations of this study. Life cycle assessment relies on the quality and accuracy of available input data, including material weights, transport distances, and process energy use. While reasonable assumptions were made where necessary, actual transport routes and energy mixes may vary across regions and facilities. The study is also limited to a single healthcare centre, which may affect the generalisability of results. Future research should explore life cycle assessments of alternative acid delivery methods, including emerging technologies or configurations in other settings. Further investigation into renewable energy integration and water treatment innovations within dialysis could also provide additional sustainability benefits.

Overall, this study contributes to a growing evidence base supporting more sustainable practices in kidney care, and highlights the role of procurement and system design in reducing the environmental burden of haemodialysis.

While OpenLCA is a robust and widely used platform for life cycle assessment, it has several limitations. The software relies on background databases (e.g., Ecoinvent) that may contain regionally generalised or outdated data, which can limit the precision of localised environmental modelling. Additionally, OpenLCA uses predefined impact assessment methods and fixed process assumptions, which can constrain flexibility when modelling complex or unique medical systems. These factors may introduce uncertainties, particularly in processes such as waste treatment or transport logistics where real-world variations are not fully captured. Despite these limitations, OpenLCA remains appropriate for comparative analyses like this study, where the relative difference between two systems is the primary focus.

Conclusion

The Fresenius Granumix system offers a promising alternative to traditional acid concentrate bags in haemodialysis. Significant reductions have been made in environmental impact across multiple categories. As the healthcare sector continues to seek more sustainable practices, systems like Granumix could play a crucial role in reducing the environmental burden of life saving treatments such as haemodialysis.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40620-025-02416-0.

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Data availability statement All data generated or analysed during this study are publicly available in the Zenodo repository: Larkin, J. (2025). *Green Haemodialysis: Comparison of Dialysis Bags Versus Fresenius Granumix Water Recycling System at the AOU Policlinico di Modena, Italy* (Version v1). Zenodo. https://doi.org/10.5281/zenodo.14610055.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval Ethical approval was not required for this study as it did not involve human participants or animal research. The study focused solely on environmental data collection and analysis related to haemodialysis systems.

Informed consent and consent to participate Not applicable. This research did not involve any individual participants, patients, or human data.

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ORIGINAL ARTICLE

But how green is it actually? Calculating the environmental footprint of kidney care environmental optimizations within haemodialysis

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ABSTRACT

Background. Environmental optimizations in kidney care have been analysed as part of the European Union co-funded KitNewCare project.
Methods. Life Cycle Assessments (LCA) using Ecoinvent database and OpenLCA software quantified optimizing resource use (e.g. dialysis machines, reducing flow rates, incremental dialysis), energy-saving measures (e.g. solar energy, efficient lighting) and travel reduction (e.g. home dialysis, telemedicine). Efforts in waste management involve transitioning clinical waste to domestic waste streams, recycling and pyrolysis. Water-saving practices include reclaiming water for non-potable uses and efficient treatment systems.
Results. LCA quantified these interventions, revealing significant environmental particularly in reducing travel and resource use. Travel optimizations yielded the most significant CO_2 equivalent savings, while incremental dialysis also conserved water and reduced greenhouse gas emissions.
Conclusion. The study underlines the importance of prioritizing impactful interventions to minimize the environmental footprint of chronic kidney disease care while maintaining clinical efficacy. Challenges include adapting strategies to local contexts, ensuring economic feasibility and integrating renewable energy sources based on regional energy mixes.

Keywords: carbon footprint, kidney care, water footprint, forced labour

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INTRODUCTION

Kidney disease affects approximately 850 million people worldwide [1], with chronic kidney disease (CKD) recognized as a leading contributor to global morbidity and mortality. By 2050 CKD is projected to become one of the top 10 causes of death [2]. CKD accelerates biological aging and increases the risk of premature death. However, some patients survive to progress to kidney failure, a condition which would potentially require kidney replacement therapy (KRT) by dialysis (usually haemodialysis) or kidney transplantation. Countries that can afford to offer KRT to their population dedicate 2%–4% of the healthcare budget to treat just 0.1%–0.2% of the population with kidney failure [3]. As the global population ages, the prevalence of CKD will continue to rise, and with it, the environmental impact of KRT will increase [4], as more countries provide this level of care. At the same time, climate change poses a growing threat to human health driving urgent efforts to reduce greenhouse gas (GHG) emissions [5]. The European Commission has introduced a series of proposals aimed at aligning the European Union (EU)'s climate, energy, transport and taxation policies with the goal of cutting net GHG emissions by at least 55% by 2030, compared with 1990 levels [6]. Given the resource-intensive nature of kidney care—requiring substantial energy, water and medical supplies—the nephrology community must take proactive steps to align with these sustainability goals.

Recognizing this need, the Centre for Sustainable Healthcare (CSH) as part of their Green Nephrology Programme (started in 2009) are exploring how kidney care could reduce its environmental footprint while maintaining high-quality patient care. The CSH applies the Triple Bottom Line framework, which evaluates healthcare sustainability across three key dimensions [7]:

(i) People (social impact)—ensuring quality patient care, equitable access to services, employee well-being and community health outcomes.
(ii) Planet (environmental impact)—implementing sustainable practices to reduce waste, improve energy efficiency and minimize the carbon footprint of kidney care.
(iii) Profit (economic sustainability)—enhancing cost-effectiveness, ensuring the financial viability of kidney care services and maintaining affordability for patients. The optimizations evaluated were diverse, ranging from processes to minimise resource use (medical supplies, energy), to innovative waste disposal strategies.

Since then, additional sustainable initiatives have been developed. Some of the interventions range from a reduction in resource use (procurement, energy, waste production, travel) to a focus on education, behavioural change or comparison of resource use across sites. These interventions had been reviewed inside the KitNewCare project, an EU co-funded initiative focused on improving the environmental sustainability of kidney healthcare. The project positions kidney care—known for its high disease burden and substantial resource use—as a model to drive systemic changes towards sustainability prioritizing impactful interventions to minimize the environmental footprint of CKD care while maintaining clinical efficacy and patient safety [8].

Evaluating the environmental impact of healthcare products and processes requires a structured approach. Attributional Life Cycle Assessment (LCA) is widely used method that examines the direct environmental burdens of a product, process or system throughout its life cycle on the existing system and the direct contributions to environmental burdens. It provides a static snapshot of emissions and resource use, typically using average data rather than predicting future changes or indirect market effects [9].

In a recently published textbook on a different aspect of healthcare, we highlight that an ideal healthcare process or product should prioritize patient safety while minimizing reliance on fossil fuels. Wherever possible, the products should be sourced from renewable materials while allowing for repeated reuse or local processing. Additionally, they should be packaged sustainably or minimally, biodegrading into harmless natural components. Where feasible, the product should be easy to clean and reuse, designed for straightforward recycling, and either transported via clean energy vehicles or produced directly at the point of care. Ethical manufacturing practices and the use of renewable energy should also be fundamental to its production [10].

Water use is an environmental impact measure in LCA, similar to how carbon footprint is measured. The LCA analysis refers to the total volume of freshwater consumed directly and indirectly during the production, use and disposal of the specified items or activities. This includes water extracted for raw materials, manufacturing processes and wastewater treatment [11].

This paper was written to calculate and compare a diverse range of interventions in terms of the triple bottom line specifically looking at changes in carbon and water footprint using attributional LCA. The social impact is covered in the second paper in this series.

METHODOLOGY

As part of the KitNewCare project, a rapid review of sustainability interventions in kidney care was conducted. The reviewed interventions were categorized into procurement and resource optimization, energy reduction, travel reduction, water conservation and waste management. The environmental impact of these interventions was quantified using LCA, assessing changes in carbon and water footprints to provide a standardized evaluation of their sustainability benefits.

Procurement/reducing demand for procured products

Resource optimizations included managing the dialysis machine, adjusting the dialysis fluid flow (Qd) to patient body size (K16) [12], saving dialysate by automating control of flow rates [12] or increasing the treatment time/blood flow rate (rather than dialysate flow rate) [13] using incremental haemodialysis [14], lowering the dialysis fluid temperature to manage intradialytic hypotension [15], online priming to reduce need for saline bags [16], using the dialysate autoflow facility on the Fresenius 5008 machine [17], and reducing the number of disinfections of the dialysis machines to once in 24 h in a staggered manner and replacing the others with a rinsing process [18].

Centres also focused on making smaller changes, such as asking people to bring their own blankets [19], reducing food waste by asking patients to pre-order their preferred sandwiches [16] and reducing paper use through paperless haemodialysis blood result reporting [20].

Energy

Energy reduction initiatives included heat exchangers [21], lighting upgrades [22], using solar power to assist with haemodialysis [23] and automatic IT shutdown [24].

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Table 1:

Innovation	Functional unit	Comparative unit/standard care	Summary and assumptions
Procurement optimizations			
Using a 3 mL syringe	A 3 mL Luer lock syringe	A 10 mL Luer lock syringe	The LCA of a Luer lock syringe was assessed—70% of the syringe was estimated to calculate environment savings
Going paperless	The use of electronic resources equivalent to paper used for patient records	Six pieces of paper per patient per hospital visit used for patient records	We assumed one piece of paper was the same as 1 min use of (i) a computer and (ii) the internet. In addition, a Carnegie Mellon University study concluded that the (iii) energy cost of data transfer and storage is about 7 kWh per gigabyte One page is 5 kbyte, which works out at 0.00024 kWh for each piece of paper [41] We subtracted the environmental cost of the data storage and electronic appliance from the saved paper costs
Pre-ordering sandwiches	Providing sandwiches during patient care using an ordering process to reduce waste	Providing sandwiches during patient care without ordering	
Food choices: using vegetarian vs beef lasagne	Providing vegetarian lasagne for each patient visit	Providing beef lasagne for each patient visit	
Incremental HD	Patients start with fewer dialysis sessions per week and increase as needed, to conserve resources and reduce patient burden	Patients have usual standard of care	See Appendix 3 for more details. Only the use of the machine was measured not the build of the machine
Not using the saline bag	Not using a 1-L saline bag for every dialysis session	The use of a 1-L saline bag for every dialysis session	
Not offering blankets	The use of a 100% cotton blanket weighing 2 kg for 30% of visits	The use of a 100% cotton blanket weighing 2 kg for 100% of visits	The seed, cotton, yarn processes all taken from Ecoinvent 3.7.1. It was assumed based on Vozzola like a gown the cotton blanket would be used 60 times before discarded [42]. Calculations were made using laundry processes (transport, washing, drying) as per 3.7.1. In order to calculate the environmental impact, 70% of a blanket was calculated. The blanket was assumed to weigh 2.2 kg based on products online [43]
Energy optimizations			
Automatic IT shutdown	The use of a laptop for one patient for 1 year of HD which is always shut down when not in use	The use of a laptop for one patient for 1 year of HD which is never shut down	It was assumed that one laptop would be used for four patients. The study was based on a CSH case study [44] with 16× laptops running for 24 h and 7 days a week would (consume 3916 kWh annually); we then compared 16× laptops running 14 h a day for seven days (consume 2563 kWh annually)
Heat exchange	The use of a standard dialyser with a heat exchanger for one patient for 1 year of HD	The use of a standard dialyser without a heat exchanger for one patient for 1 year of HD	Energy savings were estimated by comparing a standard cycle on a machine with heat exchanger to one without. Results in the dialysis unit showed 5.2 kWh vs 4.7 kWh (with heat exchanger), a saving of 0.5 kWh per treatment, or approx. 10%. This was mapped for the year
Changing lightbulb	The use of a T8 lighting for one patient for 1 year of HD.	The use of a T5 lighting for one patient for 1 year of HD	Assume lighting was needed for each patient for 3 half days a week, and machine savings were calculated at 12 sessions a week (not working Sunday) Assume T5 are 9% more efficient [45]

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Table 1: Continued

Innovation	Functional unit	Comparative unit/standard care	Summary and assumptions
Using solar energy	The energy use for one patient for 1 year of HD using roof mounted solar energy	The energy use for one patient for 1 year of HD using standard Spanish grid electricity	The energy used was derived from Arias-Guillén [46]
Lowering the dialysis fluid temperature	The energy use setting standard dialysate temperature at 36.5°C	Personalised cooler dialysate: 0.5–0.9°C below each patient's measured pre-dialysis body temperature, with a lowest recommended dialysate temperature of 35.5°C (ref)	To decrease from 36.5°C to 35.5°C save 80 Wh in a 4 h dialysis treatment, representing 2% of the total energy expenditure of the dialysis monitor [47]
Travel optimizations			
Travel optimizations	The mode of transport for a patient for 1 year of HD consists of 10% of patients using a minibus and 90% using a car	The distance a patient travels for 1 year of HD using a car	We know that patients travel far for their HD. We used the Irish figure of 29 km [48] one way and calculated a 10% reduction
	The mode of transport for a patient for 1 year of HD consists of 50% of patients using a minibus and 50% using a car		An average of four patients sharing a minibus when going to a HD centre
Waste optimizations			
Optimizing waste	The amount of waste for a HD patient for 1 year of HD using sophisticated pyrolysis treatment for 90% of clinical waste/10% incineration	The amount of waste for a HD patient for 1 year of HD using incineration only	Used 2.9 kg of waste per dialysis session (three times a week for 1 year of HD)
Saving water	The amount of water for a HD patient for 1 year of HD when this water is diverted for grey water uses, e.g. toilet use throughout the hospital	The amount of water for a HD patient for 1 year of HD	This does not include the environmental footprint or energy used in reprocessing the water for other uses

HD, haemodialysis.

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Travel reduction

Travel reduction initiatives included developing a renal database to allow remote monitoring of patients, increasing home haemodialysis [25, 26], managing patients in primary care to reduce travel distance [27], using remote monitoring for transplantation follow-up [28] and working [29]. The use of central delivery of acid [30] and/or more concentrated acid dialysis bags (diluted on site) also reduce transportation and therefore associated GHG emissions [31].

Water reduction

Many renal centres used systems to reclaim reverse osmosis water [32–34] or upgraded their water treatment system [35]. Some focused on optimizing the size and location of the reverse osmosis plant [36].

Waste management

Waste was segregated in various establishments. Domestic waste was segregated into black bags rather than all waste being discarded in clinical waste bags, as was the previous practice, and diverting bicarbonate containers from the clinical waste stream to domestic waste. Centres opted for reduction of Griff Bins [37], other centres introduced baling and recycling for their plastic and cardboard waste [38, 39], or removing their black bag waste attempted to redirect their non-contaminated dialysis waste from clinical to domestic waste.

To ensure an LCA is reproducible, it is essential to define a precise functional unit (a well-specified comparison unit), clearly state information sources, outline necessary assumptions, address ethical and data protection considerations, and establish a methodology for deriving environmental impacts from the collected data. Detailed descriptions of these elements are provided in the following subheadings.

Functional unit

The comparative functional unit represents a specific innovative intervention applied over 1 year, assuming three haemodialysis sessions per week allocated to one patient. In contrast, the standard functional unit is the same but corresponds to the conventional care approach.

Sources of information

To ensure consistency and comparability, the LCA relied on data sourced from publicly available online resources or Spanish clinical dialysis centres, as well as information gathered during the KitNewCare study [8].

Overall assumptions

Assumptions can be seen in Table 1. To provide a more concise analysis, only a few indices were considered, such as carbon equivalent emissions (CO2e using Ecoinvent EF v3.1) and water deprivation (Ecoinvent EF v3.1). The decision on environmental aligns with KitNewCare methodology and was informed by advice from the KitNewCare stakeholder group and our external stakeholder group.

To ensure comparability, the functional unit for each process was that used for dialysis three times a week for 1 year.

Despite most of these interventions happening in the UK, for these analyses to fit with European funding, and for consistency, we modelled the interventions as if they were happening in Spain. Spanish data (e.g. electricity use) were used where possible, to ensure that consistent comparisons could be made. The only exception was patient travel which used Irish published travel data relating to kidney care as Spanish data was unavailable [40].

The innovations are summarized in Table 1; more detail can be found the flow diagrams seen in Appendix 1 as well as the inputs for the processes in Appendix 2 (Open LCA).

Ethics and data protection

No personal or identifiable information was gathered from any organization or individual to calculate these footprints.

Data collection and analysis

The LCA methodology was applied in line with International Organisation for Standardisation standards 14 040 and European Union Product Environmental Footprint (PEF) guidance [49, 50].

In total, two separate impact environmental categories (CO2e emissions, water deprivation) were examined in this study and the Life Cycle Impact Assessment (LCIA) methods were based on PEF guidance. All inputs for each functional/comparative unit can be found in Appendix 2.

The software OpenLCA v2.11was used alongside the reference database Ecoinvent v3.7.1 for the LCIA.

RESULTS

Small numbers less than a whole number have been rounded to '0'—the actual number can be seen in our data set here [51]. Contributions analysis can be seen in Appendix 4.

The results highlight the extent to which different interventions influence carbon emissions (CO2e) and water deprivation.

Resource savings and procurement (Table 2)

The procurement-related interventions demonstrated a varied impact on environmental sustainability. The most significant reductions in water deprivation were observed in eliminating cotton blankets (116 kg CO_2, 899 m^3 water). Incremental haemodialysis resulted in the highest environmental saving with an additional 316 kg of CO_2 emissions saved along with 137 m^3 of water deprivation. Surprisingly, pre-ordering sandwiches saved 53 kg CO_2 and 90 m^3 of water. Smaller but notable improvements were seen with simple changes, such as going paperless (saving 1 kg CO_2, 0 m^3 water) and eliminating saline bags (saving 3 kg CO_2, 2 m^3 water).

Table 2: The carbon and water footprint of saving in resources.

Item	CO2e (kg)	Water deprivation (m^3)
Procurement		
Using a 3 mL syringe	4	2
Going paperless	1	0
Pre-ordering sandwiches	53	90
Using beef vs vegetarian lasagne	19	23
Incremental haemodialysis	316	137
Not using the saline bag	3	2
Not offering cotton blankets	116	899

[a]A negative score implies a worsening rather than an improvement.

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Energy savings (Table 3)

Energy conservation strategies showed varied potential in reducing environmental footprints. The greatest impact was achieved using solar energy, which saved 646 kg of CO_2 emissions and 52 m^3 of water. Other interventions, such as heat exchange (savings of 31 kg CO_2, 9 m^3 water) and automatic IT shutdown (saving 8 kg CO_2, 2 m^3 water), contributed to moderate reductions, while switching lightbulbs had little environmental effect.

Table 3: The carbon and water footprint of saving in energy.

Energy Item	CO2e (kg)	Water deprivation (m^3)
Automatic IT shutdown	8	2
Heat exchange	31	9
Changing lightbulbs	Neg	Neg
Using solar energy	646	52

Reducing patient travel (Table 4)

Optimizing patient travel demonstrated a significant opportunity to reduce emissions and water usage. A 10% reduction in travel resulted in 282 kg of CO_2 savings and 34 m^3 of water. More substantial savings were achieved with greater reductions in travel, with a 50% reduction yielding 1411 kg CO_2 and 170 m^3 water saved.

Table 4: The environmental and water footprint of saving in patient travel.

Travel Item	CO2e (kg)	Water use (m^3)
Travel optimizations 10%	175	32
Travel optimizations 50%	710	129

Waste reduction strategies (Table 5)

Waste management practices also played a role in reducing environmental impact. Pyrolysis of waste resulted in a 735 kg reduction in CO_2 emissions and 71 m^3 of water savings.

Table 5: The carbon and water footprint of saving in waste.

Waste item	CO2e (kg)	Water deprivation (m^3)
Optimising waste (optimal waste e.g. pyrolysis of medical waste)	735	71

Water conservation (Table 6)

Direct efforts to reduce water usage contributed modest but meaningful reductions in environmental impact. Water-saving interventions resulted in a total reduction of 16 kg CO_2 and 19 m^3 of water saved.

Table 6: The carbon and water footprint of saving in water.

	CO2e (kg)	Water deprivation (m^3)
Saving water	16	19

DISCUSSION

Initiatives like KitNewCare project aim to address the sustainability of kidney care, serving as a model for reducing the carbon footprint of healthcare. It is important to weigh the impact of optimizations against each other to inform sustainability efforts and help clinical sites to prioritize their implementation. Numerous innovations are occurring in this field, their impacts vary across the two chosen measurements for environmental footprint (CO2e, water) The social impact of these interventions will be discussed in a later paper.

LCA involve various assumptions for much of the resource use. To ensure consistency, activity data from a renal centre in Spain were used whenever possible. However, travel patterns may differ in urban areas, especially where individuals have better access to public transport. Energy savings can also vary significantly. Where the energy mix of an EU country is high in coal and other fossil fuels, the energy savings stated here could be substantially higher. Conversely, in countries who already have a high proportion of renewable energy, installing solar panels may result in lower GHG emissions savings associated with electricity use.

For reference regarding the figures below, the average carbon footprint of a person in Europe is 5.66 tons, or 5660 kg [52], an average month's carbon footprint is around 471 kg; and the carbon footprint of driving 100 km in a large car is around 25 kg [53]. An average person uses 0.2–0.4 m^3 every day [54].

Patient travel-related interventions demonstrated the highest savings in GHG emissions, ranging from 175 kg (10% using minibus instead of car) to 710 kg (50% using minibus instead of car). These GHG emissions primarily stem from the maintenance and distance the car travels, rather than the car's production. We did not measure changes in staff travel although we assume that similar (proportional) changes will happen with a staff travel intervention.

Water savings of between 32 and 129 m^3 also resulted from significant changes in travel. However, unlike CO2e emissions, this water consumption is primarily associated with the production of the car's components, rather than the distance travelled or maintenance.

Ecoinvent allocates 8 g of car production for every km that the car is driven [8]. It could be argued that this allocation is only accurate for an 'average car' that drives a specific number of kilometres before being redundant. To reduce the amount of carbon emissions associated with car travel, it would be necessary to reduce car ownership.

Within this study, we calculated a 10% change and 50% change in patients using a shared minibus instead of car. These choices of a 10% and 50% reduction were arbitrary and solely related to plausible reductions in patient travel. Moving to a green energy powered public transport only system, e.g. through government policy, etc., might be feasible.

Travel can be reduced through various means, including increased use of public transportation, and the provision of home-based care. Home-based dialysis could be one solution. It may also be possible to allocate the patient to a closer facility,

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reducing travel distance. By increasing the availability of home dialysis, implementing telemedicine where clinically appropriate or coordinating ambulance services, centres have successfully reduced the number of trips patients need to make. Reducing patient travel in this respect not only decreases carbon emissions but also enhances patient convenience and access to care.

Another significant area of focus is water management. Improving the efficiency of dialysate concentrate delivery systems can contribute to overall sustainability in dialysis care. Zawierucha *et al.* highlight that liquid dialysate concentrates, commonly delivered in 10-L canisters, have a higher environmental impact due to increased transportation emissions and packaging waste [55]. In contrast, powder and semi-dry concentrates significantly reduce carbon emissions, storage space requirements and transport-related environmental burdens. The study also emphasizes the benefits of in-centre mixing systems, such as EcoMix (B. Braun) and Granumix Plus (Fresenius Medical Care), which enable the on-site production of dialysate. These systems lower packaging waste, minimize transport emissions and enhance cost-efficiency, while also reducing the risk of preparation errors. Shifting towards these more sustainable options could be a key strategy in reducing the environmental footprint of dialysis centres.

We also know from a recent Spanish paper that both water and energy consumption were lower per patient in larger centres compared with smaller ones, and in those operating daily versus those with a thrice-weekly schedule [56]. These factors had a notable impact on water usage. Despite conducting fewer dialysis sessions annually, smaller centres and those with a thrice-weekly schedule exhibited proportionally higher water and energy consumption per session. This is because the water treatment system consumes energy and water during start-up, priming, rinsing and disinfection processes, irrespective of the number of sessions conducted. Dialysis requires large volumes of water, and many centres have developed systems to reclaim and reuse water, either within the dialysis process itself or for non-potable uses such as via hospital greywater systems. These innovations can reduce the environmental burden associated with water use and lower operating costs for healthcare facilities [57]. Interestingly, water management (tap water production and associated sewerage) also has relatively high CO2e emissions, primarily due to the construction and maintenance of water production and sewerage plants. Sustainability innovators should consider the strong correlation between water use and carbon emissions [58].

Waste management strategies have also been explored to mitigate the environmental impact of dialysis. Waste management in renal centres can be expensive with the incineration costs of healthcare waste in the UK at £337 per ton (in 2018), which equates to £437 (today) when adjusted for inflation using the Bank of England calculator, yet many centres do little to manage their waste appropriately [59]. Changes in how waste is categorized, such as diverting certain materials from clinical waste streams to domestic waste, have reduced the environmental load. In addition, there have been attempts to reduce waste at the source by rethinking supply chain logistics and the materials used in dialysis care, such as switching from single-use to reusable or recyclable materials where possible. Some centres have moved away from the traditional practice of sending all dialysis waste to be incinerated, instead focusing on segregating recyclable materials and using pyrolysis or other advanced waste treatment technologies to convert clinical to domestic waste [60]. Despite offering significant planetary and health benefits, this technology is not widely implemented in Europe.

The impact of changes in resource use varied from negligible (avoiding saline bags e.g. close to 0 kg CO2e, going paperless) to moderate (altering meat types, pre-ordering sandwiches to minimize waste) to significant (not offering blankets, e.g., 116 kg CO2e, and implementing incremental dialysis).

Cotton blankets, like most textiles, are well known for their high environmental footprints [61] with textiles worldwide accounting for approximately 20% of global water production.

The current paradigm is to start and continue thrice weekly haemodialysis once kidney replacement therapy is deemed necessary. However, when dialysis is first started, there is often residual kidney function that contributes positively to patients' wellbeing but is progressively lost over time. The blood pressure changes that occur with haemodialysis can accelerate the loss of residual kidney function; thus, it has been suggested that dialysis can be initiated incrementally, starting with once or twice weekly haemodialysis, increasing as needed to achieve adequate clearance. Incremental dialysis showed a significant reduction in CO2e, water use and frequency of forced labour. Likewise, observational studies suggest that this approach is safe and may better preserve kidney function, but clinical trials are ongoing [62–64].

GHG emission results associated with energy use revealed minimal savings from altering lighting within the nephrology organization. Automatic IT shutdown and heat exchange yielded some environmental benefits.

Another saving, albeit modest, was made using heat exchangers. Since dialysis fluid interacts with blood in the extracorporeal circuit, it must be heated to a temperature close to body temperature. Conventional systems use energy for this purpose. Heat exchangers utilize the residual heat in drained dialysate to pre-heat fresh fluid, thereby reducing the energy required to heat fluid to body temperature. It was estimated that this may reduce energy consumption for heating fluid up to 17% [65]. Savings of 31 kg CO_2 emissions and 9 m^3 were saved using these techniques per patient treatment per year.

The main GHG emissions savings associated with energy use were achieved by installing solar panels to meet all the energy needs of the unit. Installing solar energy is cost-effective and offers a straightforward way for some nephrology units to reduce their environmental footprint. However readers should also consider their country's energy mix before making this decision. If a country is moving towards a low carbon energy mix, the level of reduction in CO2e will not be as high.

Transitioning to vegetarian meals can substantially reduce the environmental footprint of healthcare facilities. Meat production, particularly beef, is a significant contributor to environmental deterioration. Livestock production systems contribute significantly to environmental impact globally, with meat consumption projected to increase alongside the population. By substituting meat based meals with plant based alternatives, healthcare facilities can achieve notable reductions in carbon emissions, estimated to reduce the carbon footprint of a meal by up to 50% [66].

CONCLUSIONS

This study highlights the most effective strategies for reducing the environmental impact of kidney care. Among procurement-related interventions, incremental haemodialysis had the greatest impact, significantly reducing both CO_2 emissions and water use. Eliminating cotton blankets and pre-ordering meals also led to substantial savings. In energy conservation, solar power was the most effective intervention, while reducing patient travel—even by 10%—demonstrated a major opportunity for

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environmental benefit. Waste reduction and water conservation strategies contributed to smaller but meaningful improvements. The KitNewCare study provides data-driven insights to help sustainability programs prioritize high-impact interventions. As CKD prevalence rises, ongoing innovation and policy changes will be key to reducing the environmental footprint of kidney care. By focusing on the most effective solutions, healthcare systems can integrate sustainability without compromising patient care.

SUPPLEMENTARY DATA

Supplementary data are available at *Clinical Kidney Journal* online.

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DATA AVAILABILITY STATEMENT

The data underlying this article are available in the article and in its online supplementary material.

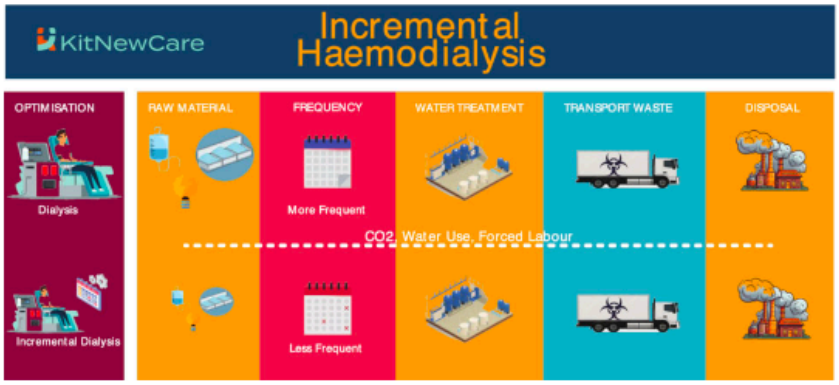
CONFLICT OF INTEREST STATEMENT

None declared.

APPENDICES

Appendix 1: Flow diagrams

Incremental haemodialysis



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NEPHROLOGY – ORIGINAL PAPER

Advancing green nephrology: a scoping review of sustainability interventions in kidney care

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Abstract

Objective To map and synthesise existing interventions aimed at improving environmental sustainability in kidney care and to identify challenges and opportunities for implementation across treatment modalities.

Design Scoping review following PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) methodology. The study merged two existing frameworks to form appropriate review questions.

Data sources Embase, MEDLINE, Scopus, and CINAHL alongside relevant grey literature, searched in September 2024.

Eligibility criteria for selecting studies The review included studies from 1 January 2005 to 30 September 2024 that reported on environmental sustainability interventions in kidney care, including chronic kidney disease, haemodialysis, peritoneal dialysis, kidney transplantation, and conservative management and that provided measurable or descriptive information about the intervention. Conference abstracts and opinion pieces without intervention data were excluded.

Results Out of 2,512 records screened, 95 studies were included. Environmental interventions were most commonly implemented in haemodialysis ($n=58$), followed by chronic kidney disease ($n=19$), transplantation ($n=6$), peritoneal dialysis ($n=5$), and conservative management ($n=1$). Some studies addressed multiple modalities; therefore, categories are not mutually exclusive. The most frequent sustainability categories were water use, waste management, procurement optimisation, energy efficiency, and travel reduction. Interventions ranged from dialysate flow reduction and RO water reuse to telemedicine and supply chain redesign. While many demonstrated environmental and economic benefits, reporting was heterogeneous, and studies were concentrated in high-resource settings.

Conclusions There is growing interest in sustainability within kidney care, particularly in haemodialysis. However, adoption across other modalities remains limited. Future work should prioritise underrepresented areas, standardise metrics, and ensure inclusion of low-resource contexts. Co-design of interventions with patients and staff, combined with consistent reporting using frameworks such as SQUIRE 2.0, is essential. Integration of sustainability into clinical practice and policy is urgently needed to align kidney care with global climate and health goals.

keywords Advancing green nephrology · Sustainability interventions · Kidney care · Environmental sustainability · Chronic kidney disease · End-stage kidney disease · Haemodialysis · Peritoneal dialysis · Kidney transplantation · Conservative management

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Introduction

Chronic Kidney Disease (CKD) is a growing global health concern, affecting around 10% of the European population [1]. It is projected to increase to 18% of the population in some countries by 2040 and 28% by 2100 [2, 3]. Sustainability in nephrology matters not only due to the high environmental intensity of treatment modalities such as haemodialysis (HD), but also because kidney care is a growing global health burden. Green nephrology can reduce healthcare emissions, preserve resources, and improve health equity by ensuring resilient, low-carbon models of care [1, 4]. As patients progress to end-stage kidney disease (ESKD), treatment choices differ in environmental impact. In-centre haemodialysis has the highest documented life-cycle emissions and resource use per patient year. Kidney transplantation has substantially lower long-term emissions than in-centre haemodialysis, though peri-operative and pharmaceutical stages contribute to its footprint. Peritoneal dialysis typically falls between home and centre-based options depending on context. The annual carbon footprint for a patient receiving thrice-weekly HD is estimated at 3.8–10 tonnes of Carbon Dioxide Equivalent (CO_2e), which is substantially higher than the per capita healthcare emissions in many countries [5, 6]. This is mostly due to high energy consumption and substantial waste generation. Studies have shown that patient and staff transportation also contributes significantly to the carbon footprint of dialysis units, adding up to 25–30% to the total carbon footprint of HD, particularly in in-centre models with long travel distances [5, 7]. High volume of water use for dialysis presents an additional environmental impact [8].

With over 2.6 million people receiving dialysis globally as of 2020 and projections suggesting this may rise to 7 million by 2030, the environmental footprint of kidney care is expected to grow significantly [9, 10]. As of December 2022, 56% of prevalent kidney replacement therapy patients in Europe were receiving HD and 5% receiving peritoneal dialysis (PD), representing over 346,000 individuals on dialysis in total, a figure driven by ageing populations and rising rates of diabetes and hypertension [11]. Although technological advances have led to more efficient and home-based therapies, these have not consistently translated into lower environmental impact. The implementation of green nephrology initiatives remains limited, largely due to economic and regulatory barriers such as high upfront costs, lack of financial incentives, and the absence of specific guidelines or mandates for environmental performance [12].

With kidney care contributing a substantial amount of healthcare-based greenhouse gas (GHG) emissions, interventions reducing kidney care's carbon footprint would positively impact overall healthcare emissions. Modelling from England indicated measurable reductions in emissions following sustainability interventions at renal centres [13]. While this analysis was specific to England, similar opportunities are likely across Europe: applying comparable process optimisations across EU kidney centres would be expected to yield substantially larger absolute carbon savings, given the higher number of patients treated and dialysis facilities in operation. In practice, sustainable kidney care interventions have already been documented in multiple European countries, targeting clinical transformation, procurement, waste management, water use, and energy efficiency. This scoping review explores sustainable process optimisations and technological interventions implemented globally in kidney care to reduce its environmental impact alongside identifying key challenges and opportunities.

Materials and methods

Search strategy

A scoping review was performed to identify literature exploring environmentally sustainable interventions in kidney care. This scoping review followed the PRISMA-ScR methodology that systematically searches and reports on scoping reviews [14]. The search was conducted in September 2024 using the databases of Embase, MEDLINE, Scopus, CINAHL alongside grey literature aligning with the search terms, such as case studies on sustainable kidney care interventions. Keywords and phrases that were used in the search included: chronic kidney disease, end-stage kidney disease, renal care, kidney care, environmental impact, dialysis, carbon footprint, environmental sustainability, optimisations, systematic review, hospitals, dialysis units, greenhouse gas emissions, life cycle assessment. The exact search strategy can be found in Appendix 1.

This study is focussed on the overall environmental impacts of kidney care and has reviewed initiatives that reduce the environmental impact of ESKD and its pathways, including HD, PD, transplant, and conservative care. The settings considered were hospitals, dialysis units or renal centres and home in the case of home-based dialysis treatments.

We searched grey literature through the Centre for Sustainable Healthcare, NHS sustainability pages, and professional repositories. We did not employ CADTH 'Grey Matters' due to the domain-specific nature of renal sustainability sources. Search terms and procedures are detailed in Appendix 1.

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Study selection

The screening of all abstracts identified in the search was done independently by two reviewers (A.Y and J.L) from September to November 2024. Both reviewers met to resolve any discrepancies and confirmed the list of papers to be included in the full paper review stage. The same two reviewers then conducted full text screening of the papers that were included in this stage. A third reviewer (M.A) was asked to resolve any discrepancies.

Data extraction

Covidence was used as the online software tool for managing the scoping review process. Data extraction was conducted by the same two reviewers. Covidence was used for reference import, automatic deduplication, blinded dual screening, and consensus management. The platform facilitated title and abstract screening, full-text review, and data extraction. Data fields were pre-defined within Covidence, allowing export to Excel for charting and synthesis. Reviewer decisions and exclusion reasons were recorded directly in the system to maintain an audit trail.

Reviewers used standardised questions to extract information from the papers. General information on the paper such as the title and authors was noted, alongside a description of the intervention, the sustainability category the intervention fit into and the modality of kidney disease it aligned with. Data on the environmental impact (e.g. CO_2e reductions) and reported outcomes were also extracted. Economic and social aspects were also considered.

Two existing frameworks were used as a guide to shape the review questions: the Non-adoption, Abandonment, and challenges to Scale-up, Spread, and Sustainability (NASSS) framework alongside The Centre for Sustainable Healthcare's (CSH) Green Team Competition Success Factors criteria.

The NASSS is a framework developed to systematically evaluate the outcomes of complex innovation projects in health and social care [15]. The framework specifically analyses non-adoption, abandonment, scale-up, spread, and sustainability. It includes seven domains: the technology, the adopters, the wider system, the condition, the value proposition, the organisation(s) embedding and adaption over time. The NASSS allows domains to be graded from complex to simple where more complex projects can be deemed as more likely to fail and provides a guide for implementing useful strategies. Figure 1 displays a visual of the NASSS framework.

The CSH's Green Team Competition Success Factors include 4 categories: people, process, resources and context. For people, it evaluates the involvement of patients, engagement of staff, cross-departmental communication, and support of senior leadership. For process, it analyses the level of guidance, strategy incentives, measurable targets, long-term strategy, and integrations into natural workflow. For resource, it evaluates the dedicated time, the degree of quality improvement training, infrastructure and equipment availability, evidence of implementation success elsewhere, and financial investment. Lastly for context, it looks at whether the aims align with the wider service, if it links to patient and staff benefits, and the organisational permissions, capacities and culture [16].

With the integration of the two frameworks, the reviewers came up with the following questions to assess the process optimisations and technological interventions:

- Does the paper discuss the optimisation/ technology and have information on the level of certainty by staff on what the optimisation is, where it comes from, its performance, usability, acceptability, any required adjustments to routine, and research evidence of change successfully implemented elsewhere?
- Does the paper discuss the organisation's capacity and permissions, readiness for the change, ability to finance the investment, whether it is easy to embed the change to normal routine and workflow, the team functions, the IT and infrastructure to provide teams with data, equipment and dedicated time, the training and support process for the quality improvement, incentivisation of strategies, and clear guidance and evidence?
- Does the paper have information on the value proposition including its commercial value, the benefit to staff, patients and the healthcare system, whether there are any links to clinical outcomes, whether the aims aligned with wider service, organisational or system goals?
- Does the paper mention who the intended adopters are and the certainty level about how staff and patients will adopt the optimisation, any long-term strategies for embedding change at outset, measurable targets, systematic and coordinated approaches, support from senior leaders, team agreement on the changes being suitable, skills/capability of staff, MDT/cross-departmental communication, staff and patient engagement?
- Does the paper talk about the external context including adversity/conduciveness: political, professional bodies, patient groups, regulatory, commercial context, limited learning from others?

Furthermore, the inclusion criteria followed in this review were:

- Studies assessing environmental interventions in kidney care around the world.

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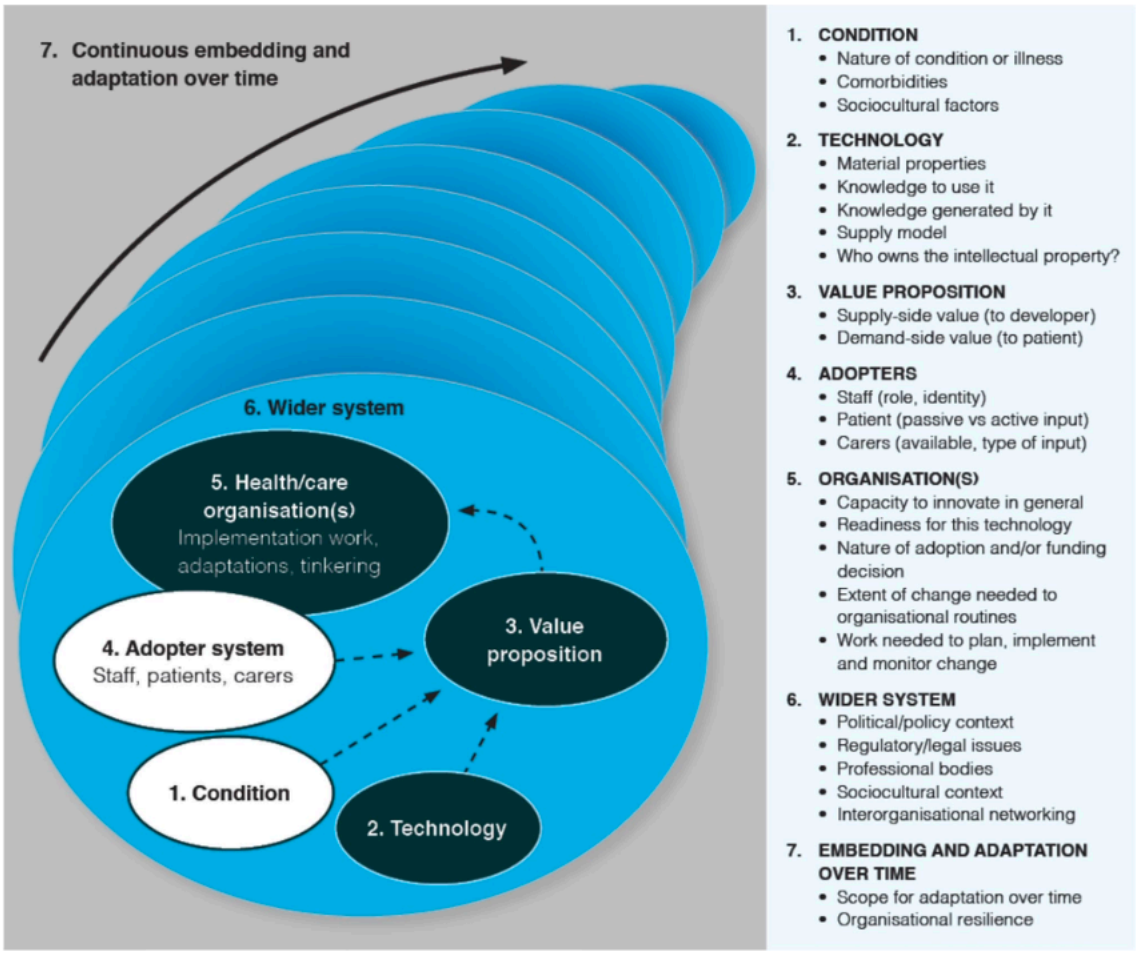

Fig. 1 NASSS Framework, from Greenhalgh T, How to improve the success of technology projects in health and social care

- Articles evaluating carbon footprint reduction strategies in kidney care and its pathways, including HD, PD, transplant, and conservative care.
- The settings considered were hospitals, dialysis units, renal centres or home settings for home based treatments.
- Papers addressing implementation challenges for sustainable kidney care practices.
- Papers published after the year 2005. This was decided as the number of papers published on the topic increased significantly from this point onwards, reflecting more focus on the area. The reviewers therefore thought that papers before this date may not align with contemporary perspectives.
- This review focussed on interventions explicitly designed or reported to improve environmental sustainability in kidney care. Broader nephrology studies addressing sustainability indirectly, such as deprescribing or laboratory stewardship, were excluded from the main dataset but are cited in the Discussion for context. Papers needed to include an identifiable intervention; purely descriptive or editorial material was excluded

The exclusion criteria followed in this review were:

- Conference abstracts
- Opinion pieces or call for action papers with no actual intervention
- Studies not explicitly related to kidney care sustainability
- Studies before the year 2005

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Results

Study selection

A total of 2,512 records were identified through electronic databases including Embase ($n=867$), MEDLINE ($n=847$), Scopus ($n=685$), CINAHL ($n=51$), and grey literature ($n=62$). After the removal of 12 duplicates, 2,500 records were screened by title and abstract. Based on the inclusion criteria, 221 studies were chosen to assess for eligibility, leading to the exclusion of 2,255 articles. Upon the full paper review of the 221 studies, 95 papers were deemed suitable to include in the scoping review, further excluding 126 articles (Fig. 2).

Distribution by modality

Most studies focussed on interventions in HD ($n=58$), followed by CKD ($n=19$), transplantation ($n=6$), PD ($n=5$), haemodiafiltration (HDF) ($n=3$), and very low kidney function care (VKD)/ conservative care ($n=1$) (Fig. 3). This distribution reflects both the high environmental burden of HD and the relative availability of interventions documented in the literature. Nevertheless, several relevant initiatives were identified across all modalities.

Sustainability categories and type of interventions

The 95 included studies were mapped into 16 sustainability categories, grouped by categories (Fig. 4). The most frequently addressed categories were:

- Water use ($n=18$): including reverse osmosis (RO) water reuse for non-clinical purposes like cleaning and sanitation [8, 17–33].
- Waste management ($n=17$): such as improved clinical waste segregation, plastic reduction, and packaging redesign [34–49].
- Procurement optimisation ($n=11$): including high-ratio concentrate solutions (e.g. 44:1, central acid delivery), reusable containers, and environmentally preferable materials [50–60].
- Travel-related emissions ($n=9$): mainly tackled via telemedicine, home-based care, and virtual consultations [61–69].
- Policy ($n=8$): targeting changes in institutional governance, reporting frameworks, and integrated sustainability planning [70–77]
- Energy efficiency ($n=7$): including dialysate flow reductions, LED lighting, solar energy installations, and heat exchangers [78–84].
- Reuse ($n=6$): e.g. filters, or durable items [32, 85–89]

Other less frequent categories included treatment pathway redesign and pharmaceutical waste reduction [90–107].

No included study directly compared the scale of environmental savings between different renal replacement modalities.

Haemodialysis

HD related sustainability interventions were the most frequent and diverse, spanning all sustainability categories. Key strategies included:

- Clinical transformation through remote consultations (e.g. phone clinics, asynchronous platforms like *Patients Know Best*), reducing unnecessary travel and facilitating patient-centred care.
- Supply chain optimisation, such as:
    - Central Acid Delivery Systems to eliminate single-use containers
    - High-concentration acid solutions (e.g. 44:1), reducing packaging and shipping needs [91]
    - Packaging redesigns using low-density polyethylene (LDPE) to reduce plastic use [5]
- Water efficiency, primarily through reuse of RO reject water for non-clinical applications, avoiding potable water waste [19, 23, 25, 35].
- Energy savings, including:
    - Dialysate flow reductions from 500 to 400 mL/min [93, 94, 105, 108]
    - Solar-assisted dialysis [29, 80].
    - Heat recovery systems and efficient lighting [82].
- Waste management, with interventions in material segregation, medication waste reduction, and infrastructure changes [34, 40, 106, 107].

Chronic kidney disease

In CKD settings, interventions targeted upstream practices, often involving paper use reduction, pharmaceutical waste management, and remote monitoring. Key findings include:

- Paperless systems and automation of lab results, reducing material use and clerical errors [47]
- Medication optimisation: better prescribing, stock management, and deprescription practices aimed at reducing unused drugs [106, 107]

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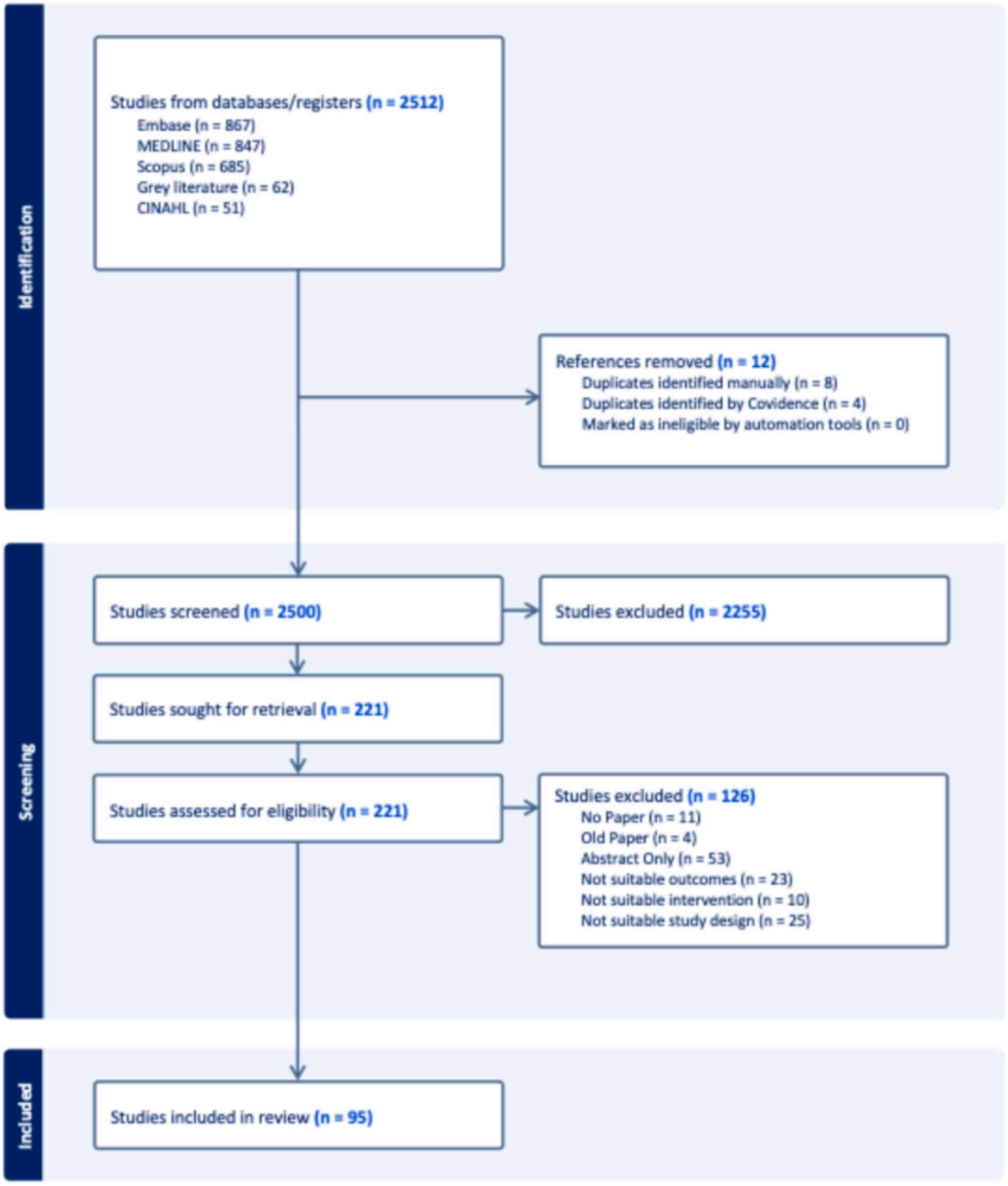

Fig. 2 PRISMA Flow Diagram

- Travel reduction strategies such as remote care pathways (e.g. home BP monitoring, digital records), virtual check-ins or community-based services were also observed in some nephrology clinics resulting in improved access while reducing emissions associated with it [67, 68, 109, 110]

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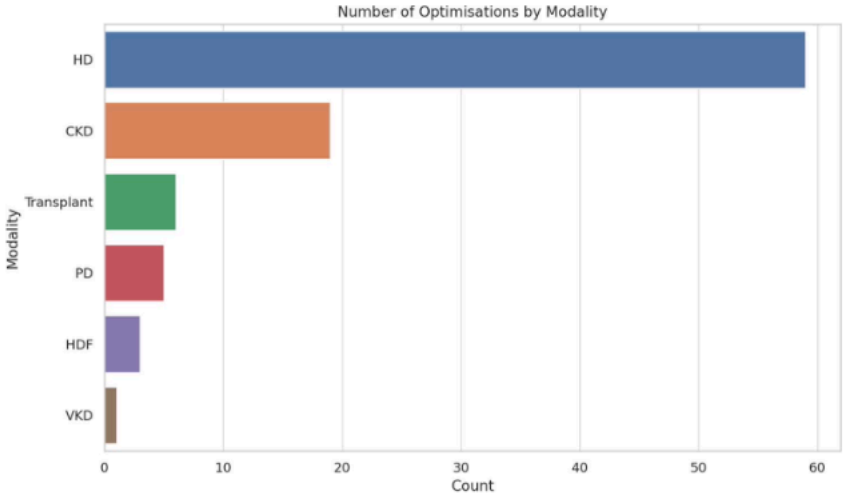

Fig. 3 Number of optimisations by modality

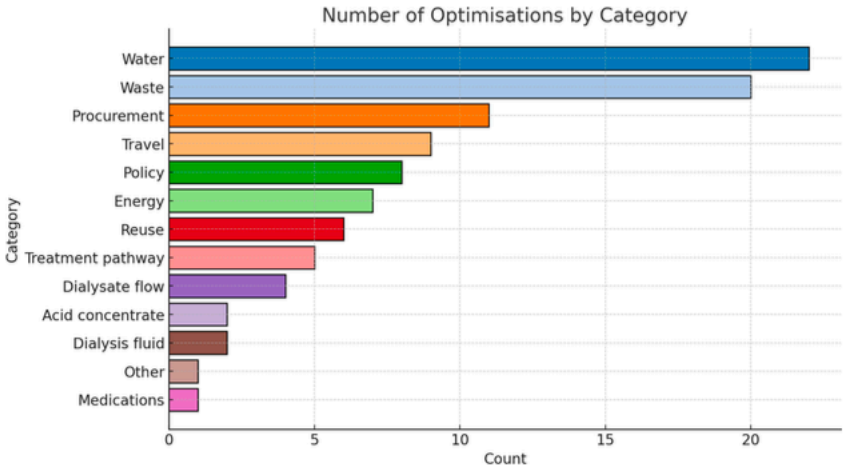

Fig. 4 Number of optimisations by sustainability category

Transplantation

Few studies focussed specifically on transplant settings, but those included:

- Digital tools to coordinate pre- and post-transplant care [61, 63]
- Efforts to optimise medication use and delivery logistics [65]
- Education platforms and teleconsultation services that allowed stable patients to be managed closer to home [62, 69]

In the UK, the number of transplant recipients exceeds that of patients receiving in-centre HD.

Peritoneal dialysis

PD was underrepresented despite being a home-based and potentially lower-impact modality. Notable examples included:

- Delivery optimisation to reduce packaging and shipment frequency [64]
- Local storage and reuse of packaging materials [43, 44]
- Training adaptations to encourage environmentally conscious practices (e.g. appropriate disposal of dialysate bags and medication vials) [38]

One study addressed energy savings in PD cyclers, although data were limited [42].

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Haemodiafiltration and conservative management

HDF is a refinement of HD, and most process-based interventions described for HD are also applicable to HDF, though water use is typically higher.

Only a few studies were explicitly focussed on HDF, with interventions similar to those in HD regarding flow rates, energy usage, and waste minimisation [103, 111]. VKD patients (very low kidney function opting for conservative management) were the least represented, with only one mention related to telemedicine and home monitoring [68].

Settings

Most HD studies were conducted in tertiary and satellite hospital units in high-income countries, with a minority involving home therapies. PD studies were mainly home-based. Transplantation interventions occurred in tertiary centres and telehealth-supported follow-up programmes. Chronic kidney disease studies focussed on outpatient or community nephrology services.

Distribution by review questions

When analysed in light of the review questions derived from the integrated frameworks (NASSS and CSH's Green Team Success Factors), a clear pattern emerges (Fig. 5). Each study was assessed against five domains—*Technology*, *Organisation*, *Value Proposition*, *Intended Adopters*, and *External Context*. For each domain, we recorded a "yes" if the paper provided information relevant to that domain (e.g. describing a technological optimisation, organisational readiness, value for patients or health systems, intended adopters, or contextual enablers/barriers). Figure 5 therefore illustrates the number of studies that addressed each domain ("yes counts") across different kidney care modalities, showing where evidence is more concentrated and where it is comparatively lacking. The majority of interventions were mapped under the Technology and Value Proposition domains, particularly in haemodialysis, reflecting the strong emphasis on equipment-level optimisations, process efficiencies, and demonstrable environmental and economic gains. Organisation and External Context followed a similar trend, again with haemodialysis predominating but also notable contributions from CKD-focussed interventions, which often addressed broader systemic or upstream factors such as policy alignment, resource use, and digital care models. By contrast, Intended Adopters was consistently the least represented category across modalities, indicating that staff engagement, patient perspectives, and long-term embedding strategies were less frequently considered or reported.

Taken together, this distribution highlights how most published interventions were designed and reported primarily through a technological and value-for-money lens, with relatively less explicit attention given to organisational readiness, contextual enablers, and especially adopter engagement—dimensions emphasised by the NASSS and Green Team Competition frameworks. This suggests that while many interventions demonstrate environmental and economic benefits, further research should more systematically assess how such initiatives perform in terms of stakeholder engagement, equity, and alignment with system-wide sustainability goals.

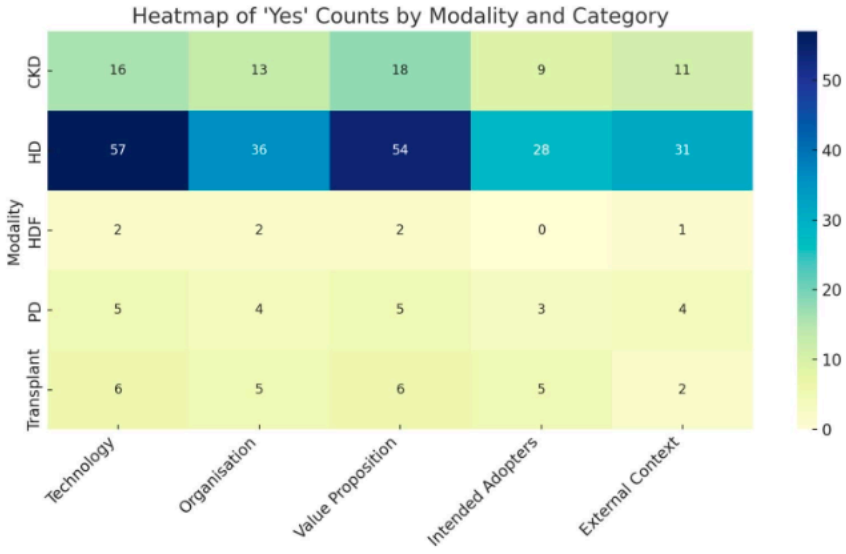

Fig. 5 Heatmap of 'Yes' counts by kidney care modality and the review questions based on the NASSS and CSH's Green Team Competition Success Factors (Categorised by: Technology, Organisation, Value Proposition, Intended Adopters, External Context)

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Interventions with impacts on carbon emissions

Table 1 shows the interventions' impacts on actual carbon emissions, categorised by intervention type and treatment modality. Waste management strategies together with water reduction and travel minimisation prove to have a great impact on sustainability.

Discussion

This scoping review mapped 95 sustainability interventions across all major areas of kidney care. While HD dominated both the number and diversity of interventions—reflecting its resource-intensive nature—important and novel strategies were also identified in CKD, transplantation, PD, HDF, and conservative care/ VKD. Some general nephrology initiatives not labelled as environmental, such as deprescribing, test stewardship, and patient-led improvement work, also support sustainable practice and merit integration into future sustainability analyses.

The interventions covered a wide spectrum of sustainability categories, with water efficiency, waste reduction, procurement, and travel-related emissions emerging as the most common targets. Across modalities, the reviewed interventions included both structural and behavioural approaches, from telemedicine and digital health platforms to supply chain redesign, packaging improvements, and equipment-level optimisation.

Haemodialysis: high impact, high innovation

HD interventions were the most extensively documented, likely due to the modality's disproportionate contribution to healthcare-related environmental impacts, particularly greenhouse gas emissions, water use, energy consumption, and plastic waste, as well as its higher global prevalence compared to PD, which positions it as a natural focal point for sustainability efforts. Studies targeting dialysate flow reductions, acid concentrate packaging, central acid delivery systems, and heat exchangers offer replicable solutions with demonstrable environmental and economic benefits.

Clinical transformation initiatives—such as remote consultations and asynchronous care via platforms like *Patients Know Best*—reflect a growing move toward low-carbon models of care delivery that enhance patient autonomy while reducing emissions from patient and staff travel [112].

Some clinical transformations focus on reducing travel to the hospital. For example, through setting up telephone clinics and virtual consultations, patients can access appointments without the need of going into hospital, hence reducing GHG emissions associated with travel and the outpatient appointment itself. Developing a system where the hospital schedules appointments over the phone, and blood tests, blood pressure and weight readings are taken prior to the phone appointment will facilitate virtual appointments [61]. Establishing phone tariffs to cover the calls might be required if not in place already [69]. Other methods to carry out virtual consultations include the use of software or apps which have two-way messaging features and accessible patient care plans [63, 67].

Switching to central acid delivery is another optimisation where acid is delivered to dialysis units in bulk load, pumped into holding tanks and then distributed to dialysis machines via a piped loop system [90]. This initiative helps to make HD more sustainable as it reduces both acid waste and packaging waste. Other options for more sustainable acid solutions include working with manufacturers to change acid concentration levels. For example, the development of 44:1 concentrate solutions has reduced container size and helped lower transport-related emissions by decreasing road freight volume [91, 113]. Additionally, manufacturers using low density polyethylene (LDPE) lightweight packaging to replace the rigid high density polyethylene plastic packaging also help to significantly reduce the plastic waste of a kidney unit [92].

Other changes implemented to reduce the carbon footprint of ESKD can involve infrastructure- and estates-level changes. Installing solar panels to dialysis units can allow dialysis sessions to be powered with renewable energy [29, 78]. This could help to reduce the environmental burden of dialysis sessions and lead to energy cost savings.

Water use is one of the most wasteful components of dialysis with around 500 l used per treatment [114]. This is assuming that the dialysate flow is 500 ml per minute requiring 125 l of water for a patient where two thirds of the water is rejected in reverse osmosis [92]. Therefore, initiatives to reduce water use and reuse reject water are also impactful in reducing the environmental impact of dialysis. Reducing water use could be done through initiatives such as reducing dialysis fluid flow rate to 400 ml per minute where water will be saved without compromising clinical outcomes [94, 102]. Also, as the rejected water does not encounter the patient and does not carry any infection risks, it could be reused in activities such as toilet flushing or laundry, through the installation of a reverse osmosis plant [23, 26, 27].

Other hotspots that could be targeted to reduce the environmental impact of ESKD are reducing paper use in clinical practices, for example by automating blood test results [47], and introducing waste segregation systems to improve waste management at the hospital [40, 106, 107].

CKD, PD, and transplantation: emerging opportunities

CKD-focussed interventions were generally broader in scope and upstream in nature, addressing prescription practices,

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Table 1 Table of interventions with carbon emission savings, categorised by intervention type and treatment modality

Intervention	Category	Treatment modality	Impact on carbon emissions
Central delivery of acid for haemodialysis	Acid concentrate	HD	Reduced acid wastage, saving 8,330 $kgCO_2e$ per year. Reduced packaging waste, saving 7,699 $kgCO_2e$ per year.
44:1 Haemodialysis concentrate solution	Acid concentrate	HD	Carbon savings estimated at 16.22 tonnes CO_2e per year from saved road freight.
Using Citrate as an alternative to Heparin in Haemodialysis	Medications	HD	Using citrate has less than 1.5% of the carbon footprint of heparin.
Waste reduction- bolus administration of intravenous antibiotics	Procurement	CKD	Carbon savings estimated at 6.73 tonnes CO_2e a year.
Telephone clinics to follow-up renal transplant recipients	Travel	Transplant	Carbon savings estimated at 2000 $kgCO_2e$ per year.
Remote CKD monitoring as a part of a disease management programme	Travel	CKD	Carbon savings estimated at 40kg CO_2e per year.
Dialysing nearer to home	Travel	HD	Carbon savings at 6.74 tonnes of CO_2e per year.
Establishing a tele-clinic service for kidney transplant recipients through a patient-codesigned quality improvement project	Travel	Transplant	Saved 3,527 miles of motorised travel in total. This equates to a saving of 1,035 $kgCO_2$.
The follow-up of renal transplant recipients by telephone consultation.	Travel	Transplant	Carbon savings estimated at 2000 kgCO2e annually.
The environmental impact of dialysis vs transplantation	Treatment pathway	VKD	Transplants over a 15 year period decreases environmental impact by 95.7% compared to haemodialysis and 90.9% compared to peritoneal dialysis.
Waste reduction - stopping the unnecessary practice of hanging a saline bag for emergencies and bicarbonate bag diverted away from the clinical waste stream to domestic waste.	Waste	HD	Carbon savings estimated at 26.847 tonnes CO2e per. Reduced clinical waste, 21.5 tonnes per year.
Paperless reporting of routine dialysis haematology and biochemistry results	Waste	HD	Carbon savings estimated at 380kgCO2e per year.
Paper reduction, reuse and recycling	Waste	HD	Carbon savings estimated at 109 kg CO2e per year.
Diversion of waste to the recycling Stream through the use of baling machines	Waste	CKD	Carbon savings at 85.2 tonnes of CO_2e per year.
The carbon footprint of waste streams in a UK hospital	Waste	CKD	The carbon footprint per tonne of hospital waste was lowest when it is recycled (21-65 $kgCO_2e$), followed by low temperature incineration with energy from waste (172-249 $kgCO_2e$).
Baling and recycling of bottles and cardboard	Waste	CKD	Carbon savings estimated at 8665 kg CO_2e per year.
Managing medical waste	Waste	HD	The usage of the lighter dialysis set can create 17 million kg reduction of medical waste.
Quantification of recyclable Peritoneal Dialysis plastics in a home dialysis programme	Waste	PD	Carbon savings of 21.99 metric tons CO_2e though recycling PD PP waste.
Reuse of reject water from reverse osmosis for steam production	Water	HD	Carbon savings estimated at 764.88 kg CO_2e per year.
Recycling reject water from the dialysis unit	Water	HD	Carbon savings estimated at 764.88 kg CO_2e per year.
Renewable generation of electricity from haemodialysis effluent water	Water	HD	Cut down up to 300 kg CO_2e per year through this system. Device was able to generate up to 1.6 kWh of electricity per day and 487 kWh per year. This energy can be used to power a 100-W lightbulb for 16 h or a 50-W LED TV for 32 h.
Replacing the old water purification system with new systems that have an ECO mode to regulate output according to demand and variable speed pumps to minimise energy consumption	Water	HD	Reduced carbon emissions by 20%.

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paperless administration, and patient self-monitoring [73]. These efforts align well with planetary health principles by preventing disease progression and reducing dependence on high-resource interventions [115].

PD despite its theoretical advantage as a home-based therapy with fewer infrastructural demands, was underrepresented. A handful of studies addressed waste reduction in supply deliveries, local material reuse, and training for sustainable practices, but further research is needed—especially regarding environmental trade-offs between CAPD and APD modalities [116, 117].

Transplantation-related sustainability remains a research gap. While studies highlighted remote follow-up and medication logistics, more comprehensive evaluations are needed to understand the full environmental and economic implications of transplantation compared to dialysis, particularly over the long term [118].

Underexplored areas: pharmaceuticals, reuse and conservative care/ VKD and co-benefits

Pharmaceutical waste, though a recognised issue in nephrology (particularly in CKD and post-transplant patients) [119], was infrequently addressed. Optimising medication stocks and prescribing behaviours can reduce both waste and costs, yet this area remains underdeveloped compared to others such as water or energy efficiency.

Dialyser reuse, historically associated with cost-containment in low- and middle-income countries, is now being reconsidered in high-income settings as a sustainability strategy in response to the ecological emergency [120]. When conducted under validated protocols, dialyser reprocessing has been shown to preserve clinical adequacy and safety while significantly reducing plastic and packaging waste. Nonetheless, adoption remains limited due to persistent cultural concerns, regulatory restrictions, and the absence of updated guidelines [121]. Reintroducing dialyser reuse into routine practice would require a multipronged effort: further research into safety and cost-effectiveness, regulatory reform (e.g. enabling Article 17 in EU countries), engagement of industry stakeholders in viable economic models, and a gradual shift of healthcare systems towards circular resource use. These developments reflect a growing consensus that circularity principles, long underutilised in nephrology, offer promising co-benefits for both environmental sustainability and system resilience.

The complete lack of sustainability research in patients with very low kidney function opting for conservative care is striking. As the population ages and more patients opt for conservative care, it is essential to develop low-impact, supportive models that prioritise quality of life and avoid unnecessary interventions [122–124].

Finally, the adoption of sustainable interventions such as remote consultations, home-based dialysis modalities, incremental haemodialysis, and conservative kidney management offers not only environmental benefits but also recognised health co-benefits. Remote care pathways have been associated with improved patient experience, engagement, and treatment adherence, while reducing the burden of travel without compromising care quality [125, 126]. Home-based therapies, particularly peritoneal dialysis with remote monitoring, have demonstrated improvements in quality of life, autonomy, and patient-reported outcomes [127]. Incremental haemodialysis, which individualises treatment frequency according to residual kidney function, has been associated with better preservation of residual function, fewer hospitalisations, lower symptom burden, and non-inferior survival compared to conventional thrice-weekly schedules [128]. When aligned with patient values and preferences, conservative management may further reduce unnecessary interventions and hospital admissions, facilitating more holistic, low-impact models of care that support both planetary and patient wellbeing [129].

This review highlights a need for standardised metrics to assess environmental performance in kidney care. Only a small number of interventions reported quantitative outcomes in terms of kg CO_2 equivalence, kWh, litres of water saved, or waste volumes. Adoption of LCA methodologies or alignment with ISO 14040/44 standards would significantly improve comparability and validity [130].

Additionally, the heterogeneity in study design—from audits and case reports to full implementation projects—limits generalisability [5]. Many reports lacked economic evaluation or stakeholder feedback, and few addressed unintended consequences (e.g. workload shifts, digital exclusion, or rebound effects) [15].

The analysis of the review categories, based on the NASSS framework and the CSH's Green Team Competition Success Factors (Fig. 5), reveals that sustainability interventions in kidney care are unevenly distributed across modalities and categories. Haemodialysis showed the highest number of optimisations in all domains, particularly in the *Technology* and *Value Proposition* categories, reflecting the high material and energy intensity of HD and the focus of innovation efforts on equipment, consumables, and process efficiency. Chronic kidney disease interventions, while fewer overall, were more evenly spread across categories, suggesting a broader range of intervention types at earlier stages of the patient pathway. In contrast, peritoneal dialysis, haemodiafiltration, and transplantation had fewer documented optimisations, indicating potential gaps or under-reporting of sustainability initiatives in these areas. This imbalance highlights an opportunity for future research and intervention design to extend beyond HD, ensuring that

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sustainability strategies are applied comprehensively across all kidney care modalities.

Beyond this descriptive mapping, triangulation of the CSH's Green Team success factors with frameworks like the Sustainable Value framework [131] will provide further insights. We combined the NASSS and CSH Green Team frameworks because no single validated framework exists for assessing environmental interventions in healthcare. This highlights the need for standardisation of evaluation tools to strengthen future research.

While many interventions quantified environmental and economic benefits, relatively few addressed cross-disciplinary teamwork, staff engagement, or long-term integration into clinical workflow—dimensions emphasised by the Green Team framework [16]. Indeed, an integrative review of healthcare "Green Team" initiatives found that staff engagement, alongside policy support, external collaboration and organisational structure, was one of the four main facilitators of success in environmentally sustainable initiatives [132]. Likewise, applying the Sustainable Value lens shows that social dimensions such as patient experience, equity of access, and staff wellbeing were rarely considered. Recent evidence shows that organisational culture and job satisfaction are central to sustainable healthcare quality: by optimising processes and reducing waste, healthcare services can enhance staff wellbeing and ultimately improve patient care—underscoring the importance of embedding social value criteria into sustainability interventions [133]. Taken together, these findings suggest that the current literature has largely prioritised measurable technical and economic outcomes, while underreporting organisational, contextual, and social aspects that are equally important for long-term adoption and system-wide sustainability. Embedding Green Team and Sustainable Value criteria more explicitly in future studies would strengthen the evidence base, ensuring that sustainability interventions in kidney care are not only environmentally and economically effective but also feasible, acceptable, and equitable across diverse contexts.

While the search was comprehensive, potential limitations include publication bias toward positive or innovative results, and underrepresentation of grey literature and non-English sources [14]. Moreover, most interventions originated from high-income countries, highlighting the need for context-specific solutions in low- and middle-income settings. Also, as is consistent with scoping review methodology, no formal risk of bias or certainty assessment was performed, and no meta-analysis or synthesis of effect measures was conducted. This approach is appropriate given the exploratory nature of the review and the heterogeneity of study designs, but it should be noted as a limitation in the interpretation of results.

Our findings support the integration of sustainability principles into routine nephrology care, aligning clinical outcomes with respect for planetary boundaries. This shift can be facilitated by professional societies, regulators, and procurement agencies through the incentivisation of low-impact practices such as low-flow HD and the use of reusable consumables, the incorporation of environmental criteria into procurement tenders and clinical guidelines, and the promotion of staff education and sustainability literacy across kidney care services.

Healthcare organisations can also implement multimodal interventions that address travel, procurement, and waste simultaneously, maximising co-benefits for patients, providers, and the environment [134, 135].

Crucially, many sustainability interventions identified in this review were cost-saving or cost-neutral, offering a strong economic case for action even in resource-constrained systems.

Few studies incorporated patient or donor perspectives. One relevant report from Canada included patient-generated sustainability ideas. Greater inclusion of patient voice and co-design is needed in future sustainability work.

Environmental sustainability should be embedded within all kidney care activities rather than treated as a specialist niche. Many established practices already align with sustainability principles, including extending transplantation and peritoneal dialysis where clinically appropriate. Integrating environmental goals into everyday decision-making supports a planetary health model of kidney care.

Optimising clinical management choices has significant sustainability implications. Examples include promoting home rather than centre-based haemodialysis where safe, supporting peritoneal dialysis, using incremental starts, balancing RRT versus conservative management, and timely transition to palliative approaches. These decisions should integrate both clinical and environmental considerations.

Environmental context modifies the impact of sustainability interventions. For example, water reuse or recovery is particularly relevant in arid or semi-arid regions, while energy-related interventions yield greater benefits in areas with high grid carbon intensity.

Future research should prioritise longitudinal studies that include robust environmental and economic impact assessments [13, 50], while also ensuring the inclusion of diverse patient populations and treatment modalities such as PD, conservative kidney management, and transplantation. Co-design with patients and healthcare staff is essential to enhance the acceptability, feasibility, and equity of interventions, and consistent reporting using tools like the SQUIRE 2.0 checklist or a dedicated environmental quality framework will be key to improving transparency and comparability across studies [136].

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Conclusion

This scoping review reveals a growing landscape of innovation in sustainable kidney care, yet underscores the urgent need for coordination, standardisation, and system-level thinking. Nephrology faces a pivotal moment: rising environmental challenges and growing inequities make sustainable transformation both urgent and achievable. By advancing interventions that are evidence-based, environmentally sound, and designed with attention to equity and access, the kidney community can lead by example toward a greener, healthier future.

Limitations

However, despite the maturity of this field in HD, interventions were highly variable in methodology, scope, and reporting standards. Many were pilot programmes or quality improvement projects without long-term follow-up or consistent metrics, limiting comparability and scalability.

Implementation challenges included short project timelines, limited follow-up, staff turnover, inconsistent funding, and lack of evaluation metrics. Some digital or waste interventions increased workload for staff or patients, or shifted impacts to other parts of the system. Infection control and regulatory barriers also limited scale-up. These findings highlight the need for long-term monitoring and system-level coordination.

Most included studies originated from the United Kingdom and other high-income regions, reflecting the current distribution of published work. This geographic concentration limits generalisability to low- and middle-income settings.

The review included studies published from 2005 to 2025. Earlier sustainability initiatives may have been excluded, though few pre-2005 renal publications addressed environmental topics. Future reviews could examine archival material to assess this potential gap.

Due to heterogeneity in intervention design, outcome units, and reporting standards, quantitative synthesis or meta-analysis was not feasible. Standardised reporting frameworks are required to enable future comparative analysis.

Appendix 1

Keywords and phrases used in the search strategy included the below:

1	Chronic kidney disease
2	End stage kidney disease
3	Renal care
4	Kidney care
5	Environmental impact
6	Dialysis
7	Carbon footprint
8	Environmental sustainability
9	Optimisations
10	Systematic review
11	Hospitals
12	Dialysis units
13	Greenhouse gas emissions
14	Life cycle assessment

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interests The authors declare no competing interests.

Ethical approval Ethical approval was not required for this study as it did not involve human participants or animal research. The study focussed solely on the analysis of papers related to kidney care sustainability.

Informed consent to participate Informed consent was not applicable to this study, as it did not involve any individual participants, patients, or human data.

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Scientific Research Report

Prompt-Driven ChatGPT Carbon Calculator for Dental Practices: Estimation and Tailored Improvement Strategies

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ABSTRACT

Introduction and aims: This study investigates the feasibility of applying ChatGPT, a generative artificial intelligence (AI) language model, to develop a user-friendly carbon footprint calculator tailored for dental practices. Building on a previously developed Excel-based tool, the research aimed to evaluate ChatGPT's capacity to generate accurate emissions estimates and sustainability recommendations using different prompting strategies.

Methods: Three prompting variants were tested. Variant 1 employed an unstructured request to assess general responses. Variant 2 used structured data entry with predefined emission factors. Variant 3 combined structured input with instructions to rely exclusively on outputs from a previously validated sustainability tool. ChatGPT-generated results were compared with the Excel benchmark, focusing on accuracy, contextual relevance and alignment with peer-reviewed guidance.

Results: Unstructured prompts (Variant 1) produced general recommendations of limited contextual relevance. Structured prompts improved both accuracy and specificity. Variant 2 generated tailored outputs using emission factors, while Variant 3 provided detailed, evidence-based recommendations consistent with established literature. Across variants, ChatGPT's carbon footprint estimates were largely comparable to the Excel benchmark, with only minor discrepancies in waste-related emissions.

Conclusion: Structured prompting significantly enhances ChatGPT's performance in generating reliable carbon footprint data and recommendations for dental practices. When supported by transparent emission factors and credible literature, generative AI tools can increase access to environmental data, support sustainability decision-making and facilitate climate action in clinical contexts. However, limitations remain, including risks of inaccurate outputs ('hallucinations') and regional generalisations. Effective use requires prompt literacy and open access to validated emission factor databases to maximise impact and reliability.

Clinical relevance: AI-driven calculators such as ChatGPT can help dental teams without carbon accounting expertise to understand and reduce their environmental impacts, supporting the integration of sustainability into routine clinical practice.

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Introduction

In 2024, we published a carbon calculator using Excel.[1] While some users found it simple and effective, others reported difficulties navigating the spreadsheet format. There is a clear need for a more intuitive, accessible tool.[2] Dental practices – whether independent or part of larger groups – require quick, reasonably accurate estimates of their environmental impacts to inform actions that will reduce their carbon footprint.

AI based tools are increasingly used to help solve a wide range of real-world problems, from everyday queries to complex analytical tasks. ChatGPT (Generative Pretrained Transformer) is a widely used and accessible large language model (LLM), demonstrating consistent performance across various

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domains, including sustainability and healthcare analysis.[3-5] Its conversational interface makes it well-suited for structured user engagement.[6] Although alternatives such as Claude, Gemini and LLaMA are emerging, ChatGPT remains one of the most accessible models for non-expert users and offers reproducible results across user groups.[7] Several papers have recently been published in dentistry on its use.[8,9]

As an alternative to traditional search engines like Google, ChatGPT offers conversational accessibility and the potential for rapid, structured reasoning. However, its outputs are not without challenges. ChatGPT type tools can produce incorrect assumptions, misinterpretations, or hallucinated references – fabricating sources that do not exist.[10]

ChatGPT has notable limitations in sustainability assessments. It may overlook relevant but less-cited datasets, exclude entire categories of environmental information, or be biased by ranking algorithms or because of access restrictions.[11] ChatGPT frequently produces flawed outputs. These issues underline the need for caution and critical engagement when relying on AI for environmental impact analysis.

However, in our experience (within sustainability, healthcare and dentistry), the performance of ChatGPT improves markedly when users provide detailed, well-structured prompts.

The aim of this paper was to validate the use of different prompts to create a tailored ChatGPT tool designed to allow dental practices to estimate their carbon footprints.

Methods

In this manuscript, 'ChatGPT' refers specifically to OpenAI's platform, while 'LLM' is used to describe the broader category of generative models.

A series of tailored prompts were developed to explore the reliability of ChatGPT (https://chatgpt.com/) in producing dental carbon footprints and sustainability recommendations. These prompts (Variants 1, 2 and 3) varied in their specificity and the inclusion of structured data inputs. Outcomes were assessed based on the relevance and completeness of the outputs, the degree of personalisation in recommendations and the inclusion of verifiable references. We used our previously published Excel-based carbon calculator as a benchmark to evaluate ChatGPT's performance across these 3 variants. The comparison focused on the plausibility of emissions estimates, the contextual relevance of sustainability recommendations and the use of evidence-based references.[1]

Variant 1

ChatGPT was asked to create a sustainability footprint for a dental practice and provide recommendations for improvement based on no directions that is, 'Please provide me with a carbon footprint for my dental practice and provide recommendations and references to help me reduce my footprint'.

Variant 2

ChatGPT was asked to collect specific data based on a structured prompt (Table 1) without specifying specific literature to draw down personalised recommendations

Variant 3

ChatGPT was asked to collect specific data based on the attached prompt, but this time to draw on the Centre for Sustainable Healthcare sustainability tool which is freely accessible online[12] (see Table 2).

For all variants the following fictitious information was used to test the prompts. These figures were drawn from the BDJ publication[1] (Table 3).

To understand the usefulness of providing prompts, we compared ChatGPT's outputs across the 3 variants against the Excel-based calculator as a benchmark. Outputs were evaluated based on specificity of carbon estimates, the range and applicability of recommendations and the presence of credible sources. While subjective, this comparative review helped identify the strengths and limitations of different prompting approaches. Despite asking ChatGPT to not remember previous prompts, ChatGPT did 'learn' as it went, meaning that we tested our 3 different approaches on 2 different ChatGPT accounts (B Duane's ChatGPT account and then J Larkin).

Results

Variant 1

Variant 1 did not produce a carbon footprint based on any specific practice information – as ChatGPT did not request any additional information to produce the carbon footprint. The AI tool simply provided references from published data. Variant 1 provided a detailed number of recommendations drawn from many references including 2; we were aware of and have been involved with (the Green impact tool,[13] the Centre for Sustainable Healthcare[12]), and 2 other sites the Eco-Dentistry Association site[14] and the American Dental Association.[15] See Figure 1 for the discussion with ChatGPT.

Variant 2

Variant 2 as requested produced a much more detailed tailored carbon footprint of the dental clinic. The AI tool requested further information when some questions were missed. It provided 12 tailored recommendations to further improve the footprint. However, none of these were referenced (see Figure 2 and Figure 3).

Variant 3

Variant 3 provided 17 tailored recommendations referencing the centre for sustainable healthcare resource but also Wikipedia[12,16] (see Figure 4).

In Table 4, Chat-based outputs are largely aligned with Excel calculations, though minor discrepancies were noted – particularly in waste emissions (Chat: 232.2 kg vs Excel: 246.1 kg). While energy, water and procurement estimates were identical, the Chat tool did not provide detailed breakdowns for patient transport modes or waste types, limiting transparency.

Table 1 – Variant 2. A prompt to calculate an appropriate dental footprint.

You are a carbon footprint calculator specifically trained for dental clinics. I will answer a few simple questions about my dental practice, and you will estimate our carbon footprint in kg or tonnes of CO_2 equivalent (CO_2e), based on reasonable emission factors.
Then, give me a breakdown of emissions by category (eg, travel, energy, waste, procurement), and offer 3-5 tailored recommendations to help us reduce emissions.
Please do this in 3 steps:
###A. Ask me these questions:
Practice Information (Annual figures)
1. How many days is the practice open on an average year?
2. How many full-time staff are in the practice?
3. How many patient visits does the practice see every year?
Staff Travel (in miles)
4. How far do all staff travel (return trip) to work or for work by car per day?
Patient Travel (in miles)
5. What is the total distance travelled by 30 patients using:
- Petrol/Diesel Car?
- Electric Car?
- Bus?
- Train?
- Motorbike?
- Bike/Walk?

Waste (Number of bags disposed per day)
6. How many bags of plastic waste for recycling?
7. How many bags of cardboard waste for recycling?
8. How many bags of infectious waste for incineration?
9. How many bags of domestic waste for disposal?
Energy Use (in kilowatt-hours – kWh)
(This year – make sure it's a normal year)
10. How much standard electricity did the practice use?
11. How much green electricity did the practice use?
12. How much electricity did you generate from solar panels on your roof?
13. How much gas did the practice use?
Water
14. What was the total water usage annually in cubic metres?
Procurement
15. How much did you spend annually on other things, equipment, and materials in pounds sterling (£)?
(Do not include rent or interest)
B. Use these emission factors:
Travel
- Staff car travel per mile: **0.5300 kg CO_2e**
- Patient travel per mile:
  - Petrol/Diesel Car: 0.5300
  - Electric Car: 0.1830
  - Bus: 0.1500
  - Train: 0.1900
  - Motorbike: 0.1600
  - Bike/Walk: 0.0000

Waste per bag
- Plastic recycling: 0.0000
- Cardboard recycling: 0.0000
- Infectious waste (incineration): **7.5869 kg CO_2e**
- Domestic waste (disposal): **1.1558 kg CO_2e**

Energy per kWh
- Standard electricity: 0.2749
- Green electricity: 0.0110
- Solar on roof: 0.0410
- Gas: 0.2100

Water
- Per m^3: **0.3378**

Procurement
- Per £ spent: **0.1315**

C. After I provide the answers, calculate and present:
1. **Total CO_2e per year for my practice**
2. **Which category is the highest emitter**
3. **Recommendations to reduce emissions**, draw on own data

Table 2 – A prompt to calculate an appropriate dental footprint with tailored recommendations.

C. After I provide the answers, calculate and present:
1. **Total CO_2e per year for my practice**
2. **Which category is the highest emitter**
3. **Recommendations to reduce emissions**, focussed and based on my answers, but solely using information from https://sustainablehealthcare.org.uk/wp-content/uploads/2024/09/how_to_guide_sustainable_dentistry.pdf
Question 2:
C. After I provide the answers, calculate and present:
1. **Total CO_2e per year for my practice**
2. **Which category is the highest emitter**
3. **Recommendations to reduce emissions**, focussed and based on my answers, but solely using information from https://sustainablehealthcare.org.uk/wp-content/uploads/2024/09/how_to_guide_sustainable_dentistry.pdf

Recommendations

V 1. Non-tailored. Optimise travel and appointments. Enhance energy efficiency. Adopt sustainable procurement practices. Improve waste management. Conserve water- educate and engage.[13-15]

V2. Tailored (with no reference to literature). Implementing sustainable travel initiatives for staff, cluster appointments, optimise energy use, reduce procurement emissions, nothing on waste.

V3. Tailored (referenced to the CSH guide[12]). Implementing travel (detailed), waste segregation (detailed) energy efficiency (detailed for elect, nothing on gas), procurement (detailed)

Discussion

This research showed how use of a tailored prompt could significantly improve the accuracy of ChatGPT as a tool to estimate dental practice carbon emissions when compared to the currently validated approach.

While prompting ChatGPT with a resource developed by the authors introduces the possibility of bias, this was a deliberate methodological choice to evaluate whether AI outputs could be improved through alignment with credible, open-access sustainability literature.[17] The approach reflects real-world use, where practitioners can (if knowledgeable) guide AI tools using trusted and accessible sources. This technique – prompt tuning – has been shown to significantly influence output quality, especially in domain-specific tasks.[18,19]

In variants 2 and 3, the tool prompt used predefined emission factors and structured questions informed by prior research. The tool prioritised usability and speed over precision, offering a 'quick and easy' entry point into environmental footprinting. By aligning AI outputs with peer-reviewed evidence and transparent assumptions, we aimed to support the use of a tool to create not only a carbon footprint but also targeted sustainability recommendations for the dental team.

While the spreadsheet tool provided greater transparency (in terms of understanding how the figures are calculated) ChatGPT showed promise in producing practical outputs when guided by structured prompts. ChatGPT produced identical results to the use of the Excel tool with only a negligible difference in its calculation of the waste footprint. Individuals without Excel proficiency can calculate their carbon footprint using this approach. This ChatGPT-based method provides a significantly more user-friendly and accessible template.

The tool may be particularly valuable for time-constrained dental professionals who lack access to sustainability consultants, life cycle assessment expertise, or carbon accounting resources. However, while the potential of AI to support environmental analysis is considerable, caution is warranted. ChatGPT's outputs and suggestions are not yet equivalent in accuracy or comprehensiveness to those generated through traditional, peer-reviewed methods.

Table 3 – Summary of sustainability-related inputs for the general practice (mock data).

Category	Answer to question	Value (mock data)	Unit / Notes
Practice Activity	Practice open days (annual)	220	Days
	Full-time staff	2.5	Full-Time Equivalent (FTE)
	Annual patient visits	2,654	Visits
Staff Travel	Total weekly travel (car)	587.5	Miles (return journeys)
Patient Travel	Petrol/Diesel car	174.3	Miles (30 patients sampled)
	Electric car	0.0	Miles
	Bus	7.6	Miles
	Train	37.2	Miles
	Motorbike	10.0	Miles
	Bike/Walk	6.0	Miles
Waste (weekly)	Plastic (recycling)	0.5	Number of bags
	Cardboard (recycling)	0.4	Number of bags
	Infectious waste (incineration)	0.6	Number of bags
	Domestic waste (general disposal)	0.9	Number of bags
Energy Use (annual)	Electricity (standard)	5,387	kWh
	Electricity (green)	0.0	kWh
	Solar power	0.0	kWh
	Gas	11,457	kWh
Water Use (annual)	Total water usage	41.5	Cubic metres (m^3)
Procurement	Equipment, materials, consumables	£45,454.80	GBP, excludes rent and interest

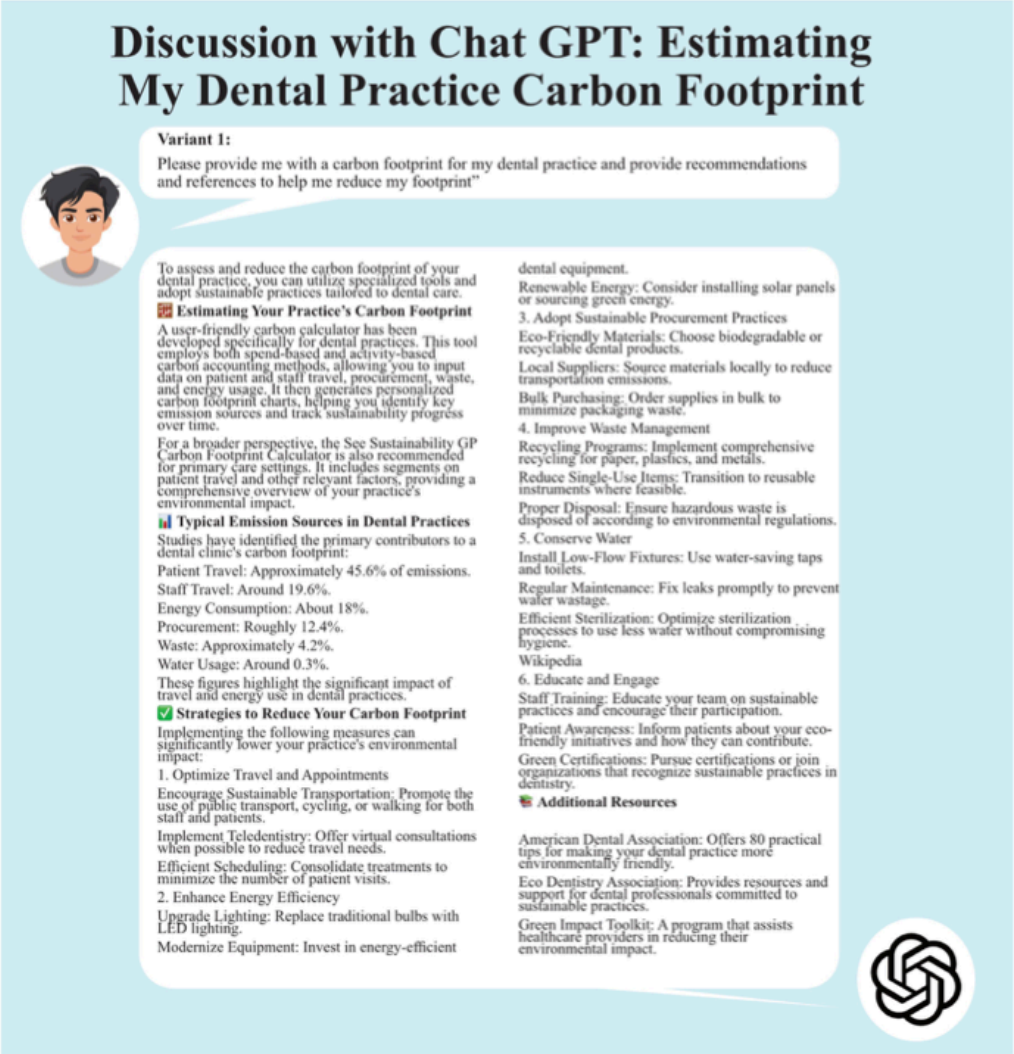

Figure 1 – Discussion with ChatGPT using variant 1.

This investigation showed that a generic request for a carbon footprint (variant 1) yielded broad, unspecific information, with less tailored relevance to the actual operations of a dental clinic. In contrast, prompting ChatGPT with structured questions and predefined emission factors produced a more accurate and context-specific carbon estimate. In Variant 2 we did not ask it to link any recommendations to a specific site but its recommendations drawn from other sites were still valid, although perhaps less detailed than Variant 3. ChatGPT did draw on a site that we were previously unfamiliar (the Eco-Dentistry Association site), the only comment we would make here is it is important for ChatGPT to draw on known trusted sites that can be linked to academic references.[14]

When directed to draw exclusively from the Centre for Sustainable Healthcare's (CSH) dental guide, the tool returned 16 detailed recommendations. Despite there being little difference between the recommendations in Variant 2 and 3, it is the author's opinion that a ChatGPT tool should be prompted with open access trusted references to draw on for personalised recommendations. Recommendations can include tools such as the CSH, or more recently the FDI sustainability guidance.[20]

It is important to note that ChatGPT can only draw information from products which are not behind sign in or payment firewalls. Where possible this information should be open access and freely available. Given the potential benefit of this sort of approach, placing information behind a paywall will only limit the use of these sorts of tools in the future which will hamper professionals looking for support with estimation of their climate impact.

Figure 2 – Discussion with ChatGPT using variant 2: Refining the questions.

AI systems like ChatGPT may offer a compelling alternative to proprietary carbon calculators, which often require licensing, detailed datasets, or restrict methodological transparency. However, their effectiveness hinges on the user's ability to construct clear and specific prompts. This introduces a new dimension of digital equity and 'prompt literacy' may increasingly shape access to high-quality AI outputs.

The approach taken in this paper – using a scripted, structured input for ChatGPT – is freely replicable and adaptable to other areas of healthcare sustainability. It demonstrates the broader potential of low-barrier AI tools in engaging health professionals in environmental action. It was noted during our literature search that others are now using this approach to help quantify carbon.[21]

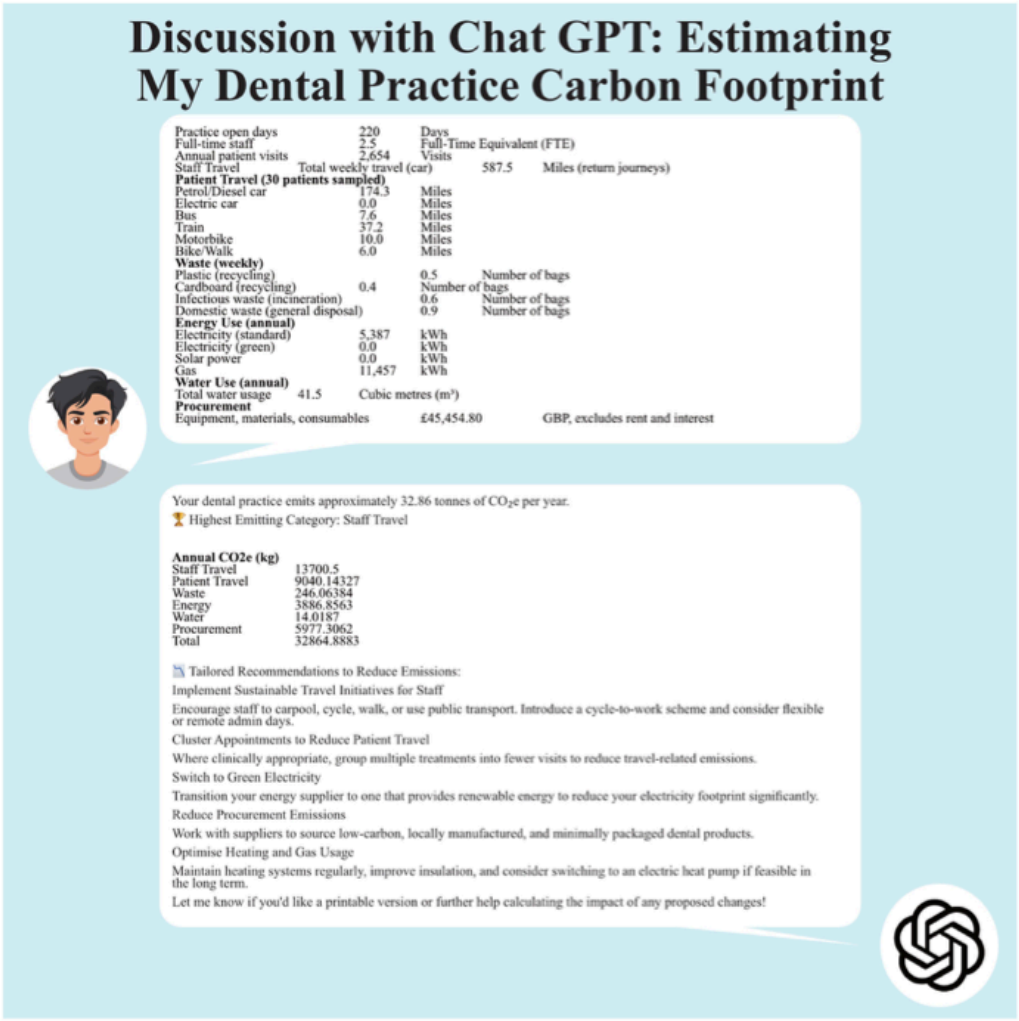

Figure 3 – Discussion with ChatGPT using variant 2: The footprint and recommendations.

One limitation of the prompts used is that they rely on UK-specific emission factors. While adequate for indicative estimates, these values may not accurately reflect conditions in regions with different electricity generation mixes, transport behaviours, or waste processing systems. For increased accuracy, local adaptation of emission factors is advised, this could readily be edited into the tool.[22] However availability of emission factors is sometimes limited; and the development of prompts such as this also underscores the need for an internationally peer-reviewed, open-access library of validated emission factors. Such a repository would reduce hallucination risks and improve reproducibility and reliability across AI-driven tools. AI prompt templates would also be useful.

Finally, it is worth noting the environmental footprint of the AI tool itself. An interactive session of approximately 50 prompts is estimated to consume about 50 watt-hours of electricity, translating to around 24 grams of CO_2 equivalent emissions – assuming a global average of 0.475 $kgCO_2e$/kWh.[23] Although negligible in comparison to clinical activities, these estimates exclude the embodied emissions from infrastructure and the considerable carbon cost of training large language models. Additionally, the energy mix of the data centre and model complexity further influence these figures. As AI becomes more embedded in sustainability assessments, transparency regarding its environmental impact is critical.

Further work

Further development of this work would be beneficial but is outside of the scope of this project. This could include

- Real-world testing with diverse dental practices.
- User feedback on practicality and accessibility.

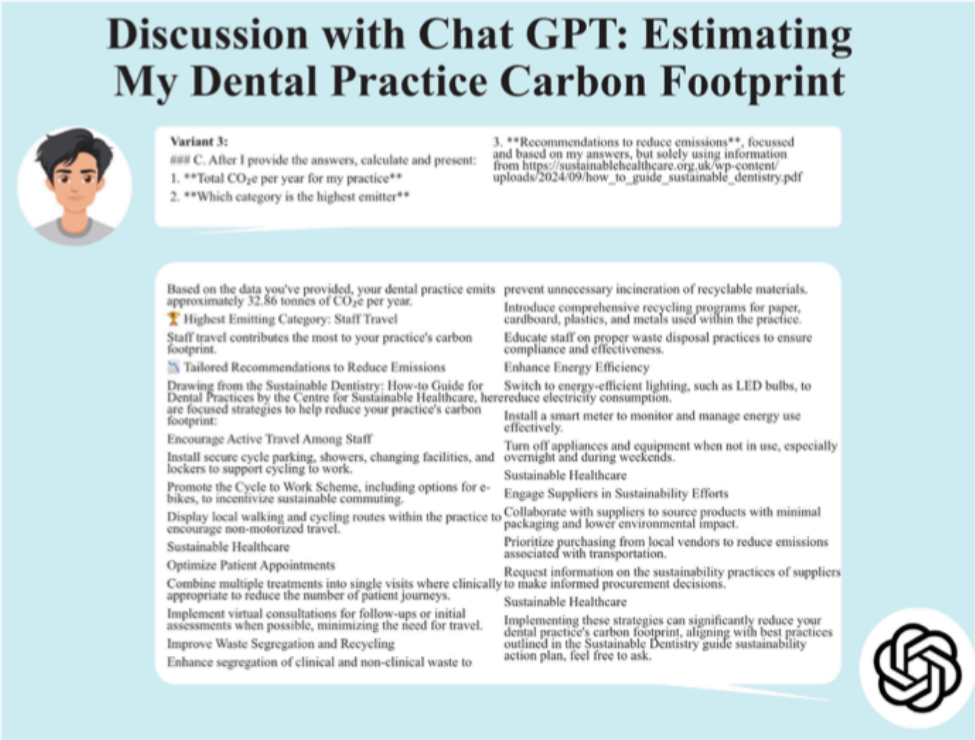

Figure 4 – Discussion with ChatGPT using variant 3.

Table 4 – Comparison of V1,V2 and V3.

Inserted mock data	Practice information	CO_2e Annual from Excel in kg	CO_2e Annual from Chat	CO_2e Annual from Chat (v2)	CO_2e Annual from Chat (v3)
220.0 d	How many days is the practice open on an average year?				
2.5 people	How many full time staff in the practice?				
2654 visits	How many patients' visits does the practice see every year?				
587.5 miles	This week (make sure it's a normal week) how far do all staff travel return to work or for work by car.	**13701.6**	Advised 45.6% CO_2e comes from patient travel	Identical to Excel	
Do the simple patient survey for 30 patients (see notes) and total the distance of all patients travel by each method					
174.3 miles	Petrol/Diesel Car	92.4	Didn't ask	No breakdown given	
0.0	Electric Car	0.0			
7.6 miles	Bus	1.1			
37.2 miles	Train	7.1			
10.0 miles	Motorbike	1.6			
6.0 miles	Bike/Walk	0.0			
	Travel total	**9040.1**	Advised 19.6% CO_2e comes from staff travel No breakdown given	Identical to Excel	
	Total number of bags of waste				
0.5 bags	Plastic waste for recycling	0.0			
0.4 bags	Cardboard waste for recycling	0.0			
0.6 bags	Infectious waste for incineration	4.3			

(continued)

Table 4. (*Continued*)

Inserted mock data	Practice information	CO_2e Annual from Excel in kg	CO_2e Annual from Chat	CO_2e Annual from Chat (v2)	CO_2e Annual from Chat (v3)
0.9 bags	Domestic waste for disposal	1.0			
	Waste total	**232.2**	Advised 4.2 % CO_2e comes from waste	Minor difference 246.1	
5387.0 Kwhr	Standard electricity	1480.7	Didn't ask	No breakdown given	
0.0	Green electricity	0.0			
0.0	Solar power on your roof	0.0			
11457.0 Kwhr	Gas	2406.0			
	Energy total	**3886.6**	Advised 15.3 % CO_2e comes from energy	Identical to Excel	
41.5m^3	**Water total**	**14.0**	Advised 0.3% CO_2e comes from water	Identical to Excel	
£45454.8	**Procurement total: The things you buy: How much did you spend on other things, equipment, materials in pounds stirling £ (don't include rent, interest)**	**5975.8**	**Advised 12.4% CO_2e comes from procurement**	Identical to Excel	
Grand Total	**Your total results for your practice**	**32,850.4**	**675 tonnes**	**32.86 tonnes**	

In conclusion, the authors found that a 'tuned' prompt written to direct ChatGPT to use evidence based sources produced comparable outputs to the current recommended methodology. It is recommended that GDPs consider using a ChatGPT methodology with variant 3 identified in this work as an exemplar.

Author contributions

The conception and design of the study, or acquisition of data, or analysis and interpretation of data: Brett Duane, James Larkin and Paul Ashley. Drafting the article or revising it critically for important intellectual content Paul Ashley, Brett Duane and James Larkin. Final approval of the version to be submitted: Paul Ashley, Brett Duane and James Larkin.

Conflict of interest

None disclosed.

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Sustainable kidney care: A life cycle assessment of the peritoneal dialysis pathways

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Abstract

Background: Peritoneal dialysis (PD) is a home-based treatment for kidney failure, offering significant social, economic and environmental advantages over haemodialysis (HD). It allows patients greater independence and flexibility, can reduce healthcare costs in some settings, and is reported to generate a smaller environmental footprint compared to HD. However, despite this, its environmental impact, particularly in terms of resource use and waste generation, is an area of growing concern. Evaluating PD through a sustainability lens, considering environmental, social, health and economic dimensions is crucial to improving its long-term viability and reducing the healthcare sector's environmental footprint.

Methods: An LCA of the PD treatment pathway was conducted at the Nephrology Dialysis and Kidney Transplantation Unit, 'Azienda Ospedaliero-Universitaria (AOU), Policlinico di Modena, Italy. Data were collected between April and July 2024 and was categorised into 17 PD-related procedures. Key activities assessed were electricity use, resource consumption (procurement), water consumption, patient and staff travel and waste disposal. Flow diagrams were created to model the PD pathway and product components were dismantled and weighed to determine material contributions. Environmental impacts were analysed using OpenLCA and the Ecoinvent database.

Results: Automated peritoneal dialysis (APD) treatments produced greater emissions than continuous ambulatory peritoneal dialysis (CAPD), primarily due to higher electricity consumption and the use of polyvinylchloride. APD generated 3267 kg CO_2e annually compared to 2975 kg CO_2e for CAPD. Monthly patient examinations contributed 250 kg CO_2e per year, largely from travel. CAPD produced more healthcare waste (320 kg), leading to 810 kg CO_2e emissions, while APD waste emissions were lower at 374 kg CO_2e. Incremental dialysis approaches showed substantial reductions, with emissions falling to 1642 kg CO_2e (APD) and 1517 kg CO_2e (CAPD). The most impactful materials included polyethylene and PVC, with plastic components contributing significantly to overall emissions.

Conclusion: This comprehensive life cycle assessment (LCA) highlights the environmental challenges associated with PD, particularly in waste generation and resource use. Key areas for improvement include reducing single-use plastic reliance, increasing recycling efforts and integrating energy-efficient solutions. This study provides a foundation for targeted sustainability interventions in PD and contributes to the broader goals of the KitNewCare project, which aims to optimise health outcomes while minimising environmental impacts in kidney care.

Keywords

Energy consumption, environmental impact, global warming potential, life cycle assessment, patient travel, peritoneal dialysis, single-use plastics, waste disposal

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Introduction

Kidney disease is a significant health burden, affecting over 850 million people worldwide.[1] Kidney failure, the most advanced stage of disease, may be treated with renal replacement therapy such as dialysis or kidney transplantation, though not all patients access or choose these options.[2] Dialysis remains the most common therapy, but its provision generates substantial environmental, social and economic burdens.

Peritoneal dialysis (PD) is a home-based therapy that provides greater flexibility and independence compared with haemodialysis (HD).[3,4] It reduces patient travel to hospital and is associated with lower infrastructure and staffing needs. Despite these advantages, PD is highly dependent on single-use plastics and packaging. Fluid bags, tubing and catheters contribute large volumes of non-biodegradable waste.[5] Delivering treatment at home also shifts some electricity and water consumption from hospital to household settings, as the APD cycler operates using domestic electricity and additional water is required for hygiene and waste disposal, even though the dialysate fluid itself is manufactured remotely.

The healthcare sector contributes around 5% of global greenhouse gas emissions and nephrology services are recognised hotspots within this footprint.[6] Life cycle assessment (LCA) is the established method for evaluating environmental impacts across the full life span of a product or process, from raw material extraction through disposal.[7] While LCA studies have been carried out for HD in Europe and Australia, no comprehensive LCA of the entire PD pathway in a European context has been published. Existing research has focused either on selected products, waste volumes, or partial system boundaries, leaving a significant evidence gap.

This study forms part of the KitNewCare project, an EU-funded initiative that aims to reduce the carbon footprint of kidney care while optimising health outcomes, equity and costs.[8] By mapping the full PD treatment pathway at a large Italian centre, this work addresses the lack of detailed environmental evidence for PD in Europe. It also provides data to inform targeted interventions in procurement, product design and service delivery.

Aim of study

This article maps the environmental footprint of the full PD treatment pathway using LCA. It aims to identify high-impact components and processes, supporting strategies to reduce environmental burden without compromising patient care. Data were collected at the Nephrology Dialysis and Kidney Transplant Unit, AOU Policlinico di Modena, Italy.

Methods

LCA was conducted between April and July 2024, following ISO 14040/14044 standards.[9,10]

Patient pathways

Identification of procedures and pathways. The LCA included all stages of PD care, including education, medical evaluations, treatment and waste disposal. Key data categories included energy and water use, travel, procurement and waste. It covered both automated peritoneal dialysis (APD) and continuous ambulatory peritoneal dialysis (CAPD), including incremental approaches that start with reduced exchanges and increase as needed based on residual kidney function or as clinically indicated.[11]

The main stages of the PD pathway evaluated are as shown in Supplementary Table S1 in the appendices.

Flow diagrams. Flow diagrams for each step were developed using Visio[10] and verified with clinical staff Supplementary Figure S1. These diagrams captured all activities and material usage. All data were compiled into a dataset published in the study appendices.

Dismantling products and weighing components. To estimate the environmental impact of the healthcare products used in PD, the products were dismantled into their individual components, the materials of each component identified and their weights measured.

A list of all products used in PD was collected. This included dialysis solutions, plastic tubing, connectors, bags and other consumables.

Each product was carefully dismantled to separate its components. For example, Dialysis bags were separated into plastic bags, caps and any other distinct parts.

Each component was weighed using a precision scale.[12] The weights were recorded and categorised based on component and material type (e.g., polyvinylchloride), polyethylene, polypropylene).

The recorded weights and material types were recorded for analysis.

APD machines were modelled using the Fresenius SleepSafe and Baxter HomeChoice systems, representing the main devices in clinical use at Modena. Inventories were built from prescriptions and consumables: CAPD involved three 2 L manual exchanges daily; APD used a cycler with two 5 L bags. Associated items included connectors, dressing kits and transfer sets. Brand-specific products from Baxter and Fresenius were modelled where data were available. A complete product inventory, including dressings, packaging and consumables, is provided in the supplementary dataset.

Incremental PD. Incremental prescriptions were defined as approximately half of the full dose prescription for each modality. For CAPD, the incremental regimen used around 50% of the exchanges and dialysate volume of the full dose (three 2 L manual exchanges per day; 6 L total dialysate for full prescription). For APD, incremental prescriptions similarly used roughly 50% of the dialysate

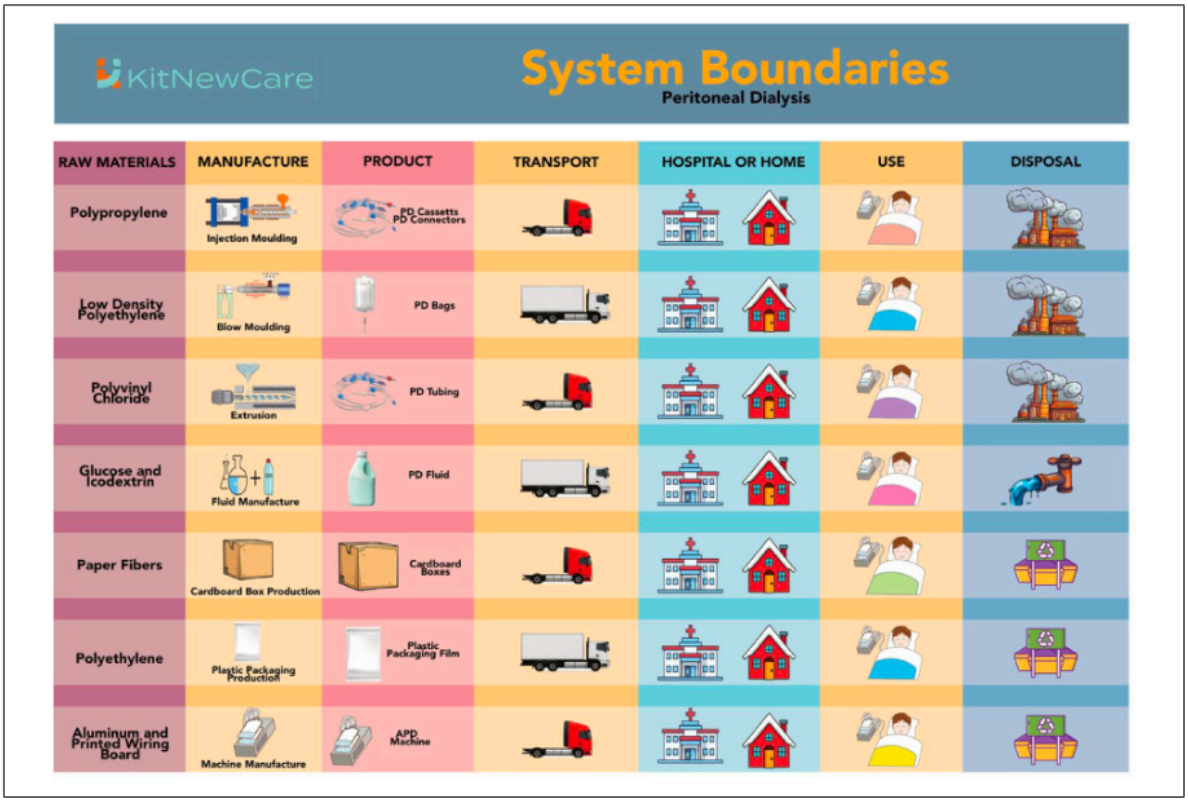

Figure 1. System boundaries for peritoneal dialysis. APD and CAPD are both included. The system boundary shows the 'cradle to grave' analysis of the LCA.

volume compared with the full dose APD regimen of two 5 L automated exchanges per night (10 L total dialysate).

Inputting data into OpenLCA. Material weights and types, alongside the flow diagrams, were input into OpenLCA.[10] Processes for each step were modelled and linked to the flow diagrams. Environmental impacts were then calculated using the Ecoinvent v3.10 database.[13]

To aid interpretation, results were normalised by scaling them relative to average environmental impacts per person, which indicates whether a process exceeds or falls below population-level benchmarks.

The incremental factors (0.5 for APD and CAPD) were applied as a pragmatic scaling method based on the observed reduction in annual dialysate volume and treatment intensity between full dose and incremental prescriptions. Where component level differences (for example specific consumables or materials) were directly quantified in the inventory, those measured values were used. For components that were not separately quantified, the same scaling factors were applied to the full dose data to ensure a consistent and transparent approach across all 17 procedures in the pathway.

System boundaries. The system boundaries (Figure 1) cover raw material extraction, manufacturing, transport, use and disposal. This includes materials for PD equipment such as dialysis solutions, tubing, connectors and disposal bags, as well as their processing into final products. Transport accounts for all freight and passenger journeys, including delivery from manufacturers to clinics or patients and waste disposal logistics. Packaging materials were included in procurement impacts. The use phase reflects solution preparation, administration, exchanges and drainage in the home setting. Disposal covers the treatment of medical waste, including used solutions, components and other consumables. Supplies originated mainly from European manufacturers and were delivered to Modena. Waste was segregated into clinical, recyclable and general streams.

Processes

Product manufacture. Component weights were measured in April 2024. Manufacturing processes were identified through product safety data sheets and informed assumptions. Machinery energy use was sourced from Eco Invent.[13]

Transportation. Transportation impacts included both freight of medical products and travel by patients and staff. All relevant data were modelled under a single process category for clarity.

Staff and patient travel. To avoid delays related to General data protection regulation (GDPR), staff and patient travel data were sourced from an Irish study on PD travel patterns.[14, 15] This served as a proxy to estimate transportation-related environmental impacts, including average distances for PD sessions and staff commutes. Patients travelled an average 29 km round trip, with similar distances for staff. These figures were reviewed and agreed upon by Modena staff as representative for the region.

Freight transport for supplies. All freight transport of consumables, machines, and packaging materials was modelled within the same transportation process. Distances were calculated using Google Maps for road freight and Fluentcargo.com for shipping. Modes included truck and ship transport, based on Italian and European datasets.[16,17] Where specific manufacturer data were unavailable, average European freight datasets from Ecoinvent v3.10[13] were used. Transport impacts covered the full journey from manufacturer to AOU Policlinico di Modena and included return of medical waste to disposal facilities.

Disposal. Waste management was modelled based on the segregation practices reported by hospital staff. Waste was categorised into clinical, recyclable and general streams. For home-based treatment, it was assumed that patients separated recyclable and general waste in line with hospital protocols, while clinical waste was collected for incineration.

Ethics

No ethical approval was required as the study involved only environmental assessment of devices and processes, with no personal data collected.

Functional unit

The functional unit for this study is defined as the complete PD treatment for a single patient over an average one-year period, allowing standardised comparison between treatment modalities. One-off activities such as education, surgery, catheter placement, peritonitis management and training were annualised by dividing their total footprint across an expected five-year treatment duration. This approach reduces their apparent contribution compared with recurrent activities such as monthly examinations or regular education sessions.

Results

The results have been analysed overall, by patient pathway and by process (e.g., transportation, procurement etc).

Results by patient pathway

The results by patient pathway can be found in Table 1. Results have been divided to show the difference in APD and CAPD. For simplicity the patient pathways are shown for carbon only PD treatment, monthly exam (the two highest patient pathways can be seen in (Table 2 and Supplementary Table 2).

Table 2 reflects a case mix of 30% APD, 4% CAPD, 30% incremental APD and 36% incremental CAPD, representing the treatment distribution in Modena. For transparency, results are also presented disaggregated by modality.

Laparoscopic insertion shows a lower annualised value than local insertion because it was less frequent in the cohort, whereas post-operative evaluation applies to all patients and therefore has a higher annualised contribution.

Catheter-related procedures contribute a small share of the annual footprint in the one-year functional unit. Laparoscopic insertion produces higher emissions per procedure due to theatre energy use, sterilisation and surgical instruments. However, it was performed less frequently than local anaesthetic insertion in the Modena cohort, so its impact appears smaller once annualised across all patients. The annualised values therefore reflect frequency of occurrence rather than per-event intensity.

Table 2 pathway 11 values represent a case mix of full dose and incremental prescriptions (30% APD, 4% CAPD, 30% incremental APD and 36% incremental CAPD), reflecting the treatment distribution in Modena. In contrast, Table 3 presents disaggregated modality-specific values for each modality (full dose APD, full dose CAPD, incremental APD and incremental CAPD) modelled separately. The APD value in Table 2 is therefore higher than the incremental APD value in Table 3 because it reflects a mixture of full dose and incremental treatment, rather than incremental APD alone.

PD treatment APD and CAPD. Figure 2 details the CO_2e contributions of key processes and materials involved in APD and CAPD. The top contributors are freight transport (1062 kg CO_2e for APD and 720 kg CO_2e for CAPD), followed by hazardous waste (359 kg CO_2e for APD and 436 kg CO_2e for CAPD), electricity (347 kg CO_2e for APD and 329 kg CO_2e for CAPD), polyethylene production (275 kg CO_2e for APD and 310 kg CO_2e for CAPD) and passenger car travel (239 kg CO_2e for APD and CAPD). Travel emissions associated with other pathways such as Monthly Examination and excluded from the treatment itself which is home based.

Monthly examination. Supplementary Table S2 presents the CO_2e emission associated with a single Monthly

Table 1. Carbon footprint patient pathways CO_2e emissions.

Pathway		Result APD [kg CO_2-Eq]	Result CAPD [kg CO_2-Eq]
1. Education for renal replacement therapy	Initial education on PD, HD, transplantation, or conservative care. Includes eligibility assessment by nephrologist.	17	17
2. Surgical evaluation for PD suitability	Surgeon assesses feasibility of peritoneal catheter placement.	7	7
3. Patient home suitability	Nurse visit to verify that home conditions meet PD safety requirements.	11	11
4. Pre-surgery evaluation	Preoperative testing by surgeon, anaesthesiologist and nurse.	4	4
5. Peritoneal catheter placement local aesthetic	Catheter inserted under local anaesthesia, followed by post-surgery function check.	7	7
6. Surgical placement of PD catheter laparoscopy	Catheter inserted laparoscopically in theatre.	0.6	0.6
7. Post-catheter surgical evaluation	Brief surgical wound review after catheter placement.	4	4
8. PD pre-training visit	Nurse performs a low-volume dwell to confirm catheter function.	9	9
9. CAPD training	Hands on training in manual exchanges and hygiene.	19	0
10. APD training	Training in cycler use and overnight connection setup.	0	28
11. PD treatment	Ongoing treatment at home with exchanges according to modality.	2145	1886
12. Monthly examination	Regular in-centre review, blood tests and clinical evaluation.	250	250
13. PET	Annual test of peritoneal membrane function.	34	34
14. Change terminal catheter set	Replacement every 6–12 months.	30	30
15. Malfunctioning catheter	Troubleshooting steps to restore flow.	0.4	0.4
16. Peritonitis procedure	Assessment, cultures and antibiotic therapy when infection is suspected.	0.6	0.6
17. Catheter removal	Removal of PD catheter when treatment ceases or changes modality.	0.4	0.4
Total annual emissions	-	2565	2289

Table 2. Pathway 11: PD treatment by process (including 30% APD, 4% CAPD, 30% incremental APD and 36% incremental CAPD).

Process	APD (kg CO_2e)	CAPD (kg CO_2e)	Incremental APD (kg CO_2e)	Incremental CAPD (kg CO_2e)
Freight transport	1062	720	534	367
Hazardous waste	359	436	180	222
Electricity (cycler and use)	347	329	174	168
Polyethylene (production/use)	275	310	138	158

(a) Treatment-only values exclude patient and staff travel, which are allocated to the Monthly Examination pathway. (b) Incremental prescription values were derived by applying the observed annual reduction factors to each APD and CAPD process component, consistent with Table 4 totals: APD factor 0.503 (1642/3267), CAPD factor 0.510 (1517/2975). (c) Incremental prescription values were derived by applying the observed annual reduction factors to each APD and CAPD process component, consistent with the modality totals: APD factor 0.5 (1642/3267 kg CO_2e) and CAPD factor 0.5 (1517/2975 kg CO_2e). Component-level data are available in the supplementary dataset for transparency.

Examination. Patient travel contributes the largest share at 208 kg CO_2, followed by staff travel at 28 kg CO_2e. Other emissions include waste (4 kg CO_2), plastic and other materials (7 kg CO_2e combined), electricity for medical equipment (2 kg CO_2) and manufacturing impacts (2 kg CO_2).

Incremental approach. Table 3 compares the annual carbon footprint of different dialysis modalities. Standard APD results in the highest emissions at 3267 kg CO_2e, followed by CAPD at 2975 kg CO_2. Incremental approaches significantly lower emissions: Incremental APD emits 1642 kg CO_2 and Incremental CAPD 1517 kg CO_2e.

Results by process

Staff and patient travel (the same among APD and CAPD). Supplementary Figure S2 shows that patient journeys

Table 3. APD versus CAPD versus incremental approach (1 year).

	kg CO_2e eq
APD	3267
CAPD	2975
Incremental APD	1642
Incremental CAPD	1517

contribute 311 kg CO_2e per year while staff travel contributes 80 kg CO_2.

Plastic material for APD and CAPD. Supplementary Figure S3 compares the amount of plastic materials used between APD and CAPD. CAPD involves more polyethylene (310 g vs. 275 g in APD), whereas APD uses more polypropylene (43 g vs. 30 g) and significantly more PVC (44 g vs. 1 g).

Disposal for APD and CAPD consumables. Supplementary Tables S3 and S4 present a comparison of waste profiles for APD and CAPD. APD generates a total of 145 kg of healthcare waste (general + clinical as PD takes place at home) resulting in 374 kg CO_2, while CAPD generates a combined 320 kg healthcare waste with a higher impact of 810 kg CO_2. CAPD also produces more cardboard and paper waste.

Results by environmental impacts

The results of the LCA are shown in Table 4. All results are reported as annual impacts per patient. The results include all 16 impact categories of PD and emphasise its environmental impact. The analysis included 16 distinct impact categories, reflecting a wide range of environmental concerns. These results highlight the environmental burden of PD and where improvements could be targeted.

The results reveal that the environmental impacts of PD are significant across various categories, particularly climate change, acidification, ecotoxicity, eutrophication, resource use and human health impacts.

The results were normalised as recorded in Figure 3. Normalisation is the process of comparing the environmental impacts of the system to a broader reference for comparison.

The highest environmental burdens were associated with non-renewable energy use (2.63), freshwater ecotoxicity (1.59) and climate change (1.38). Other notable impacts included photochemical oxidants (1.29), acidification (1.05) and particulate matter (0.99). These categories align with KitNewCare key performance indicators, highlighting them as priority areas for intervention.

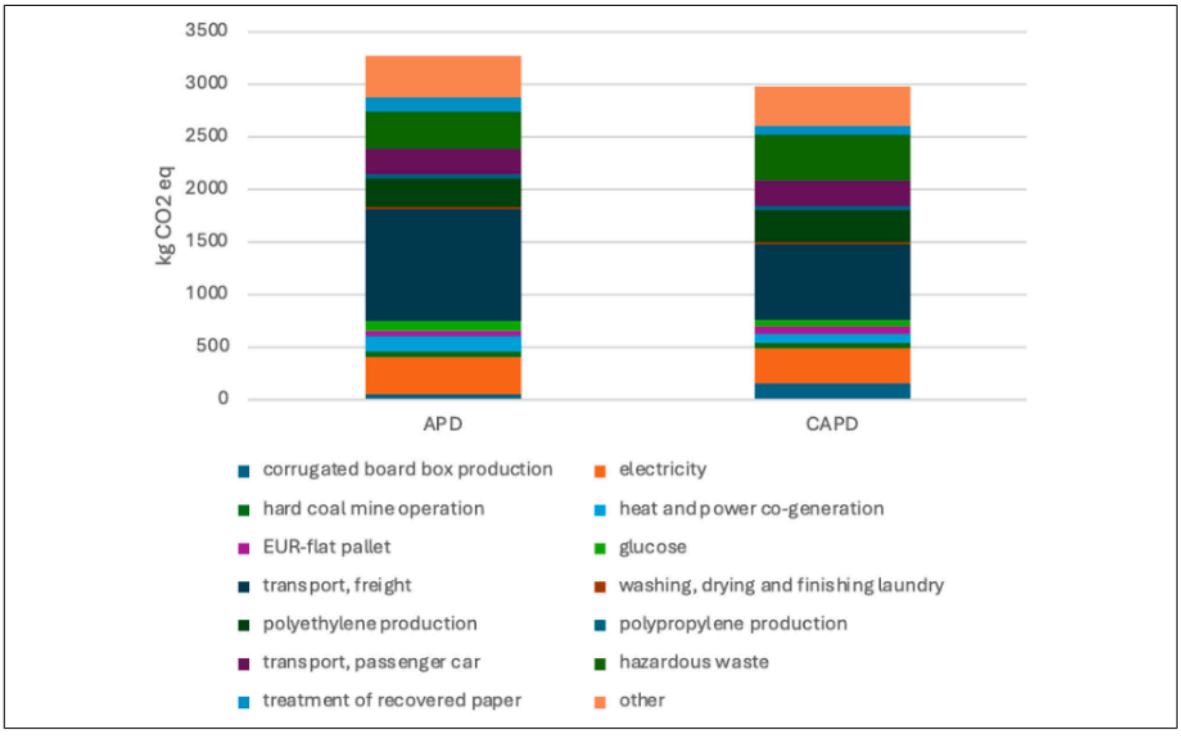

Figure 2. Contribution analysis of APD and CAPD.

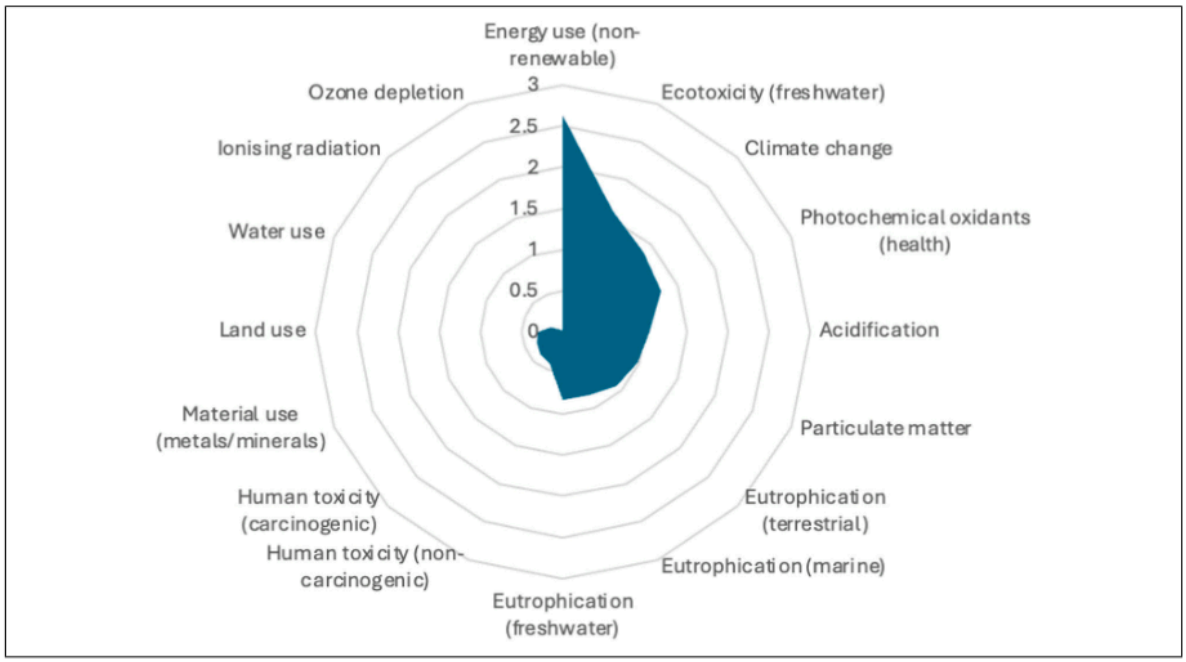

Figure 3. Normalised scores across 16 impacts.

Table 4. LCA results across 16 impacts.

Impact category	Impact assessment result	Unit
Acidification	11.716775	mol H^+-Eq
Climate change	2230.69738	kg CO_2-Eq
Ecotoxicity (freshwater)	13,564.4985	CTUe
Energy use (non-renewable)	34,256.0595	MJ (net calorific value)
Eutrophication (freshwater)	0.26351371	kg P-Eq
Eutrophication (marine)	3.24341716	kg N-Eq
Eutrophication (terrestrial)	32.4510544	mol N-Eq
Human toxicity (carcinogenic)	1.30E-06	CTUh
Human toxicity (non-carcinogenic)	1.89E-05	CTUh
Ionising radiation	40.1352328	kBq U235-Eq
Land use	50,457.6262	dimensionless
Material use (metals/minerals)	0.00438602	kg Sb-Eq
Ozone depletion	1.69E-04	kg CFC-11-Eq
Particulate matter	1.18E-04	disease incidence
Photochemical oxidants (human health)	10.4932758	kg NMVOC-Eq
Water use	362.027239	m^3 world eq. deprived

Supplementary Figures S4–S8 show the comparison between the APD and CAPD treatments across the main environmental categories.

- Acidification: APD results in higher total emissions across freight (6.97 vs. 2.28 AE), electricity (0.28 vs. 0.07 AE) and PVC-related processes (0.16 AE in APD only). CAPD shows higher values for corrugated box use (0.52 AE) and hazardous waste (0.37 vs. 0.20 AE).
- Ecotoxicity (Freshwater): CAPD is more affected by hazardous waste (4172.28 CTUe vs. 3432.84 CTUe), while APD contributes more via transport (4470.99 vs. 3110.75 CTUe) and glucose (1345.14 vs. 807.08 CTUe).
- Energy Resources: APD has larger footprints for freight (9062.07 MJ vs. 7246.36 MJ), polyethylene (8041.63 vs. 5993.98 MJ) and PVC (795.23 MJ, not used in CAPD). CAPD's other significant contributors include uranium (387.40 MJ) and lignite (715.14 MJ).
- Photochemical Oxidants: APD sees larger impacts from freight (6.86 vs. 3.14 kg NMVOC-Eq) and PVC (0.13, not used in CAPD), while CAPD has higher contributions from hazardous waste (0.31 vs. 0.17).

Table 5. Summary of key improvement opportunities across the PD pathway.

Environmental issue	Main source or process	Responsible stakeholder	Suggested intervention
High CO_2e and energy use	Electricity consumption during APD	Manufacturers, energy suppliers, hospital sustainability teams	Improve cycler energy efficiency; source renewable electricity for home use
Plastic-related emissions and waste	Single-use PVC and polyethylene components	Manufacturers, procurement teams	Substitute PVC with recyclable polymers; redesign for modularity; increase take-back schemes
Freight and packaging emissions	Long-distance transport of consumables and excessive packaging	Manufacturers, distributors	Source locally; optimise packaging size; shift to low-carbon logistics
Hazardous waste from disposables	Incineration of mixed materials	Hospitals, waste contractors	Improve waste segregation; expand recycling for non-contaminated components
Patient and staff travel	Monthly hospital visits for examinations	Healthcare providers, policy makers	Expand telehealth and home testing; decentralise blood sampling
Water and material use in product manufacture	Resource-intensive production of plastics and textiles	Manufacturers, regulators	Adopt water-efficient manufacturing; prioritise suppliers with environmental certifications
Eutrophication and ecotoxicity impacts	Chemical discharges from upstream manufacturing	Manufacturers, environmental agencies	Tighten supplier standards; use cleaner production methods
Limited public awareness of environmental burden	Knowledge gap among clinicians and patients	Healthcare educators, professional bodies	Integrate sustainability training into clinical education; communicate environmental data transparently

- Water Use: APD's glucose use (178.33 m^3 vs. 107.00 m^3), polyethylene (27.44 m^3) and extrusion (8.09 m^3, not found in CAPD) dominate. CAPD leads in corrugated board (29.76 m^3) and hazardous waste (38.47 m^3 vs. 10.87 m^3).

Supplementary Figures S9 through S20 provide detailed breakdowns of environmental impacts by the top five more impactful procedure types (Monthly Examination, PET, APD Training and Changing Catheter) across the five highest environmental impacts from the normalisation and also including water use.

- Climate Change: Monthly Examination contributes the most to climate change at 135.65 kg CO_2-Eq, primarily from passenger car travel. PET produces 17.92 kg CO_2-Eq, APD Training 16.59 kg CO_2-Eq and Changing Catheter 15.03 kg CO_2-Eq.
- Acidification: Monthly Examination has the highest impact at 0.299 mol H^+-Eq, primarily from freight and passenger car transport and natural gas. PET contributes 0.063 mol H^+-Eq, while APD Training and Changing Catheter have lower impacts at 0.050 and 0.005 mol H^+-Eq respectively.
- Ecotoxicity, Freshwater: The largest contributor is Monthly Examination at 259.39 CTUe, primarily due to benzene and petroleum emissions. PET follows at 34.27 CTUe, with APD Training at 31.73 CTUe and Changing Catheter at 27.53 CTUe.
- Energy Resource Use: Monthly Examination again shows the highest impact at 2532.70 MJ, followed by PET at 334.96 MJ, APD Training at 308.66 MJ and Changing Catheter at 271.02 MJ. Petroleum dominates the energy resource category.
- Photochemical Oxidants: Monthly Examination leads with 0.281 kg NMVOC-Eq, driven by passenger car and freight transport. PET and APD Training follow at 0.042 and 0.033 kg respectively, while Changing Catheter contributes 0.036 kg.
- Water Use: Monthly Examination has the highest water use at 49.05 m^3 world eq. deprived, predominantly from textile usage. PET, APD Training and Changing Catheter result in 1.60, 0.44 and 1.22 m^3 respectively.

Discussion

This European LCA of the full PD pathway identifies the main contributors to environmental burden across materials, energy, waste, transport and clinical workflows. Aggregate results across 16 categories are in Table 1. Normalised scores in Figure 3 highlight non-renewable energy use, freshwater ecotoxicity and climate change as dominant categories, consistent with LCA method guidance and prior multi-category healthcare LCAs.[7,18,19] Process contributions for APD and CAPD are in Figure 2.

APD showed higher total impacts than CAPD, driven by electricity for the cycler and PVC-containing disposables, while CAPD generated larger packaging and clinical waste streams. These treatment differences appear in Table 2 and in the contribution profiles in Figure 3.

Plastic materials, in particular polyethylene and PVC, were consistent hotspots across categories. Within PD treatment, plastics account for about 41% of total CO_2e in Pathway 11 based on the contribution analysis in Table 3. These patterns align with recent PD carbon studies in Australia and China that reported large contributions from dialysate, plastics and logistics, noting product and supply-chain differences between settings.[17,20–22] The Australian study[21] analysed Baxter products, which contain higher proportions of PVC in dialysis bags and tubing, leading to PVC dominating the material footprint. The Modena centre used a mixed product supply that included Fresenius components with lower PVC content and a greater proportion of polyethylene, resulting in a smaller PVC contribution in this study. Chinese data[22] reported higher emissions per exchange, likely due to differences in supply chain energy sources and manufacturing processes.

Incremental prescriptions reduced impacts by lowering dialysate volume and consumable use during earlier treatment phases. Annual carbon footprints for the four modalities are in Table 4, with incremental APD and incremental CAPD showing the lowest CO_2e. This is consistent with evidence that staged PD intensity can reduce plastic use and glucose exposure while preserving adequacy as residual kidney function declines.[6,11]

Normalisation results in Figure 2 show that focusing only on climate change misses other pressures. High freshwater ecotoxicity relates to upstream plastics production and end-of-life management. Energy resource use reflects fossil energy across manufacturing and freight. Photochemical oxidants are linked to transport and combustion. These findings are consistent with harmonisation work on toxicity in life cycle impact assessment and with guidance on water use indicators.[18,19] Ozone depletion remains low, but related photochemical oxidants still warrant attention in transport and manufacturing.[23]

Travel was a recurring hotspot for monthly in-centre reviews rather than for home treatment. Table 2 reports 250 kg CO_2e per patient per year for monthly examinations, with patient travel the largest contributor as shown in Supplementary Table S2. Shifting routine reviews toward telehealth, community phlebotomy and validated home sampling can reduce travel emissions while maintaining clinical oversight.[24–26]

Waste and product design offer near-term improvement opportunities. CAPD generated more healthcare waste and higher disposal impacts than APD, as shown in Supplementary Tables S3 and S4. Material substitution away from PVC, design for disassembly and better segregation increase recovery of non-contaminated components, supporting lower toxicity and lower end-of-life burdens.[18] Freight and packaging also contribute, as shown in Figure 3, which supports local sourcing, packaging optimisation and lower-carbon logistics.[17,21,24]

Key take-away points for practice

1. Prioritise incremental PD where clinically appropriate to reduce dialysate volume and consumables.[6,11]
2. Reduce electricity impacts in APD through higher-efficiency cyclers and renewable household electricity, supported by energy supplier programmes and hospital facilitation.[1,21]
3. Substitute PVC and redesign components for recyclability to address toxicity and disposal burdens, using supplier standards aligned with LCIA characterisation guidance.[18]
4. Consider incorporating telehealth and home or community testing approaches, where clinically appropriate and evidence-supported, to potentially reduce travel emissions while maintaining clinical oversight and patient safety.[25,26]
5. Optimise freight and packaging to lower upstream energy and transport impacts, building on lessons from recent PD carbon footprints in other regions.[17,21,22]

These findings provide a practical basis for the improvement opportunities summarised in Table 5 and align with the goals of KitNewCare to reduce environmental burdens while supporting high-quality care.[8]

Limitations

This study has several limitations. Data collection was confined to a single site (AOU Policlinico di Modena) and a limited timeframe (April–July 2024), which may not reflect broader PD practices. Pharmaceuticals were excluded due to lack of reliable datasets, which may underestimate total environmental impacts. However, the KitNewCare project plans to replicate the study across three additional sites, enabling comparative analysis.

The LCA depends on the accuracy of input data, including material weights and types, which are available in the 'Life Cycle Assessment Dataset for Peritoneal Dialysis in Modena'. Environmental modelling was limited by the available impact categories in OpenLCA and the Ecoinvent v3.10 database. While some healthcare-specific impacts (e.g., pharmaceutical emissions) are not fully represented, we selected 16 robust indicators to ensure methodological consistency and international relevance. Assumptions regarding patient travel mode, supply origins and household waste segregation may not fully reflect real-world variation and could influence results.

Conclusion

This article provides a comprehensive analysis of the environmental impacts of the PD treatment pathway over one year. The findings highlight product production, waste disposal and procurement as key contributors to the overall environmental burden. By addressing these areas, healthcare systems can reduce the environmental footprint of PD and promote more sustainable practices in kidney care.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data availability statement

All data generated or analysed during this study are publicly available in the Zenodo repositories: Larkin, J. (2024) 'Life Cycle Assessment Dataset For Peritoneal Dialysis in Modena'. Brett Duane. doi: 10.5281/zenodo.14258866; Larkin, J. (2024) 'Product Images for Life Cycle Assessment Dataset For Peritoneal Dialysis in Modena'. Brett Duane. doi: 10.5281/zenodo.14258920.

Ethical approval

Ethical approval was not required for this study as it did not involve human participants or animal research. The study focused solely on environmental data collection and analysis related to peritoneal dialysis systems.

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Informed consent to participate

Not applicable. This research did not involve any individual participants, patients, or human data.

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Supplemental material

Supplemental material for this article is available online.

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NEPHROLOGY – ORIGINAL PAPER

Comparing environmental footprints of haemodialysis and online haemodiafiltration in Italy

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Abstract

Background Haemodialysis (HD) and online haemodiafiltration (OLHDF) are the main in-centre treatments for kidney failure. Both rely on high water and energy use and produce substantial greenhouse gas emissions. OLHDF provides superior solute clearance and improved survival compared with high-flux HD, but its environmental burden remains less defined. Clarifying these differences supports evidence-based and sustainable treatment decisions.

Methods A process-based life cycle assessment (LCA) was performed at the Nephrology, Dialysis and Kidney Transplant Unit, AOU Policlinico di Modena, Italy, in 2024, following ISO 14040 and 14,044 standards. The functional unit was one patient year of treatment, equal to 156 sessions. System boundaries included procurement, water treatment, session operations, travel and waste management. Modelling used OpenLCA with Ecoinvent 3.11 and the Italian electricity grid factor of 0.25 kg CO2 per kWh. Scenarios assessed HD-only, OLHDF-only and the real-world Modena treatment mix. Sensitivity analysis varied the share of OLHDF, session frequency, grid intensity and reverse-osmosis (RO) recovery rate and included a reduced-flow OLHDF prescription.

Results The annual footprint was 4469 kg CO2-eq, 60,290 MJ and 1364 m3 world-eq deprived water per patient year. HD generated 4427 kg CO2-eq and OLHDF 4548 kg CO2-eq, reflecting slightly higher electricity and water consumption and greater plastic use in OLHDF. Travel contributed 71% of total emissions and procurement 21%. Sensitivity analysis showed changes in RO efficiency and electricity mix had stronger effects than treatment type.

Conclusions HD and OLHDF have comparable environmental profiles. Clinical outcomes should drive modality choice, while sustainability gains depend on improving transport, water recovery, energy management and renewable integration.

Keywords Haemodialysis · Haemodiafiltration · Life cycle assessment · Environmental impact · Carbon footprint · Energy use · Water consumption · Sustainable kidney care

Introduction

Chronic kidney disease (CKD) affects more than 850 million people globally, making it a major public health challenge [1]. Many patients progress to kidney failure requiring kidney replacement therapy (KRT) in the form of transplantation or dialysis [2]. Haemodialysis (HD) remains the most widely used KRT, delivered primarily in hospital or satellite centres. Online haemodiafiltration (OLHDF), which combines diffusive and convective clearance, is increasingly adopted because of its clinical benefits, including improved survival compared with high-flux HD [3].

Dialysis is among the most resource-intensive areas of healthcare. A single HD session typically consumes up to 370–600 L of water and 5–15 kWh of electric energy from optimal to conventional settings [4–6]. This equates to tens of thousands of litres of water and thousands of kilowatt-hours per patient each year. In one Australian study, dialysis services were estimated to account for up to 7% of total hospital carbon emissions, driven primarily by patient transport, electricity use, water consumption and single use consumables. This figure, derived for a specific high income hospital context, provides an order of magnitude indication of dialysis-related impacts rather than a centre specific estimate [7]. Such figures are particularly concerning in light of international commitments to healthcare decarbonisation,

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including the European Green Deal and net-zero targets set by health systems, such as the NHS [8, 9].

Life cycle assessment (LCA) provides a systematic framework to evaluate environmental impacts from cradle to grave, covering resource extraction, manufacturing, transport, use and disposal [10, 11]. LCA has been applied to healthcare in several contexts, including surgical equipment, imaging and pharmaceuticals [12, 13]. In nephrology, it has been used to map peritoneal dialysis (PD) pathways, HD consumables and entire treatment pathways [14–16].

Quantifying the environmental impacts of medical treatments can support decarbonisation policies, procurement and technology development by identifying hotspots and enabling evidence-based mitigation strategies. At the same time, disclosing environmental performance carries a risk of misinterpretation or inappropriate trade-offs if environmental indicators are considered in isolation from clinical outcomes, equity and patient preferences. Incorporating LCA findings into kidney care, therefore, requires careful communication and integration with broader quality and safety goals [12].

In dialysis LCAs, system boundaries are typically defined from cradle to grave, encompassing production and transport of consumables, water treatment, session operations and waste management, with or without patient transport depending on data availability. Functional units often use a patient year or single dialysis session as a declared unit of service, allowing comparison across modalities while recognising that clinical outcomes, such as survival and hospitalisation rates, may differ between treatments. This study adopts this convention while explicitly acknowledging its limitations for comparing modalities with unequal effectiveness [12, 13].

Clinically, OLHDF has been shown to improve outcomes. The CONVINCE trial demonstrated reduced mortality and higher quality-adjusted life years compared with high-flux HD, while a pooled analysis of four large randomised controlled trials comparing HD and OLHDF also showed improved overall and cardiovascular mortality with OLHDF [3], [17, 18]. Cost–utility analysis suggests these benefits come at higher financial cost, largely due to extended survival [19]. Environmentally, however, OLHDF requires additional resources, including higher water use and dedicated tubing sets with integrated substitution lines that increase plastic consumption. This indicates that while HDF may be clinically superior, it is likely more resource intensive.

This study aimed to compare HD and OLHDF using detailed LCA based on primary data from the Nephrology Dialysis and Kidney Transplant Unit of the Policlinico di Modena, Italy. Objectives were to (a) quantify the total HD pathway footprint, (b) calculate separate footprints for HD and OLHDF and (c) present weighted results reflecting real-world treatment distribution. Findings are intended to inform clinical decision-making, policy and technology development in sustainable kidney care. This paper is part of the KitNewCare project, which seeks to reduce the environmental impact of kidney care through sustainable innovations [20].

Methods

Goal and scope definition

In line with ISO 14040/44, the Methods are organised into goal and scope definition, life cycle inventory and life cycle impact assessment.

The functional unit was defined as one patient year of in-centre dialysis, equivalent to 156 sessions, reflecting a typical thrice-weekly treatment schedule used in routine practice and previous dialysis LCAs. Functionally, this represents the provision of kidney replacement therapy for one patient over 1 year in an in-centre setting, including all associated consumables, water treatment, session operations, travel and waste management. Because OLHDF improves clinical outcomes relative to high-flux HD, this patient year is treated as a declared unit for comparative environmental profiling rather than a strictly functionally equivalent unit, and the limitations of this approach are discussed in the Discussion [21].

A cradle-to-grave boundary was applied, covering:

1. Procurement: production and inbound transport of dialysers, bloodlines, concentrates, needles and other single-use consumables, including associated plastics, packaging and manufacturing energy.
2. Water treatment: At the Modena centre, feed water is municipal tap water, treated on-site by an RO system to produce ultrapure product water for HD and OLHDF; no separate deionised water system is used. Supply of municipal tap water, on-site reverse osmosis (RO) treatment and distribution loops to generate ultrapure product water, including electricity use and discharge of reject water. Data on the disinfection of internal water distribution pipelines were not available and were, therefore, not included; this omission is expected to have minimal influence on total impacts.
3. Session operations: electricity use of Fresenius 5008 machines, dialysate preparation and substitution fluid generation for OLHDF, and ancillary processes during treatment (including standby and thermal disinfection cycles).
4. Waste management: segregation, collection, transport and treatment (autoclaving, incineration, landfill) of haz-

ardous and non-hazardous solid and liquid wastes from dialysis sessions.

5. Travel: patient and staff commuting to and from the dialysis centre, modelled as round-trip journeys per session.

System boundaries included procurement, water treatment, session operations, travel and waste management [12, 13]. The analysis excluded pharmaceuticals, vascular access creation and maintenance, upstream building and equipment infrastructure and other hospital services outside the dialysis unit. These elements were omitted due to limited data and an expected relatively small contribution at the level of a single centre; their exclusion is noted as a limitation Fig. 1.

Life cycle inventory

Procurement

Procurement data were obtained from hospital purchasing records and supplier specifications. Each consumable was dismantled and weighed to determine material composition, similar to approaches used in previous dialysis LCAs [14, 15].

Energy

Energy consumption was directly measured for both HD and OLHDF during active treatment and disinfection cycles using a calibrated plug-in energy meter connected to the Fresenius 5008 machines. Measurements covered the full 4-h treatment duration plus thermal disinfection and were repeated across

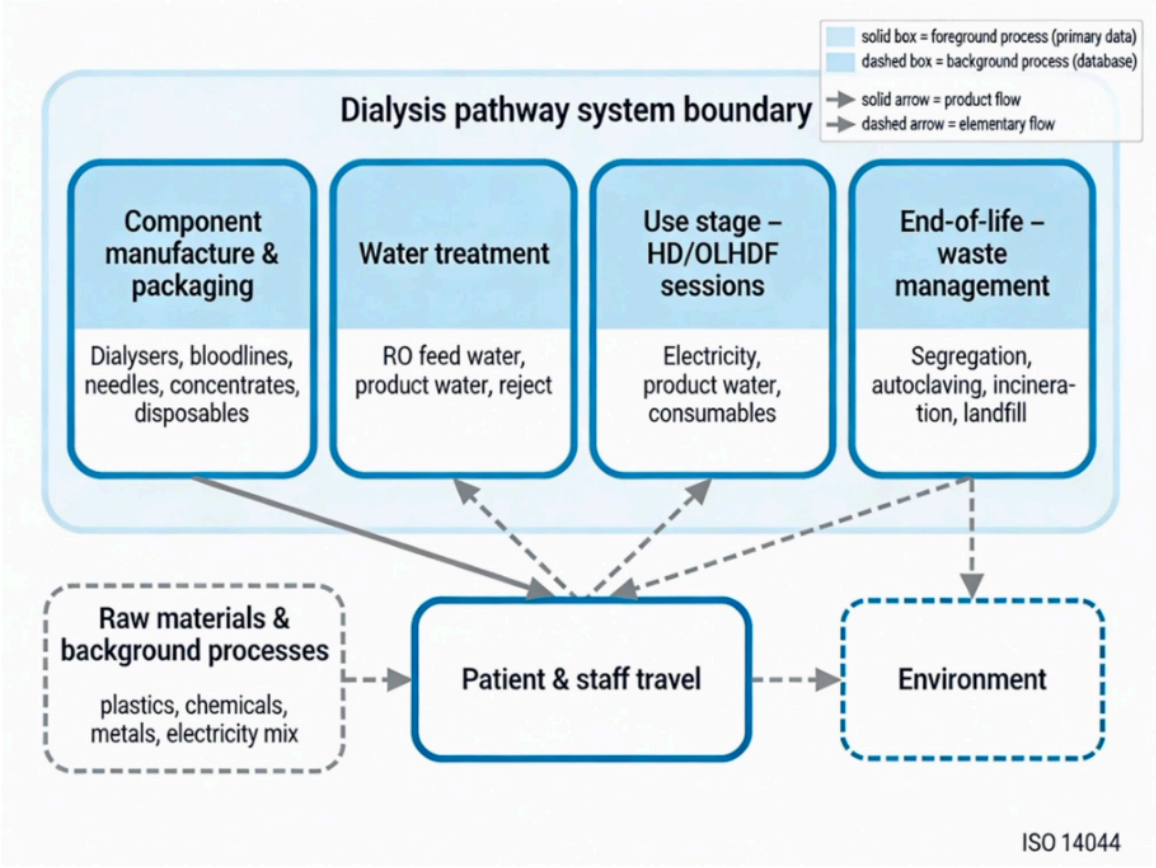

Fig. 1 System boundary (ISO 14040/44 aligned). Upstream: raw materials, component manufacturing, packaging and inbound transport for dialysers, bloodlines, concentrates and other consumables. Core/use: municipal tap water supply and RO treatment, electricity use of Fresenius 5008 machines, dialysate and substitution fluid preparation, and use-phase consumables. Downstream: segregation, collection, transport and treatment of solid and liquid wastes, and patient and staff travel to and from the dialysis centre. Foreground processes (primary data from Modena) are shown as solid boxes; background processes (Ecoinvent 3.11) are shown as dashed boxes

multiple sessions for each modality; average per-session values were then derived. These data replaced previous assumptions of negligible difference between modalities. Energy use included active treatment and standby modes.

Water

Water use was measured at the on-site RO system using a dedicated flow meter installed on the product water line. Volumes were recorded over the data collection period and averaged per session, distinguishing HD and OLHDF based on the number of sessions delivered for each modality. Operational water requirements were, therefore, assigned as 382 L per session for HD and 409 L for OLHDF, with values cross-checked against published data for similar RO systems [4].

Waste

Waste management practices were confirmed with the hospital's waste contractor, including segregation into hazardous and non-hazardous streams, autoclaving, incineration and landfill.

All underlying data sets and product images used for this analysis are openly available through Zenodo and referenced in the Supplementary Material.

Transport

Patient and staff travel were included in the system boundaries. Patient round trip distances per session were derived from an Irish HD cohort study, because equivalent patient level transport data were not available for Modena; the distribution of dialysis centres and reliance on in centre treatment are broadly similar in both settings, making these data a reasonable proxy for average travel distances. Staff commuting was modelled using average round-trip distance and car use from national statistics. Travel was represented using a mix of passenger car transport processes from Ecoinvent 3.11, reflecting the vehicle types and fuel classes documented in the supplementary modelling workbook [29].

A summary table distinguishing primary measured data, secondary literature-based parameters and background Ecoinvent data sets for key inventory items is provided in the Supplementary Material and referenced in Appendix 1.

Life cycle impact assessment

At Modena, the treatment mix was 52% HD, 47% OLHDF and 1% Haemodiafiltration with online reinfusion of the endogenous ultrafiltrate (HFR). HFR was excluded due to negligible use and not the purpose of this study. Scenario modelling was conducted for HD-only, OLHDF-only and the weighted Modena mix.

All inventories were modelled in OpenLCA version 2.5.0 using the Ecoinvent 3.11 database [22]. LCIA was performed using the EF v 3.1 midpoint method without normalisation or weighting. Background processes included European data sets for plastics, transport and electricity generation. The Italian electricity grid was modelled at an average carbon intensity of 0.25 kg CO_2/kWh [23].

Machine production was excluded, consistent with conventions in healthcare LCAs [12],[24]. Previous work has shown that capital equipment typically contributes < 5% of the footprint of high-intensity therapies [25].

Three midpoint categories were reported:

- Climate change: kg CO_2 equivalents,
- Energy resources: MJ, net calorific value,
- Water use: m^3 world eq deprived.

Operational litres were reported alongside LCA water scarcity values to ensure transparency, since LCIA water metrics do not directly reflect volumetric use [26].

Climate change, water use and energy resources were selected as impact categories, because they represent the most material environmental concerns for dialysis care. Climate change is the most widely reported and policy-relevant endpoint in healthcare LCAs, allowing comparability across studies and alignment with decarbonisation targets [10], [12]. Water use was included due to the high operational volumes required for dialysate preparation and the growing recognition of water scarcity as a critical planetary boundary [26]. Energy resources were reported, because electricity use is a major contributor to dialysis impacts, with results sensitive to regional grid intensities [23]. Other categories such as toxicity, land use and resource depletion were not prioritised, as prior studies have shown these to be relatively minor contributors in dialysis pathways compared with carbon, water and energy [14, 15].

Accordingly, this study is presented as a process-based life cycle assessment focusing on three key midpoint categories (climate change, energy resources, water use). Other impact pathways (e.g., toxicity, land use, and resource depletion) were not quantified and their omission is acknowledged as a limitation. The reported climate change results do not constitute a standalone ISO 14067 carbon footprint study.

Differences between HD and OLHDF were modelled as follows:

- Water: HD consumes 382 L per session, OLHDF 409 L, based on measured substitution volumes [4]. Blood flow rates of approximately 350 mL/min were applied as well as a convective volume of at least 23L/session [27]. RO recovery was set at 65%, meaning the 35% of feed water is discharged as reject [28].

- Procurement: Both modalities used the Fresenius 5008 machine. OLHDF required two dialysate-side ultrafilters for online substitution fluid generation, replaced quarterly as per manufacturer guidance, while HD did not use these additional filters. The tubing set for OLHDF included integrated substitution lines, resulting in higher plastic mass and associated emissions.

Foreground flows were matched to Ecoinvent 3.11 processes based on technology similarity and regional scope (European or global averages, where Italian data were not available), following cutoff allocation. A mapping table listing the main foreground flows (e.g., dialyser plastic types, tubing sets, electricity, transport, and waste treatments) and their associated Ecoinvent processes is provided in the Supplementary Material Appendix 1 to support transparency and reproducibility.

Sensitivity analysis examined the influence of operational and external parameters on total results. Variables tested included:

(1) The proportion of OLHDF treatments (0–100%),
(2) Treatment frequency (150–160 sessions per year),
(3) Electricity grid carbon intensity (Italy 0.25 vs EU average 0.29 kg CO_2/kWh) and
(4) RO recovery efficiency (50–80%).

A reduced-flow OLHDF scenario was also modelled using a Qd/Qb (dialysate to blood flow) ratio of 1.2 and a convective volume of 25 L, consistent with literature-reported water-saving prescriptions. Directly measured energy and water values replaced earlier assumptions of equivalence between modalities. For each scenario, total annual results were recalculated and compared with the baseline in absolute terms and as percentage changes to facilitate interpretation.Complete results are presented in Appendix 2.

Ethical approval was not required for the project detailed in the document, because it involved the environmental assessment of procurement processes and medical devices, rather than research on human participants, patient data, or any other ethical domain requiring institutional review board (IRB) oversight. The focus was on analysing the lifecycle and environmental impacts of products, which does not typically intersect with areas necessitating formal ethical considerations.

Results

Total haemodialysis pathway

The full HD pathway at the Nephrology Dialysis and Kidney Transplant Unit of the AOU Policlinico di Modena produced an annual environmental footprint of 4,469 kg CO_2-eq, 60,136 MJ energy resources and 1,361 m^3 world eq deprived water per patient year (Fig. 2).

The water use indicator (m^3 world-eq deprived) expresses potential deprivation of water availability for other users in water-scarce regions, and, therefore, does not equal volumetric water consumption; both scarcity-weighted results and measured litres are reported for transparency.

Category contributions

The largest contributor to emissions was patient travel, responsible for 2,548 kg CO_2-eq, or about 57% of the total pathway footprint. Staff travel contributed 615 kg CO_2-eq. (14%), representing commuting by clinical staff working in the dialysis unit. These figures were based on an average round-trip distance of 29 km per session, derived from Irish haemodialysis travel data, as equivalent Italian patient-level data were not available for ethical reasons as equivalent Italian patient level data were not available for ethical reasons; this proxy influences absolute footprint values but does not affect the relative comparison between HD and OLHDF, because both modalities share the same travel assumptions. The travel distance is considered representative of typical in-centre dialysis access patterns in Modena [29].

Procurement generated 919 kg CO_2-eq in the combined pathway, with 896 kg CO_2-eq for HD and 942 kg CO_2-eq for OLHDF. The higher value for OLHDF reflects the use of a dedicated tubing set with an integrated substitution line, which increases the quantity of plastic and packaging compared with the standard HD bloodline set. OLHDF also requires two additional ultrafilters within the machine, replaced quarterly, which contribute a negligible increase of approximately 0.00011 kg CO_2-eq per patient year to the total footprint.

Electricity use, including the dialysis machine and RO system, accounted for 192 kg CO_2-eq for HD and 215 kg CO_2-eq for OLHDF. Machine electricity, including both the dialysis machine (2.1 kwh per patient per session for HD) and RO systems (3.1 kwh per patient per session) were taken. Direct measurements also showed that OLHDF consumed approximately 5.7% more electricity than HD, mainly due to the additional substitution pump and convective flow operation.

Water production contributed 32 kg CO_2-eq for HD and 35 kg CO_2-eq for OLHDF, consistent with the additional 125 L of ultrapure water required per session to generate substitution fluid. Healthcare waste accounted for 130 kg CO_2-eq for HD and 143 kg CO_2-eq for OLHDF, again reflecting the larger volume of plastic consumables used in OLHDF. The residual "Other" category contributed 14 kg

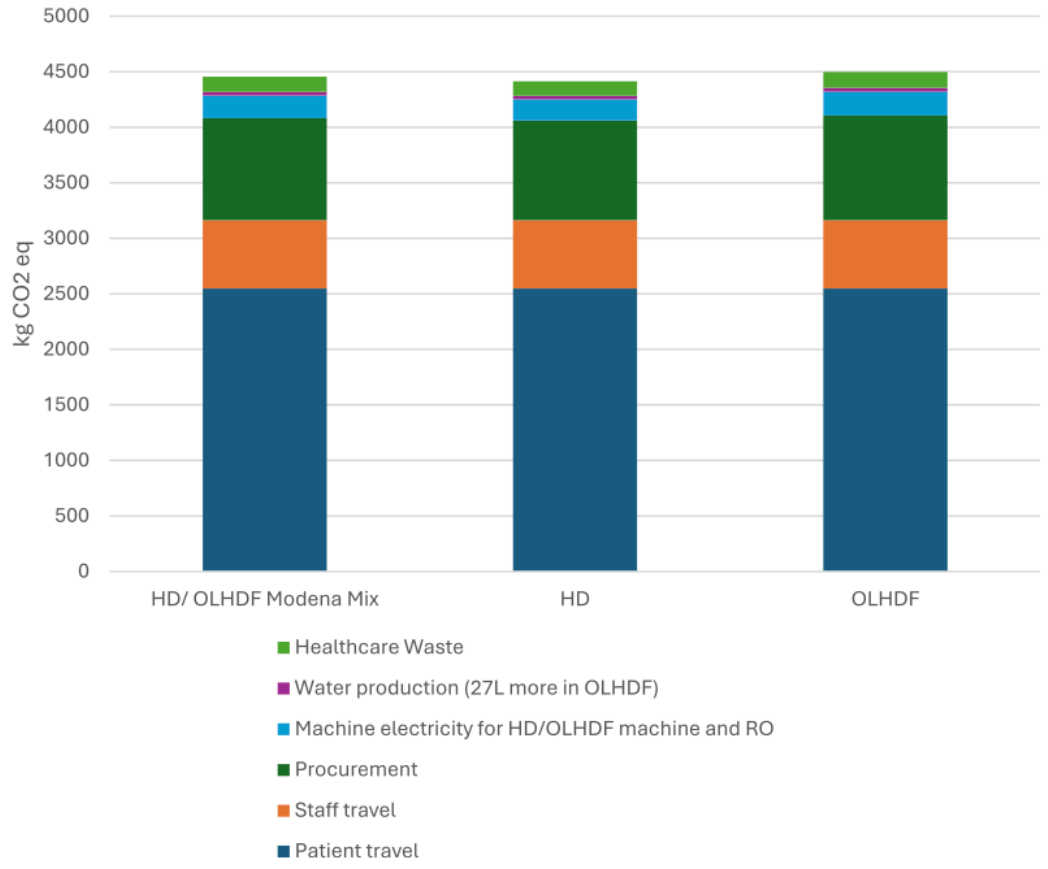

Fig. 2 Annual climate impact (kg CO_2 -eq) of the full HD pathway for one patient year at Modena (52%, 47% OLHDF), including patient and staff travel, procurement, water treatment, session operations and waste management. Bars show contributions by life cycle stage

CO_2-eq (< 1%), covering supporting hospital services, such as lighting, cleaning and administration.

Session contributions and modality comparison

Environmental burdens at the session level were similar between modalities, with only small differences arising from higher material use, energy demand and water consumption in OLHDF.

- HD only: 4,427 kg CO_2-eq per patient year (28.38 kg CO_2-eq per session).
- OLHDF only: 4,548 kg CO_2-eq per patient year (29.16 kg CO_2-eq per session), reflecting the additional electricity required for substitution pumping, slightly greater water use and the higher material demand from HDF-specific tubing and waste.
- Weighted mix (centre practice): 4,469 kg CO_2-eq, 60,290 MJ and 1,364 m^3 world-eq deprived water per patient year.

Per-session values for the weighted Modena mix were 28.6 kg CO_2-eq, 386 MJ and 8.7 m^3 world-eq water Table 1.

Minor differences in total impacts were mainly due to higher procurement, electricity and water use in OLHDF. The overall variation between modalities remained below 3%, showing that treatment type has minimal influence on total pathway emissions.

Table 1 Annual environmental footprints of HD, HDF and weighted mix

Scenario	Carbon (kg CO_2-eq/year)	Energy (MJ/year)	Water (m^3 world-eq/ year)
Full pathway (weighted mix)	4469	60,290	1,364
HD only	4,427	58,900	1,364
OLHDF only	4,548	62,250	1,366

To isolate the effects of the dialysis technologies and facility operations, we also calculated results excluding patient and staff travel. Without transport, annual climate impacts were 1,306 kg CO_2-eq for HD and 1,427 kg CO_2-eq for OLHDF, a 9.3% difference driven mainly by higher material use, water consumption and electricity demand in OLHDF. This confirms that travel assumptions strongly affect absolute pathway footprints but do not materially alter the relative comparison between modalities.

The water use indicator (m^3 world-eq deprived) expresses potential deprivation of water availability for other users in water-scarce regions, and, therefore, does not equal volumetric water consumption; both scarcity-weighted results and measured litres are reported for transparency.

Sensitivity analysis

A sensitivity analysis was performed to assess the effect of treatment modality and operational parameters on total environmental results. The baseline scenario represented one patient year of in-centre dialysis at AOU Policlinico di Modena (52% HD, 47% OLHDF, 156 sessions, Italian grid factor 0.25 kg CO_2/kWh).

Conventional HD produced 4,427 kg CO_2-eq per patient year, while standard high-volume OLHDF reached 4,548 kg CO_2-eq, a 2.7% increase due to higher consumable use, 27 L more ultrapure water per session and 5.7% higher electricity consumption.

A reduced-flow OLHDF scenario was modelled using a Qd/Qb ratio of 1.2 and a convective flow of 25 L [30]. This configuration reduced dialysate flow from 125 to 100 L per session, saving about 25 L of water and reducing carbon emissions by 3–4 kg CO_2-eq per patient year while maintaining a similar Kt/V (urea clearance time volume index).

Varying the share of OLHDF from 0 to 100% changed total emissions by less than 3%. Adjusting the number of sessions between 150 and 160 shifted results by under 3%. Applying the EU-average grid factor (0.29 kg CO_2/kWh) increased total emissions by 0.7%.

Improving RO recovery from 50 to 70% reduced total feed and reject water volumes by roughly 30%. For HD, feed water decreased from 119 m^3 to 85 m^3 and reject water from 59.6 m^3 to 25.6 m^3 per patient year. For OLHDF, feed water decreased from 128 m^3 to 91 m^3 and reject water from 63.8 m^3 to 27.3 m^3. The carbon saving from this improvement was approximately 3–4 kg CO_2-eq per patient year Table 2.

According to Bendine et al. (2020), total water use per dialysis session, including disinfection, is about 300 L using the same RO system as Modena, indicating that roughly 175 L of water are consumed for disinfection outside the treatment cycle [4].

Discussion

This study quantified the environmental impacts of HD and OLHDF using a process-based life cycle assessment based on primary data from a large Italian centre. The reconciled annual footprint of the dialysis pathway was 4,469 kg CO_2-eq, 60,290 MJ and 1,364 m^3 world-eq deprived water per patient year. This provides a benchmark

Table 2 Sensitivity analysis results

Scenario	Carbon (kg CO_2-eq/year)	Energy (MJ/year)	LCIA water (m^3 world-eq/year)	Notes
Baseline (52% HD, 47% OLHDF, Italy grid)	4469	60 290	1364	Full pathway
0% OLHDF (HD only)	4427	58 900	1364	All HD
75% OLHDF	4509	61 700	1365	Higher HDF share
100% OLHDF	4548	62 250	1366	All HDF
150 sessions (HD only)	4270	57 940	1312	Fewer sessions
160 sessions (HD only)	4555	61 730	1384	More sessions
EU grid factor (0.29 kg CO_2/kWh)	4500	n/a	n/a	Approximately 0.7% CO_2 increase vs baseline
RO recovery 50%	n/a	n/a	HD feed 119 m^3/reject 59.6 m^3; HDF feed 128 m^3/reject 63.8 m^3	Less efficient RO
RO recovery 70%	n/a	n/a	HD feed 85 m^3/reject 25.6 m^3; HDF feed 91 m^3/reject 27.3 m^3	30% less reject water
Reduced-flow HDF (100 L dialysate, 25 L convective)	4515	60 290	1339	25 L less water per session; 3–4 kg CO_2-eq reduction per year

for the environmental burden associated with in-centre kidney replacement therapy, reflecting real-world clinical practice.

Patient and staff travel were the dominant contributors, together accounting for about 71% of total emissions. Transport not only represents the largest environmental burden but also a major economic cost in kidney care, estimated to account for roughly half of total dialysis expenditure in some healthcare systems, including the United States, where annual transportation costs for in-centre dialysis have been reported at about 3 billion USD [31].

At the session level, HD and OLHDF showed almost identical results. Per-session impacts were 28.7 kg CO_2-eq, 386.5 MJ and 8.74 m^3 world eq for the weighted treatment mix. Annual totals were 4,479 kg CO_2-eq for HD and 4,482 kg CO_2-eq for OLHDF, a small difference per patient year. This small gap arose from the additional 27 L of purified water used per OLHDF session to generate substitution fluid.

The magnitude of the dialysis footprint observed here aligns with studies in other high-income settings. In Australia, HD was estimated to generate 4–6 tonnes CO_2-eq per patient annually [16], while UK data reported similar figures when including water and procurement 18. Our results are also consistent with earlier pathway-based analyses in Italy, where session operations and water systems were identified as hotspots [15]. These consistencies strengthen the external validity of our findings and suggest that treatment setting and system organisation, including whether patient and staff travel are included within system boundaries, play a major role in shaping reported footprints. Differences in transport patterns, electricity grids and boundary choices across studies mean that cross-country comparisons should be interpreted cautiously.

PD provides a useful comparator. A recent PD pathway LCA showed lower energy use but higher reliance on plastics, with procurement and waste dominating environmental burdens [14]. By contrast, HD and OLHDF impacts are dominated by patient and staff travel, followed by materials and devices, with machine electricity and water production contributing a smaller share in this centre's context. These modality specific differences underscore the need for tailored sustainability strategies in kidney care.

The additional water requirement for OLHDF is consistent with prior reports. Maduell et al. documented a higher fluid demand for OLHDF compared with HD across European centres 19. Minor increases in energy consumption have been reported for OLHDF systems, though these have yet to be quantified, reflecting the extra loads required for convection and substitution fluid generation [4, 27, 18],. From a nephrology standpoint, these operational differences mirror the physiological advantage of OLHDF in convective clearance, achieved through higher filtration volumes.

The CONVINCE trial demonstrated that high-dose OLHDF improved survival compared with high-flux HD, supporting the clinical superiority of OLHDF [3]. A cost–utility analysis alongside the trial reported gains in quality-adjusted life years but higher overall costs due to longer survival and increased healthcare utilisation [17]. From an environmental perspective, the difference between modalities over a single treatment year was small. However, considering the longer average patient survival and reduced complication rates associated with OLHDF, an alternative functional unit based on lifetime treatment rather than 1 year could alter the relative interpretation. Over a full patient lifetime, cumulative environmental impacts for OLHDF would be higher because of extended treatment duration, even if per-session efficiency remains similar. This distinction highlights the importance of aligning environmental comparisons with clinically meaningful time horizons.

Opportunities to reduce the environmental footprint of dialysis were identified across operational, technical and systemic aspects of care:

Water system efficiency. OLHDF requires approximately 27 L more ultrapure water per session than HD due to substitution fluid generation. Some RO systems typically reject 40–60% of input water **[19]**. Increasing recovery efficiency to 70–80%, as already implemented at the Modena centre, can reduce feed and reject water volumes by about 30%, equivalent to tens of thousands of litres saved per patient per year. Reuse of RO reject water for cleaning or irrigation has been successfully demonstrated **[20]**. Such measures can be integrated into existing dialysis unit operations without affecting patient throughput or safety.

Energy reduction. Measured electricity use for OLHDF was 5.7% higher than for HD, mainly due to the substitution pump and convective flow. Optimising machine standby modes, scheduling sessions to flatten demand peaks and integrating renewable energy into dialysis units could reduce emissions [22]. Heat recovery from RO reject water is another underexplored opportunity [23].

Procurement improvements. OLHDF uses a dedicated tubing set with integrated substitution lines, leading to slightly higher plastic consumption. Previous LCAs have also shown that disposables contribute significantly to emissions [15]. Substituting lower-impact materials, reducing packaging and piloting reuse models (e.g., dialyser reprocessing) could help, provided patient safety is maintained [24].

Waste management. The higher material input for OLHDF produces slightly greater waste volumes. Innovations such as pyrolysis of dialysis plastics could reduce emissions compared with incineration [25]. Improved segregation can also decrease hazardous waste volumes, reducing treatment requirements.

Policy integration. Health systems such as the NHS have committed to net-zero emissions [9]. Dialysis services, as a high-impact specialty, should be prioritised for environmental reporting and targeted interventions within national sustainability plans [26].

Travel reduction. With patient and staff travel accounting for almost three quarters of total impacts, interventions such as home dialysis, shared care closer to home, or low-emission transport could have the largest effect. Future scenario analyses could examine the impact of shifting patient and staff transport to low-emission vehicles and of sourcing electricity from low-carbon or 24/7 carbon-free supply contracts. These options were not modelled quantitatively in this study due to limited data on local implementation but represent important directions for further work.

The sensitivity analysis showed that increasing the share of OLHDF from 0 to 100% increased total annual emissions from 4,427 to 4,548 kg CO_2-eq, a small difference between modalities, indicating that modality choice had only a minor effect on overall impacts. Varying the annual number of sessions between 150 and 160 changed total results by less than 3%, consistent with the linear relationship between session frequency and resource use. External parameters had a greater influence: applying the EU-average electricity grid factor increased emissions by about 0.7% while improving RO recovery from 50 to 70% reduced feed and reject water volumes by approximately 30%, corresponding to savings of around 40,000 L per patient year and 3–4 kg CO_2-eq. A reduced-flow OLHDF scenario, based on a Qd/Qb ratio of 1.2 and 25 L convective volume, achieved a 25-L reduction in water use per session and a 3–4 kg CO_2-eq saving per patient year while maintaining comparable Kt/V. These results indicate that water system efficiency and electricity supply characteristics exert far greater influence on overall environmental outcomes than the proportion of HD and OLHDF treatments.

Conclusion

This study assessed the environmental impacts of HD and OLHDF at a large Italian centre using life cycle assessment. The reconciled annual footprint was 4,469 kg CO_2-eq, 60,290 MJ and 1,364 m^3 world-eq water per patient year. Patient and staff travel were the dominant contributors, together accounting for about 71% of total emissions, followed by the procurement of consumables. Machine electricity, water production and waste management contributed much smaller shares.

Environmental differences between HD and OLHDF were modest, with OLHDF producing 4,548 kg CO_2-eq per patient year compared with 4,427 kg CO_2-eq for HD. The higher footprint for OLHDF resulted from 5.7% greater electricity use, 27 L more ultrapure water per session and higher plastic use from the dedicated HDF tubing set. These small differences confirm that the environmental implications of modality choice are limited and that clinical decisions should continue to prioritise patient outcomes.

The findings highlight the greatest opportunities for improvement through travel reduction, procurement redesign, improved water recovery systems, renewable electricity integration and sustainable waste management. Changes in grid carbon intensity and RO recovery efficiency have a much greater influence on total impacts than the mix of HD and OLHDF treatments. Integrating these measures into kidney care pathways will be necessary to align dialysis services with national and international net-zero targets.

Strengths and limitations

A key strength of this study is the use of primary data from a large clinical centre, allowing accurate representation of real operational conditions. Detailed process mapping and consistent life cycle modelling across both modalities provide a comprehensive and comparable assessment. The patient-year functional unit enables alignment with other dialysis LCAs, while reporting both LICA water scarcity results and measured operational water volumes improves transparency. Direct measurement of machine energy confirmed that OLHDF consumes approximately 5.7% more electricity than HD, while measured water use showed an additional 27 L per OLHDF session. Including these empirical data strengthens confidence in the small observed differences between modalities.

Both HD and OLHDF used two dialysate-side ultrafilters within the Fresenius 5008 machine, replaced quarterly in accordance with current clinical practice. This configuration minimises potential bias in comparing system performance and reflects modern operational standards.

Interpretation according to ISO 14044. In terms of completeness, the study includes the main life-cycle stages for in-centre HD and OLHDF (procurement, water treatment, session operations, travel and waste) while excluding pharmaceuticals, vascular access and infrastructure, which are expected to make a smaller contribution at the level of a single centre. Consistency was maintained by applying the same functional unit, system boundary and modelling assumptions across modalities and scenarios, and using Ecoinvent 3.11 as a common background database. Data

quality is strongest for directly measured parameters (water, electricity, and material masses) and more uncertain for secondary data, such as travel distances and some waste flows. Parameter uncertainty, particularly in travel and RO performance, is partly explored through the sensitivity analysis; a full probabilistic uncertainty assessment was beyond the scope of this study and is highlighted as an area for future work.

Limitations include potential variation in equipment efficiency, infrastructure and clinical practices across dialysis centres, which may influence absolute results. The analysis was based on a single site and, therefore, reflects local electricity mix, treatment schedules and procurement sources. Despite these factors, the magnitude of the difference between HD and OLHDF was small, suggesting that moderate changes in input parameters would not alter the main conclusion that modality choice has minimal influence on overall environmental performance.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11255-026-05033-3.

Author Contribution J.L. designed the study, collected and analysed data, performed the life cycle modelling and wrote the main manuscript text. G.L. and N.M. contributed to data collection, validation and clinical interpretation. G.A. supervised data acquisition at AOU Policlinico di Modena and provided clinical oversight. R.M.C. supported methodological validation and results interpretation. A.F. contributed to data analysis and manuscript editing. I.S., A.Y. and M.A.G. contributed to contextual framing and literature review. F.M.C. and K.G.F.G. provided expert review on clinical and sustainability relevance. F.M. contributed to the environmental interpretation and discussion. G.D. supervised the clinical aspects of the study at Modena. B.D. conceived the research concept, supervised the project and reviewed the final manuscript. All authors reviewed and approved the final version of the manuscript.

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Data availability Supplementary material is available through Zenodo. This includes the life cycle assessment dataset for HD in Modena (Larkin, J. 2024. https://doi.org/10.5281/zenodo.14259304) and product images for the HD/HDF dataset (Larkin, J. 2024. https://doi.org/10.5281/zenodo.14258920).

Declarations

Conflict of interest The authors declare no competing interests.

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Theoretically redesigning peritoneal dialysis products for sustainability: A life cycle inventory approach

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Abstract

Peritoneal dialysis (PD) is a life-sustaining treatment for end-stage kidney disease but contributes significantly to environmental degradation due to its reliance on single-use plastics, energy-intensive manufacturing and high-volume transport. Redesigning PD products for sustainability is increasingly important as healthcare systems seek to reduce their carbon footprint. In this study, ten high-use peritoneal dialysis (PD) products were redesigned using life cycle thinking. Interventions included low-carbon transport (electric vans), renewable energy and improved waste treatment (pyrolysis). Life cycle inventories (LCIs) were modelled in Open Life Cycle Assessment (OpenLCA)and modelled using cradle-to-gate carbon footprints (kg CO⊠-eq) to compare redesigned and conventional versions. All redesigned products achieved carbon footprint reductions, with eight showing decreases greater than 40%. The automated PD set and 2 L dialysate bag saw reductions of 63% and 54%, respectively (saving 1.15 and 0.86 kg CO_2-eq per item). The APD machine achieved the largest percentage reduction at 87%, primarily driven by the elimination of printed packaging and the use of renewable electricity. Key contributors to emissions savings across products included lower-impact transport, sustainable packaging materials and circular waste strategies. Redesigning PD products using sustainable materials and processes can deliver substantial environmental benefits without compromising functionality. These findings support evidence-based pathways for reducing emissions in kidney care through product innovation and procurement reform.

Keywords

Peritoneal dialysis, sustainable healthcare, life cycle assessment, medical device design, carbon footprint, circular economy

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Introduction

Peritoneal dialysis (PD) is a widely used renal replacement therapy for patients with end-stage kidney disease (ESKD), yet its environmental impact is substantial due to the large volume of single-use medical products and associated packaging, energy use and waste generation.[1,2] The healthcare sector as a whole contributes approximately 4%–5% of global greenhouse gas (GHG) emissions,[3] with dialysis treatments identified as particularly resource-intensive and emission-heavy.[4,5]

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Growing global awareness of healthcare's ecological footprint has spurred efforts to make clinical practices more sustainable. Within nephrology, the field of green dialysis has emerged to assess and mitigate the environmental impacts of dialysis care.

This study aims to redesign 10 core products and their life cycles used in PD to reduce their environmental impact, with a focus on carbon emissions, resource use and end-of-life outcomes. Conducted as part of the KitNewCare project, the goal is to identify the products and processes contributing most significantly to environmental impacts and model interventions which could reduce their negative impact. By doing so, the study supports the development of evidence-based strategies to reduce the ecological burden of PD while upholding high standards of patient care. Data were collected at the Nephrology Dialysis and Kidney Transplant Unit of the AOU Policlinico di Modena in Modena, Italy.

Literature review

This study focusses on the redesign of ten commonly used PD products, ranging from dialysate bags and drainage systems to disinfectants and medical kits, with the aim of reducing their carbon footprints through sustainable design principles. The approach involves using renewable energy and low-carbon transport, and improving recyclability and waste treatment strategies such as pyrolysis. Although bio-based plastics were evaluated during the modelling phase, they were not adopted due to limited emissions savings and unresolved barriers to real-world use in medical contexts.

Several life cycle assessments (LCAs) have quantified the impacts of PD and haemodialysis, identifying hotspots such as polymer production, transport and waste treatment.[6,7] Sustainable product design presents a key intervention point to address these hotspots by substituting materials, optimising manufacturing and improving end-of-life options.

This work contributes to the growing body of research advocating for low-carbon, circular healthcare systems. By demonstrating feasible and quantifiable environmental improvements at the product level, it offers practical pathways for manufacturers, healthcare providers and policymakers to reduce the environmental impact of PD care without compromising patient safety or product performance.

This assessment is part of the KitNewCare project, an EU co-funded initiative aimed at making kidney healthcare more environmentally sustainable. KitNewCare focusses on kidney care, an area with significant disease burden and resource footprint, and identifies sustainable solutions to reduce carbon emissions while optimising health outcomes, social equity and costs. Starting with selected Nephrology clinics, including Modena, Italy, the project's mission is to drive the adoption of sustainable practices across nephrology care.[8]

Methods

Study design

This study aimed to redesign ten core products and their life cycles used in PD to reduce their environmental impact, with a focus on carbon emissions, resource use and end-of-life outcomes. A product-level life cycle approach was taken, following ISO 14040 and ISO 14044 guidelines for life cycle assessment (LCA).[9,10] The study did not conduct full impact assessments for each redesigned product but instead focussed on compiling revised life cycle inventories (LCIs) for more sustainable product alternatives.

Product scope

The ten products redesigned in this study were:

1. 5 L Dialysate Bag
2. 2 L Dialysate Bag
3. Automated Drainage System
4. Automated PD Set
5. APD Machine
6. 3 L Empty Drainage Bag
7. Drainage Set (tubing and connectors)
8. Hand Washing Gel
9. Disinfectant Spray
10. Medical Kit (gloves, dressings and masks)

Functional unit

The functional unit for this study is defined as one complete item of each redesigned PD product, representing typical use within the treatment pathway. This unit allows for a consistent comparison of environmental impacts between conventional and redesigned product versions on a per-item basis.

Redesign strategy

Redesigns were guided by sustainable product design principles, including:

- Material substitution: Recycled cardboard and recycled paper for printed and packaging components.
- Energy sourcing: Use of renewable electricity for manufacturing where feasible.
- Waste reduction: Lighter-weight packaging and recyclable product designs (e.g. instruction leaflet from recycled paper).

Table 1. Sustainability interventions applied to peritoneal dialysis products.

Product	Recycled plastics	Recycled packaging	Electric transport	Sustainable manufacture	Waste treatment
5 L dialysate bag	Yes	Yes	Yes	Yes	Yes
2 L dialysate bag	Yes	Yes	Yes	Yes	Yes
Automated drainage system	Yes	Yes	Yes	Yes	Yes
Automated PD set	Yes	Yes	Yes	Yes	Yes
APD machine	Partial	Yes	Yes	Yes	Yes
3 L empty bag	Yes	Yes	Yes	Yes	Yes
Drainage set	Yes	Yes	Yes	Yes	Yes
Hand washing gel	Yes	Yes	Yes	Yes	Yes
Disinfectant	Yes	Yes	Yes	Yes	Yes
Medical kit	Yes	Yes	Yes	Yes	Yes

Inventory modelling approach

Each product's life cycle inventory was developed using:

- Primary data: material identification (e.g. weights, polymers and packaging) from actual products and packaging used in Italian PD practice.
- Secondary data: Ecoinvent v3.1 (cut-off system model) for background processes, including material production, energy use, transport and waste treatment.[11]

Where specific med recycled materials were not present in Ecoinvent, custom unit processes were created using literature-based conversion efficiencies and energy use estimates (e.g. bio-based LDPE from sugarcane ethanol, recycled corrugated cardboard and recycled plastic pallet production).

Outputs

For each redesigned product, a revised list of inputs and outputs was compiled in OpenLCA based on:

- Material inputs (e.g. plastics, paper and chemicals)
- Energy use (electricity and steam)
- Water consumption
- Emissions (fossil CO_2 and wastewater)
- Waste generation (recyclable plastic, general waste and hazardous clinical waste)

These inventories were compared against baseline configurations from existing LCI models to evaluate potential reductions in carbon and material impacts. The complete list of inputs and outputs for each product is available at: James Larkin.[12]

Table 1 outlines the specific sustainability interventions applied to each product, including the use of recycled plastics, low-carbon logistics and circular end-of-life strategies.

Tools

Modelling was conducted using *OpenLCA 1.10.3*,12 with *ecoinvent v3.1* as the background database.[13] Microsoft Excel was used to prepare inventory data, and visual modelling was supported by schematic process maps for each redesigned item.[14]

Ethics

Ethical approval was not required for this study, as it focussed exclusively on the environmental assessment of medical products and treatment processes within peritoneal dialysis. The research did not involve human participants, patient data or any activities falling under the scope of institutional review board (IRB) oversight. All data collected related solely to the physical characteristics, material composition and life cycle impacts of medical devices and associated logistics, with no personal or identifiable information involved.

Results

The environmental performance of the ten redesigned PD products was compared with their conventional counterparts using cradle-to-gate carbon footprint values expressed in kilograms of CO2-equivalent (kg CO2-eq) per item. The redesigned products demonstrated substantial reductions in carbon emissions across nearly all categories.

Contribution Graphs Figure 1 displays the comparison between the normal product and redesigned product, displaying which exact factors contribute to the decrease in carbon footprint.

The largest absolute reduction was observed in the 5 L dialysate bag, the carbon footprint of which decreased from 2.37 to 1.36 kg CO2-eq per item, representing a 42% reduction. This was primarily due to the replacement of virgin corrugated cardboard with recycled board, the use of electric van transport instead of diesel freight, and

Figure 1. LCA results (kg CO2-eq).
PD: peritoneal dialysis; APD: automated peritoneal dialysis.

Table 2. Percentage carbon footprint reductions achieved through product redesign.

Product	Recycled plastics (%)	Recycled packaging (%)	Electric transport (%)	Sustainable manufacture (%)	Waste treatment (%)	Total reduction (%)
5 L dialysate bag	12.8	6.4	10.6	4.3	8.5	42.6
2 L dialysate bag	16.2	8.1	13.5	5.4	10.8	54.1
Automated PD set	18.8	9.4	15.7	6.3	12.6	62.8
APD machine	26	13	21.7	8.7	17.3	86.7
3 L empty bag	18.2	9.1	15.2	6.1	12.1	60.7
Drainage set	18.9	9.4	15.8	6.3	12.6	63
Hand washing gel	10	5	8.3	3.3	6.7	33.3
Disinfectant	1.9	0.9	1.6	0.6	1.3	6.3
Medical kit	12	6	10	4	8	40
Automated drainage system	16.3	8.2	13.6	5.4	10.9	54.4

inclusion of a pyrolysis end-of-life scenario. Similarly, the 2 L dialysate bag achieved a 54% reduction, from 1.59 to 0.73 kg CO2-eq.

The automated PD set, previously one of the most impactful items (1.83 kg CO2-eq), had its carbon footprint reduced to 0.68 kg CO2-eq (63% reduction) through the substitution of virgin corrugated cardboard with recycled board and recycled alternatives, sustainable manufacturing processes using renewable energy and improved end-of-life waste treatment. These items are commonly manufactured using virgin plastics such as polypropylene or polyethylene.

The 3 L empty drainage bag showed a 61% reduction in emissions, from 0.89 to 0.35 kg CO2-eq. Likewise, the footprint of the automated drainage set was reduced from 1.25 to 0.57 kg CO2-eq (54%). These improvements were primarily due to the use of recycled packaging and more sustainable blow moulding using renewable electricity.

The APD machine, a more complex electrical product, saw a dramatic reduction of 87% from 0.75 to 0.10 kg CO2-eq. This was achieved through renewable electricity during the treatment and elimination of unnecessary printed materials and packaging.

The drainage set dropped from 0.54 to 0.20 kg CO2-eq (63%), while the medical kit was reduced by 39%, from 0.25 to 0.15 kg CO2-eq. The hand washing gel and disinfectant both demonstrated significant reductions, dropping by 34% and 6% respectively.

Table 2 presents the percentage reductions achieved for each product through the applied interventions.

These were achieved mainly through improvements in packaging and minimised transport emissions.

Overall, eight of the ten products experienced reductions greater than 40%, with most improvements driven by material substitution of packaging, low-carbon transport, renewable energy use and end-of-life waste diversion via pyrolysis. These results support the feasibility of sustainable redesign for common PD products without compromising function.

Discussion

This study demonstrates that substantial reductions in the environmental impact of PD products can be achieved through targeted product redesign. By integrating recycled materials, using renewable energy sources, switching to electric vehicle transport and implementing improved end-of-life waste treatment methods such as pyrolysis, the carbon footprints of all ten redesigned PD products were notably reduced. These interventions reflect feasible and scalable sustainability strategies in medical device supply chains.

The most significant reductions were observed in high-volume, single-use products such as dialysate bags and components of automated PD systems. These items are packaged with energy-intensive materials like corrugated cardboard boxes and plastic films, making them particularly impactful targets for redesign. Transitioning from conventional lorry and container shipping to electric van transport also contributed meaningfully to emissions reductions. Our results align with studies that highlight energy sources, freight transport and packaging as key environmental hotspots in healthcare supply chains.[15,16]

This policy provides clear, actionable means for manufacturers to reduce their environmental footprint, aligning with emerging requirements from national procurement agencies. As one example, NHS Supply Chain has begun incorporating environmental criteria into tenders, setting a precedent for lifecycle carbon footprint thresholds in public healthcare procurement.[17] This paper provides additional support for building a framework to guide manufacturers in adapting to these evolving expectations.

Pyrolysis is a process that thermally decomposes plastic waste in the absence of oxygen to generate useful outputs such as fuels, gases or chemical feedstocks. It is adopted in this study as an end-of-life strategy for plastic waste, demonstrating environmental benefits by diverting waste from landfill and incineration and recovering energy or chemical feedstocks. Although still in development, and more open loop focussed (as products can be

used to create other different plastics) pyrolysis still aligns with the EU Circular Economy Action Plan and offers an innovative route to enhance waste circularity in medical settings.[18] Future iterations could also explore closed-loop recycling and producer responsibility schemes to further reduce the environmental footprint of PD components.

While this study primarily focussed on environmental impacts, cost-effectiveness is also a critical area for future exploration. Renewable energy can require infrastructure change, for example, the installation of solar panels, but can also be a change in supplier with cost repercussions.[19] Sustainable materials may incur higher upfront costs but could lead to savings via reduced waste disposal fees and packaging efficiencies. For example, pyrolysis may offer financial as well as environmental advantages in managing medical waste.[20]

Scalability of these interventions is an important consideration for broader implementation. Although the study's data collection was based in Italy, the core redesign strategies, such as material substitution, electrified transport and improved waste management, are applicable across healthcare systems. While absolute carbon reductions may differ based on regional factors like energy mix, transport logistics and waste infrastructure, the underlying principles of sustainable product redesign remain consistent and replicable.

Although this study focussed on clinical settings, home-based PD presents additional opportunities and considerations for emission reductions. While the logistics of patient delivery and waste collection are different, existing evidence suggests that variations in waste incineration temperatures between hospital and general waste streams may not result in major differences in carbon emissions. For example, special waste incinerators used in hospitals typically operate between 850°C and 1200°C, while general waste incinerators reach 950°C–1000°C, resulting in relatively comparable thermal profiles.[21,22] Future research should explore emissions profiles across home and clinic contexts, particularly considering the decentralisation of treatment delivery.

Behavioural aspects such as patient and clinician acceptance also warrant attention. While usability issues were not part of this paper, future co-design with stakeholders could help fine-tune product acceptability and identify potential trade-offs. Research in healthcare waste management suggests that behavioural interventions can enhance waste categorisation, segregation and therefore sustainability.[23]

One of the key barriers to further reducing the environmental burden of PD products lies in the current limitations of bio-based plastics in medical applications. Bio-based high-density polyethylene (bio-HDPE), though environmentally preferable in terms of life-cycle greenhouse gas emissions, cannot yet replace fossil-derived polymers in most medical products. This is due to unmet regulatory requirements for biocompatibility, sterilisation stability and mechanical performance.[24,25] While bio-HDPE derived from renewable sources such as sugarcane ethanol exists, data on its durability under medical sterilisation and clinical usage is lacking, and its supply chain remains underdeveloped.[26] Current EU Medical Device Regulation (EU MDR 2017/745) and ISO 10993 standards present additional barriers, particularly for Class II and III medical devices, by requiring extensive biocompatibility testing, sterility validation and long-term safety data that many bio-based plastics have yet to meet. Engaging regulators early in the innovation process is essential to enable approval pathways for sustainable materials.[27]

In addition to regulatory and technical challenges, the sustainability of bio-based plastics also depends critically on the feedstock used. To ensure true environmental benefit, bioplastics should ideally be derived from agricultural waste or non-food biomass rather than crops grown specifically for polymer production. Using first-generation bio-feedstocks such as sugarcane or maize risks indirect land use change, deforestation and competition with food production, potentially leading to greater environmental harm. Thus, future development of bio-based medical plastics should prioritise second-generation feedstocks, such as bagasse, corn stover or other lignocellulosic residues, to avoid trade-offs with land use, biodiversity and food security. A precautionary approach should be taken before recommending wide adoption of bioplastics, ensuring that material substitution does not inadvertently shift environmental burdens elsewhere in the healthcare system.

Future directions for sustainable PD practice

Digitalisation offers a novel route to reduce environmental impact. Replacing printed instruction leaflets with QR code-based digital resources could reduce paper use and packaging bulk.[28]

Programmes facilitating the collection and recycling of PD materials from patients' homes have shown promise. For instance, Baxter's initiative allows patients to recycle plastic and cardboard waste, which is then collected by delivery drivers. Such programmes improve waste management and contribute to sustainability efforts in home dialysis settings.[29]

Implementing incremental PD, where the dialysis dose is gradually increased, can lead to significant environmental benefits. This approach not only lessens environmental impact but also maintains clinical effectiveness.[30]

The adoption of telemedicine in PD care has been associated with reduced carbon emissions. Telehealth not only reduces the need for patient travel but also supports continuous patient monitoring and education.[31]

Transitioning to electric vehicles (EVs) for patient transportation can significantly lower healthcare related

carbon emissions. Research indicates that a 30% shift to EVs could reduce healthcare travel emissions to 27.6 Mt CO_2e annually. Implementing EVs for routine patient visits and supply deliveries in PD programmes can contribute to environmental sustainability.[32]

Overall, this work supports the transition to sustainable healthcare by offering a replicable model for low-carbon product design in nephrology. It demonstrates how nephrology, through initiatives like KitNewCare, is leading the healthcare sector in sustainable innovation. Further studies should integrate broader environmental impact categories, economic analyses and policy engagement to drive system-wide change.

Limitations

While this study achieved significant reductions in product-level carbon footprints through redesign, some limitations must be noted. Bio-based plastics, initially considered as substitutes for fossil-derived materials, were ultimately excluded after modelling revealed only marginal environmental improvements and ongoing challenges related to regulatory approval, supply consistency and performance in clinical settings. This highlights a key limitation of current sustainable materials science, where promising alternatives are not yet ready for widespread adoption in healthcare.

Additionally, the study primarily focussed on carbon footprint as the impact metric, omitting other important environmental and social categories such as water use, toxicity or cost. The findings are based on cradle-to-gate approach, which capture use-phase or disposal scenarios beyond modelled end-of-life processes like pyrolysis. Finally, while the redesigns were grounded in practical feasibility, clinical validation of the modified products was beyond the scope of this study and remains a necessary step for implementation.

Conclusion

This study demonstrates that redesigning PD products using sustainable materials, renewable energy and low-carbon logistics can substantially reduce their environmental impact. Most redesigned items achieved carbon footprint reductions exceeding 40% without compromising functional performance.

These findings offer clear, actionable guidance for manufacturers and healthcare providers aiming to decarbonise medical supply chains. Policymakers are encouraged to support procurement standards that incentivise sustainable design. Future research should build on this work by incorporating full life cycle impact assessments, engaging with clinical stakeholders and evaluating real-world implementation to inform scalable sustainable practices in kidney care.

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Ethical considerations

Ethical approval was not required for this study as it did not involve human participants or animal research. The study focussed solely on environmental data collection and analysis related to peritoneal dialysis systems.

Consent to participate

Not applicable. This research did not involve any individual participants, patients or human data.

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Data availability statement

All data generated or analysed during this study are publicly available in the Zenodo repositories: James Larkin.[12]

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Appendix

Notation

CO_2-eq	Carbon dioxide equivalent, a standard unit for measuring carbon footprints by converting different greenhouse gases into the amount of CO_2 that would have the same global warming potential.
kg	Kilogram, a unit of mass.
kg CO_2-eq	Kilograms of carbon dioxide equivalent, used to express the carbon footprint of materials or processes.
LCA	Life Cycle Assessment, a method for evaluating the environmental impacts associated with all stages of a product's life.
LCI	Life Cycle Inventory, a phase of LCA involving data collection of material and energy inputs and outputs for a product or system.
MJ	Megajoule, a unit of energy equal to one million joules.
PD	Peritoneal dialysis, a treatment for end-stage kidney disease using the peritoneum as a membrane for fluid exchange.
%	Percent, a unit expressing a number as a fraction of 100.

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