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ORIGINAL ARTICLE

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Life cycle assessment of new wood-based composite panel integrated with bio-based phase change material for energy storage in buildings

Saniye Karaman Öztaş [a], Ali Temiz [b], Nasko Terziev [c], Güliz Öztürk [b], Meysam Nazari [c], Gaye Köse Demirel [b], Sabrina Palanti [d], Thomas Schnabel [e], Mohamed Jebrane [c], Jakub Grzybek [e], Özge Nur Erdeyer [b] and İbrahim Yıldırım[b]

[a]Department of Architecture, Gebze Technical University, Kocaeli, Türkiye; [b]Department of Forest Industrial Engineering, Karadeniz Technical University, Trabzon, Türkiye; [c]Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden; [d]Laboratorio Biodegradazione e Preservazione, Italian National Research Council (CNR-IBE), Firenze, Italy; [e]Design and Green Engineering, Salzburg University of Applied Sciences, Kuchl, Austria

ABSTRACT

The integration of phase change materials (PCMs) into buildings can reduce operational energy (OE) but may increase embodied energy (EE), particularly with fossil-based PCMs, affecting total energy efficiency. Bio-based PCMs (BPCMs) offer a sustainable alternative, lowering EE and environmental impacts. Using a cradle-to-grave approach, this study assessed the environmental impacts of a newly developed wood-BPCM composite panel in Uppsala, Sweden. To investigate the relationship between EE and OE consumption and monitor energy use during operation, the operational phase was analysed for two experimental cubes in Uppsala. A process-based Life Cycle Assessment (LCA) was used, based on the Environmental Footprint (EF) and ReCiPe methods. In the wood-BPCM panel production, over 95% of environmental impacts originated from manufacturing and raw materials. For the cubes, the BPCM cube showed high environmental performance over 50 years, offsetting its initially higher climate impact compared to the medium-density fibreboard (MDF) reference cube by year 14 and achieving a 15% reduction. Despite MDF's higher density resulting in greater biogenic carbon uptake and energy recovery, biogenic carbon negatively affected the BPCM cube. Nonetheless, the BPCM cube maintained a 10% lower climate impact, emphasising its potential for sustainable applications.

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Introduction

Buildings consume 151 EJ of energy, 36% of the world's final energy consumption, while the operation of buildings consumes about 130 EJ, or 30% of global energy consumption (UNEP 2020). Without improving building energy efficiency, global energy demand is expected to increase by about 50% by 2050 (IEA 2013). Phase Change Materials (PCMs) have significant potential to improve energy efficiency in buildings (Shohan *et al*. 2024). PCMs can play a significant role in reducing the heating and cooling load in buildings by storing and releasing thermal energy, stabilising the indoor temperature and increasing user comfort through passive and active systems (Rahimpour *et al*. 2017, Soudian and Berardi 2017, Chen *et al*. 2019). In passive systems, heat is stored and released through natural processes without any energy source, with PCMs typically integrated into walls, windows, ceilings, or floors (Cui *et al*. 2017; Soares 2013). At this point, indoor temperature ranges can limit the effectiveness of PCMs due to phase change temperatures. Since the temperature range for indoor comfort is generally between 18 and 25 °C, the melting temperature of PCMs in passive systems should be between 17 and 25 °C. In contrast, the melting temperature of PCMs used in active systems, which rely on mechanical or external energy support, is higher, usually between 30 and 40 °C (Kenisarin and Mahkamov 2016).

PCMs can provide significant energy savings when used in the building envelope (Cabeza *et al*. 2007, de Gracia and Cabeza 2015, Iten *et al*. 2016, Reddy *et al*. 2024). An experimental study in Iraq showed that paraffin integrated into the building envelope improved energy performance under extremely hot weather conditions, thus reducing energy costs and emissions (Al-Yasiri and Szabıo 2023). A numerical study in Singapore indicated that a building envelope with PCM integrated reduced cooling loads in a tropical climate. The building envelope with PCMs reduced the heat gain by 21-32% throughout the year. The study concluded that PCMs applied to the exterior wall perform better than those used in the interior wall by emphasising the importance of the optimum phase change temperature in the selected PCMs (Lei *et al*. 2016). Another study on different cities of the subarctic climate focused on the energy performance of residential buildings integrated with different PCMs. PCMs with higher transition temperatures were more effective in hot climates, while PCMs with lower transition temperatures were more effective in cold climates. Increasing the thickness of PCMs and applying them to the inner layer resulted in more energy savings (Kenzhekhanov *et al*. 2020). Studies indicated that PCM integration in building applications, considering climate zones and the properties of PCM, can significantly increase energy and cost efficiency and reduce emissions.

CONTACT Saniye Karaman Öztaş saniyekaraman@gtu.edu.tr Department of Architecture, Gebze Technical University, Kocaeli 41400, Türkiye
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In addition to improving building energy performance, PCMs are expected to have low environmental impacts, high recycling potential and non-polluting properties (Castell *et al*. 2013, Memon 2014). In this context, the Life Cycle Assessment (LCA) method stands out in analysing the environmental impacts of PCMs (Aranda-Uson *et al*. 2013, Venettacci *et al*. 2022, Vega *et al*. 2024). An LCA study of PCMs integrated into the building envelope revealed that esters and salt hydrates use was environmentally more favourable than paraffin (Menoufi *et al*. 2013). Similarly, glycerine and fatty acid use were found to have higher environmental performance than paraffin (Baldassari *et al*. 2017). The use of fossil-based PCMs such as paraffin in buildings is disadvantageous as it reduces operational energy (OE) but increases embodied energy (EE) (Eller *et al*. 2021, Struhala and Ostry 2022) and has high flammability (Mehrizi *et al*. 2023). Therefore, bio-based PCMs (BPCMs) that can reduce EE are being studied (Baylis and Cruickshank 2023, Mehrizi *et al*. 2023). BPCMs have favourable properties such as high latent heat, minimal supercooling, self-nucleation behaviour, moderate melting/freezing temperatures, thermal and chemical stability, non-corrosiveness, non-flammability, renewability, non-toxicity and low cost. On the other hand, they have problems such as biodegradability, odour formation, leakage and supply-demand (Junaid *et al*. 2022, Mehrizi *et al*. 2023, Sharma *et al*. 2024). Among BPCMs, fatty acids are encouraged in low to medium-temperature energy storage applications (Simonsen *et al*. 2023).

Several studies have reported that BPCMs can improve the energy performance of buildings. An experimental study on the impact of BPCMs on the energy performance and indoor comfort of buildings in a temperate climate revealed that BPCMs could reduce heating energy by up to 57% in winter and moderate indoor temperatures in summer (Nghana and Tariku 2016). Similarly, coconut oil-based BPCM composite was reported to be promising for passive thermal energy storage systems in the building envelope (Boussaba *et al*. 2018). However, more experimental studies are needed to evaluate the effectiveness of BPCMs in improving energy performance and managing thermal conditions in building applications (Mehrizi *et al*. 2023, Sharma *et al*. 2024). Overall, LCA is significant for the environmental assessment of BPCMs integrated into buildings (Nazari *et al*. 2020, Simonsen *et al*. 2023). In this context, it is necessary to analyse the energy consumption and emissions associated with the production, transportation, use and disposal processes of BPCMs. However, studies on this issue remain insufficient (Mehrizi *et al*. 2023) and require a holistic assessment that considers both the impact of BPCMs on building energy performance and their environmental impacts.

The environmental impact of buildings with PCMs depends on the building element materials along with the PCM type. Wood, a sustainable material with BPCMs, may offer a more sustainable approach. In this context, Heidari *et al*. (2019) first assessed the environmental impact of wood-based panels with lauric and capric acids. This study underlined the need for further case studies on the environmental assessment of BPCMs (Heidari *et al*. 2019). Addressing this gap, the present study aimed to assess the environmental impacts of a newly developed wood-BPCM (ethyl palmitate – EP) composite panel in Uppsala, Sweden, considering a cradle-to-grave approach. The scope of the assessment includes wood-BPCM composite panel production (A1-3), OE use (B6), waste processing (C3), disposal (C4) and potential benefits and burdens (D). At the product level, an LCA was applied using characterisation factors from the International EPD (Environmental Product Declaration) system (IES), allowing direct comparisons with other materials assessed under the same framework. Uppsala, where the panels were developed and tested, is in the 'Cfb' climate zone according to the Köppen Climate Classification and has a humid continental climate characterised by cold winters and warm summers. Two experimental cubes ($1 \times 1 \times 1$ m) were constructed to investigate the relationship between EE and OE consumption and to assess energy use during operation. One is a reference cube without BPCM, and the other is a cube with wood-BPCM panels for walls and roof. The effects of the operational process were measured using energy consumption data recorded from the heating system in these cubes, and the environmental payback period was calculated.

Materials and methods

Manufacturing process of the wood-BPCM composite panel

A wood-BPCM composite panel ($50 \times 50 \times 1$ cm) with a density of 800 kg/m^3 was manufactured at Swedish University of Agricultural Sciences Laboratory in Uppsala. EP, an ester (CAS number: 628-97-7, 95% purity, supplied by Sigma-Aldrich) with suitable thermal properties for indoor applications (Ke and Li 2017), was incorporated as a BPCM into wood particles serving as capsules. The phase transition temperature of EP is 25°C, which is favourable for building applications. To produce the bio-based composite panel, 37.5% epoxidized linseed oil (ELO) was used as a binder. EP was impregnated into the wood particles under vacuum pressure in an autoclave. Pine wood sawdust (Pinus sylvestris L.) was dried at 80 °C and sieved to a particle size of approximately 2 mm. EP was melted in a 60°C autoclave, and the wood particles were immersed in it, followed by vacuum impregnation. To test EP leakage, the impregnated particles were placed in a 40 °C oven. Additionally, recycled paper insulation (iCell®) was added to the impregnated wood particles to further reduce EP leaching. ELO was pre-polymerised at room temperature using 0.2%. Tris (pentafluoro phenyl) borane, a strong Lewis acid (CAS number: 1109-15-5, 95% purity, supplied by Sigma-Aldrich), and subsequently blended with the wood particles and fibres. The mixture was cold pressed in a Teflon mould at room temperature and subsequently polymerised in a 50°C oven (Nazari 2023, Nazari *et al*. 2023).

To ensure reliable long-term performance, more rigorous leakage and cycling tests were conducted at the laboratory scale. During the pressing stage, some EP leached from the particle surfaces. To minimise EP leaching, different press forces and component ratios were tested. The results indicated that a press force of 1000 kg (12.3 kg/cm^2) with 12.5% non-impregnated fibres was optimal for reducing leakage. The composite panel consisted of 50% impregnated wood particles (25%

wood particles and 25% EP) and 12.5% non-impregnated fibres absorbed exuded EP from the impregnated particles, assisting in the polymerisation of ELO (37.5%) as the matrix binder. During the 12-hour curing process of ELO at 50 °C, no leaching occurred, indicating that this composition effectively prevents leakage (Nazari 2023, Nazari *et al*. 2023).

Construction and material composition of the wood-BPCM cube and the reference cube

Each cube constructed in Uppsala measured 1 × 1 × 1 m (width, length, height). The envelopes consisted of 7 mm thick plywood, 120 mm of loose fill cellulose insulation (LFCI), and 18 mm of oriented strand board (OSB) beneath the composite panels on the inner walls. This is significant because OSB panels with plywood have the highest modulus of elasticity and modulus of rupture values among sandwich panels made from standard wood-based materials (Gozdecki and Kociszewski 2021). The reference cube incorporated MDF for its inner walls, selected for its smoothness and workability, which makes it a versatile material suitable for patterning, painting, or coating (Pour *et al*. 2022). In contrast, the BPCM – enhanced cube used wood – BPCM composite panels for its inner walls. Both cubes featured a window (20 × 50 cm) with double glazing and a door. The roof structures utilised solid wood profiles (45 × 45 mm) as beams, 120 mm of recycled paper insulation, and a waterproofing layer. Additionally, three-layer wood flooring was installed. EP was used as the BPCM, integrated into the walls and floors through BPCM composite panels. Temperature and energy consumption within the cubes were continuously monitored. Although the experimental cubes used in this study do not directly reflect the complexity or scale of a real building, they were designed as simplified and controlled models to evaluate the OE performance of the wood – BPCM panel. The design allowed for a comparative analysis between the reference and the wood-BPCM cubes, while the use of construction materials and components such as OSB, plywood, recycled paper insulation and double-glazed windows preserved the relevance of the data obtained to real-world building applications (Figure 1).

During the winter period, the indoor temperature was kept at 20 °C using a heater rated at 100W, with an air exchange rate of two exchanges per hour. During the summer period, the heater was set to 17 °C and turned off between 8 pm and 6 am, with ten air changes per hour; from 6 am to 8 pm, no air changes occurred. Annual heating energy consumption data for the cubes were recorded to assess the environmental impacts during the operational phase. This heating schedule, including summer operation, was necessary to ensure consistent and comparable thermal performance monitoring between the BPCM-integrated and reference cubes, as part of a controlled experimental setup.

Life Cycle Assessment (LCA)

LCA identifies the inputs and outputs of a product system throughout its life cycle and assesses its environmental impacts. The method includes the aim and scope definition, inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation. In the LCI phase, the inputs and outputs of the system are compiled through a functional unit depending on the purpose and scope of the study. In the LCIA phase, environmental impacts are calculated based on the data obtained from the inventory analysis. In the interpretation

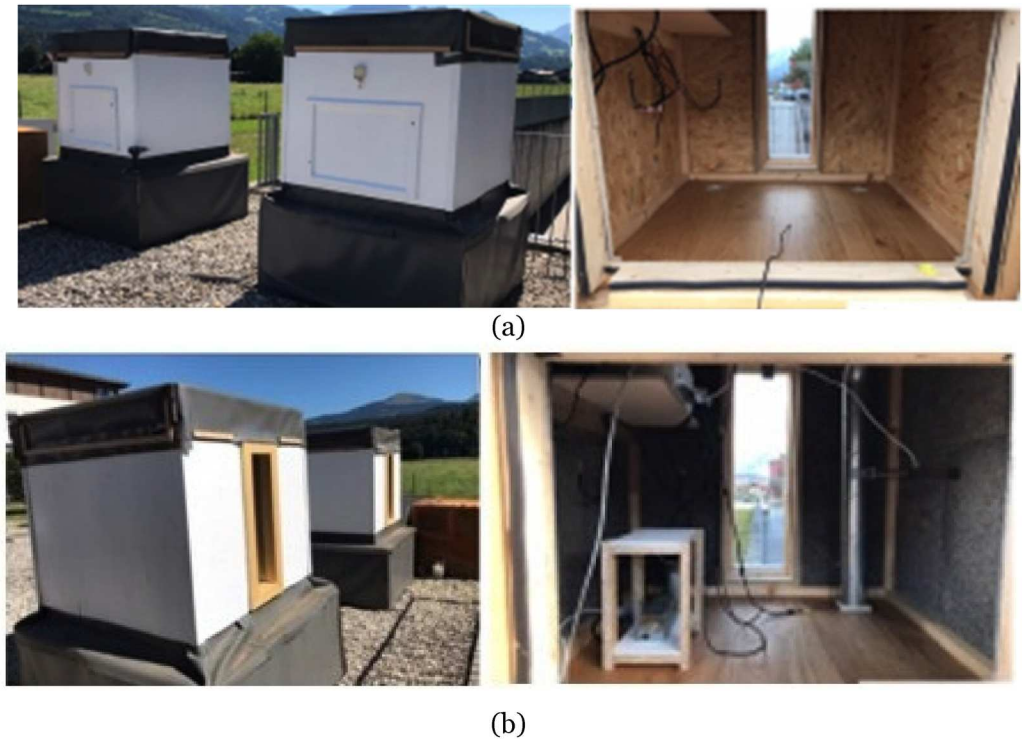

Figure 1. The experimental BPCM cube (a) and the reference cube (b).

phase, LCI and LCIA results are evaluated considering the purpose and scope of the study (ISO14040-44, 2006). LCA is a commonly used method for assessing the environmental impact of buildings and building materials (Bejo 2017). The process-based LCA method is widely applied in this field due to its ability to produce precise results (Heinonen *et al*. 2016). In this study, a process-based LCA in accordance with ISO 14040–44 (2006) was used to calculate the environmental impacts of the wood-BPCM panel.

Goal and scope definition

This study aimed to evaluate the environmental impacts of the newly developed wood-BPCM composite panel at the laboratory scale using LCA. The assessment was conducted to identify key environmental hotspots and to demonstrate the potential applicability of the material for future upscaling to higher technology readiness level (TRL) or industrial production. It also compared the environmental performance of the BPCM-integrated cube and the reference cube, focusing on the effects of BPCM on EE and OE. The LCA was conducted using a process-based approach in accordance with ISO 14040 and ISO 14044 standards for methodological consistency (ISO14040-44, 2006). Additionally, the study structure partially follows the modular approach defined in EN 15804: 2012 + A2: 2019, which is commonly used for construction products in Europe (EN 15804, 2012 + a2:2019).

The declared unit was the production of 1 m^3 of the wood-BPCM composite panel. In line with EN 15804:2012 + A2:2019, wood-based products containing biogenic carbon must declare product stage: A1–3, end-of-life stage: C1–4, and module D: beyond the system boundary (EN 15804, 2012 + a2:2019). Other stages (construction process stage: A4–5 and use stage: B1–7) remain scenario-dependent and can be included if relevant. Therefore, the system boundaries were initially defined as cradle-to-gate (A1-3), with end-of-life (EOL) stage (C1-4) and beyond-the-life cycle (D) considerations. This decision was based on the scope and objectives of the study, which was conducted at the laboratory scale to assess the environmental impacts of the wood-BPCM material in its early development phase. As the material has not yet been applied in real construction settings, transportation to a construction site (A4) and on-site installation activities (A5) are not yet representative or standardised. Including hypothetical A4 and A5 data would have introduced significant uncertainty, potentially obscuring rather than clarifying the material's environmental performance. In contrast, simplified but consistent assumptions were applied for EOL stages, including demolition/deconstruction (C1), transportation to a representative waste processing facility (C2), processing and preparation of waste (C3), and treatment of waste wood via municipal incineration (C4). Module D credited the recovered energy from the incineration modelled in C4. The phases of the wood-BPCM composite material are given below.

A1: The assessment considered the raw materials required for manufacturing the wood-BPCM model.

A2: Transport assumed a 100 km distance for raw material transportation.

A3: Manufacturing, with electricity consumption for wood-BPCM production calculated based on national grids data.

C1: Demolition/ deconstruction of wood.

C2: Transport assumed an 80 km distance for waste processing facility

C3: Processing and preparation of waste

C4: Treatment of waste wood, untreated, municipal incineration.

D: The recovered energy from the municipal incineration of untreated waste wood (modelled in C4) was credited as a benefit in Module D.

Comparing the OE use of the BPCM-integrated cube and the reference cube, identical inputs between the two cubes (e.g. exterior wall materials, paints, windows, roof and floor materials) were excluded from the model. The electric heaters used in both reference and BPCM cubes were also identical. The analysis covered modules A1-3, B6 (OE use), C1-4 and D. Since the study was conducted using experimental-scale building cubes rather than full-scale buildings, it did not reflect the full complexity or logistics of real-world construction processes. These controlled cubes were specifically developed to assess the OE performance of the wood-based BPCM panel. Therefore, transportation to a construction site (A4) and on-site installation (A5) could not be meaningfully represented and were deliberately excluded to avoid introducing unsupported assumptions. Moreover, several studies have emphasised that the impacts of the construction and transportation phases are lower compared to those of the product stage. In this context, Liang *et al*. (2020) reported that for both mass timber and concrete buildings, A1–3 was the dominant contributor to environmental impacts, accounting for 88–98% across all categories. In contrast, A4 and A5 contributed only 3–8% and 1–5%, respectively. In this study, only module B6 was included among the use-stage modules (B1–7), as the primary goal was to assess the impact of the wood-based BPCM composite panel on OE during the use phase. Modules C1-4 and D were included in line with the EN 15804: 2012 + A2: 2019 modular approach (EN 15804, 2012 + a2:2019). These phases were modelled using established disposal scenarios and EOL credit methods, providing insight into future environmental impacts and benefits.

The functional unit for comparing the BPCM cube and the reference cube was the heating of the cube volume over a 50-year lifespan, as typically considered for buildings in LCA studies (Gracia *et al*. 2010, Aranda-Uson *et al*. 2013, Carbonaro *et al*. 2015). While the use of BPCMs in wood-based composites is a recent development, and lacks extensive long-term performance testing, preliminary indicators suggest stability over time. Chemically, saturated PCMs (as used in this study) helped mitigate reactions during use, enhancing stability. Biological testing also showed reduced mold growth in PCM-containing composites due to enhanced water repellency. Lastly, intensive cycling tests confirmed both thermal and physical stability across extended use by the authors of this study in the previous publications (Palanti *et al*. 2022, Nazari 2023, Nazari *et al*. 2023). Figure 2 presents the LCA stages and system boundaries of the study.

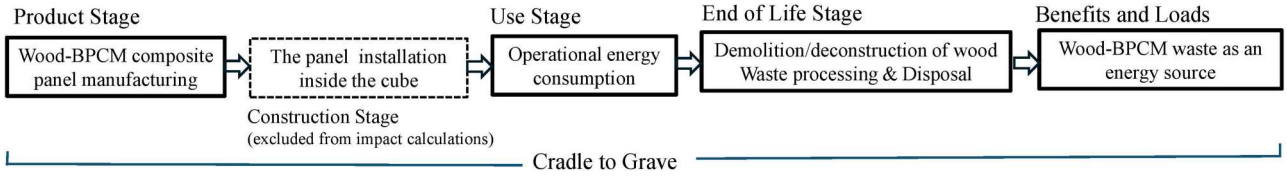

Figure 2. Flow diagram of the panel LCA stages, illustrating the defined system boundary.

Inventory analysis

This study used both primary and secondary data. Primary data on the manufacturing process of the wood-BPCM composite panel were gathered directly from the Swedish University of Agricultural Sciences in 2023. When primary data were unavailable, secondary data were obtained from the Ecoinvent database (Ecoinvent, 2022) within the Open-LCA tool. The database was developed using Excel (Table 1). For the modelling of modules C1 and C2, default data were used, based on the studies of Erlandsson and Peterson (2015) and OVAM (Openbare Vlaamse Afvalstoffenmaatschappij) (2018), as also specified in the International EPD product category rules 2019:14 for construction materials (International EPD System, 2019). For module C1, the energy requirement for the demolition/deconstruction of wood was assumed to be 1.1 kWh per ton of material, with diesel identified as the energy carrier. In relation to module C2, the subsequent transport of wood was assumed to cover a distance of 80 km, using a 16–32 ton lorry. The EOL scenario (C3, C4 and D) was modelled using the Ecoinvent database (Ecoinvent, 2022). It was assumed that 98.766% of the 800 kg of waste wood was sent to municipal incineration, 1.222% to sanitary landfill, and 0.011% to open burning. The dataset reflects a lower heating value of 13.99 MJ/kg and reports net energy outputs of 1.74 MJ/kg for electricity and 3.40 MJ/kg for thermal energy. These values already account for conversion losses during incineration and represent the energy that is effectively recovered and supplied. In Module D, these outputs were credited by assuming substitution with Sweden-specific electricity from the grid and heat from natural gas-based district heating systems, reflecting a realistic regional energy context and maintaining country dependency (Table 1). In this study, datasets from the Ecoinvent database covering different geographical regions were utilised to represent the materials and processes involved. Whenever available, country-specific datasets for Sweden (SE) were applied to ensure regional accuracy. However, due to the inherent limitations of the database, not all datasets are available for every geographical region. Some materials or processes have datasets only for Rest of World (RoW), some for specific regions such as Europe (RER), and others for global (GLO) coverage (Table 1).

For both the reference cube and the wood-BPCM cube, a heater, integrated sensors, and a data logger were installed on a shelf. Real-time data collection through Internet of Things (IoT) technology facilitated continuous monitoring and detailed analysis of energy usage. The energy data were visualised through hourly and daily graphs. The analyses for both cubes were based on the heater's real-time power consumption (W) and the temperature differentials between the external and internal environments. Additionally, the total energy consumed over one year (kWh) was incorporated into the LCA analysis. Energy consumption within the cubes was recorded using Swedish electricity data. Measurements were conducted separately during four distinct three-month periods, each corresponding to one season – summer, autumn, winter, and spring

Table 1. Inventory data for the wood-BPCM panel.

		The components and process in the Ecoinvent database	m^3 Composite panel
Materials	EP	Market for fatty acid methyl ester | Cutoff, U – RoW	180 kg
	ELO	Market for linseed oil, crude | Cutoff, U – RoW (modified dataset from rapeseed oil, utilises linseeds)	336 kg
	Solvent (Ethanol)	Market for ethanol, without water, in 99.7% solution state, from ethylene | Cutoff, U – RER	16.8 kg
	Wood particles (sawdust)	Market for wood chips and particles, willow | Cutoff, U – RER	180 kg
	Recycled fibres	Market for cellulose fibre | Cutoff, U – RoW	140 kg
	Catalyst	Market for chemical, inorganic | Cutoff, U – GLO	0.67 kg
Energy	Melting of EP in oven	Market for electricity, medium voltage | electricity, medium voltage | Cutoff, U – SE	9800 MJ
	Impregnation of the samples in an autoclave	(National Grid – SE)	2520 MJ
	Drying the fibres in an oven		55987 MJ
	Blending materials		29.16 MJ
	Pressing		936 MJ
	Curing		4320 MJ
	Total Electricity		73592 MJ
	Transport for raw material	Market for transport, freight, lorry 16–32 metric ton, EURO6 | Cutoff, U – RER	100 KM
	Demolition/deconstruction of wood	Market for diesel, burned in building machine | diesel, burned in building machine | Cutoff, U	1.1 kWh/ton x 0.8 ton = 0.88 kWh
	Transport for waste processing	Market for transport, freight, lorry 16–32 metric ton, EURO5 | Cutoff, U – RER	80 KM
	Waste processing	Market for waste wood, untreated | waste wood, untreated | Cutoff, U – SE (Ecoinvent) (sanitary landfill, municipal incineration, open burning)	
	Benefits beyond the boundary	Market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U – SE market for electricity, medium voltage | Cutoff, U – SE	

– so that energy use was monitored over the course of a full year. During these seasonal measurements, the average external air temperatures were assumed to be 15°C in summer, 5°C in autumn, – 10°C in winter, and 5°C in spring. Heating was employed to maintain an internal temperature of 20°C for 90 days during each season. The OE consumption values presented in Table 2 were derived from direct measurements based on experimental data collected during the study. The power values, expressed in watts [W], indicate the rate of energy consumption during the operational phase. These values were estimated from the average energy consumption observed in the experimental setup, using the wood-BPCM panels under controlled conditions. The corresponding energy values, given in [kWh] in parentheses, represent the total energy consumption over a seasonal period of 90 days, reflecting the OE demand of the heating system within the experimental cubes.

In the study by Xavier *et al*. (2013), MDF panels were produced with 13% and 16% urea-formaldehyde resin. In this study, the average of these values, 14.5%, was adopted for calculations of the reference cube. It was assumed that 68.4 kg of MDF waste was generated, of which 85.5% (58.482 kg) was collected as wood and directed to Swedish wood processing facilities. Subsequently, 98.77% of this fraction was incinerated to produce heat and electricity. The remaining 14.5% (9.918 kg), consisting of resin, was collected as resin waste and incinerated within the solid waste management system, also contributing to heat and electricity generation (Table 2).

Results and discussion

The LCIA results for the wood-BPCM panel

Upon collecting the relevant data for each life cycle phase, the modelling was conducted using OpenLCA 2.0.0 LCA software (GreenDelta, 2024). The impact categories and associated methods were derived from the characterisation factors of the IES, in accordance with ISO 14025: 2006 and EN 15804: 2012 + A2: 2019, as implemented in OpenLCA using the EF v3.0 method (ISO 14025, 2006; EN 15804, 2012 + a2:2019). The net freshwater use was calculated based on a select list of environmental flows from the LCI, following the EN 15804 standard. Table 3 presents the environmental results for the wood-BPCM panel, covering the A1-3 + C1-4 and D modules.

The manufacturing phase exhibited the highest environmental impacts in the categories of CC-B, CC-F, Eutro. – F, OD, POF, WSP, FW, ADPF, and ADPE. The raw materials phase showed the highest impacts in Acidif., CC-total, CC – luluc, Eutro. – M, and Eutro. – T categories. The environmental impacts of the raw material transport and EOL phases were below 5% in all impact categories, except for CC – F (5.22%) and POF (7.04%). Utilising the panel waste a substitute for natural gas in both heat and electricity generation mitigated the impacts across all categories, with particularly significant reductions observed in OD, CC-F, and CC-total categories (Figure 3).

Table 2. Inventory data for the reference cube and the wood-BPCM cube.

		The MDF panel (5 m^2)				
The Reference Cube	Materials	MDF production, uncoated, Cutoff, U-RER (includes urea-formaldehyde resin – Ecoinvent)				
	Thickness assumption	2 cm MDF				
	Total volume	$0.02 \times 5 \times 1 = 0.1$ m^3				
	MDF density	684 kg / m^3 (Ecoinvent)				
	MDF weight	68.4 kg				
	Moisture content	7% (Ecoinvent)				
	The thermal conductivity	0.2 W/m K				
	Energy use	Market for electricity, medium voltage, Cutoff, U – SE (Ecoinvent)				
	Waste processing	Market for waste wood, untreated | waste wood, untreated | Cutoff, U – SE (Ecoinvent) (sanitary landfill, municipal incineration, open burning) treatment of waste polyurethane, municipal incineration | waste polyurethane | Cutoff, U (Ecoinvent)				
	Benefits	Market for electricity, medium voltage, Cutoff, U – SE (Ecoinvent) market for heat, district or industrial, natural gas, Cutoff, U – Europe without Switzerland (Ecoinvent)				
	The Reference Cube					
	OE consumption	Summer period	Winter period	Autumn period	Spring period	Whole period
		32.4 kWh	194.4 kWh	64.8 kWh	64.8 kWh	356.4 kWh
The Wood – BPCM Cube	The wood – BPCM panel (5 m^2)					
	Materials	EP, ELO, solvent (ethanol), wood particles (sawdust), recycled fibres, catalyst				
	Thickness assumption	1 cm wood-BPCM panel				
	Total volume	$0.01 \times 5 \times 1 = 0.05$ m^3				
	Density	800 kg / m^3				
	Weight	40 kg				
	The thermal conductivity	0.35 W/m K				
	Energy use	Market for electricity, medium voltage, Cutoff, U – SE (Ecoinvent)				
	Waste processing	Market for waste wood, untreated | waste wood, untreated | Cutoff, U – SE (Ecoinvent) (sanitary landfill, municipal incineration, open burning)				
	Benefits	Market for electricity, medium voltage, Cutoff, U – SE (Ecoinvent) market for heat, district or industrial, natural gas, Cutoff, U – Europe without Switzerland (Ecoinvent)				
	The Wood – BPCM Cube					
	OE consumption	Summer period	Winter period	Autumn period	Spring period	Whole period
		28.08 kWh (energy saving % 13.3)	162 kWh (energy saving % 16.6)	54 kWh (energy saving % 16.6)	54 kWh (energy saving % 16.6)	298.08kWh (energy saving % 16.3)

Table 3. The environmental impact results for 1 m^3 of the wood-BPCM panel.

Impact Indicator	Acronyms	Units	A1-3 + C1-4	D
Acidification	Acidif.	mol H + eq.	10.95	−0.20
Climate change – total	CC-total	kg CO_2 eq.	1599.62	−105.70
Climate change, biogenic	CC-B	kg CO_2 eq.	20.16	−0.57
Climate change, fossil	CC-F	kg CO_2 eq.	1206.57	−102.71
Climate change, land-use change	CC-luluc	kg CO_2 eq.	372.89	−2.42
Eutrophication, freshwater	Eutro.-F	kg *P* eq.	0.47	−0.01
Eutrophication, marine	Eutro. – M	kg N eq.	6.92	−0.07
Eutrophication, terrestrial	Eutro. – T	mol N eq.	39.50	−0.65
Ozone depletion	OD	kg CFC11 eq.	4.22E-05	−4.27E-06
Photochemical ozone formation	POF	kg NMVOC eq.	5.47	−0.24
Water scarcity potential	WSP	m^3 depriv.	3581.05	−103.72
Net freshwater use	FW	m^3	127.21	−3.77
Abiotic depletion (fossils)	ADPF	MJ	121540.86	−5356.24
Abiotic depletion (non-fossils)	ADPE	kg Sb eq.	2.25E-02	−4.58E-04

Biogenic carbon content adjustment

The biogenic carbon in wood originates from biological processes and cycles rapidly through the global carbon system (Breton *et al.* 2018). Biogenic CO_2, initially absorbed from the atmosphere by forests or plantations, is eventually released at the end of the product's life. When wood products are burned for energy, like in power plants, they generate electricity or heat, which can substitute for fossil fuel-based energy, thereby reducing associated emissions and potential impacts on global warming (Vogtländer *et al.* 2014). Biogenic carbon was calculated using Equation (1) below, incorporating atomic weights of carbon and CO_2, along with carbon fraction and biomass mass. When the product's exact carbon content was unknown, a default fraction of 0.5 (50% of dry matter) was applied (CEN 2014).

$$P_{CO_2} = \frac{44}{12} \times cf \times \frac{p_\omega \, x \, V_\omega}{1+\omega} \quad (1)$$

Acronyms: P_{CO2} = biogenic carbon oxidised as carbon dioxide emission from the product system into the atmosphere (e.g. energy use at the EOL) (kg), c_f = carbon fraction of woody biomass (oven dry mass), 0.5 as the default value, w = moisture content of the product in %, ρ_w = density of woody biomass of the product at that moisture content (kg/ m^3), W_v = volume of the solid wood product at that moisture content (m^3) (CEN 2014).

A moisture content of 7% was assumed for the wood-BPCM panel. Biogenic carbon is expected to be neutralised over the product's life cycle, with biogenic uptake occurring during the raw material phase, assuming its natural release during the disposal phase. The biogenic carbon content of the wood-BPCM panel was calculated as follows:

Biogenic carbon of the wood-BPCM panel = (44/12) x (0.5) ((800 × 1)/ (1 + (0.07)) = 1370.71 (per m^3) kg CO_2 eq.

Following the adjustment of biogenic carbon content, climate change impacts were analysed for the A1-3, A1-3 + C1-4, and A1-3 + C1-4 + D phases. The carbon sequestration properties of wood during production help mitigate impacts in modules A1-3, while CO_2 emissions occur during C1-4 and D phases due to waste processing and energy recovery. The contributions of C1 and C2 are limited to fossil fuel use in machinery and transport. In contrast, CO_2 emissions increase in C3 and C4, as stored biogenic carbon is released into the atmosphere during waste incineration. These impacts decrease when the energy is recovered and substituted for conventional sources in Module D. In the biogenic climate change category, CO_2 uptake in A1-3 results in negative

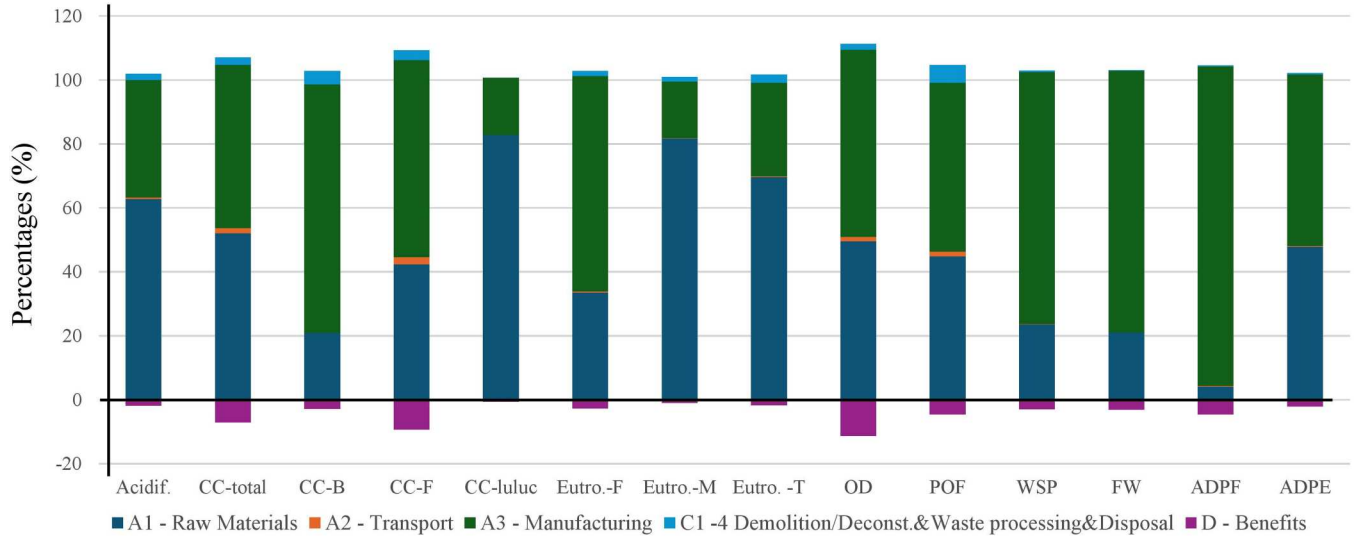

Figure 3. The contribution of each phase for 1 m^3 of the wood-BPCM panel.

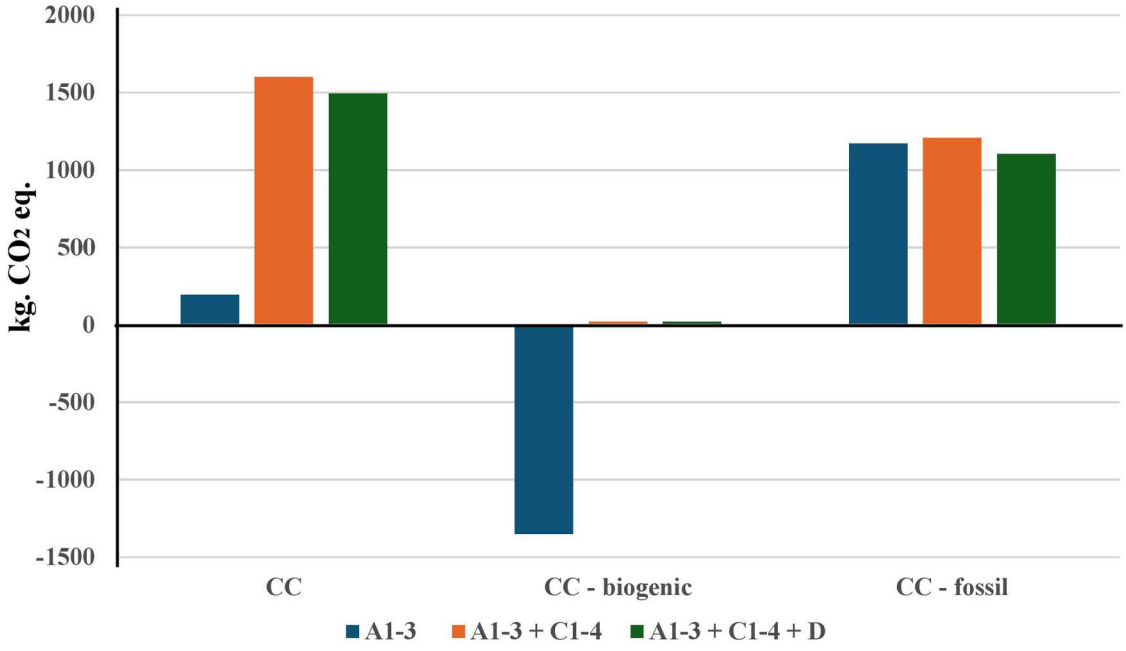

Figure 4. CC impacts for 1 m^3 of the wood-BPCM panel following the adjustment of biogenic carbon.

emissions, which subsequently rise during the C3, C4 and D phases (Figure 4).

In this study, the wood-based BPCM panel was evaluated as part of a controlled experimental setup to investigate its impact on OE and environmental performance. However, unlike commercial products, it has not yet been industrially produced or optimised, so the results indicate potential rather than provide definitive comparisons. In this context, Moni *et al.* (2020) highlighted the challenges of comparing low-TRL innovations with mature products due to differences in data quality, scale, and uncertainty. Therefore, LCA of emerging technologies should aim to identify environmental hotspots and inform future development, rather than offer conclusive performance rankings.

LCIA results for the experimental cubes

The ReCiPe 2016 Midpoint (H) and Endpoint (H) methods were employed to compare the cubes. ReCiPe 2016 offers the most comprehensive set of midpoint impact categories and facilitates the implementation of characterisation factors on a global scale. Unlike other methodologies (e.g. EI99, Impact 2002+), ReCiPe excludes potential impacts from future extractions in the LCIA, assuming these impacts have been integrated into the inventory analysis. The method includes eighteen midpoint and three endpoint indicators (ReCiPe 2016).

In this study, the default model of ReCiPe, known as the Hierarchist perspective (H), was utilised to present the outcomes across both midpoint and endpoint categories. The Hierarchist perspective, a consensus model frequently

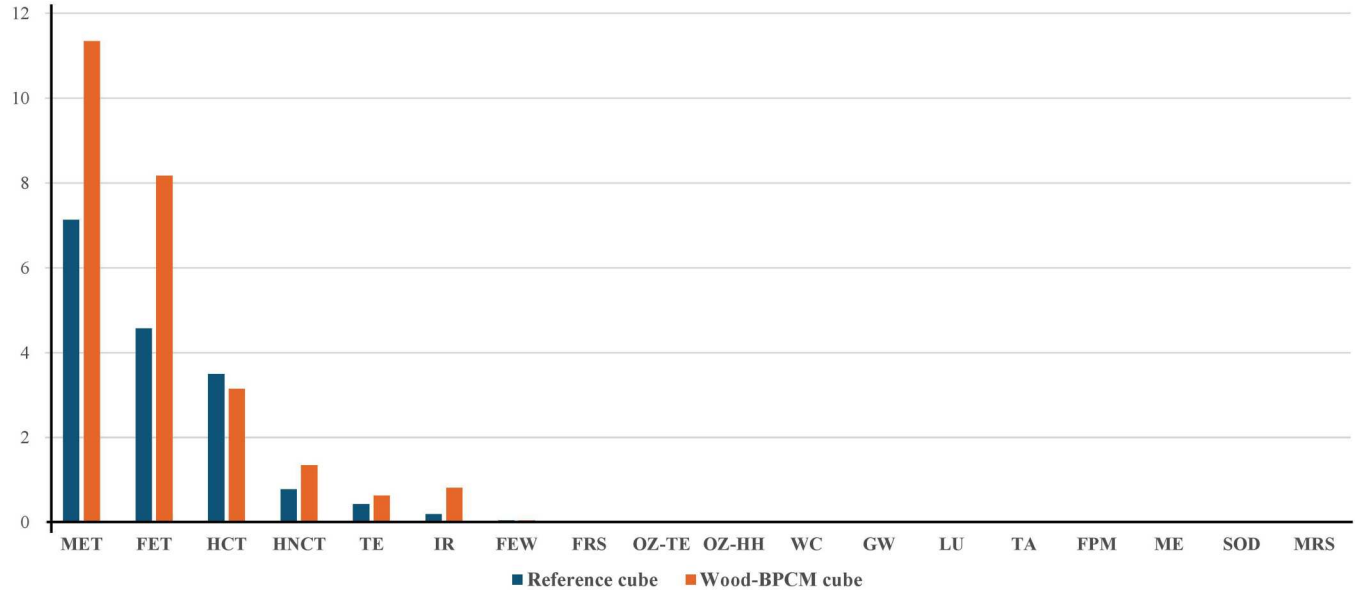

Figure 5. The normalised impact results for the reference cube and wood-BPCM cube based on a heated volume of 1 m^3 (ReCiPe 2016).

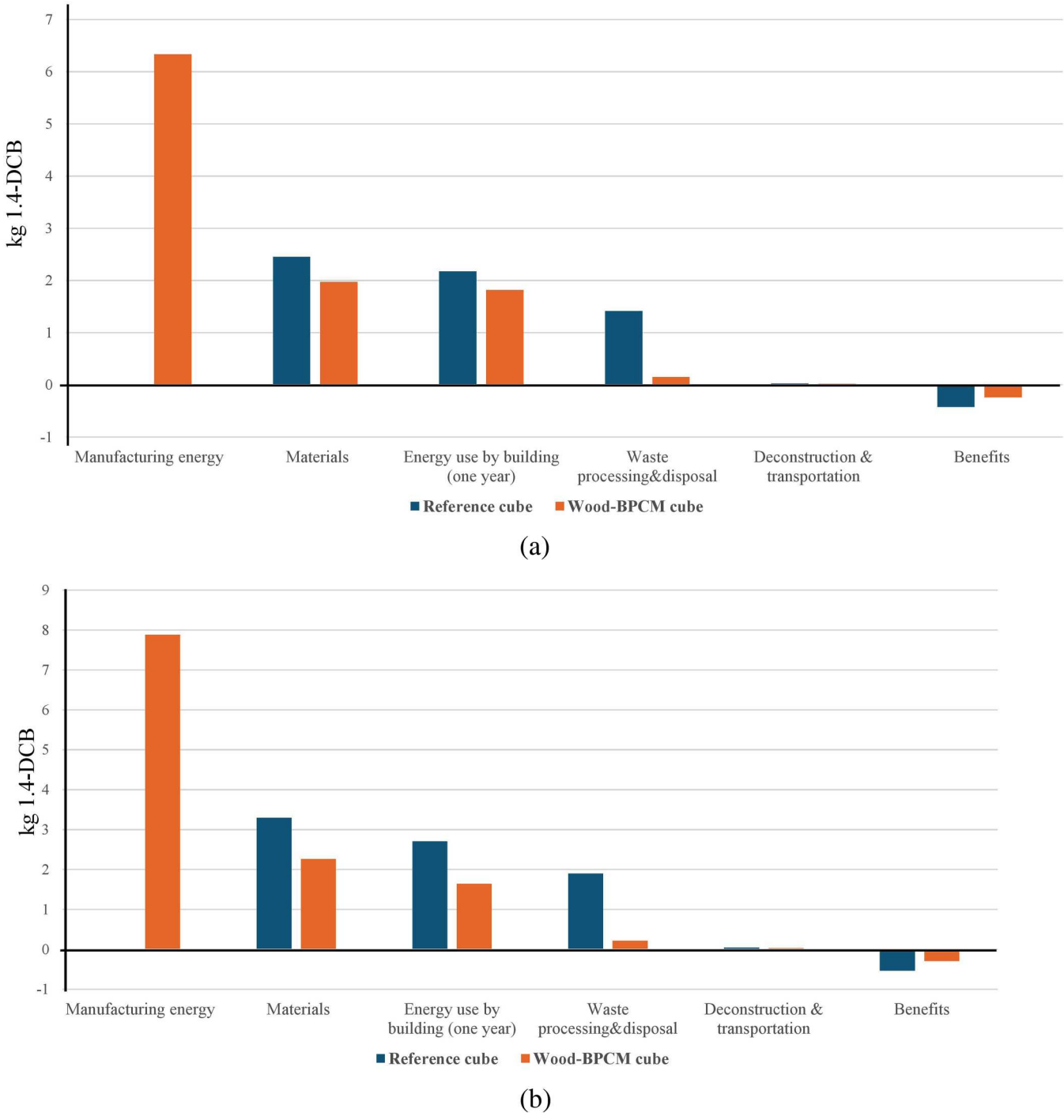

Figure 6. The characterisation results of FET (a) and MET (b) for the reference cube and wood-BPCM cube based on a heated volume of 1 m^3 (ReCiPe 2016).

employed in scientific models and typically utilising a 100-year timeframe, as referenced in ISO standards on LCA (14044) (ReCiPe 2016), was therefore selected. The ReCiPe 2016 (H) method typically includes eighteen midpoint impact categories: global warming (GW, kg CO_2 eq.), stratospheric ozone depletion (SOD, kg CFC11 eq.), ionising radiation (IR, kBq Co-60 eq.), ozone formation, human health (OZ-HH, kg NO_x eq.), fine particle matter formation (FPM, kg PM2.5 eq.), ozone formation, terrestrial ecosystems (OZ-TE, kg NOx eq.), terrestrial acidification (TA, kg SO_2 eq.), freshwater eutrophication (FEW, kg P eq.), marine eutrophication (ME, kg N eq.), terrestrial ecotoxicity (TE, kg 1.4-DCB), freshwater ecotoxicity (FET, kg 1.4-DCB), marine ecotoxicity (MET, kg 1.4-DCB), human carcinogenic toxicity (HCT, kg 1.4-DCB), human non-carcinogenic toxicity (HNCT, kg 1.4-DCB), land use (m^2a crop eq.), mineral resource scarcity (MRS, kg Cu eq.), fossil resource scarcity (FRS, kg oil eq.), and water consumption (WC, m^3) (Huijbregts *et al.* 2017). Figure 5 presents the normalised impact results across the eighteen midpoint impact categories. For FET and MET, the environmental impact was higher for the wood-BPCM cube compared to the reference cube. Conversely, the reference

cube exhibited higher impacts in HCT, compared to the wood-BPCM cube (Figure 5).

The FET and MET impacts in the life cycle processes of both cubes were analysed. The impact of the reference cube was higher in the processes of material consumption, energy consumption over one year, waste demolition processing and disposal. In contrast, the impacts of the wood-BPCM cube were higher in the production process due to the energy consumed (Figure 6). The reference cube exhibited higher environmental impacts on HCT compared to the wood-BPCM cube, primarily due to the materials used in the panel manufacturing. Similarly, energy consumption during BPCM manufacturing contributed to increased environmental impacts in the wood-BPCM cube (Figure 7). Although the reference cube showed higher impacts in the deconstruction and transportation phases compared to the wood-BPCM cube, its overall environmental burden in these phases remained lower for FET, MET and HCT (Figures 6 and 7). Considering the endpoint damage categories, the reference cube had a larger contribution in the resources category, indicating higher fossil and mineral resource depletion, the wood – BPCM cube showed a shift of environmental burdens towards the human health and ecosystem categories (Figure 8).

Studies comparing the environmental impacts of reference and PCM-integrated cubicles have similarly indicated that PCM integration increases embodied impacts while reducing operational impacts. De Gracia *et al*. (2010) analysed a reference cube without insulation, a cube with walls insulated with polyurethane (PU), and a cube with PU and compact storage module (CSM) panels containing paraffin-based PCM in Lleida, Spain. EI99 was used as the LCIA method, and the effects of the cube in the production, dismantling and operation phases were evaluated over a 50-year lifetime. While PCM reduced OE demand, its high manufacturing impact resulted in minimal lifecycle benefits, with the PU cubicle showing slightly lower overall impacts despite the PCM cubicle's operational efficiency. Similarly, Castell *et al*. (2013) studied two cubicles in Lleida with alveolar brick facades, one with macroencapsulated salt hydrate PCM in CSM panels and a reference without PCM. Using the EI99 method, they found a minimal 0.8% reduction in overall impact due to the high manufacturing burdens of PCM. Its benefits were limited mainly to summer. In a recent study, Vega *et al*. (2022) evaluated two lightweight cubicles using paraffin wax-based PCMs in walls and roofs in a cold desert climate. Using the ReCiPe LCIA method over a 20-year lifespan, they found that the PCM-enhanced cubicle reduced operational impacts, but its total impacts were 2.9% higher than the reference cubicle due to increased manufacturing burdens.

Limitations

La Scalia *et al*. (2021) highlighted that studies that limit material production process data to laboratory scale generally have higher environmental impacts compared to commercially available materials. In cradle-to-gate LCA of transparent wood, Rai *et al*. (2022) demonstrated that modelled industrial-scale production significantly reduces electricity consumption – by approximately 98.8% – compared to laboratory-scale production. In addition, the industrial-scale scenario resulted in 28% lower GWP and approximately 97% lower human toxicity impacts, highlighting the substantial environmental benefits of scaling up the process. These findings suggest that the high energy consumption and associated environmental impacts observed in this study are due to the use of laboratory-scale equipment and procedures, which tend to be less efficient. However, data generated at laboratory scale are valuable as they provide critical early-stage insights into the environmental profile of the new material, help identify environmental hotspots and inform future development directions.

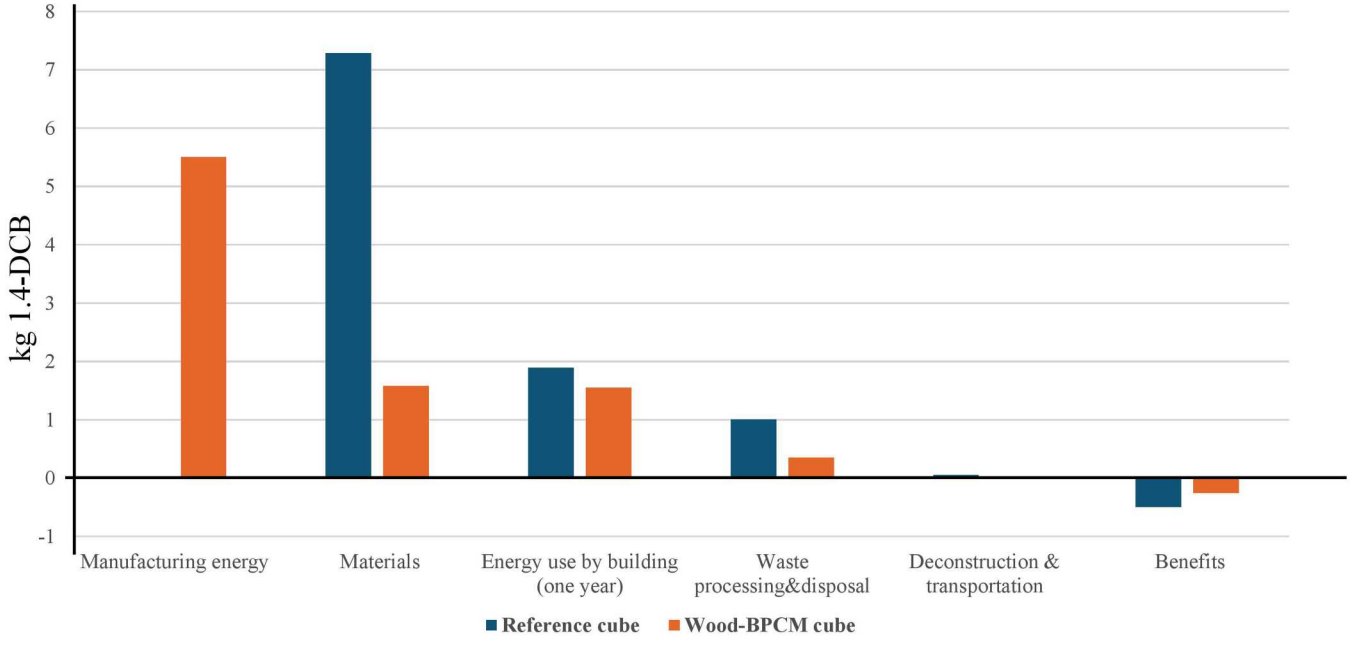

Figure 7. The characterisation results of HCT for the reference cube and wood-BPCM cube based on a heated volume of 1 m^3 (ReCiPe 2016).

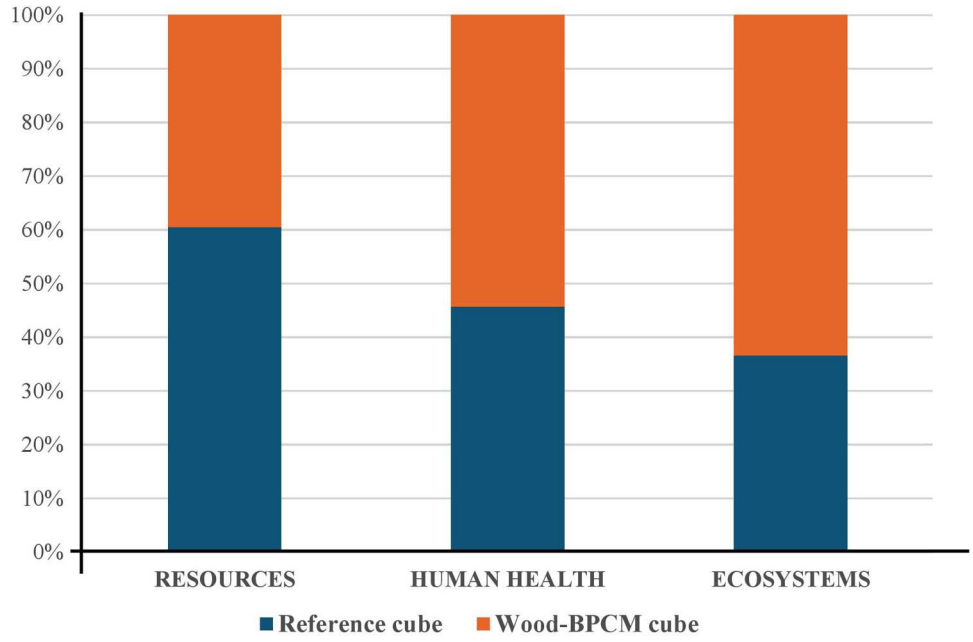

Figure 8. The normalised single score results of endpoint categories for the reference cube and wood-BPCM cube based on a heated volume of 1 m^3 (ReCiPe 2016).

In this study, the selection of datasets from the Ecoinvent database was based on the availability of data and their relevance to the study context, aiming to represent real supply chains best. The datasets used from multiple regions may lead to some variability or uncertainty in the results due to regional differences in production technologies and energy mixes. However, given the scope of the study and the limitations of the available datasets, this approach was considered the most reasonable approach to provide a comprehensive and realistic environmental assessment. In this context, Potouillard *et al*. (2019) underlined that studies on the regionalisation of inventories are essential for preparing data at the impact assessment level and will provide significant opportunities for future research.

Limited studies have investigated wood composites with BPCMs under comparable conditions, limiting direct references for validation. Existing LCA studies primarily focus on paraffin-based PCMs integrated into materials for indoor applications (de Gracia *et al*. 2010, Dara *et al*. 2019, Vega *et al*. 2022), a fundamentally different context in terms of aim and scope from the present study. Consequently, comparisons with these studies are of limited relevance to our focus on BPCMs in wood composites, particularly regarding their long-term thermal and material performance.

Environmental payback period

The environmental payback period (EP) represents the environmental impact timing between the wood-BPCM cube and the reference cube. EP was calculated using Equation (2) below (Vega *et al*. 2022):

$$EP = Impact\ manufacturing\ phase + \frac{Impact\ operational\ phase}{Lifetime} \times Usage\ time \quad (2)$$

An environmental payback period was calculated to evaluate the impact of BPCM on the global warming impact category for the experimental cubes over a 50-year service life. In this calculation, the waste processing and benefits processes were excluded to focus specifically on the relationship between material production energy and OE. However, the impacts of these processes on global warming results for the two cubes are presented in Table 4.

At the conclusion of the 50-year lifespan, BPCM consistently emerged as the preferable option, achieving an 15.1% reduction in climate impact. The cube's EP for global warming was calculated as 14 years using Equation 2. Considering the cubes' expected lifespan of 50 years, the BPCM cube exhibited superior environmental performance regarding

Table 4. Global warming results for the reference cube and the wood-BPCM cube based on a heated volume of 1 m^3.

The reference cube		The wood-BPCM cube	
Process	Global warming results ReCiPe2016 – Midpoint (H)	Process	Global warming results ReCiPe2016 – Midpoint (H)
Materials	59.17 (kg CO_2 eq.)	Materials	50.28 (kg CO_2 eq.)
		Manufacturing energy	38.59 (kg CO_2 eq.)
Energy use by building (one year)	13.24 (kg CO_2 eq.)	Energy use by building (one year)	11.07 (kg CO_2 eq.)
Waste processing and disposal	32.03 (kg CO_2 eq.)	Waste processing and disposal	3.05 (kg CO_2 eq.)
Deconstruction& transportation	1.08 (kg CO_2 eq.)	Deconstruction& transportation	0.63 (kg CO_2 eq.)
Benefits	−12.40 (kg CO_2 eq.)	Benefits	−5.26 (kg CO_2 eq.)
Total results	93.12 (kg CO_2 eq.)	Total results	98.37 (kg CO_2 eq.)

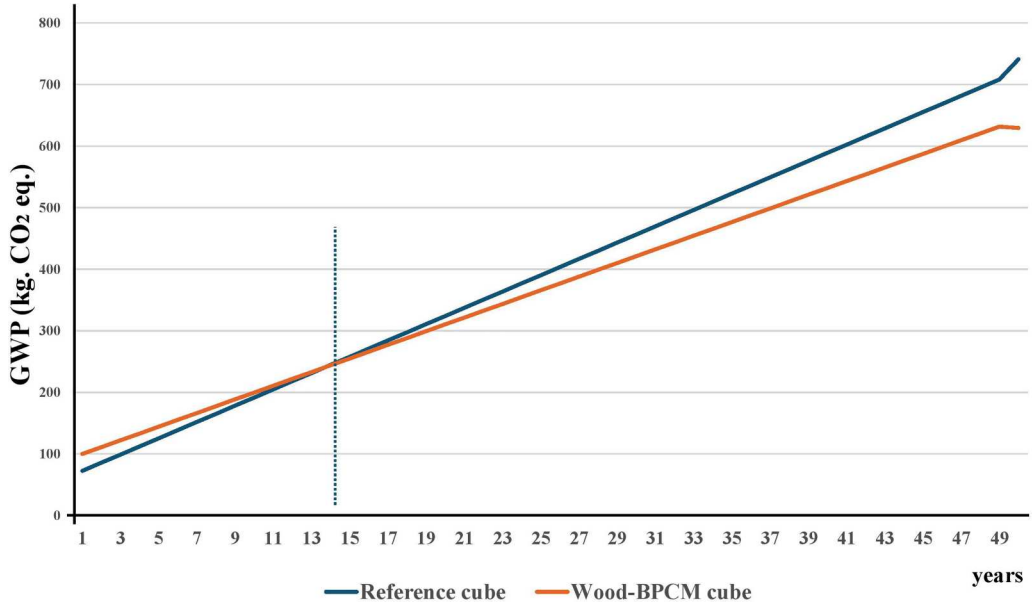

Figure 9. GWP results for the reference cube and wood-BPCM cube by year based on a heated volume of 1 m^3.

climate change. After the 14th year, the wood-BPCM cube surpassed its initial higher climate impact compared to the MDF-based cube and continued to maintain a lower climate impact thereafter (Figure 9). EPs reported in the literature vary significantly depending on the scope of the study, with both longer and shorter durations observed. De Gracia *et al*. (2010) calculated the global impact payback time as 25 years for hydrated salts and 61 years for paraffins. Similarly, De Gracia *et al*. (2014) analysed two cubicles over a 50-year lifespan and determined the EP period for the ventilated facade system to be 30 years. In another study by Vega *et al*. (2022), which incorporated paraffin wax into lightweight prefabricated structures, the EP began in the seventh month (3.3%) for Antofagasta and the third month (1.2%) for Calama in Chile, based on ReCiPe 2016.

Energy consumption and climate change impact are significantly influenced by energy mixes. Countries with a greater reliance on renewables or nuclear energy, such as Norway, Sweden, and France, tend to demonstrate regional processes with lower GHG emissions than the regional average (Alaux *et al*. 2024). In 2022, Sweden's energy supply consisted of 29% biofuels and waste, 28%, nuclear, 12.5% hydro, 7.3%, wind, 1.3% natural gas, 18.6% oil, and 3.3% coal (IEA 2025). Sweden's considerable progress in enhancing energy efficiency and reducing CO_2 emissions through the increased use of renewable energy resources (Adebayo and Ullah 2023) have effectively reduced the climate change impact associated with the wood-BPCM panel.

Conclusion

The study aimed to assess the life cycle effects of the new wood-BPCM composite panel produced under laboratory conditions in Uppsala. To this end, an inventory database for the BPCM composite panel was developed, and their environmental impacts from cradle-to-grave were evaluated using the LCA method. The EF v3.0 method was applied in the LCA study of the composite panel. Further, the environmental burdens were assessed by comparing the energy consumption values of both the wood-BPCM cube and the reference cube, using the ReCiPe 2016 LCIA method in Uppsala. The conclusions are as follows:

- In wood composite panel production, the manufacturing and raw material processes accounted for over 95% of the environmental impacts.
- The LCA results from Uppsala emphasised the critical role of the manufacturing phase on the environmental impacts of the BPCM composite panel. The renewable-rich energy mix in Uppsala contributed to reducing climate change impacts.
- Biogenic carbon in the composite panels' life cycle mitigated climate change impacts during manufacturing due to wood's carbon sequestration properties. However, the disposal phase increased climate change impacts across all categories except the climate change-fossil category. On the other hand, utilising wood waste for energy reduced fossil resource consumption, thereby lowering both climate change and fossil-related impacts.
- The production of EP involves chemical synthesis, which is both energy and resource-intensive, resulting in higher EE and greater environmental burdens, particularly in categories such as climate change, acidification, and resource depletion. These higher values are further accentuated by the nature of the production process assessed in this study. It should be noted that the energy use related to the development of the wood-BPCM panel in this study reflects a laboratory-scale process that involves less efficient equipment and often non-optimised procedures. As a result, the energy demand to produce the material is significantly higher than that of comparable industrially produced materials. This discrepancy can be attributed to the non-scaled nature of the laboratory process and does not necessarily reflect the potential energy demand at the

industrial scale. For this reason, this is a key limitation of the study. In future, a scenario analysis estimating energy use under assumed industrial-scale production conditions would be valuable for assessing the comparative performance and feasibility of the proposed material.

- According to the midpoint LCIA results, the wood-BPCM cube had higher environmental impacts in FET and MET, due to energy consumption in the manufacturing process. In contrast, the reference cube had higher impacts in HCT due to its material consumption, annual OE consumption and waste processing and disposal processes, primarily the materials used in its production. When considering the endpoint LCIA results, the BPCM cube exhibited increased impacts in the human health and ecosytems categories; while the reference cube had a larger contribution in the resources category,
- Assuming a 50-year lifespan, the BPCM cube in Uppsala demonstrated superior climate performance. By year 14, it offset its initially higher climate impact compared to the reference cube and maintained a lower impact. At the end of its lifespan, the BPCM cube achieved an 15.1% reduction in climate impact. Although the higher density of the reference MDF cube enabled greater biogenic carbon uptake and energy recovery at the EOL, this biogenic carbon presence had adverse effects for the BPCM cube. However, the BPCM cube had a 10.1% lower climate impact over the fifty years.

The comparison of studies on buildings with PCMs is difficult due to factors such as different types of PCMs used, climate differences, materials used in cube construction for experimental studies, the scope and limitations of LCA, and the use of different LCIA methods. Despite the growing interest in bio-based PCMs, studies applying LCA to wood-based composite materials with BPCMs are still limited. Differences in climatic conditions, functional units, LCIA methods and system boundaries make it difficult to compare existing results. Therefore, more consistent and comprehensive research is needed to develop standardised approaches. This would make environmental comparisons more reliable and help assess the potential for using such materials on a broader, industrial scale in sustainable building applications.

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Author contributions

CRediT: **Saniye Karaman Öztaş:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing; **Ali Temiz:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing; **Nasko Terziev:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing; **Güliz Öztürk:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing; **Meysam Nazari:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing; **Gaye Köse Demirel:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing; **Sabrina Palanti:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing; **Thomas Schnabel:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing; **Mohamed Jebrane:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing; **Jakub Grzybek:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing; **Özge Nur Erdeyer:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing.

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ORCID

Saniye Karaman Öztaş http://orcid.org/0000-0003-1955-0013
Ali Temiz http://orcid.org/0000-0002-8987-6556
Nasko Terziev http://orcid.org/0000-0001-6938-9155
Güliz Öztürk http://orcid.org/0009-0004-5589-3886
Meysam Nazari http://orcid.org/0000-0001-9736-5150
Gaye Köse Demirel http://orcid.org/0000-0002-1443-6943
Sabrina Palanti http://orcid.org/0000-0002-9033-8827
Thomas Schnabel http://orcid.org/0000-0003-2468-5967
Mohamed Jebrane http://orcid.org/0000-0003-0173-9467
Jakub Grzybek http://orcid.org/0000-0002-0517-294X
Özge Nur Erdeyer http://orcid.org/0000-0001-6672-0332

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