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Sustainability of PCM-lime mortars for heritage retrofitting: Carbon footprint and impact on energy demand across climates

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ABSTRACT

Recent research on PCM–lime mortars has predominantly addressed material-scale behaviour or single-climate cases, with limited integration of embodied carbon and operational energy at the building scale—particularly for heritage envelopes under conservation constraints. To address this gap, the present study develops a climate-resolved, building-scale assessment that couples cradle-to-gate embodied impacts with operational energy effects for PCM-enhanced lime mortars in heritage retrofitting. Specifically, cradle-to-gate global warming potential (A1–A3) is combined with a screening-level estimate of operational energy savings (B6) over a 50-year service life. Three PCMs were examined: two paraffin-based (melting points of 18 °C and 24 °C) and one bio-based, derived from agricultural by-products (melting point of 29 °C). These were integrated into lime mortars and modelled across three retrofit strategies—internal grouting, internal rendering, and a combined approach—applied to the 13th-century Hermitage of Santa Brígida (Spain), with extrapolation to all Spanish climate zones to assess performance under varying thermal conditions. Simulations reveal that PCM-enhanced mortars can eliminate cooling demands and significantly reduce heating needs. Maximum total carbon footprint reductions were achieved with the bio-based PCM (89.1 %), followed by the 24 °C paraffin PCM (87.2 %) and the 18 °C paraffin PCM (74.6 %), depending on the climate zone. This work provides a comparative assessment of paraffin versus bio-based PCMs, highlighting the importance of climate-PCM compatibility and delivering critical insights into the embodied carbon and long-term environmental impact of these mortars in heritage retrofitting.

1. Introduction

The building sector accounts for a substantial share of global greenhouse gas (GHG) emissions, responsible for approximately 40 % of the EU's total energy consumption and 36 % of its energy-related greenhouse gas emissions [1]. This is particularly concerning given the age and poor energy performance of the European building stock. A significant proportion of buildings in the EU are over 50 years old, with many constructed centuries ago and still in use today. Notably, over 40 % of the residential stock predates the 1960s, well before the introduction of meaningful energy regulations, and more than 90 % was built before 1990, highlighting the immense

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energy-saving potential embedded in existing and historic buildings [1–3]. In this context, prioritising renovation over demolition and new construction emerges as a crucial strategy for reducing operational emissions while preserving cultural heritage. Sustainable and compatible retrofitting solutions are urgently needed to support the EU's decarbonisation goals, as outlined in the European Green Deal and the Renovation Wave Strategy [1,4].

Despite this imperative, renovation rates across the EU remain insufficient. While approximately 11 % of the building stock undergoes some form of renovation annually, only around 1 % constitutes energy-related improvements that significantly enhance building performance [1]. Historic and vernacular buildings are frequently overlooked from large-scale renovation initiatives, often deemed incompatible with conventional energy-retrofitting approaches due to their material sensitivity, architectural constraints, and cultural value [1,3]. Nevertheless, they hold significant potential for reducing their operational energy. However, retrofitting measures must be carefully designed to respect the architectural and historical significance of these structures. Interventions must preserve visual and material integrity, embrace traditional construction techniques, and adhere to principles of compatibility and minimal intervention, acknowledging that sustainability in heritage buildings cannot come at the cost of their authenticity [1,3,5].

Lime-based mortars are a cornerstone material in the conservation of historic buildings. Their use spans millennia and is documented across traditional European construction systems. In particular, hydrated lime offers excellent compatibility with historic substrates due to its chemical affinity with traditional stones and bricks, flexibility, and vapour permeability [6]. From an environmental perspective, lime also presents key advantages over ordinary Portland cement (CEM I) and its blended variants (CEM II and CEM III). Whereas cement production requires clinker formation at approximately 1450 °C, limestone calcination for lime production occurs around 900 °C, reducing energy consumption and associated emissions [7,8]. Furthermore, lime mortars naturally reabsorb part of the CO_2 released during calcination through the carbonation process, serving as partial carbon sinks [9,10]. These characteristics position lime mortars not only technically appropriate but also environmentally advantageous for retrofitting traditional and heritage buildings [6,9,10].

To further enhance their thermal performance, lime mortars can be engineered to improve indoor temperature regulation, reducing the need for active heating and cooling, especially important under increasingly variable and extreme climate conditions. One promising strategy involves the incorporation of Phase Change Materials (PCMs), which absorb and release thermal energy through phase transitions, typically from solid to liquid and vice versa [11–15]. By absorbing heat when indoor temperatures exceed their melting point and releasing it when temperatures fall, PCMs help stabilise indoor environments, mitigate thermal peaks, and improve occupant comfort without relying on mechanical systems [11–15].

PCMs are available in various formats, each with specific implications for compatibility and performance. Macroencapsulated PCMs, enclosed in rigid or flexible containers (e.g., panels, pipes, spheres), are typically integrated into wall assemblies or ceilings [11,15]. However, these formats often require intrusive interventions that can compromise the architectural authenticity of historic buildings. In conservation, preserving the external and internal appearance of surfaces, particularly renders and façades, is critical. Therefore, the use of discrete and non-invasive technologies is essential for maintaining heritage value [1,5].

Microencapsulated PCMs offer a more compatible alternative for heritage applications. These consist of microscopic PCM cores, typically paraffin waxes, encapsulated within robust polymeric shells (e.g., melamine or urea-formaldehyde resins). With diameters ranging from 1 to 30 μm, these microcapsules can be uniformly dispersed in lime mortars, yielding composites that retain the appearance, workability, and vapour permeability of traditional lime-based renders [11,12,16]. Their small size allows seamless integration into thin plaster layers, embedding latent thermal storage energy directly into the surface without altering the building's aesthetic or material character. Moreover, microencapsulation enhances PCM thermal cycling stability and mechanical integrity, reducing the risks of leakage or degradation over time [11,12,16]. These features make microencapsulated PCMs particularly suitable for minimally invasive and materially compatible heritage retrofits.

A material's carbon footprint, commonly quantified as Global Warming Potential (GWP), captures the total amount of CO_2-equivalent emissions generated across its life cycle. GWP is a key indicator used to estimate the carbon footprint of construction materials, considering CO_2-equivalent emissions across selected life cycle stages. A widely recognised framework for structuring these analyses is Life Cycle Assessment (LCA), as defined by ISO 14040 and ISO 14044 standards [17,18], and tailored in the construction sector by EN 15804 [19]. EN 15804 further defines specific stages for building products: A1–A3 (raw material supply, transport to manufacturing site, and manufacturing), A4–A5 (construction and installation), B1–B7 (use phase including maintenance, operational energy and water use) and C1–C4 (end-of-life stage including demolition, transport, waste processing, and disposal). Module D optionally accounts for potential environmental benefits or burdens beyond the system boundary, such as avoided impacts from material reuse, recycling, or energy recovery.

Despite the growing use of Life Cycle Assessment (LCA) to evaluate conventional construction materials, only few studies address the environmental performance of mortars with Phase Change Materials (PCMs), particularly those compatible with built heritage. Most existing LCA studies focus on macroencapsulated PCMs which are typically applied as panels, pipes, or modular inserts [20,21]. Cabeza et al. [20], for instance, analysed paraffin, salt hydrates, and natural esters encapsulated in aluminium and integrated into experimental concrete cubicles under Mediterranean climatic conditions. Their results showed that while energy savings occurred mainly during summer, the overall environmental benefits were modest (global impact reductions below 1 %) and heavily influenced by the high embodied emissions of the aluminium encapsulation. Kyriaki et al. [21] further reviewed the available LCA and LCC studies on PCMs, highlighting that most were limited to small-scale cubicles and partial life-cycle stages, with environmental benefits strongly dependent on climatic context, service life, and PCM durability. These solutions, while functionally effective, are often incompatible with heritage buildings due to their visual intrusiveness, volume, and integration requirements. In contrast, there is a notable lack of LCA research evaluating the environmental profile of microencapsulated PCMs incorporated into lime mortars, despite their greater conservation compatibility.

Among the use-phase modules in the EN 15804 standard, B6 module is particularly relevant, as it accounts for operational energy use. Capturing the energy savings enabled by PCMs during this stage is essential for assessing the full performance of PCM-lime mortars. The real sustainability of these materials hinges in the balance between their embodied emissions during production (modules A1–A3, according to the standard) and the operational energy reductions (module B6, in agreement with the standard) they enable.

This study quantifies the carbon footprint of a PCM-enhanced lime mortars by evaluating their Global Warming Potential (GWP) across production, transport, and on-site mortar preparation (modules A1–A3), and estimating their operational heating and cooling energy savings attributable to the PCM (module B6). PCM thermal contribution is quantified through an energy balance model based on the material's phase change enthalpy and the number of effective annual phase transitions, following the methodology proposed by [22]. This approach enables a robust and context-specific evaluation of the operational benefits provided by the PCM. This methodology is particularly well suited to heritage buildings, where detailed dynamic energy modelling is often impractical due to limited data availability.

As a representative case, this study focuses on the Hermitage de Santa Brígida, a 13th-century Gothic hermitage located in Olite (Navarre, Spain). Constructed from limestone masonry originally bound with lime mortars, and modest dimensions and plain façades, the building typifies rural ecclesiastical architecture. Its historic significance and lack of prior thermal retrofitting make it an ideal candidate for evaluating the environmental implications of compatible lime-based interventions. Although the building is situated in Spain's D1 climate zone [23], the analysis is extended to encompass all official Spanish climate zones in order to assess thermal performance under diverse conditions. This comparative analysis identifies the climates where PCM integration offers the greatest environmental benefit and enables broader extrapolation to other countries.

By applying the carbon and energy balance framework across multiple climatic scenarios, this study delivers context-specific insights into the trade-offs between embodied impacts and operational energy savings. It highlights the potential of PCM-lime mortars to advance sustainable conservation and address the climatic sensitivity of such materials, a dimension rarely explored in depth. Ultimately, the findings bridge material-level environmental impacts with building-level energy performance in a heritage-compatible framework, offering valuable guidance for conservation professionals and sustainability researchers on the viability of advanced, energy-efficient solutions that respect and preserve the cultural value of historic buildings. However, it is important to emphasize that comprehensive in situ exposure studies and long-term monitoring in pilot applications will be essential to complement laboratory-scale findings. Such investigations will provide critical data regarding application feasibility, effectiveness, performance, durability, and compatibility with historic built structures. This research direction is currently being pursued within the framework of the SINCERE project, and the corresponding results are anticipated to be disseminated in forthcoming publications.

Accordingly, the present study addresses the current lack of environmental performance studies on microencapsulated PCM–lime mortars for heritage retrofitting by providing a systematic assessment of their embodied carbon and operational energy benefits. The work combines cradle-to-gate embodied carbon analysis (modules A1–A3) with simulated operational energy savings (module B6), thereby linking material-level environmental burdens with building-scale performance. Three different PCMs were investigated—two paraffin-based (melting at 18 °C and 24 °C) and one bio-based (29 °C)—all previously validated in terms of mechanical, thermal, and

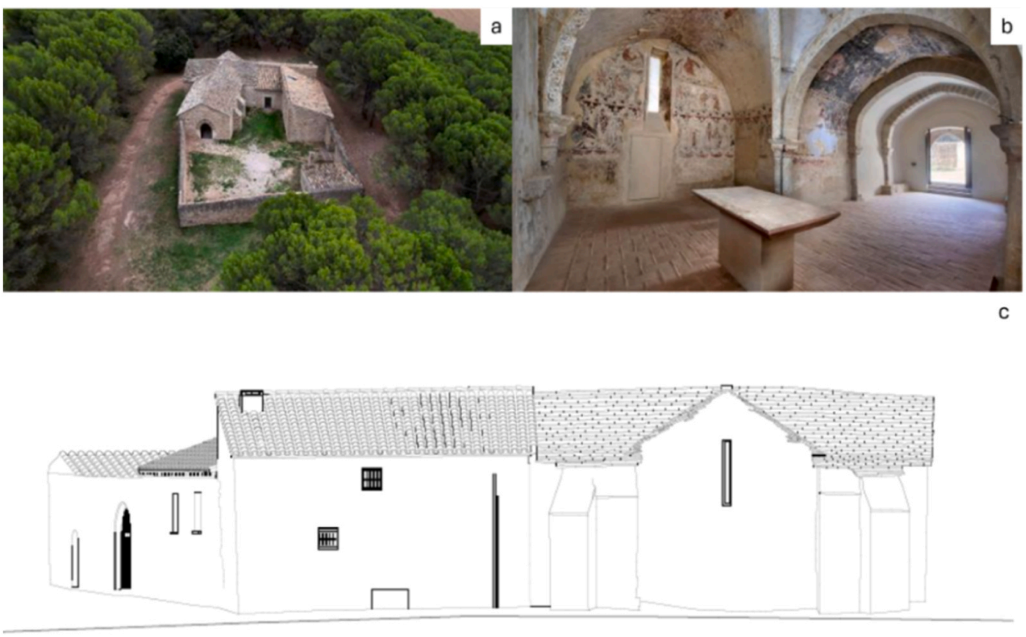

Fig. 1. Hermitage of Santa Brígida (Olite, Spain). (a) Aerial view of the building nestled within surrounding woodland; (b) interior view highlighting lime mortar finishes and historic mural paintings; (c) architectural elevation illustrating the building envelope, adapted from reference [24].

durability properties. A real case study was performed on the 13th-century Hermitage of Santa Brígida in Spain (climate zone D1), with extrapolation to all twelve official Spanish climate zones to capture the climatic sensitivity of PCM performance. By situating the analysis within a heritage-compatible framework and extending it to a national multi-climatic scale, this work provides novel insights into the environmental viability of PCM–lime mortars and establishes a reference point for their future implementation in conservation practice.

2. Materials and methods

2.1. Case study: The Hermitage of Santa Brígida

The Hermitage of Santa Brígida, located in Olite (Navarre, Spain), was selected as the case study for assessing the thermal performance enhancement of lime mortars incorporating Phase Change Materials (PCMs) in historic buildings. This modest rural church, constructed between the 13th and 14th centuries and officially protected as a listed monument since 2013, is a representative example of proto-Gothic architecture. It features a three-bay nave, a transept, and thick masonry walls built from a combination of ashlar and rubble stone, originally bonded with lime mortar [24].

The external walls are approximately 1.4 m thick and follow a traditional multilayered construction technique: two stone leaves (ashlar on the exterior and rubble on the interior) enclosing a core infill of lime mortar and stone fragments [24]. Although a major restoration was carried out in 2021, addressing structural stability, repointing façades with lime mortar, and restoring interior lime-based finishes, no energy efficiency measures were directly implemented. This study introduces heritage-compatible retrofit strategies that incorporate thermal functionality within the conservation framework.

The three PCM-lime mortar application scenarios modelled in this research are illustrated in Fig. 2:

(i) Internal grouting: injection of PCM-lime mortar into the wall core;
(ii) Internal rendering: application of a PCM-enhanced lime plaster layer on interior wall surfaces;
(iii) Combined intervention: simultaneous implementation of internal rendering and internal grouting.

The estimated wall volume of the Hermitage of Santa Brígida, calculated from the architectural plans and elevations [24], is approximately 705 m^3 . For scenario (i), internal grouting, it is assumed that 10 % of this volume is filled with PCM-enhanced mortar, corresponding to 71 m^3 of injected material. In scenario (ii), internal rendering, an interior wall surface area of approximately 234 m^2 was considered for the application of an 18 mm thick layer of PCM-lime plaster, yielding a total render volume of 4.2 m^3. This surface area is slightly overestimated due to the presence of vaults. The selected plaster thickness lies within the typical range for historic finishes (12–18 mm) [25], ensuring compatibility with traditional construction practices while enabling latent heat storage. Scenario (iii), the combined intervention, involves the simultaneous application of both surface rendering and core grouting across the same surfaces and volumes as in scenarios (i) and (ii).

The Hermitage of Santa Brígida offers an especially appropriate context for testing these strategies, given its uninsulated envelope, use of traditional lime-based materials, and architectural significance as a heritage-listed site. The three scenarios will be evaluated in terms of energy savings and environmental impact to determine their overall sustainability and to identify the most effective solution for enhancing indoor thermal comfort in historic building envelopes.

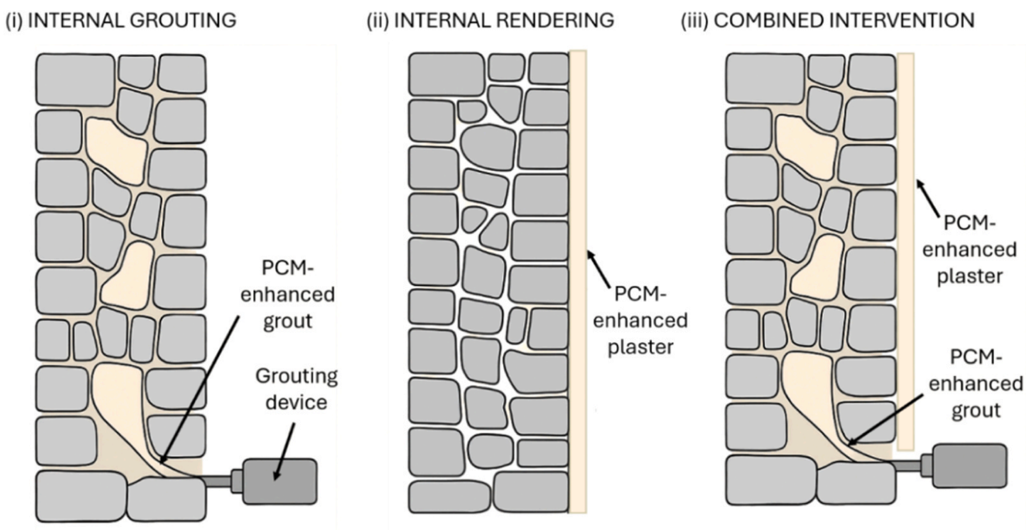

Fig. 2. Schematic representation of the three retrofit heritage-compatible retrofit strategies: (i) internal grouting with PCM-enhanced mortar, (ii) internal rendering with PCM-enhanced lime plaster, and (iii) combined intervention incorporating both approaches.

2.2. PCM-enhanced mortars

This study evaluates the carbon footprint and potential energy savings of lime mortars incorporating Phase Change Materials (PCMs), selected for their compatibility with heritage structures. Two PCM types were investigated: (i) paraffin-based microencapsulated PCMs with melamine shells, and (ii) a microencapsulated PCM with a bio-based core derived from agricultural by-products, also encapsulated in melamine. Together, these materials span a broad functional range, with melting temperatures between 18 °C and 29 °C, allowing passive thermal regulation across diverse climate conditions. Their microencapsulated format ensures the highest level of compatibility with traditional materials and restoration practices in historic environments.

The paraffin-based PCMs used in this study are supplied in dry powder form, featuring a melamine shell and a mean particle size of 15–30 μm, which facilitates uniform dispersion within lime-based matrices. Each microcapsule consists of approximately 80 wt% active PCM core and 20 wt% polymeric shell. Two commercial variants from Microtek were employed, with melting temperatures of 24 °C and 18 °C, designated in this work as P24 and P18, respectively. Their thermal storage capacity (absorb and release heat during phase transitions) was characterised by Differential Scanning Calorimetry (DSC), following a protocol of three heating–cooling cycles between −20 °C and 50 °C at a constant rate of 5 °C/min, following procedures outlined in [11]. The average melting (ΔH_m) and crystallisation enthalpies (ΔH_c), which quantify the latent thermal energy stored and released during phase change, were calculated across the three cycles [11]. P24 exhibited a ΔH_m of 166 kJ/kg and a ΔH_c of 168 kJ/kg, while P18 presented values of 162 kJ/kg and 159 kJ/kg, respectively. The melamine shell ensures thermal stability and prevents leakage during phase transitions, supporting reliable long-term performance and compatibility with lime-based mortars for conservation use [11,16]. These two PCMs, with melting points of 24 °C and 18 °C, were selected as representative of the most common ranges available for building applications, enabling comparative evaluation of their performance under different climatic contexts.

A third PCM, referred to as BIO29, was also evaluated. This material features a fully renewable organic core, derived from agricultural by-products, and encapsulated within a melamine-based polymeric shell. Manufactured by Microtek and supplied in wet cake form, BIO29 consists of 60 wt% bio-based PCM core, 15 wt% polymeric shell, and 25 wt% water. Its microcapsules range in size from 14–24 μm, enabling smooth integration into lime-based mortars. With a melting temperature of approximately 29 °C, BIO29 is particularly suited for enhancing indoor comfort in warm climates, especially during summer. Its thermal performance was assessed using Differential Scanning Calorimetry (DSC), according to the procedure described in [12], yielding a melting enthalpy (ΔH_m) of 171 kJ/kg and a crystallisation enthalpy (ΔH_c) of 164 kJ/kg. The use of a PCM derived from agricultural by-products significantly enhances the material's environmental profile and supports current goals in sustainable construction and circular resource use. With its higher melting point (29 °C), BIO29 extends the assessment towards warmer conditions, while also allowing a sustainability comparison between paraffin-based and bio-based PCMs.

Over recent years, our research group has developed and optimised PCM-lime mortar formulations that are both thermally functional and suitable for use in real-world heritage contexts [11,12,16]. The optimisation process prioritised workability, fluidity, adhesion to historic substrates, and resistance to cracking or segregation, resulting in mortar formulations meeting both conservation and construction standards. It included the incorporation of a polycarboxylate ether-based superplasticiser (SP) for improved workability, a potato starch-derived adhesion promoter for enhanced substrate bonding, and, in some mixes, metakaolin (MK) to improve mechanical properties and durability. Optimised formulations have been established for each PCM type, ensuring visual compatibility, ease of application, and long-term performance [11,12,16].

The formulations studied in the current work are based on prior research in which their design and mix composition were systematically optimised and validated. In the first stage, the interactions and compatibilities of the PCMs with different chemical additives and with the lime matrix were investigated through zeta potential measurements, adsorption isotherms and particle size distribution analyses [12,16]. These characterisations enabled the selection of optimal admixture dosages, leading to the development of robust and workable mortar formulations. Their properties in the fresh state, such as workability, consistency and adhesion, were evaluated to ensure their applicability as renders for the building envelope, with particular attention to the requirements of heritage conservation [12,16]. Once hardened, the mortars were subjected to comprehensive mechanical, microstructural and thermal characterisation through compressive strength testing, mercury intrusion porosimetry (MIP), Scanning Electron Microscopy (SEM), Differential Scanning Calorimetry (DSC) and thermal conductivity measurements. Microstructural studies combining MIP with SEM confirmed that the inclusion of PCMs and metakaolin did not significantly alter the pore structure and that the microcapsules remained homogeneously dispersed within the lime matrix. These investigations demonstrated that the PCM microcapsules are chemically and

Table 1
Composition and identification codes of the PCM-lime mortar formulations evaluated in this study.

Formulation ID	PCM (% bwol)	SP (% bwol)	Starch (% bwol)	MK (% bwol)
REF0	0	0.60	0.50	0
REF20	0	0.75	0.50	20
PCM_5_0	5	0.75	0.50	0
PCM_5_20	5	0.75	0.50	20
PCM_10_0	10	0.75	0.50	0
PCM_10_20	10	0.75	0.50	20
PCM_20_0	20	0.75	0.50	0
PCM_20_20	20	0.75	0.50	20

physically compatible with the alkaline lime environment, and that no signs of interfacial degradation or leakage were observed. Their capacity to moderate temperature fluctuations was also assessed through hotbox-type energy performance tests [11,12]. In these studies, the incorporation of metakaolin (MK) was specifically examined with respect to its influence on thermal behaviour. Conductivity measurements, DSC analyses and hot-box experiments confirmed that MK-bearing mortars exhibited comparable PCM activation and heat flow to MK-free mortars, indicating that MK does not compromise latent heat storage capacity. This robust experimental foundation ensures that the simulations and environmental impact estimations presented herein are grounded in technically validated and field-applicable mortar systems.

All mortar mixes share a consistent base mix design, with a fixed binder-to-aggregate weight ratio of 21.7:78.3 and a water content of 25 wt% relative to total solids. The binder consists of hydrated air lime (CL 90-S), selected for its compatibility with historic masonry, while the aggregate is fine limestone sand, chosen to match the appearance and properties of traditional mortars. Table 1 presents the optimised mortar formulations for each PCM type, based on previous studies in which PCM contents of 5 %, 10 %, and 20 % by weight of lime (bwol) were evaluated.

For clarity, all mortar formulations are identified using a compact coding system. The formulation ID indicates the type of PCM and the corresponding dosage parameters. Specifically:

- REF denotes control mixes without any PCM.

- P18 or P24 indicate paraffin-based PCMs with melamine microcapsules, with melting temperatures of 18°C and 24°C, respectively.

- BIO29 designates the bio-based PCM with a melting temperature of 29 °C.

Each formulation ID follows the structure PCM_X_Y, where X represents the PCM dosage (% bwol) and Y the metakaolin content (% bwol).

2.3. Carbon footprint analysis (A1-A3)

A cradle-to-gate carbon footprint assessment was carried out to evaluate the climate impact associated with the production and in-situ preparation of PCM-enhanced lime mortars, covering life cycle stages A1–A3 as defined by EN 15804 [19]. The analysis focuses on Global Warming Potential (GWP, expressed in kg CO_2-equivalent) as a representative and robust indicator for comparing the environmental performance of different mortar formulations.

The functional unit is defined as 1 m^3 of lime-based mortar, reflecting its application in both internal rendering and grouting within historic masonry walls, consistent with the retrofit scenarios outlined in Section 2.1.

The system boundaries include:

– A1 – Raw material extraction and processing (hydrated lime, aggregates, metakaolin, superplasticiser, adhesion booster, and PCM).
– A2 – Transport of materials to the restoration site.
– A3 – On-site mortar mixing and application.

Environmental data for hydrated lime, aggregates, metakaolin, and chemical admixtures were sourced primarily from product-specific Environmental Product Declarations (EPDs) provided by manufacturers or available in certified LCA databases.

For the paraffin-based PCMs, in the absence of manufacturer-provided EPDs, GWP values were estimated using data from Ecoinvent v3.9.1. This included emissions associated with the production of both paraffin wax and melamine, the latter being the polymer used for microencapsulation. In line with standard LCA practice using the cut-off approach, the bio-based PCM (BIO29) core—being derived from agricultural by-products—was assigned a zero-carbon footprint, as it enters the system without upstream environmental burdens. Accordingly, only the impact of the melamine-based shell, which represents approximately 15 wt% of the product, was considered in the calculation. This assumption is consistent with common practice in LCA studies involving waste-derived feedstocks [26,27].

This targeted carbon footprint analysis provides a consistent basis for comparing conventional and PCM-enhanced lime mortars across various retrofit strategies, supporting evidence-based decision-making in sustainable and heritage-compatible restoration practices.

2.4. Energy demand simulation

To estimate the theoretical annual energy demand for space heating and cooling in the Hermitage of Santa Brígida, a multi-criteria approach was adopted. This methodology integrates climatic severity, typological vulnerability, and empirical benchmarks drawn from the literature. The hermitage is situated in climate zone D1, as defined by the Spanish Technical Building Code (CTE) [28]. A comprehensive explanation of the Spanish climatic classification system, including all zone definitions and thresholds, is provided in Supplementary Material S1. Climate zone D1 is characterized by cold winters and moderate summers, implying substantial heating requirements. The analysis incorporates quantitative data from Spanish and European studies [3,29–34], which relate energy demand to building age, construction type, and climatic conditions, allowing for a realistic estimation of the hermitage's energy profile based on comparable historic structures.

Climate zone D1 has a winter climate severity index (SCI) ranging between 0.95 and 1.30, and a summer climate severity index (SCV) below 0.50, reflecting high heating needs and moderate cooling demand [23]. While cooling demand is generally low under these conditions, increasing heatwave frequency and evolving expectations for indoor comfort [35] have made summer performance a growing concern in temperate regions.

As described in Section 2.1, the Hermitage of Santa Brígida exhibits the typical characteristics of pre-industrial religious architecture: a compact, fully exposed masonry structure with uninsulated lime-bonded stone walls and no thermal regulation. To estimate its energy demand under standard thermal comfort conditions, baseline values were drawn from simulation data for pre-1980 residential buildings located in climate zone D1 [30]. According to a recent simulation study [3], such buildings typically exhibit an average heating demand of approximately 235 kWh/m^2·year and cooling demand below 6 kWh/m^2·year. These figures were used as conservative reference values, prior to further adjustments and the application of degradation-based correction factors.

However, it is widely acknowledged that these baseline estimates likely underestimate the actual energy demand of heritage buildings, as pre-1980 residential buildings often benefit from partial modernisation measures that are not representative of unaltered historic structures. A large-scale study of over 350,000 energy performance certificates in Greece [34] confirmed that buildings constructed before 1980, comprising around 75 % of the national building stock, show the highest energy consumption levels, largely due to envelope degradation and lack of thermal insulation. The study further demonstrated that energy consumption rises in correlation with climatic severity and building age and declines only after the implementation of national thermal regulations post-1980 [34]. These findings underscore the critical influence of construction period and envelope condition on energy performance, and support the use of correction factors when estimating the thermal demand of non-renovated heritage buildings.

Envelope degradation over time further exacerbates energy demand. A recent modelling study [32] examined the impact of material ageing and system deterioration, concluding that energy use can increase by 9–38 % depending on the degree of degradation. Key contributing factors included reduced airtightness, thermal bridging, insulation decay, and general envelope fatigue. While the reference study [32] focused on cooling performance in hot-humid climates, the degradation mechanisms are equally applicable to heating-driven environments. On this basis, and supported by literature ranges of degradation-related increases in energy demand (9–38 %) [32], a mid-conservative correction factor of + 25 % was applied. This parameterisation is intended to approximate long-term envelope deterioration in a realistic yet cautious manner, acknowledging performance decay without resorting to extreme assumptions.

Applying this correction to the baseline values derived from a simulation of pre-1980 residential buildings in climate zone D1 [30], the adjusted annual primary energy demand of the Hermitage of Santa Brígida is estimated at 293.8 kWh/m^2·year for heating, 7.5 kWh/m^2·year for cooling, resulting in a total of 301.3 kWh/m^2·year. These adjusted values represent the theoretical energy required to maintain basic comfort conditions within the hermitage, accounted for climatic severity, construction age, and lack of thermal upgrades. Given this high energy demand and the inherently poor efficiency of the envelope, PCM lime mortars are introduced as a passive retrofit strategy to reduce heating and cooling needs. The expected energy savings are calculated using a latent heat balance approach.

Following the same methodology and bibliographic references [3,29–34], theoretical energy demand estimates for space heating and cooling were also developed for the remaining Spanish climate zones (A3 to E1), as defined by the CTE [23]. The estimated heating and cooling demands for each of the twelve official climate zones, together with the adjusted heritage-specific values, are summarised in Table 2. These extended simulations apply the same correction criteria used for climate zone D1 to ensure consistency across climatic contexts. The resulting demand values are further discussed in Section 3.4, where the performance of the hermitage is analysed under varying climatic conditions.

The potential energy savings resulting from the incorporation of PCMs into the building envelope were estimated using a thermal balance based on latent heat storage, following the methodology proposed in [22]. This approach accounts for the capacity of PCMs to absorb and release thermal energy during phase transitions, thereby reducing reliance on active heating and cooling systems [22]. The total latent energy exchanged by the PCM over one-year period was calculated using Eq.1:

$$E_{latent,PCM} = n_{PCM} \cdot m_{PCM} \cdot \Delta H_{PCM} \quad (1)$$

Table 2
Estimated heating and cooling energy demand across Spanish climate zones: baseline values for pre-1980 residential buildings [30].

		Pre-1980 Residential Buildings		Heritage Scenario (corrected)*	
Climate zone	Representative city	Heating demand (kWh/m^2·year)	Cooling demand (kWh/m^2·year)	Heating demand (kWh/m^2·year)	Cooling demand (kWh/m^2·year)
A3	Cádiz	40.0	35.0	50.0	43.8
A4	Almería	40.0	58.0	50.0	72.5
B3	Valencia	60.0	35.0	75.0	43.8
B4	Sevilla	60.0	58.0	75.0	72.5
C1	Bilbao	125.0	6.0	156.3	7.5
C2	Barcelona	125.0	17.0	156.3	21.3
C3	Madrid	117.0	37.0	146.3	46.3
C4	Toledo	180.0	37.0	225.0	46.3
D1	**Hermitage of Santa Brígida**	**235.0**	**6.0**	**293.8**	**7.5**
D2	Zamora	178.0	17.0	222.5	21.3
D3	Cuenca	200.0	40.0	250.0	50.0
E1	León	230.0	6.0	287.5	7.5

* Adjusted heritage scenarios include a + 25 % correction factor to account for envelope degradation, consistent with reported ranges in the literature [32,34]. Representative cities were selected according to the Spanish Building Code (CTE), using the provincial capitals assigned to each climate zone.

Where:

$E_{latent,PCM}$ is the annual latent energy (kJ/year),

n_{PCM} is the number of complete phase change events, specified as $n_{PCM,melting}$ during summer and $n_{PCM,crystallization}$ during winter.

m_{PCM} is the total mass of PCM integrated into the building envelope (kg), and

ΔH_{PCM} is the specific latent heat of melting (ΔH_m during the summer period) or crystallization (ΔH_c during winter period) (kJ/kg), determined through Differential Scanning Calorimetry (DSC) in previous studies [11,12].

The product of these three variables quantifies the total amount of thermal energy the PCM can store during melting and release during solidification throughout the year. This procedure explicitly links climatic data, PCM thermophysical properties, and the latent-heat balance, ensuring that both local temperature profiles and material characteristics are consistently represented.

To estimate the number of annual phase change cycles (n_{PCM}), hourly outdoor temperature data were retrieved from the Open-Meteo API using the exact geographic coordinates of the Hermitage of Santa Brígida. The analysis was conducted separately for the heating and cooling seasons, using a five consecutive year dataset (2019–2024). Melting cycles ($n_{PCM,\ melting}$) were counted during the summer months, when latent heat absorption contributes to space cooling. Crystallisation cycles ($n_{PCM,\ crystallization}$) were evaluated during winter, when latent heat release helps reduce heating loads. Seasonal values were averaged across the five-year period to produce a representative annual estimate. The same procedure was repeated for each of the remaining climate zones using representative cities as geographical proxies (Table 2), to simulate the corresponding number of phase change events under local temperature profiles.

Once the annual latent energy contributions for both heating and cooling were computed, they were incorporated into the building's overall energy balance to estimate the adjusted energy demand after PCM implementation, using the Eq. 2:

$$E_{consumption,\ with\ PCM} = E_{consumption,\ without\ PCM} - E_{latent,PCM} \tag{2}$$

Where:

$E_{consumption,\ with\ PCM}$ is the estimated energy demand after PCM implementation, $E_{consumption,\ without\ PCM}$ is the baseline energy demand of the unretrofitted historic building, $E_{latent,PCM}$ is the annual latent thermal contribution of the PCM, offsetting part of the heating and cooling demand.

The thermal balance applied in this study assumes optimal interaction between the PCM and the indoor environment, without explicitly accounting for sensible heat gains or losses. As such, it constitutes a screening-level methodology, particularly well-suited to heritage contexts where detailed input data (e.g., occupancy, infiltration, or dynamic hygrothermal properties) are generally unavailable. This approach provides a transparent and comparative basis for evaluating PCM–lime mortars across different climatic conditions, offering a valuable first framework to assess their potential. Future research may build upon this foundation by incorporating dynamic simulation tools and in-situ monitoring to further validate and refine the outcomes of this study.

3. Results and discussion

3.1. *Carbon footprint analysis (A1-A3)*

The Global Warming Potential (GWP) associated with each raw material used in the lime-based mortar formulations was sourced from Environmental Product Declarations (EPDs) or from the Ecoinvent v3.9.1 database (see Table 3). For the starch-based adhesion promoter, the GWP value was obtained directly from the manufacturer. In cases where no specific EPDs existed, particularly for PCMs, the GWP was estimated by calculating the weighted contribution of their individual components, as described in Section 2.3 of the Materials and Methods. These components include both the PCM core and the encapsulating shell.

The Global Warming Potential (GWP) associated with the production of each component required to formulate 1 m^3 of fresh mortar

Table 3

Cradle-to-gate Global Warming Potential (GWP) values for raw materials used in the lime-based mortar formulations (life-cycle stages A1-A3), including data sources and methodological assumptions.

Material	Source	GWP ($kg\ CO_2$-eq/kg)	Notes/ Assumptions
Hydrated air lime	European Lime Association EPD	0.874	-
Calcitic sand	EPD-S-P—11716	0.00273	-
Metakaolin	EPD-S-P—03756	0.35937	-
Superplasticizer	EPD-EFC—20210198-IBG1-EN	1.53	-
Adhesion booster	Manufacturer data	32.6	Value provided directly by supplier (NeoNautilius Import, SL)
Paraffin wax	Ecoinvent v3.9.1	1.5	-
Melamine resin	Ecoinvent v3.9.1	4.69	-
PCMs:			
P24	80 % paraffin core + 20 % melamine shell (Ecoinvent v3.9.1)	2.138	Weighted average of components
P18	80 % paraffin core + 20 % melamine shell (Ecoinvent v3.9.1)	2.138	Weighted average of components
BIO29	Bio-based core (GWP = 0) + 15 % melamine shell (Ecoinvent v3.9.1)	0.7035	Weighted average of components

(corresponding to the A1 stage) was calculated using three key inputs: the material dosages presented in Table 1, the experimentally measured fresh density of each mortar formulation, and the cradle-to-gate GWP values per kilogram of material listed in Table 3. The fresh densities were determined in accordance with UNE-EN 1015–6 [36], and the measured values are reported in Supplementary Material Table S2. This approach enabled an accurate estimation of the individual and cumulative GWP contributions per constituent, resulting in the total A1 impact per cubic metre of fresh mortar.

Beyond raw material production (A1), the GWP values reported in Table 4 also include emissions associated with transport to the restoration site (A2) and on-site mixing (A3). For the transportation stage, an emission factor of 0.0912 kg CO_2-eq per tonne·km was applied, corresponding to a 33-tonne articulated lorry. This value was sourced from the ICE Database v1.2 (Inventory of Carbon and Energy, December 2024). Transport distances were estimated based on the country of origin for each component and standard logistics routes to Olite (Navarre, Spain).

For the mixing stage (A3), a GWP factor of 0.0007 kg CO_2-eq per kg of fresh mortar was used, representing the energy consumption associated with wet batching processes at the construction site. This emission factor was also obtained from the ICE Database and reflects typical energy use in concrete and mortar production.

The total GWP values for each mortar formulation, accounting for stages A1, A2, and A3, are summarised in Table 4 and visualised in Fig. 3.

The results reveal a clear variation in cradle-to-gate GWP among the mortar formulations analysed (Table 4 and Fig. 3). As anticipated, the reference mortars (REF0 and REF20) exhibit the lowest total GWP values, with REF0 reaching 363.1 kg CO_2e/m^3 and REF20 slightly higher at 383.8 kg CO_2e/m^3 , reflecting the additional impact of metakaolin.

The incorporation of microencapsulated paraffin-based PCMs (P24 and P18) results in a consistent increase in total GWP with rising PCM content. For example, the GWP for P24-based formulations increases from 373.6 kg CO_2e/m^3 (P24_5_0) to 469.0 kg CO_2e/m^3 (P24_20_20), while for P18-based mixes, it rises from 399.6 kg CO_2e/m^3 (P18_5_0) to 498.0 kg CO_2e/m^3 (P18_20_20). The transport stage (A2) becomes particularly relevant in formulations with higher PCM and metakaolin contents (e.g., 20 % PCM and 20 % MK), where transport emissions contribute significantly, typically in the range of 24–26 kg CO_2e/m^3 , due to the cumulative mass and long-distance sourcing of several imported components.

Formulations incorporating the bio-based PCM (BIO29) exhibit a more favourable environmental profile compared to their paraffin-based counterparts. In addition to their lower GWP values, such as 366.2 kg CO_2e/m^3 for BIO29_5_0 and 402.7 kg CO_2e/m^3 for BIO29_20_20, these mortars offer notable sustainability benefits (Table 4 and Fig. 3). The use of a waste-derived organic core in the microcapsules exemplifies a circular economy approach, reducing reliance on fossil-based resources and significantly lowering the carbon footprint of the PCM component.

Across all formulations, the contribution of the mixing stage (A3) is minimal, consistently ranging between 1.25 and 1.36 kg CO_2e/m^3 , and accounting for less than 0.3 % of the total cradle-to-gate GWP. Conversely, raw material production (A1) remains the dominant contributor, while transport (A2) plays ab increasingly significant role in more complex or additive-rich mixes, particularly those containing higher percentages of PCM and metakaolin.

While the cradle-to-gate GWP assessment offers a valuable estimate of the environmental impact associated with mortar production, transport, and on-site preparation, it does not reflect the material's potential to reduce operational emissions. The true sustainability value of PCM-enhanced mortars lies in their ability to lower the energy demand for heating and cooling during the use phase. To capture this operational dimension, the following section presents a simulation-based assessment of the energy performance

Table 4
Breakdown of Global Warming Potential (GWP) by life cycle stage (A1, A2, A3) per cubic meter of fresh mortar for reference mix and microencapsulated PCM-based formulations.

Formulation ID	A1 GWP (kg CO_2e/m^3 mortar)	A2 GWP (kg CO_2e/m^3 mortar)	A3 GWP (kg CO_2e/m^3 mortar)	A1-A3 GWP (kg CO_2e/m^3 mortar)
REF0	355.649	6.051	1.361	363.061
REF20	364.493	17.907	1.360	383.760
P24_5_0	364.227	8.128	1.277	373.632
P24_5_20	372.055	19.099	1.282	392.435
P24_10_0	397.807	10.627	1.292	409.725
P24_10_20	399.202	21.233	1.279	421.713
P24_20_0	440.920	14.820	1.252	456.992
P24_20_20	442.916	24.862	1.249	469.027
P18_5_0	389.533	8.693	1.366	399.592
P18_5_20	392.638	20.155	1.353	414.146
P18_10_0	415.290	11.094	1.348	427.732
P18_10_20	422.822	22.489	1.355	446.665
P18_20_0	465.209	15.636	1.321	482.166
P18_20_20	470.319	26.400	1.326	498.046
BIO29_5_0	356.397	8.475	1.332	366.204
BIO29_5_20	362.446	19.751	1.325	383.523
BIO29_10_0	361.364	10.880	1.322	373.567
BIO29_10_20	373.750	22.254	1.340	397.344
BIO29_20_0	371.129	15.459	1.306	387.893
BIO29_20_20	375.600	25.843	1.298	402.742

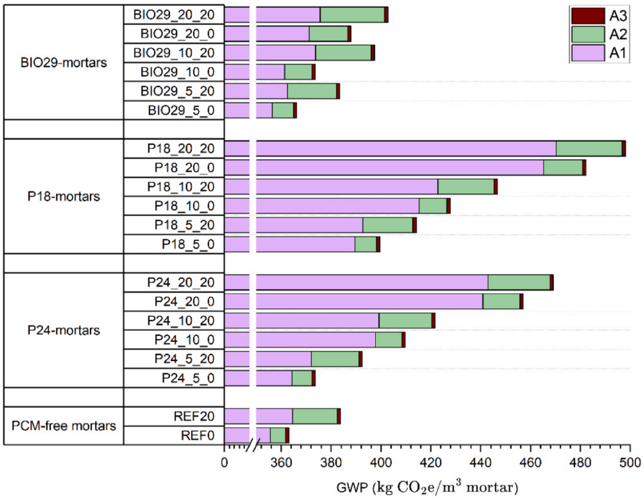

Fig. 3. Cradle-to-gate Global Warming Potential (GWP) by life cycle stage (A1, A2, A3) per cubic meter of fresh mortar for formulations incorporating microencapsulated PCMs.

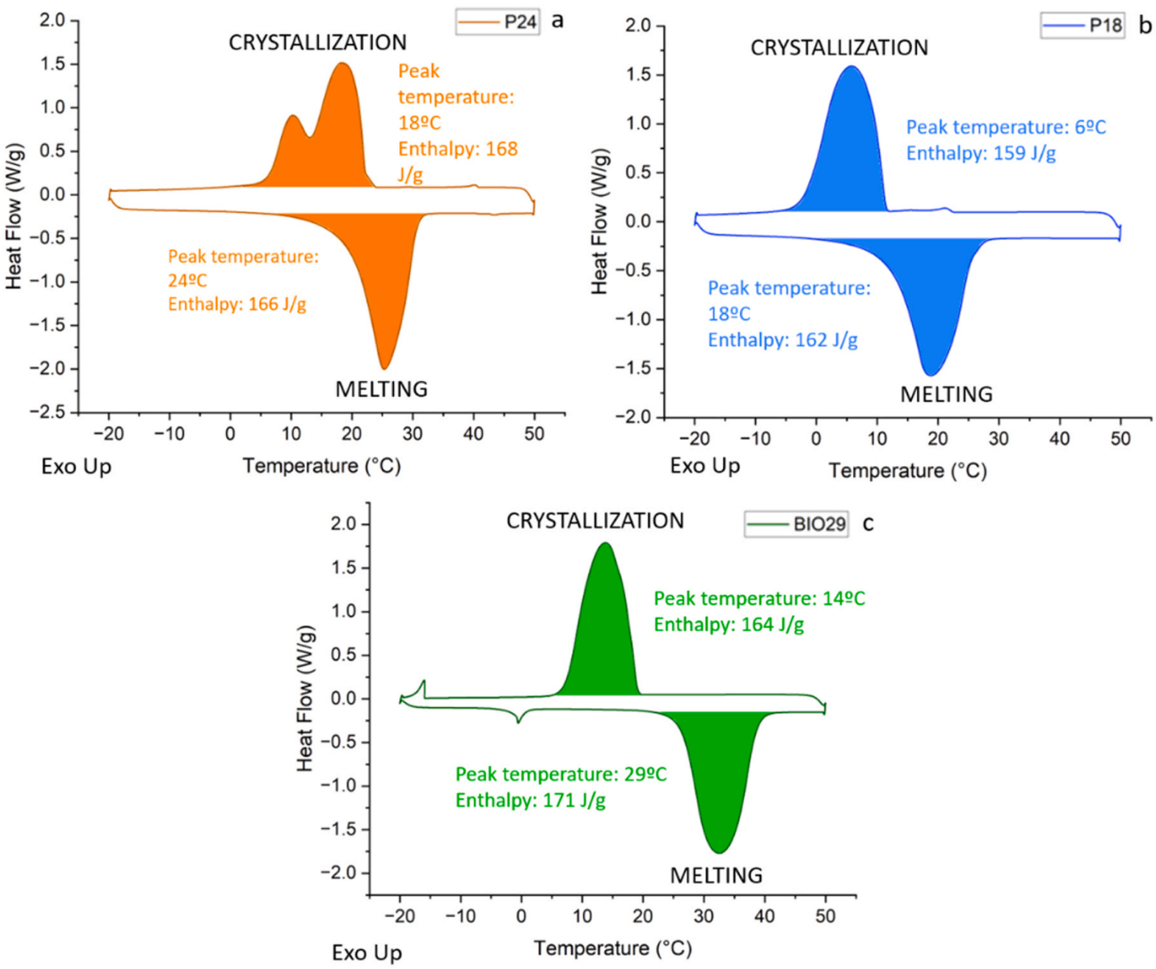

Fig. 4. DSC curves of the pure PCMs: (a) P24, (b) P18 and (c) BIO29.

of each formulation as applied to the Hermitage of Santa Brígida, within its actual climatic context.

3.2. Energy performance evaluation under real climatic conditions

To assess the performance of PCM-enhanced mortars in a representative heritage setting, the Hermitage of Santa Brígida was modelled under the actual climatic conditions of zone D1. This enabled a comparative evaluation of the three retrofit strategies (internal grouting, internal rendering, and their combined application) with a focus on their capacity to reduce seasonal energy demand through latent heat exchange.

For the summer period, hourly outdoor temperature data from 2019 to 2024 were analysed to estimate the number of effective melting cycles for each PCM formulation. Melting was assumed to occur when ambient temperatures exceeded the PCM's melting point, allowing the material to absorb excess heat, attenuate indoor thermal peaks, and reduce reliance on active cooling systems. Melting thresholds were determined through Differential Scanning Calorimetry (DSC), as described in the Materials and Methods section and previous studies [11,12]. The experimentally measured enthalpies of melting (ΔH_m) for each PCM type are illustrated in Fig. 4. As summarised in Table 5, the number of summer melting cycles varied considerably among formulations. P24-bearing mortars reached up to 77 melting cycles, while P18-bearing mortars achieved up to 69 cycles. BIO29-bearing mortars, with the highest enthalpy value per unit mass (170.7 J/g), completed 45 melting cycles.

During the winter season, the number of effective crystallisation events, which occur when ambient temperatures fall below the PCM's crystallization temperature, was similarly assessed to estimate the potential contribution to space heating via latent heat release. These thresholds were also corroborated by DSC. P18-bearing mortars demonstrated balanced bi-seasonal activity, with 70 crystallisation cycles, matching their summer melting frequency. BIO29 mortars completed 27 crystallisation cycles, offering moderate winter performance. P24 mortars, in contrast, achieved only 4 crystallisation events, due to the relatively mild winter temperatures in Olite (zone D1), which often remained above the crystallisation threshold of this PCM (Table 5 and Fig. 4). Although the enthalpies of crystallisation (ΔH_c) were similar to the melting enthalpies for each PCM, the actual thermal contribution to heating was highly dependent on the number of phase change events. These findings highlight the superior suitability of lower-melting-point PCMs, particularly P18, for improving winter energy performance under the current climate conditions.

Three energy retrofitting strategies were analysed to explore varying degrees of PCM integration within the building envelope. Strategy (i) involves the injection of PCM-enhanced lime mortars into the internal core of the historic stone walls (internal grouting). The results for this intervention scenario are presented in Fig. 5, Table 6, and Supplementary Material S3.

During the summer season, all PCM-bearing mortars demonstrated full thermal activation through melting, resulting in substantial latent heat uptake and complete elimination of the building's cooling demand. As shown in Fig. 5a, latent energy absorption increased proportionally with PCM content across all mortar families. Specifically, P18_20_0 absorbed up to 4.95×10^{10} J/year, P24_20_0 reached 5.33×10^{10} J/year, and BIO29_20_0 achieved 3.35×10^{10} J/year. These thermal gains directly translated into 100 % savings in cooling energy demand across all PCM formulations, reducing the adjusted consumption from 7.5 kWh/m^2·year to zero, as illustrated in Fig. 5b and reported in Table 6. These results confirm that Strategy (i) is highly effective in mitigating summertime overheating in climate zone D1, demonstrating the strong potential of internal PCM grouting as a passive strategy for reducing cooling energy demand in historic masonry buildings.

During the winter season, latent heat released via crystallisation also contributed to the reduction of heating demand, although the extent of this benefit varied significantly across formulations. As illustrated in Fig. 5a, P18-based mortars exhibited the highest levels of crystallisation energy release, with P18_20_0 and P18_20_20 reaching 4.91×10^{10} and 4.73×10^{10} J/year, respectively. These values correspond to substantial heating energy savings of 35.7 % and 34.4 %, as shown in Fig. 5b and detailed in Table 6. BIO29-based mortars also performed well in this regard, with BIO29_20_0 achieving 1.92×10^{10} J/year in latent heat release and delivering a 13.9 % reduction in heat demand. In contrast, P24 formulations demonstrated limited thermal activation in winter; for example, P24_20_0 released only 2.80×10^9 J/year, resulting in a modest 2.0 % energy saving. Overall, Strategy (i) (internal grouting) exhibits strong bi-seasonal performance, especially when employing medium-melting-temperature PCMs such as P18, which offer a well-balanced response to both summer and winter thermal demands in temperate climates like zone D1.

Strategy (ii), which involves the application of PCM-enhanced mortars as an internal rendering layer, was also assessed for its impact on thermal performance in climate zone D1. The simulation results are summarized in Table 7, Fig. 6 and Supplementary Material S4.

In contrast to Strategy (i), which involves the incorporation of approximately 71 m^3 of mortar within the wall structure, Strategy (ii) applies only around 4 m^3 of PCM render as an internal rendering layer. This substantial reduction in PCM volume inherently limits the total latent heat storage capacity. Nevertheless, the summer thermal performance remains noteworthy. As shown in Fig. 6a and

Table 5
Phase change temperatures and enthalpy values of PCM-bearing mortars, determined via DSC, along with the number of effective melting and crystallisation events based on historical hourly temperature data (2019–2024) for climate zone D1.

	$n_{melting}$	$T_{peak,\ melting}$ (°C)	$\Delta H_{melting}$ (J/kg)	$n_{crystallization}$	$T_{peak,\ crystallization}$ (°C)	$\Delta H_{crystallization}$ (J/kg)
PCM-free mortars	0	None	0	0	None	0
P24-mortars	77	24	165945	4	18	167575
P18-mortars	69	18	161925	70	6	159240
BIO29-mortars	45	29	170770	27	14	163810

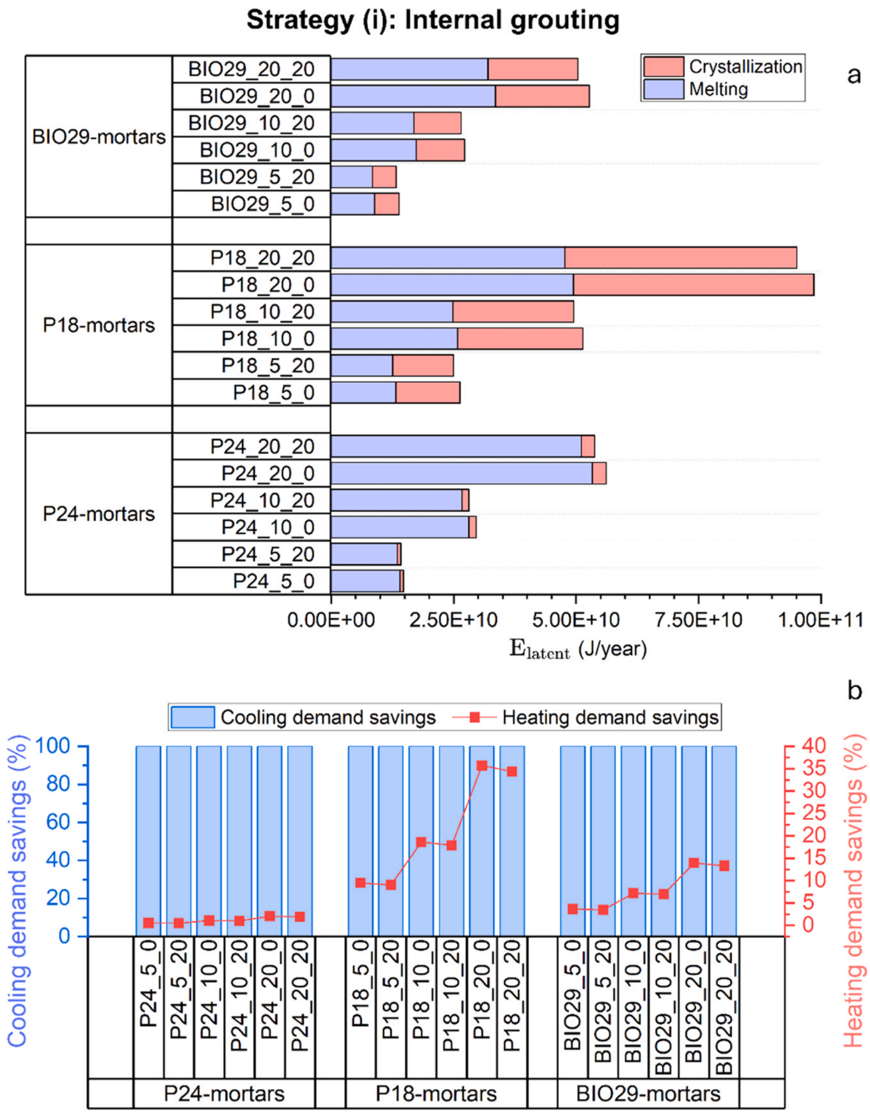

Fig. 5. (a) Seasonal latent heat exchange and (b) corresponding energy demand savings for PCM-bearing mortars under Strategy (i) (internal grouting) in climate zone D1.

Table 7, the P18_20_0 formulation absorbed 2.96 × 10^9 J/year, reducing the building's cooling demand from 7.5 to 1.2 kWh/m^2·year, equivalent to an 84 % saving. Similarly, P24_20_0 achieved 3.19 × 10^9 J/year of latent heat absorption and delivered a 90.8 % reduction in cooling energy. BIO29-based mortars also exhibited promising performance. For instance, BIO29_20_0 reached 2.00 × 10^9 J/year, lowering cooling demand to 3.2 kWh/m^2·year, or a 57.1 % saving, despite a lower number of annual melting cycles. These findings confirm that even small amounts of PCM can substantially reduce summer cooling loads in climate zone D1, demonstrating the effectiveness of internal rendering as a passive thermal strategy.

During the winter season, the latent heat released through crystallisation under Strategy (ii) (internal rendering) results in modest thermal benefits. According to Fig. 6a and Table 7, the P18_20_0 formulation released 2.93 × 10^9 J/year, translating to a 2.1 % reduction in heating demand. P24_20_0 released only 1.68 × 10^8 J/year, yielding a negligible 0.1 % saving. Similarly, BIO29-based formulations, such as BIO29_20_0, achieved 1.14 × 10^9 J/year of crystallisation energy, corresponding to a 0.8 % reduction in heating energy use. Overall, the latent heat contribution of PCM-enhanced internal renderings during winter is minimal and does not significantly affect the building's heating demand. Under the current climatic conditions of zone D1, Strategy (ii) (internal rendering) cannot be considered an effective measure for winter energy savings.

Strategy (iii) combines the interventions of Strategies (i) and (ii) by integrating PCM-enhanced mortars both within the internal wall cores (grouting) and on the interior surfaces (rendering). This hybrid approach increases the total volume of PCM introduced into the building envelope, offering the potential for improved thermal performance while preserving the material compatibility essential for heritage conservation. The corresponding simulation results, summarised in Table 8, Fig. 7 and Supplementary Material S5, provide

Table 6
Latent heat storage capacity and seasonal energy performance for PCM-enhanced mortars under Strategy (i) (internal grouting) in climate zone D1.

Formulation ID	$E_{latent,melting}$ (J/year)	Cooling demand (kWh/m²·year)	Saving in cooling (%)	$E_{latent,crystallization}$ (J/year)	Heating demand (kWh/m²·year)	Saving in heating (%)
REF0	0.00	7.5	0.0	0.00	293.8	0.0
REF20	0.00	7.5	0.0	0.00	293.8	0.0
P24_5_0	1.40E+ 10	0.0	100.0	7.39E+ 08	292.2	0.5
P24_5_20	1.35E+ 10	0.0	100.0	7.11E+ 08	292.2	0.5
P24_10_0	2.81E+ 10	0.0	100.0	1.48E+ 09	290.6	1.1
P24_10_20	2.67E+ 10	0.0	100.0	1.40E+ 09	290.8	1.0
P24_20_0	5.33E+ 10	0.0	100.0	2.80E+ 09	287.8	2.0
P24_20_20	5.11E+ 10	0.0	100.0	2.69E+ 09	288.0	2.0
P18_5_0	1.32E+ 10	0.0	100.0	1.31E+ 10	265.8	9.5
P18_5_20	1.25E+ 10	0.0	100.0	1.24E+ 10	267.2	9.0
P18_10_0	2.58E+ 10	0.0	100.0	2.56E+ 10	239.1	18.6
P18_10_20	2.49E+ 10	0.0	100.0	2.47E+ 10	241.1	17.9
P18_20_0	4.95E+ 10	0.0	100.0	4.91E+ 10	188.9	35.7
P18_20_20	4.77E+ 10	0.0	100.0	4.73E+ 10	192.6	34.4
BIO29_5_0	8.83E+ 09	0.0	100.0	5.04E+ 09	283.0	3.7
BIO29_5_20	8.42E+ 09	0.0	100.0	4.81E+ 09	283.5	3.5
BIO29_10_0	1.73E+ 10	0.0	100.0	9.91E+ 09	272.6	7.2
BIO29_10_20	1.69E+ 10	0.0	100.0	9.64E+ 09	273.2	7.0
BIO29_20_0	3.35E+ 10	0.0	100.0	1.92E+ 10	252.8	13.9
BIO29_20_20	3.20E+ 10	0.0	100.0	1.83E+ 10	254.7	13.3

Table 7
Latent heat storage capacity and seasonal energy performance of PCM-enhanced mortars under strategy (ii) (internal rendering) in climate zone D1.

Formulation ID	$E_{latent,melting}$ (J/year)	Cooling demand (kWh/m²·year)	Saving in cooling (%)	$E_{latent,crystallization}$ (J/year)	Heating demand (kWh/m²·year)	Saving in heating (%)
REF0	0.00	7.5	0.0	0.00	293.8	0.0
REF20	0.00	7.5	0.0	0.00	293.8	0.0
P24_5_0	8.39E+ 08	5.7	23.9	4.41E+ 07	293.7	0.0
P24_5_20	8.07E+ 08	5.8	23.0	4.25E+ 07	293.7	0.0
P24_10_0	1.68E+ 09	3.9	47.8	8.83E+ 07	293.6	0.1
P24_10_20	1.59E+ 09	4.1	45.4	8.39E+ 07	293.6	0.1
P24_20_0	3.19E+ 09	0.7	90.8	1.68E+ 08	293.4	0.1
P24_20_20	3.05E+ 09	1.0	87.0	1.61E+ 08	293.4	0.1
P18_5_0	7.89E+ 08	5.8	22.5	7.83E+ 08	292.1	0.6
P18_5_20	7.49E+ 08	5.9	21.3	7.43E+ 08	292.2	0.5
P18_10_0	1.54E+ 09	4.2	43.9	1.53E+ 09	290.5	1.1
P18_10_20	1.48E+ 09	4.3	42.3	1.47E+ 09	290.6	1.1
P18_20_0	2.96E+ 09	1.2	84.2	2.93E+ 09	287.5	2.1
P18_20_20	2.85E+ 09	1.4	81.2	2.83E+ 09	287.7	2.1
BIO29_5_0	5.27E+ 08	6.4	15.0	3.01E+ 08	293.1	0.2
BIO29_5_20	5.03E+ 08	6.4	14.3	2.88E+ 08	293.1	0.2
BIO29_10_0	1.04E+ 09	5.3	29.5	5.92E+ 08	292.5	0.4
BIO29_10_20	1.01E+ 09	5.3	28.7	5.76E+ 08	292.5	0.4
BIO29_20_0	2.00E+ 09	3.2	57.1	1.14E+ 09	291.3	0.8
BIO29_20_20	1.91E+ 09	3.4	54.5	1.09E+ 09	291.4	0.8

a comprehensive assessment of the cumulative impact of dual PCM application on seasonal energy demand in climate zone D1.

As anticipated, Strategy (iii), which incorporates the largest volume of PCM into the building envelope (approximately 75 m^3), resulted in the highest levels of latent heat storage and release (Table 8, Fig. 7 and Supplementary Material table S5). Consistent with the results in Strategy (i) (internal grouting), cooling demand was entirely eliminated across all PCM formulations. In terms of heating demand, Strategy (iii) (combined intervention) achieved a slight but meaningful improvement over Strategy (i) (internal grouting). Among the formulations, P18-based mortars continued to deliver the strongest performance, with P18_20_0 standing out by reaching nearly 38 % savings, highlighting its effectiveness for bi-seasonal thermal regulation under the climatic conditions of zone D1.

Nevertheless, to identify the most advantageous of the three strategies, a comprehensive overall assessment is required, one that considers not only the operational energy savings but also the carbon footprint associated with the production and application of PCM-enhanced mortars. This global balance is essential to accurately evaluate the true sustainability of each approach.

3.3. Balancing embodied carbon and energy efficiency

The true sustainability of PCM-lime mortars lies on achieving an effective balance between their embodied carbon emissions and the operational energy savings they deliver over the building's service life. A holistic assessment must therefore consider not only

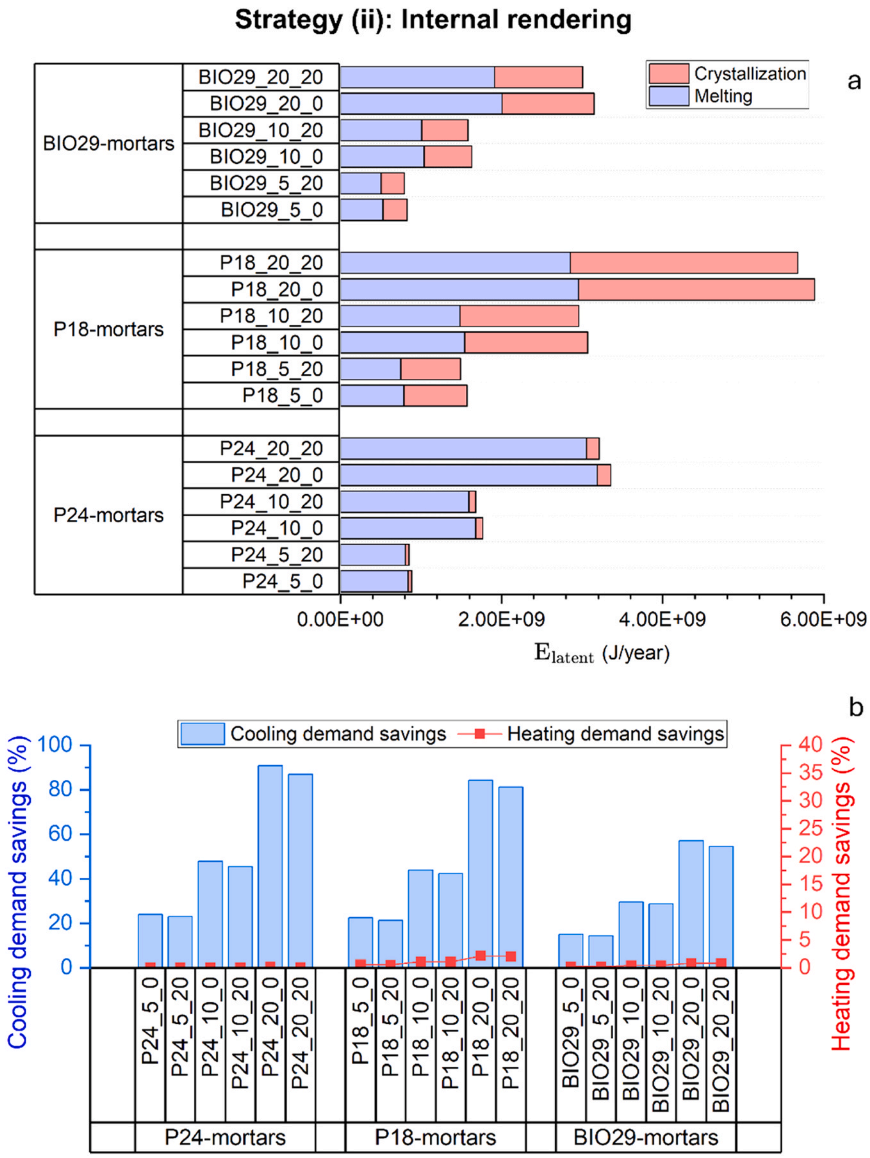

Fig. 6. (a) Seasonal latent heat exchange and (b) corresponding energy demand savings for PCM-bearing mortars under Strategy (ii) (internal rendering) in climate zone D1.

thermal performance but also which formulations provide the greatest overall reduction in total climate impact, accounting for both the production and use phases. End-of-life processes (modules C1–C4 and D) were not considered, since the demolition and waste management pathway of PCM-containing mortars is indistinguishable from that of conventional lime mortars, regardless of whether the PCM core is bio-based or paraffin-based.

To ensure a consistent basis for comparison between embodied and operational impacts, a 50-year service life was assumed, aligned with standard functional lifespans commonly used in environmental assessments of lime-based construction materials [37,38].

Based on this timeframe, the operational GWP (B6) was calculated for each formulation by multiplying the estimated annual energy demand for space heating and cooling by an emission factor of 0.25 kg CO_2e/kWh, reflecting the average carbon intensity of the Spanish electricity mix [39]. This yielded a projection of cumulative emissions from operational energy use over the building's lifetime, offering a long-term view of the environmental benefits of PCM integration. These values were then compared against the cradle-to-gate GWP (A1–A3) associated with the production, transport and application of each mortar with its respective retrofit strategy. The resulting comparison, presented in Fig. 8 and Supplementary Material S6, enables an integrated evaluation of the overall sustainability performance of each intervention.

Fig. 8 and Supplementary Material S6 reveal significant differences in the total GWP (A1–A3 + B6) across the retrofitting strategies and mortar formulations. As expected, the operational phase (B6) dominates the total carbon footprint in all cases, particularly under

Table 8
Latent heat storage capacity and seasonal energy performance for PCM-enhanced mortars under Strategy (iii) (combined internal grouting and internal rendering) in climate zone D1.

Formulation ID	$E_{latent,melting}$ (J/year)	Cooling demand (kWh/m²·year)	Saving in cooling (%)	$E_{latent,crystallization}$ (J/year)	Heating demand (kWh/m²·year)	Saving in heating (%)
REF0	0.00	7.5	0.0	0.00	293.8	0.0
REF20	0.00	7.5	0.0	0.00	293.8	0.0
P24_5_0	1.49E+ 10	0.0	100.0	7.83E+ 08	292.1	0.6
P24_5_20	1.43E+ 10	0.0	100.0	7.53E+ 08	292.1	0.5
P24_10_0	2.98E+ 10	0.0	100.0	1.57E+ 09	290.4	1.1
P24_10_20	2.83E+ 10	0.0	100.0	1.49E+ 09	290.6	1.1
P24_20_0	5.65E+ 10	0.0	100.0	2.97E+ 09	287.4	2.2
P24_20_20	5.41E+ 10	0.0	100.0	2.85E+ 09	287.7	2.1
P18_5_0	1.40E+ 10	0.0	100.0	1.39E+ 10	264.1	10.1
P18_5_20	1.33E+ 10	0.0	100.0	1.32E+ 10	265.6	9.6
P18_10_0	2.73E+ 10	0.0	100.0	2.71E+ 10	235.8	19.7
P18_10_20	2.63E+ 10	0.0	100.0	2.61E+ 10	237.9	19.0
P18_20_0	5.24E+ 10	0.0	100.0	5.20E+ 10	182.6	37.8
P18_20_20	5.06E+ 10	0.0	100.0	5.01E+ 10	186.6	36.5
BIO29_5_0	9.36E+ 09	0.0	100.0	5.35E+ 09	282.3	3.9
BIO29_5_20	8.93E+ 09	0.0	100.0	5.10E+ 09	282.9	3.7
BIO29_10_0	1.84E+ 10	0.0	100.0	1.05E+ 10	271.3	7.6
BIO29_10_20	1.79E+ 10	0.0	100.0	1.02E+ 10	271.9	7.4
BIO29_20_0	3.55E+ 10	0.0	100.0	2.03E+ 10	250.4	14.8
BIO29_20_20	3.39E+ 10	0.0	100.0	1.94E+ 10	252.3	14.1

Strategy (ii) (internal rendering), where the small volume of PCM used in surface rendering results in relatively low cradle-to-gate emissions (A1–A3). Conversely, Strategies (i) and (iii), which involve internal grouting, exhibit substantially higher A1–A3 values due to the larger PCM volumes, though these are partially offset by greater thermal performance and corresponding energy savings. Importantly, across all formulations and strategies, the PCM-enhanced mortars exhibited a lower total GWP than the unmodified reference mixes over a 50-year service life in climate zone D1, highlighting their potential to reduce lifecycle emissions.

Several of the high-performing formulations included metakaolin (MK) as a pozzolanic additive. While MK does slightly increase embodied carbon emissions, due to its energy-intensive processing (as shown in Figs. 3 and 8), its inclusion consistently results in lower total GWP compared to PCM-free references. Although MK does not contribute to thermal regulation, it significantly enhances the durability and longevity of lime mortars. Given that a uniform 50-year service life was assumed across all mixes, it is worth noting that MK-containing mortars are likely to outperform others over longer periods, as supported by previous studies [40–42]. The compatibility between PCM microcapsules and the binding matrix, previously identified as a critical parameter [43,44], has been demonstrated to be ensured within these matrices in an earlier study [12]. These results reinforce the role of MK as a sustainable additive, in heritage-compatible formulations where durability is critical.

Among all PCM types, P18-based mortars delivered the greatest reductions in operational emissions (B6), especially at high dosage levels. This superior performance is attributed to P18's phase change temperature, which aligns well with the thermal profile of climate zone D1. The PCM undergoes frequent crystallisation during winter, providing effective latent heat release during peak heating periods. As a result, P18_20_0 and P18_20_20 achieved the lowest B6 values across all strategies, approximately 300,000 kg CO_2-eq over the 50-year service life under Strategy (iii) (combined intervention), while maintaining moderate embodied emissions. These findings confirm P18 as the most thermally effective PCM for the conditions studied.

Although BIO29-based mortars underwent fewer annual phase change events than P18, they still offered significant environmental benefits, particularly in comparison to P24. While BIO29's thermal responsiveness is somewhat lower, its bio-based core, derived from agricultural waste, significantly reduces embodied GWP (A1–A3). This enhances the overall sustainability of the material. For example, BIO29_20_0 under Strategy (iii) achieved a total GWP of 436,000 kg CO_2-eq, well below that of reference mortars and outperforming all P24-based formulations. These results underscore BIO29's potential in contexts where environmental sourcing and material circularity are prioritised alongside thermal performance.

The reduction in total GWP compared to the reference mortars provides a clear indication of the environmental efficiency achieved by each formulation and strategy in climate zone D1 (Fig. 9, Supplementary Material S7). In Strategy (i), which involves internal grouting, the level of GWP saving varied by formulation but was generally moderate to high. Mortars containing P18 showed the strongest performance, with the P18_20_0 mix achieving a maximum reduction of 33.8 %. Even lower P18 dosages (5–10 %) resulted in meaningful savings ranging from 10.3 % to 18.7 %. BIO29-based mortars followed in effectiveness, producing reductions between 5.6 % and 14.9 %. In contrast, P24 formulations consistently achieved reductions of less than 3 %, indicating limited environmental benefit despite their thermal responsiveness.

In Strategy (ii), which relies exclusively on internal surface rendering, the reduced volume of PCM led to lower embodied emissions but also restricted the overall climate benefit. P18 mortars achieved at most a 4.1 % reduction, while both BIO29 and P24 mortars exhibited limited impact, with reductions below 2.3 %. These results suggest that, although this strategy is less invasive and requires less material, its potential for long-term climate impact mitigation is limited under the thermal conditions of zone D1.

Strategy (iii), which combines internal grouting and rendering and therefore incorporates the largest total volume of PCM, yielded

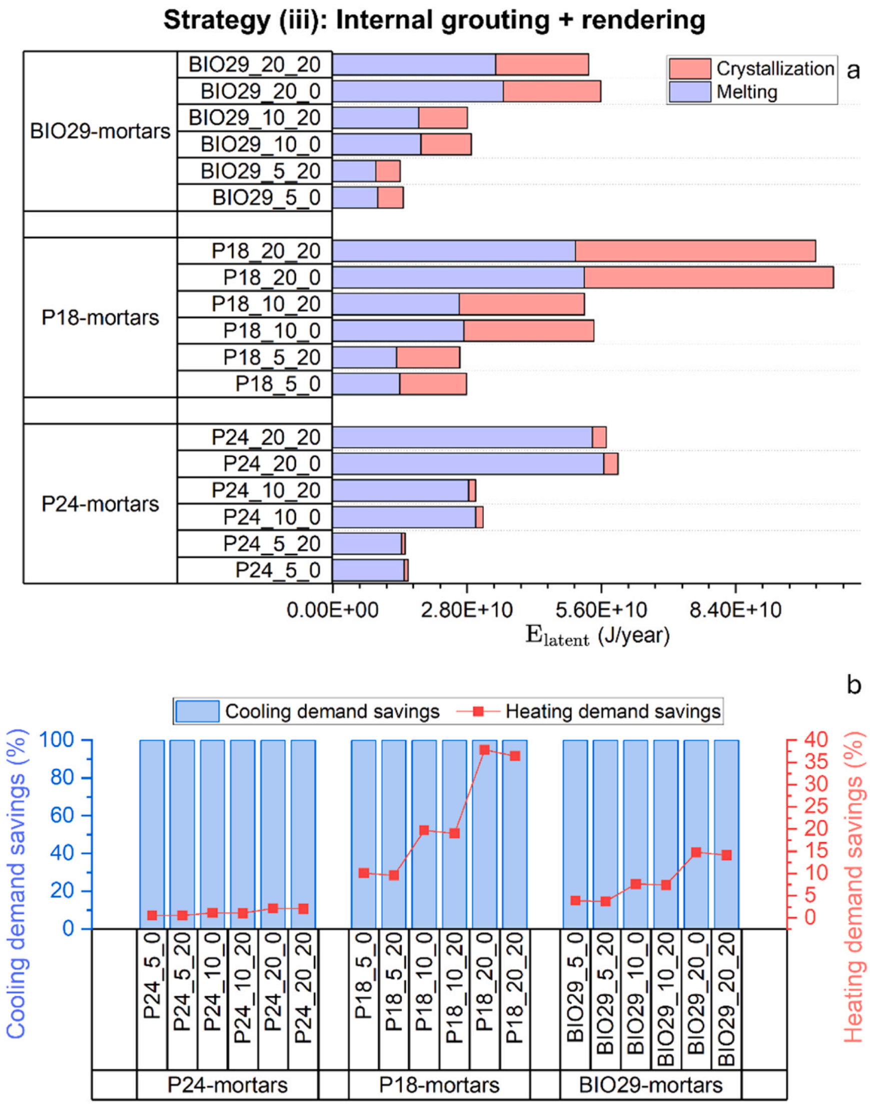

Fig. 7. (a) Seasonal latent heat exchange and (b) corresponding energy demand savings for PCM-bearing mortars under Strategy (iii) (combined internal grouting and internal rendering) in climate zone D1.

the highest GWP reductions across all formulations. P18_20_0 and P18_20_20 mortars achieved reductions of 35.6 % and 34.3 %, respectively, the highest in the entire dataset. Even mid-range P18 formulations exceeded 19 % savings. BIO29 mortars also performed well under this strategy, with BIO29_20_0 reaching a 15.7 % reduction and lower dosages maintaining reductions above 5.7 %. As observed in the other strategies, P24 mortars offered only marginal improvements, just exceeding 3 %. Overall, these findings confirm that in climate zone D1, where winter heating demand predominates, the combination of grouting and rendering with a highly responsive PCM such as P18 offers the most effective solution for lifecycle GWP mitigation in heritage retrofitting.

3.4. Influence of climatic conditions on energy savings and GWP reduction

To broaden the scope beyond the specific context of the Hermitage of Santa Brígida (climate zone D1), a multiclimatic assessment was carried out across the remaining eleven climate zones defined by the Spanish Building Code (CTE) [23]. Based on the demonstrated effectiveness of Strategy (iii), which combines internal grouting and rendering, this extended evaluation focuses exclusively on that intervention. To streamline the analysis while retaining its representativeness, only mortar formulations containing 20 % PCM were considered. This targeted approach enables a direct comparison of the most effective material combinations under varying thermal conditions, and highlights how the climatic performance of each formulation is shaped by the phase change temperature of the integrated PCM.

Fig. 10 and Supplementary Table S7 present the percentage reduction in GWP over a 50-year service life for each 20 % PCM

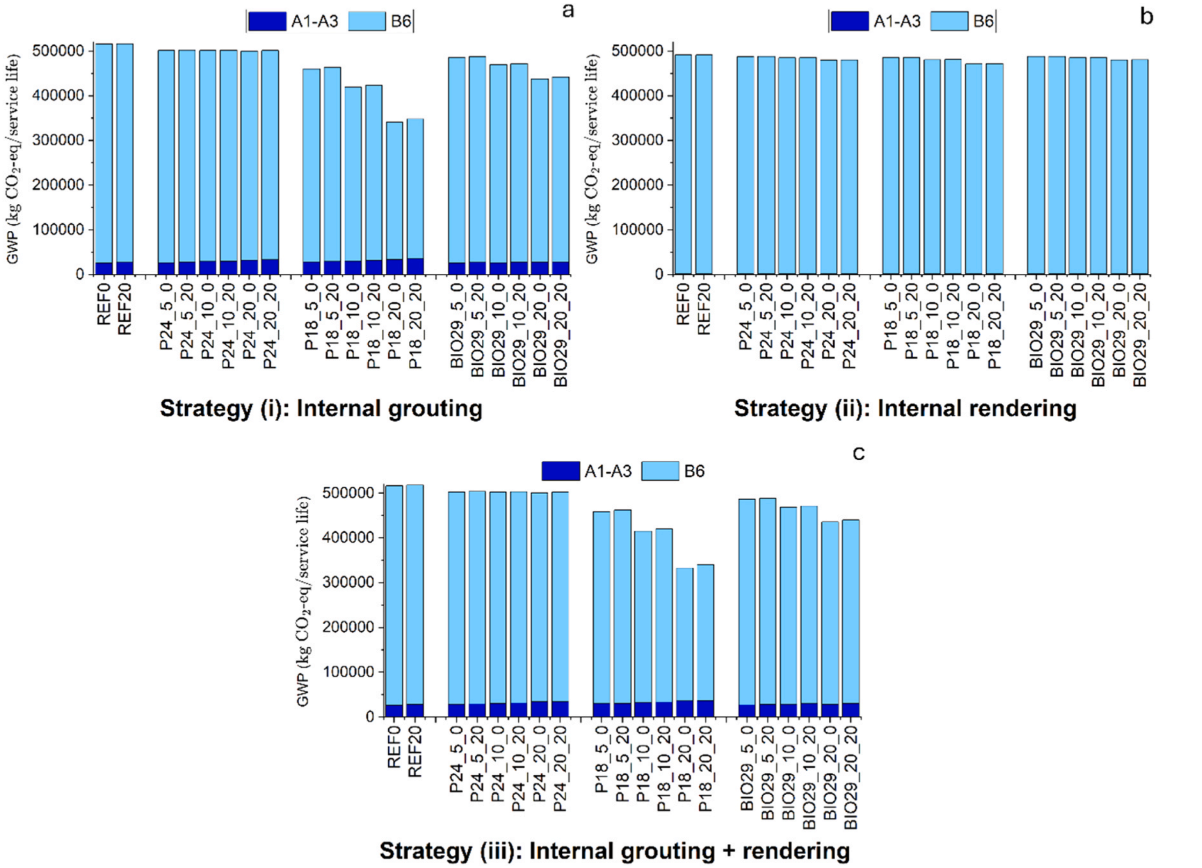

Fig. 8. Comparison of embodied and operational GWP across retrofitting strategies and PCM-enhanced mortar formulations in climate zone D1: (a) Strategy (i) (internal grouting), (b) Strategy (ii) (internal rendering) and (c) Strategy (iii) (combined intervention).

formulation across the 12 climate zones defined by the Spanish Building Code. As widely acknowledged in the literature [45–47], the effectiveness of PCM-lime mortars is highly sensitive to climatic context, with performance strongly influenced by the degree of alignment between the PCM's phase change temperatures and the local temperature profiles.

The P24-based mortars, which exhibit a melting peak at 24 °C and a crystallisation peak around 18 °C, displayed a highly selective thermal response. Their most favourable outcomes were recorded in zones B4 and A4, where daily ambient temperatures frequently exceed 24 °C for extended periods, promoting consistent melting and effective latent heat absorption. In these zones, total GWP reductions reached 87.2 % and 84.9 %, respectively. However, in colder or less thermally dynamic regions such as climate zones D1 and E1, where temperatures rarely reach the activation thresholds, the effectiveness dropped sharply, yielding reductions of only 3.0 % and 1.5 %, respectively. These findings highlight the narrow activation window of P24, which limits its suitability in cooler climates.

In contrast, P18-based mortars demonstrated a more robust and balanced performance profile across climate zones. With a melting point around 18 °C and a crystallisation point as low as 6 °C, P18 is activated during both warm daytime periods and cooler nights, enabling bi-directional thermal regulation. Their highest impact was observed in zone C3, where GWP reductions peaked at 74.6 %, followed by zone D3 (55.0 %) and zone D2 (46.0 %), all of which are characterized by frequent temperature fluctuations that align well with the PCM's activation range. By contrast, in hot and thermally stable regions such as zone A3, where temperatures rarely fall below the PCM's crystallisation threshold, the performance of P18 dropped significantly. In this case, a GWP increase of −3.8 % was recorded, indicating that the embodied emissions of the material were not offset by sufficient thermal activation during operation. This outcome underscores the critical role of aligning PCM properties with local climatic conditions to achieve meaningful lifecycle carbon reductions.

Finally, the BIO29-based mortars, incorporating a bio-based PCM with a melting peak at 29 °C and a crystallisation peak at 14 °C, demonstrated exceptional performance in the warmest climate zones, where prolonged exposure to high ambient temperatures enabled consistent thermal activation. These mortars achieved GWP reductions of 89.1 % in zone B4, 87.2 % in zone A4, and 86.8 % in zone B3, making them the most effective solution in these settings. In addition to their thermal responsiveness, their superior performance is further supported by a low embodied carbon footprint, attributed to the renewable origin of their PCM component. In contrast, performance declined in cooler regions, such as zone E1 (8.5 %), where ambient temperatures rarely reach the melting point, limiting activation to a few isolated days. Nonetheless, even under suboptimal conditions, their low A1–A3 emissions ensured modest but positive lifecycle gains.

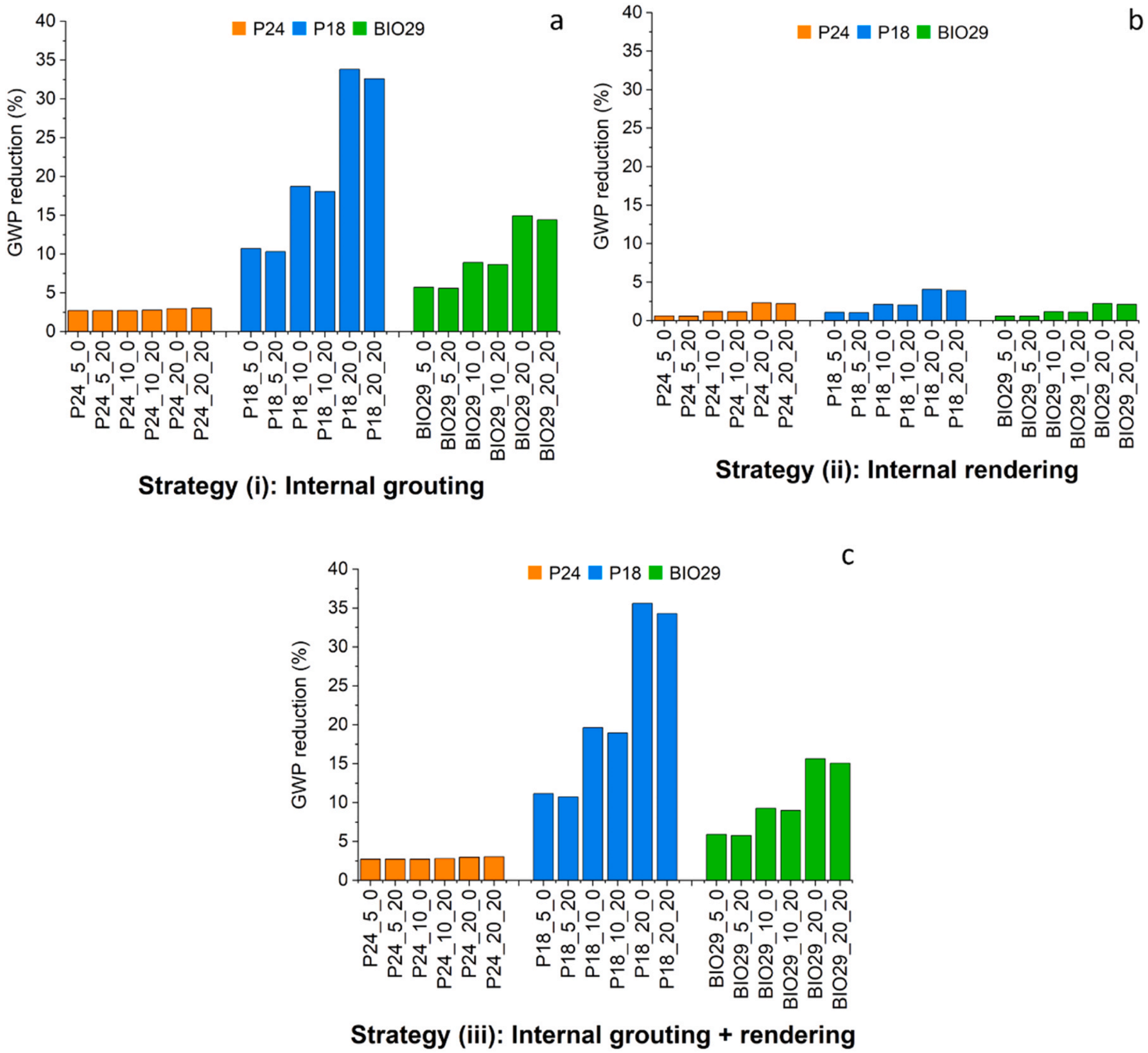

Fig. 9. Comparative GWP reduction (%) of PCM-lime mortars across retrofitting strategies in climate zone D1: (a) Strategy (i) (internal grouting), (b) Strategy (ii) (internal rendering) and (c) Strategy (iii) (combined intervention).

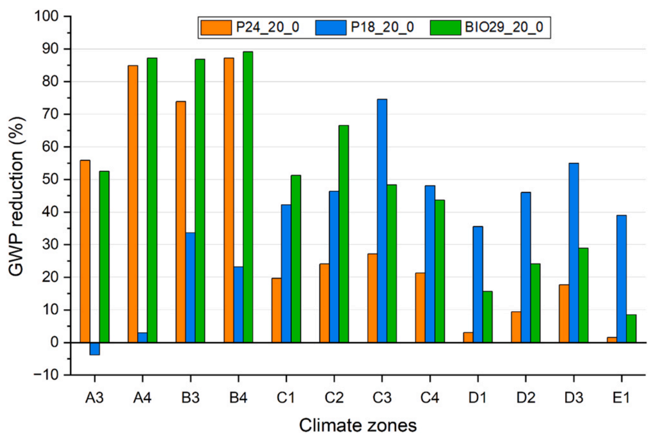

Fig. 10. GWP reduction (%) over a 50-year service life for 20 % PCM mortar formulations across the 12 climate zones defined by the Spanish Building Code (CTE) [28], under Strategy (iii) (combined internal grouting and rendering).

Taken together, the findings illustrated in Fig. 10 and detailed in Supplementary Table S7 reaffirm the critical role of temperature-responsive phase change alignment in determining the lifecycle impact of PCM-lime mortars. Specifically, P24 mortars prove beneficial only in hot climates prone to frequent overheating, P18 mortars offer broad applicability across temperate and cold zones due to their dual activation potential, and BIO29 mortars emerge as the most sustainable and effective solution for warm climates, combining strong thermal performance with low embodied emissions. To visually synthesise these findings, Fig. 11 presents a map of the Spanish climate zones (as defined by the CTE), highlighting the PCM formulation that achieved the greatest GWP reduction in each zone. As shown, P18 mortars dominate across most of the territory, particularly in zones C and D, where moderate summers and cold winters allow for frequent transitions near 18 °C (melting) and 6 °C (crystallisation), yielding consistent latent heat exchange and substantial long-term environmental benefits. BIO29 mortars prevail in southern and coastal zones, including zones A4, B3 and B4, where high summer temperatures regularly exceed the PCM's melting threshold. Their bio-based composition further enhances their environmental credentials, making them ideal for regions at risk of overheating. In contrast, P24 mortars appear optimal only in small subset of zones, notably zone A3, where extreme summer temperatures align closely with their phase change range. However, due to their narrow activation window and limited performance in the majority of climates, their overall applicability remains restricted.

4. Conclusions

This study provides a comprehensive evaluation of the environmental performance of PCM-lime mortars for heritage retrofitting, integrating cradle-to-gate embodied carbon assessment (A1–A3) with simulated operational energy savings (B6) over a 50-year service life. The results indicate that the carbon footprint of PCM-enhanced mortars increases proportionally with PCM dosage and transport distances, particularly for paraffin-based materials. However, this impact was significantly reduced in the case of BIO29, a bio-based PCM with a renewable core, resulting in the lowest embodied emissions among all materials tested. Although, the inclusion of metakaolin (MK) moderately increased embodied carbon, it improved durability, thereby extending service life and reducing maintenance needs, an essential consideration for interventions in heritage buildings where long-term compatibility is crucial.

Building on these material-level insights, the case study of the Hermitage of Santa Brígida (climate zone D1) demonstrated the practical implications of PCM-lime mortars under real climatic conditions. PCM incorporation eliminated cooling demand entirely and significantly reduced heating needs. Among the three retrofit strategies assessed, internal grouting (i), internal rendering (ii), and their combination (iii), the combined approach yielded the best performance by maximizing PCM volume while maintaining compatibility with historic masonry. Within this framework, the P18_20_0 formulation (a paraffin PCM with an 18 °C melting point) achieved the highest overall benefit, reducing heating demand by up to 38 % and carbon footprint by 35.6 %. Across all three PCM formulations, the incorporation of PCM fully eliminated summer cooling demand. Regarding heating performance, the P24-based mortar (melting at 24 °C) demonstrated limited activation in winter, delivering a modest reduction in heating demand (2.2 %) and a total GWP reduction of 3.0 %. Although BIO29 (with a 29 °C melting point) showed fewer change events under climate zone D1 conditions, it still delivered a 15.7 % reduction in total GWP due to its low embodied carbon, along with a heating demand reduction of up to 14.8 %.

These case-specific results were then expanded to a national scale, extending the analysis to all twelve official climate zones defined in Spain and offering insights that are transferable to other regions with similar climatic profiles. Results confirmed that PCM effectiveness is strongly climate-dependent. P18 mortars offered balanced performance across temperate regions, achieving a 74.6 % GWP reduction in zone C3, while P24 and BIO29 formulations excelled in warmer zones, particularly B4, achieving reductions of 87.2 % and 89.1 %, respectively. These outcomes highlight the critical importance of matching PCM phase change temperatures with local thermal profiles. This strong temperature dependence opens new avenues for the design of climate-tailored mortars, including the potential use of customised blends that combine multiple PCMs to improve responsiveness under fluctuating conditions. Notably, BIO29 demonstrated exceptional promise in hot climates, combining high thermal responsiveness with minimal embodied carbon, thus maximizing both environmental and operational benefits.

While these findings underscore the potential of PCM-lime mortars, it is equally important to reflect on the scope and limitations of the study. The present work provides a robust screening-level approach for assessing PCM–lime mortars in heritage retrofitting. The simplified latent-heat balance offers a transparent and comparative framework for evaluating performance across different climatic contexts, but it does not capture all dynamic variables such as indoor temperature fluctuations, wall orientation, thermal inertia, or occupancy-driven loads. The results therefore provide a necessary foundation for more detailed analyses—through dynamic simulation tools and in-situ monitoring—that can be developed in future work. Importantly, the formulations evaluated are not hypothetical, but have been previously validated in terms of their mechanical, microstructural, thermal, durability and cyclability performance, ensuring that the present sustainability analysis is grounded in robust experimental evidence. This experimental evidence, particularly the high phase-change cyclability and durability, supports the expectation of reliable long-term performance, which is a decisive factor for the sustainability of these mortars.

Taken together, these results confirm that PCM-lime mortars—especially those formulated with P18 or BIO29—represent viable, climate-adapted solutions for reducing lifecycle carbon emissions in heritage buildings. When used in conjunction with durable additives like metakaolin and applied through compatible strategies such as internal grouting and rendering, these mortars can effectively enhance energy efficiency and sustainability without compromising the historical integrity of the built environment. The approach presented in this study demonstrates that it is possible to achieve effective thermal regulation while preserving the material compatibility required in heritage conservation. As such, these formulations stand out not only for their environmental benefits but also for their practical applicability in real-world retrofitting of historic envelopes.

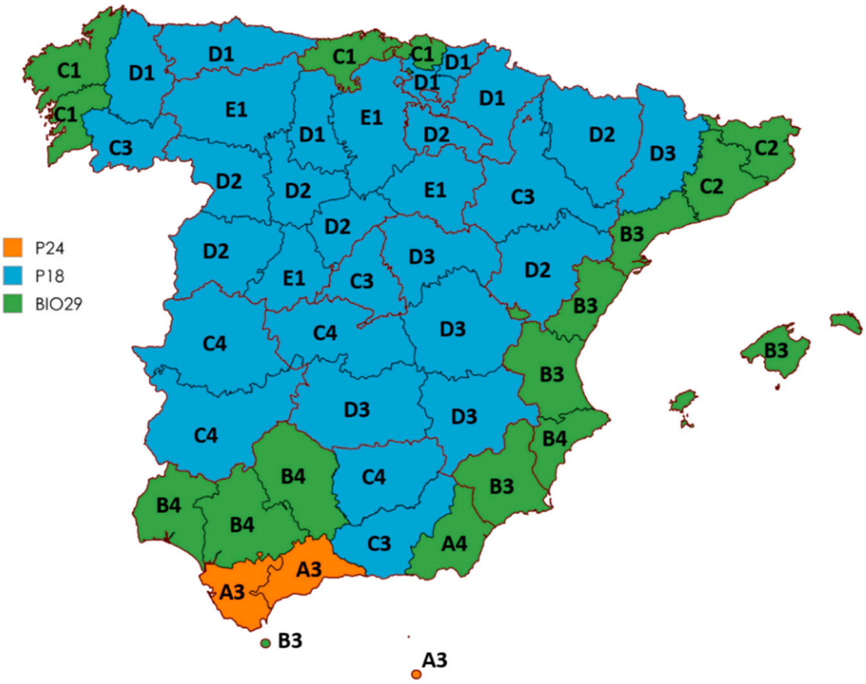

Fig. 11. Geographical distribution of the optimal PCM formulation (20 % content, Strategy (iii)) identified by the highest GWP reduction achieved in each of the 12 climate zones defined by the Spanish Building Code (CTE) [28]. The climate zone assigned to each province is based on the classification of its capital municipality.

CRediT authorship contribution statement

Conceptualization, S.P., J.I.Á., Í.N.-B., J.M.F., and A.R.-A.; data curation, A.R.-A. and S.P.; formal analysis, A.R.-A., L.K. and Í.N.-B.; funding acquisition, J.I.Á. and Í.N.-B; investigation, A.R.-A., L.K. Í.N.-B. and J.I.Á.; methodology, A.R.-A., J.I.Á., S.P.; project administration, J.I.Á. and Í.N.-B.; resources, Í.N.-B., and J.I.Á.; supervision, S.P., J.I.Á. and Í.N.-B.; validation, A.R.-A.; visualization, A.R.-A., S.P. and J.I.Á.; writing—original draft preparation, A.R.-A.; writing—review and editing, J.M.F., L.K., S.P. and J.I.Á. All authors have read and agreed to the published version of the manuscript.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cscm.2025.e05294.

Data Availability

Data will be made available on request.

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