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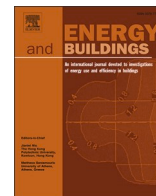
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Life cycle assessment of biocomposite material substitutions in window frames to implement circular design approach

Amirmehrab Falsafi^a, Amir Togiani^{b,*}, Mariam Abdulkareem^a, Jeremy Faludi^c, Juha Varis^b, Mika Horttanainen^a

^a Lappeenranta-Lahti University of Technology LUT, Sustainability Science, Yliopistonkatu 34, FI-53851, Lappeenranta, Finland

^b Lappeenranta-Lahti University of Technology LUT, Production Engineering, Yliopistonkatu 34, FI-53851, Lappeenranta, Finland

^c Faculty of Industrial Design Engineering, Delft University of Technology, Netherlands

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ABSTRACT

The construction sector is under increasing pressure to reduce embodied environmental impacts and support circular economy objectives through material-efficient and low-carbon design strategies. This study evaluates the environmental performance of component-level biocomposite substitutions in wood–aluminum window frames using a cradle-to-grave Life Cycle Assessment (LCA) in accordance with ISO 14040/44. Five scenarios were assessed for 1 m² of window: a baseline wood–aluminum frame (SC1), substitution of aluminum cladding (SC2), PVC glass holders (SC3), and Zamak handles (SC4) with a recycled polypropylene (rPP) + 30 wt% bleached softwood kraft pulp (BSKP) biocomposite, as well as a combined substitution scenario (SC5). The assessment was performed in LCA for Experts using the ecoinvent v3.11 database and the ReCiPe 2016 midpoint (H) method. Global warming potential (GWP), acidification, fossil resource depletion, and human toxicity were evaluated. Results identified aluminum as the dominant environmental hotspot in the baseline scenario. Aluminum substitution achieved the largest environmental improvements, reducing GWP from 47.5 to 28.8 kg CO₂-eq/m² and fossil depletion from 16.3 to 9.3 kg oil-eq/m². The combined substitution scenario (SC5) showed the best overall environmental performance, lowering GWP to 28.5 kg CO₂-eq/m², corresponding to a 40% reduction compared with the baseline. PVC and Zamak substitutions individually resulted in smaller improvements due to their limited material contribution but reinforced the overall benefits when combined. Sensitivity analyses demonstrated the importance of recycled polymers, low-carbon aluminum pathways, and end-of-life management assumptions. Mechanical recycling of rPP-based biocomposite components further reduced the GWP of SC5 to 23.9 kg CO₂-eq/m², while the environmental advantages of the substitution scenarios remained robust even when energy recovery credits from incineration were excluded. Overall, the findings highlight the potential of component-level biocomposite substitution to support circular design of window and reduce the embodied environmental impacts of window manufacturing.

1. Introduction

1.1. Overview of Window Production Worldwide

The transition toward a circular economy (CE) has emerged as a global priority due to escalating concerns over resource scarcity,

environmental degradation, and climate change [1]. Circular design principles, which aim to minimize waste and prolong the usability of materials, are increasingly being adopted across key industrial sectors [2]. The construction industry is one of the world's largest consumers of raw materials and producers of waste, making it a key sector for applying these principles [3]. Within this sector, building components

Abbreviations: Abbreviation, Definition; BSKP, Bleached softwood kraft pulp; CD, Circular design; CDS, Circular design strategies; CE, Circular economy; EoL, End-of-life; EPD, Environmental product declaration; FU, Functional unit; FD, Fossil depletion; GHG, Greenhouse gas; GWP, Global warming potential; HTNC, Human Toxicity non-cancer; LCA, Life cycle assessment; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; nZEB, Nearly zero-energy building; PP, Polypropylene; rPP, Recycled polypropylene; PVC, Polyvinyl chloride; SC, Scenario; WM, Waste Management; WPC, Wood–plastic composite; Zamak, Zinc–aluminum–magnesium–copper alloy.

* Corresponding author.

E-mail address: amir.togiani@lut.fi (A. Togiani).

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such as windows significantly influence both the operational and embodied environmental impacts of buildings [4]. While windows are essential for thermal insulation, energy efficiency, and durability, their production commonly relies on linear material flows based on virgin aluminum, PVC, and other fossil-based materials [5]. These conventional systems are typically characterized by resource intensive raw material extraction, energy-intensive manufacturing, limited recyclability, and end-of-life disposal, resulting in considerable embodied carbon emissions, fossil resource depletion, and waste generation [5,6]. Consequently, re-designing and re-evaluating material choices through the integration of recyclable and bio-based alternatives has become increasingly important for supporting circular economy objectives and reducing the environmental impacts of window manufacturing [6].

Globally, window types and their corresponding materials vary considerably based on regional climate conditions, economic factors, and local preferences [7]. In Europe and North America, PVC and aluminum window frames are extensively used due to their cost-efficiency, durability, and ease of maintenance [8]. Scandinavian countries often prefer wood or wood-aluminum hybrid frames for their superior insulation capabilities and aesthetic compatibility with traditional architecture [9–11]. In tropical and subtropical climates, aluminum frames are popular due to their resistance to humidity and durability under challenging weather conditions [12,13]. The Asian market shows a diverse range of preferences, often using aluminum or PVC for urban high-rise buildings and wood or hybrid solutions in residential and traditional structures [14,15].

1.2. Importance of material selection to implement circular design approach in the building sector

The construction industry has faced mounting pressure to minimize environmental impacts throughout the entire life cycle of its products, from raw material extraction and manufacturing to use, disposal, and recycling [24]. This transition is driven by international climate commitments, national sustainability policies, and the widespread adoption of green building certification frameworks such as Leadership in Energy and Environmental Design (LEED), the Building Research Establishment Environmental Assessment Method (BREEAM), and the European Union Level(s) framework. These frameworks promote life cycle thinking and encourage the use of materials and design practices that reduce embodied carbon, improve energy efficiency, and enhance resource efficiency [25,26]. Consequently, manufacturers and designers are increasingly expected to provide environmental transparency through environmental product declarations (EPDs) and to integrate strategies that extend product lifetimes, support reuse and recycling, and minimize waste throughout the value chain. These regulatory and market-driven developments emphasize the need to reconsider conventional material choices, particularly in essential building components such as window frames [27–29].

Life cycle thinking has become increasingly important as the operational energy demand of buildings is reduced through improved insulation standards, efficient glazing systems, and nearly zero-energy building strategies. Under these conditions, embodied emissions associated with the production, processing, transportation, and end-of-life management of construction materials represent an increasing share of total building life-cycle impacts [63–65]. Recent studies have indicated that embodied emissions may account for up to 80% of total life-cycle greenhouse gas emissions in highly energy-efficient buildings as operational energy demand decreases [30]. Therefore, material production and component-level design are becoming increasingly important for further reducing the life-cycle environmental impacts of buildings. In this context, replacing high-impact materials such as aluminum and fossil-based plastics with recycled, renewable, and bio-based alternatives represents an important strategy for lowering embodied impacts in the built environment [66–69].

Circular design refers to the development of products and systems

that minimize resource consumption, extend material and product lifetimes, facilitate repair and reuse, and improve recyclability across the product life cycle [17,18]. In the construction sector, circular design strategies may include the use of renewable and recycled materials, lightweight structures, modular construction, design for disassembly, reparability, reuse, and material recovery at end-of-life [19–21]. These approaches are closely linked to life cycle thinking, which considers environmental impacts from raw material extraction and manufacturing through use and end-of-life management. Together, circular design and life cycle thinking aim to reduce embodied carbon emissions, resource depletion, waste generation, and the loss of material value while improving long-term material circularity in buildings [22–24].

Material selection is a key means of implementing circular design because it directly influences embodied energy, greenhouse gas emissions, resource consumption, durability, recyclability, and end-of-life management [16]. Historically, material selection in construction has primarily emphasized technical performance, durability, and cost-efficiency, while environmental trade-offs have received less attention. However, as sustainability targets become increasingly stringent, greater emphasis is being placed on materials that support circular economy objectives [17,18]. Recycled, recyclable, renewable, and bio-based materials can reduce the demand for virgin resources, decrease construction and demolition waste, and support the recovery of material value at end-of-life [19–21]. Accordingly, circular design strategies that prioritize durable, resource-efficient, low-impact, and renewable materials have become central to the development of environmentally responsible building products [22–24]. For window systems, targeted substitution of high-impact materials can therefore provide a practical pathway for reducing embodied environmental impacts while supporting broader circular economy objectives.

1.3. Reduction of environmental impacts and material challenges in window frame design

Modern window frames predominantly utilize materials such as wood, aluminum, glass, various plastics (notably PVC and U-PVC), and hybrid combinations thereof. Each material type offers distinct functional properties, influencing factors like durability, maintenance requirements, thermal insulation, and aesthetic appeal [16]. Wood frames, traditionally valued for their natural insulation and visual appeal, require regular maintenance to prevent deterioration [17]. Aluminum frames offer excellent durability and structural strength with minimal maintenance, though they exhibit relatively poorer thermal insulation. On the other hand, Plastic frames, primarily PVC, are widely adopted due to their affordability, good thermal properties, and low maintenance needs [18]. Hybrid window frames, combining materials such as aluminum and wood or aluminum and plastic, attempt to optimize performance by balancing durability, insulation, and aesthetic criteria [19,20].

The choice of materials substantially impacts both environmental sustainability and functional performance of windows [21]. Wood represents a renewable and low-carbon material with favorable insulation properties. However, concerns about its durability and vulnerability to moisture persist [22]. Aluminum frames offer excellent recyclability and durability but entail high embodied energy and carbon emissions associated with extraction and production processes [19,23]. Plastics, particularly PVC, present favorable functional properties but raise environmental concerns due to their fossil-based origin, challenging recycling processes, and potential hazardous emissions during manufacture and disposal [23].

There is growing assessment of embodied carbon, recyclability, and end-of-life impacts associated with window materials, driven by increasing regulatory requirements, market preferences, and sustainability certifications [21]. Embodied carbon, the total GHG emissions attributed to the material production and manufacturing processes, has become a key consideration alongside operational energy efficiency

[24]. Additionally, recyclability and end-of-life management of materials have gained attention, particularly as conventional materials like PVC and composite structures pose significant recycling challenges [8]. This increasing focus highlights the necessity of transitioning toward materials and designs that facilitate reuse, recycling, or safe biodegradation, thereby aligning window frame manufacturing with broader circular economy objectives.

Wood/aluminum-cladded window frame consists of an inner wooden frame covered by an external aluminum layer, creating a composite structure that integrates the properties of both materials. The wooden interior primarily provides excellent thermal insulation, structural stability, and visual warmth, while the exterior aluminum cladding enhances protection against weather conditions, UV radiation, and temperature fluctuations. Key structural components include the wooden frame, aluminum cladding, insulation barriers, sealing gaskets, and glazing units [20].

The primary rationale behind using wood/aluminum-cladded frames is to combine the advantageous thermal and aesthetic properties of wood with the protective and low-maintenance qualities of aluminum [18]. Such hybrid designs enhance durability by effectively preventing moisture ingress and wood degradation, thus extending the functional lifespan of windows. Additionally, the aesthetic versatility provided by the visible wooden interior supports diverse architectural styles, meeting both traditional and contemporary design preferences [19].

Wood/aluminum-cladded window frames are especially prevalent in temperate climatic regions, notably Northern and Central Europe, due to their ability to meet stringent thermal performance standards and withstand demanding weather conditions. This prevalence aligns with regional building practices that emphasize both functionality and architectural aesthetics, contributing to the widespread adoption of these hybrid window frames in residential and commercial construction projects within these climates [25].

The selection of materials for window frames must satisfy several critical performance requirements, including fire retardancy, thermal expansion control, ultraviolet (UV) and weather resistance, and mechanical strength. Each of these factors directly impacts the long-term functionality, safety, and structural integrity of window systems [26]. Effective materials must maintain performance across diverse environmental conditions, ensuring reliable thermal stability and mechanical durability throughout the service life of the product [27].

Presently, window frame designs extensively depend on conventional fossil-based materials, notably polyvinyl chloride (PVC), aluminum, and various synthetic polymers, primarily due to their proven ability to meet stringent performance criteria [5,28]. These materials offer advantages in terms of durability, weather resistance, cost-effectiveness, and minimal maintenance requirements. However, their use poses environmental concerns related to fossil resource depletion, high embodied carbon, recycling difficulties, and disposal challenges [29,30].

1.4. Research gap and opportunity for bio-based alternatives

Despite the pressing need for more sustainable solutions, research investigating the use of biocomposites in specific window frame components remains limited. Existing LCA studies have primarily compared complete window systems or complete frame materials, including wood, PVC, aluminum, and wood–aluminum windows, rather than evaluating the environmental implications of substituting individual window components [19,23,31,32]. Thus, a research gap exists regarding the targeted use of bio-based materials in distinct, high-impact window elements. In addition, previous LCA studies have compared whole window systems made from wood, PVC, and aluminum [19,23,31,32], limited research has investigated component-level substitution strategies. Existing studies primarily focus on complete frame materials or operational energy performance, while the environmental implications of replacing specific high-impact components remain insufficiently

explored. In addition, few studies evaluate such substitutions within a circular design and life cycle assessment framework.

Biocomposites, particularly wood-plastic composites (WPCs), offer promising alternatives to conventional fossil-based materials like PVC and aluminum [33]. WPCs potentially provide a balanced combination of mechanical strength, UV and weather resistance, lower environmental impacts, and enhanced recyclability [33,34]. The utilization of WPCs could effectively address current environmental concerns while maintaining necessary functional performance standards.

To evaluate the viability of biocomposite materials thoroughly, comprehensive Life Cycle Assessment (LCA) studies are essential. LCA can quantify the environmental trade-offs associated with substituting conventional materials with biocomposites. Such assessments would provide crucial insights into practical feasibility, sustainability benefits, and potential limitations of biocomposite substitution.

Furthermore, this research addresses the following questions:

- What are the major environmental impact contributors within a conventional wood-aluminum window throughout its life cycle?
- What are the environmental implications of component-level biocomposite substitutions in a wood–aluminum window compared with the conventional design?
- How do component-level biocomposite substitutions support the implementation of a circular design approach for window systems?

By addressing these research questions through component-level material substitution scenarios and life cycle assessment, this study contributes to the broader discourse on sustainable material transitions in the construction sector. The environmental hotspots of conventional window frames are identified through the baseline assessment, while the substitution scenarios evaluate the extent to which biocomposite alternatives can reduce embodied environmental impacts across different life cycle stages. In addition, the study examines how these substitutions align with circular design strategies, including lightweighting, material efficiency, reduced reliance on virgin fossil-based materials, and resource recovery. Together, these analyses provide insights into how targeted biocomposite substitutions can support climate goals and the circular transition of building systems.

Unlike previous LCA studies have mainly focused on comparing complete window systems manufactured from different frame materials or glazing configurations rather than evaluating targeted substitutions of individual window components [19,23,31,32], the present study combines circular design strategies with component-level life cycle assessment of biocomposite substitutions within an existing wood-aluminum window system. Through scenario-based evaluation of targeted substitutions, the study assesses how circular strategies beyond recycled material utilization alone can influence embodied environmental impacts while maintaining the functional requirements of energy-efficient buildings.

1.5. State of the art

Biocomposites are composite materials composed of a polymer matrix reinforced with natural fibres, bio-based fillers, or other renewable constituents [35,36]. Depending on the matrix and reinforcement type, they may include wood–plastic composites (WPCs), natural fibre-reinforced polymer composites (NFPCs), and fully bio-based composites produced from biodegradable polymers and lignocellulosic fibres [37]. Common reinforcing materials include wood flour, cellulose fibres, hemp, flax, kenaf, rice husk, and agricultural residues, while matrices may include thermoplastics such as polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polylactic acid (PLA), and recycled polymers [45,48,50]. The construction industry has increasingly investigated these materials as alternatives to conventional materials because of their low density, renewable content, potential use of recycled resources, and potential to reduce embodied environmental impacts.

Applications include façade systems, decking, insulation panels, door elements, window profiles, and other non-structural building components [38–40]. Ahmad et al. [40] reported that natural fibre biocomposites have been investigated in applications ranging from concrete reinforcement, hollow tubes, and sandwich panels to wood-replacement boards and insulation products. However, the same review noted that life cycle and cost assessments of biocomposites remain relatively limited, although the available evidence suggests that these materials may provide environmental and economic benefits [40].

Cellulose based biocomposites are of particular interest because wood and plant fibres sequester carbon and are widely available. Wood-plastic composites (WPCs) are typically produced by blending fine wood flour with thermoplastics such as polyethylene or PVC and adding coupling agents, stabilisers and foaming agents to tailor their properties [41–43]. Their hydrophobicity and adequate strength have made them popular for decking, siding and, increasingly, window profiles and door styles [43]. WPCs can incorporate recycled plastics, thereby diverting waste from landfills and reducing demand for virgin polymer, although their mechanical properties are sensitive to formulation. For instance, higher silica content can decrease strength and increase water absorption [41].

Other natural fibre reinforced polymer composites (NFPCs) use fibres such as flax, hemp, oil palm, rice husk and bagasse. These fibres confer high stiffness-to-weight ratios, low density and partial biodegradability, and they allow agricultural residues to be transformed into construction materials [44–46]. They have been used in window frames, panels and door shutters, demonstrating the feasibility of cellulose-based composites in building components [47]. Hemp based materials such as hempcrete have also been adopted as wall, roof and window insulation owing to their low thermal conductivity and light weight [46,47]. Despite these advantages, NFPCs and WPCs still face challenges with moisture sensitivity, ultraviolet (UV) degradation and long-term durability, necessitating further research into fibre treatments and matrix modifications [46].

Early LCA studies established that timber-based windows generally outperform PVC and aluminum windows. The Wood Window Alliance commissioned a cradle-to-grave LCA comparing softwood, modified timber, aluminum clad timber and PVCU frames. The study concluded that timber windows have the lowest global warming potential across all scenarios, whereas PVCU windows perform worst. It also noted large differences in service life. Softwood windows were assumed to last 56–65 years, modified timber 68–80 years, aluminum clad timber 71–83 years and PVCU only 25–35 years. Because of their longer service life and recyclability, aluminum clad timber windows achieved lower lifetime costs than PVCU and were competitive with unclad timber [32].

Sinha and Kutnar (2012) performed a cradle-to-gate LCA to compare aluminum, PVC and wood frames of identical thermal performance. Their analysis showed that aluminum frames had a carbon footprint of 486 kg CO₂eq per 1 m² window, uPVC 258 kg CO₂eq and wood 130 kg CO₂eq. The authors concluded that wood frames offer superior thermal and environmental performance, while aluminum frames have the highest environmental impacts owing to the energy intensive nature of aluminum production [19].

Subsequent studies corroborate these findings. Kowalczyk et al. (2023) analysed triple glazed aluminum windows versus double and triple glazed PVC windows using the ReCiPe method [23]. They found that the environmental impact of aluminum window production was more than 64% higher than that of a double-glazed PVC window and over 43% higher than that of a triple glazed PVC window. The authors noted that 44% of the total environmental impact of aluminum windows is attributable to resource depletion, whereas the human health category dominates the impact structure of PVC windows. They also remarked that wooden windows, evaluated in previous research, have the lowest environmental impact [23]. These results align with earlier findings by Asif et al. and StachowiakWencek et al., which identified aluminum as the most emission intensive frame material and highlighted the low

impacts of timber windows [48,49].

Sečkář et al. (2024) conducted a comparative LCA of a wood-aluminum window produced in Slovakia and analysed the pre-use phase using both SimaPro and GaBi [31]. They emphasized that using recycled aluminum significantly reduces environmental burdens and that combining wood (for insulation and aesthetics) with aluminum (for durability) delivers a long service life with relatively low environmental impact. These findings support hybrid designs as a viable pathway toward circularity [31].

Another research investigates the benefits of renovating existing windows. A master's thesis by Salih (2024) used Environmental Product Declaration (EPD) data and One Click LCA software to compare the global warming potential of renovating double and triple glazed windows versus manufacturing new ones. The study concluded that renovation, particularly of triple glazed units, reduces GWP relative to production of new windows while meeting regulatory U-value requirements. This underscores the importance of extending product life through refurbishment and aligning with circular design principles [50].

While biocomposites have clear environmental advantages during production, their end-of-life (EOL) management poses challenges. WPCs and NFPCs often contain synthetic polymers and coupling agents that hinder mechanical recycling. Adhesives and coatings can degrade during reprocessing and reduce mechanical strength [51–53]. The study of Wronka and Kowaluk (2024) investigated the recycling of wooden window frames into three-layer particleboard. They found that panels made with over 50 parts by weight of recycled wood exhibited improved modulus of rupture and modulus of elasticity, but internal bond strength remained a limitation. Contaminants such as paints and adhesives significantly influenced the mechanical performance: removing paint improved mechanical properties, whereas residual paint increased density but reduced strength. The authors concluded that recycling wood from window joinery has substantial potential but requires additional processing to overcome chemical contaminants and achieve desirable bonding [54]. Similar issues arise in recycling WPCs and NFPCs, where separating fibres from the polymer matrix is complex and may result in downcycling rather than closed loop recycling.

Broader reviews of biocomposites also note that lifecycle data for these materials are limited, and that transport distances and processing conditions can negate their environmental benefits [40]. Moreover, current recycling methods (mechanical, thermohydraulic or chemical) face obstacles due to the presence of preservatives, paints and adhesives in wood waste and the heterogeneity of composite compositions [55,56]. Addressing these EOL challenges will be essential for the widespread adoption of biocomposite window components.

Existing studies have evaluated conventional window-frame materials and the application of biocomposites in construction. However, component-level biocomposite substitutions in hybrid wood-aluminum window systems remain insufficiently explored. Previous window LCAs have primarily compared complete window systems or frame materials, whereas limited attention has been given to the environmental implications of replacing individual high-impact components. This study addresses this gap through a scenario-based life cycle assessment of targeted biocomposite substitutions aligned with circular design strategies.

2. Materials and methods

2.1. Circular design strategies and biocomposites

To align the material substitution scenarios with CD principles, the methodology emphasises several targeted strategies. Design for resource and material efficiency calls for minimising raw material consumption through optimised section geometry and efficient manufacturing, thereby lowering embodied impacts [57–60]. Design for lightweighting aims to reduce component mass and material consumption while maintaining sufficient structural and functional performance through

the use of reinforced biocomposites with improved stiffness-to-weight properties [60,61]. Design from recycled materials prioritises the incorporation of reclaimed polymers and wood fibres, closing material loops and reducing reliance on virgin materials [62,63]. Design for low-impact manufacturing focuses on selecting processes that use less energy, chemical additives, and generate minimal waste during production [58,60].

In the use phase, design for durability ensures that frames can withstand weathering, ultraviolet exposure and mechanical loads over long service lives, delaying replacement and preserving embodied carbon [60]. Design for repairability and modularity means components such as handles, or cladding can be replaced individually without discarding the entire frame, supporting maintenance and upgradeability. Design for disassembly and recycling requires that materials be joined in ways that allow easy separation at end of life [60,64]. This facilitates design for resource recovery, where recovered materials maintain sufficient quality to be reintroduced into new products.

From a materials perspective, material substitution and innovation promote the use of bio-based composites and recycled plastics in place of high-impact materials like virgin aluminum or PVC. Complementing this, biodegradable material development explores polymers and elastomers that can break down safely when they can no longer be recycled, thus preventing accumulation in landfills [60,65]. These strategies collectively guide the selection of alternative materials in this study and underpin the attributional LCA framework used to assess their environmental benefits.

2.2. Biocomposite material composition

To assess the environmental benefits of biocomposite substitution, a single representative biocomposite formulation was selected for the life cycle assessment. During the broader material development activities of the ABiCo project, several candidate formulations with different polymer matrices, reinforcement types, and reinforcement contents were developed and evaluated (Table 1). Based on the outcomes of this material screening process, a formulation consisting of recycled polypropylene (rPP) reinforced with 30 wt% bleached softwood kraft pulp (BSKP) was selected for further environmental assessment. The selection considered multiple technical and sustainability criteria, including mechanical performance, weathering resistance, processability, and compatibility with circular design objectives. As these comparative material-development results were generated within an industry-academia collaborative project, the detailed experimental performance data are proprietary to the industrial partners and cannot be disclosed. Therefore, Table 1 presents the candidate formulations considered during material development, while the present study focuses on the environmental performance of the selected formulation rather than on comparing the engineering performance of all candidate materials.

The selected formulation uses recycled post-consumer polypropylene

Table 1
Candidate biocomposite formulations evaluated during preliminary material development and material selection.

Composite ID	Polymer Matrix	Reinforcement Type	Reinforcement Content
rPP20C	Recycled polypropylene (rPP)	Cellulose fibres	20 wt%
rPP30C	Recycled polypropylene (rPP)	Cellulose fibres	30 wt%
rPP20S	Recycled polypropylene (rPP)	Sawdust	20 wt%
rPP30S	Recycled polypropylene (rPP)	Sawdust	30 wt%
PE20C	Bio-based LDPE	Cellulose fibres	20 wt%
PE30C	Bio-based LDPE	Cellulose fibres	30 wt%
PE20S	Bio-based LDPE	Sawdust	20 wt%
PE30S	Bio-based LDPE	Sawdust	30 wt%

(rPP) as the polymer matrix. The use of recycled PP is consistent with circular design strategies because it reduces the demand for virgin fossil-based plastics, lowers embodied carbon, and supports material circularity through the utilization of secondary raw materials. In addition, polypropylene is a thermoplastic that can be mechanically recycled at end-of-life, making it suitable for circular product systems. Although natural fibre-reinforced thermoplastics may experience some fibre degradation during recycling, the use of a single polymer matrix combined with a renewable lignocellulosic reinforcement may simplify recycling compared with more complex multi-material systems [66].

For the reinforcing phase, bleached softwood kraft pulp (BSKP) was incorporated at a loading of 30 wt%. BSKP fibres are produced by removing lignin and hemicellulose from softwood pulp, resulting in fibres with improved thermal stability, reduced hydrophilicity, and enhanced fibre-matrix adhesion, particularly when compatibilizers are used [67]. Previous studies have shown that BSKP reinforcement substantially improves the stiffness and tensile strength of thermoplastic composites [67,68]. For example, incorporating 30 wt% BSKP into PLA increased tensile strength from 62.7 MPa to approximately 70–73 MPa and increased Young's modulus from 3.38 GPa to 5.9–6.7 GPa, although elongation at break decreased because of the increased fibre stiffness [68].

Compared with unbleached pulp or many other natural fibres, BSKP provides additional practical advantages for window applications. The low lignin content improves colour stability during processing and reduces thermal degradation, while the light colour produces a more uniform appearance in visible window components. Other natural fibres may exhibit greater variability in morphology, moisture content, and fibre quality, often requiring additional treatments to achieve comparable interfacial adhesion and processing performance [67]. Consequently, the selected rPP + 30 wt% BSKP formulation represents a practical material solution that combines recycled polymer, renewable reinforcement, and properties suitable for evaluating circular material substitution scenarios within window-frame applications.

2.3. LCA modelling and impact assessment

This study employs an attributional Life Cycle Assessment (LCA) to evaluate the environmental impacts associated with window production at a company in Finland under various material substitution scenarios. The LCA was conducted in accordance with ISO 14040 and ISO 14044 standards, following the four phases of the LCA framework: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation.

[69,70]. The modelling was performed in LCA for Experts integrate with the Ecoinvent v3.11 database. The ecoinvent v3.11 database, which is a process-based life cycle inventory (LCI) database providing unit-process datasets, was selected because it provides comprehensive and internationally recognized inventory data for construction materials, energy systems, recycling processes, and transportation activities [71]. Although this study adopts an attributional LCA framework, which describes the environmentally relevant material and energy flows associated with a product system under average operating conditions within a defined system boundary [72], the modelling applies the substitution (avoided burden) approach to account for recycling and energy recovery, because the study focuses on current average production systems rather than market-driven changes. Unit process modelling was applied to maintain transparency of individual material and process contributions across the system boundary. In this approach, recycled materials and recovered energy are credited by subtracting the impacts of producing equivalent virgin materials or conventional energy, respectively. This method is appropriate for:

- Recycling of aluminum, glass, and other materials, where avoided burdens from substituting virgin materials are considered.

- Energy recovery through incineration, where generated energy replaces conventional energy production.
 - Assessing the environmental benefits of substituting conventional materials with biocomposite materials.
- Goal and Scope Definition

The goal of this study is to identify the major environmental impact contributors within conventional wood–aluminum window frames, assess the environmental implications of component-level biocomposite substitution scenarios through life cycle assessment, and evaluate how these substitutions align with CD strategies for reducing embodied environmental impacts in building components. The focus is on evaluating the potential benefits of using biocomposites, particularly WPCs based on recycled polypropylene reinforced with 30 wt% bleached softwood kraft pulp (BSKP), as alternatives to conventional materials.

The scope of the study covers a cradle-to-grave analysis (excluding use phase), including raw material extraction, transportation, manufacturing, and end-of-life management. The use phase is excluded from this analysis as the functional and operational performance of the windows during their use phase is assumed to be the same across all scenarios.

The functional unit is assumed to be 1 m² of window. The studied product, however, is based on a window size of 1.23 m × 1.48 m, corresponding to an area of 1.8204 m². A conversion factor of 0.5493 is applied to adjust all material inputs to correspond to the functional unit (Eq. 1).

$$\text{Conversion factor} = \frac{1 \text{ m}^2}{1.8204 \text{ m}^2} = 0.5493$$

Equation 1 Conversion factor used to normalize the reference window dimensions to the functional unit of 1 m².

The system boundary encompasses raw material extraction, transportation, manufacturing, and end-of-life phases, while the use phase is excluded from the analysis. Fig. 1 illustrates the system boundaries applied in this study. In alignment with modular building LCA frameworks, the assessed system includes product stage processes related to raw material supply and manufacturing (A1–A3), transportation processes (A4), and end-of-life management processes including recycling, energy recovery, and disposal (C1–C4). Environmental benefits associated with recycling and energy recovery beyond the system boundary were accounted for using the avoided burden approach (Module D). Module A5 (installation) was excluded because the proposed biocomposite substitutions do not alter the installation procedure, installation materials, or construction equipment required for the window system. As all scenarios involve identical installation processes, the environmental impacts associated with Module A5 were assumed to be equivalent across the baseline and substitution scenarios and therefore would not affect the comparative results of the study. The use phase (Module B) was also excluded because the evaluated substitution scenarios focused on component-level material replacements without modifying the glazing system, overall window geometry, or intended thermal performance of the window assembly. Therefore, the

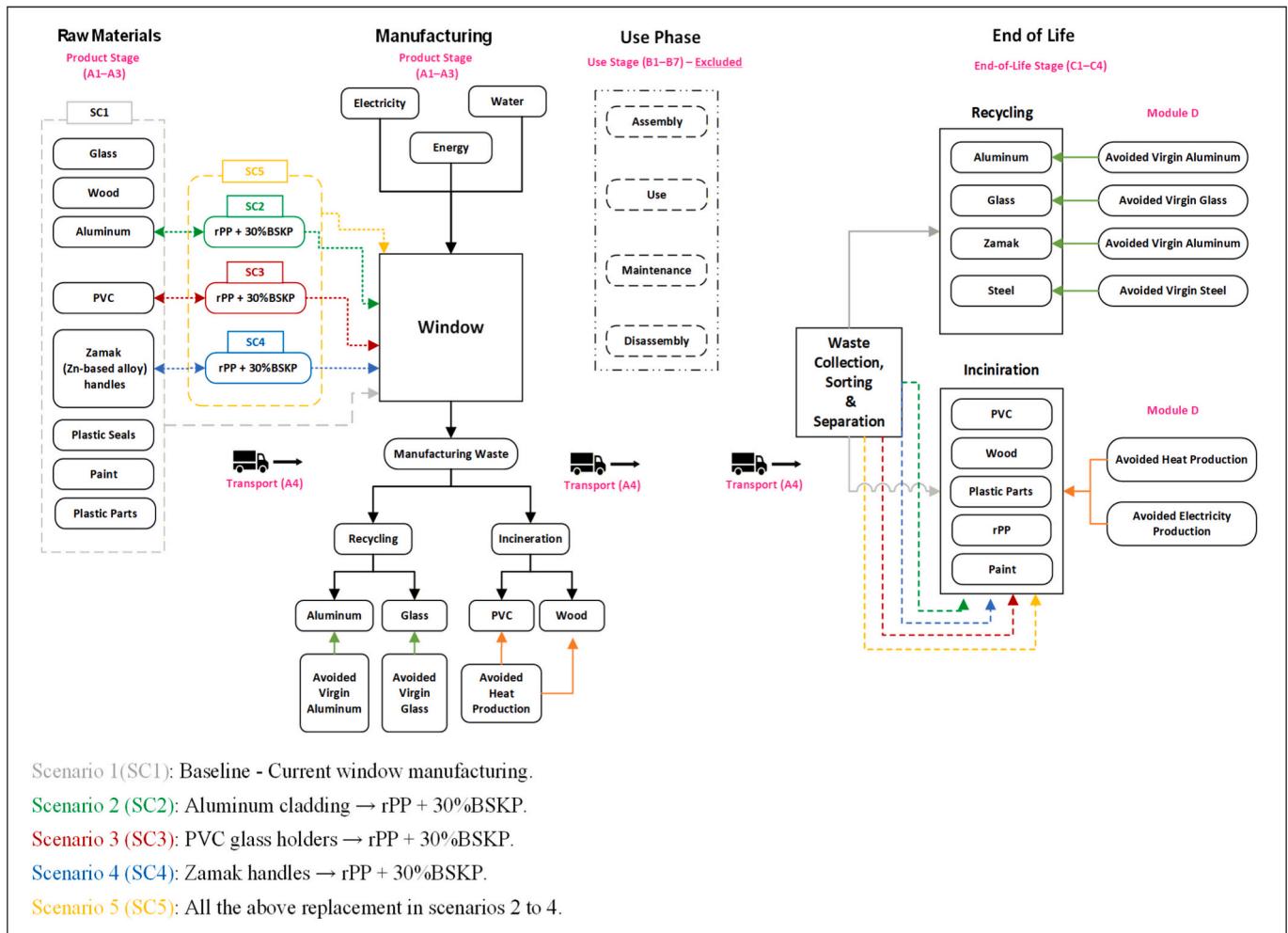


Fig. 1. System boundary of the cradle-to-grave LCA for the wood-aluminum window, covering raw material production, transportation, manufacturing, and end-of-life (EoL) management; the use phase is excluded.

operational and functional performance of the windows, including their influence on building energy demand, was assumed to remain unchanged across all scenarios, allowing the study to focus specifically on differences in embodied environmental impacts associated with material production and end-of-life management.

This LCA study evaluates five scenarios to assess the environmental benefits of substituting conventional materials with biocomposites alternatives in the reference wood-aluminum window case study (Fig. 2).

The Scenario 1 (SC1) which is the baseline, represents conventional window manufacturing at Pihla, utilizing materials such as wood, aluminum, glass, PVC, steel, seals, paint, silicone, and plastic components. Recyclable materials, notably aluminum and glass, are assumed to be recycled, while non-recyclable materials undergo energy recovery.

Scenario 2 replaces aluminum cladding with WPCs based on recycled polypropylene reinforced with 30 wt% bleached softwood kraft pulp (BSKP). This substitution aims to lower GHG emissions and energy use related to aluminum production.

Scenario 3 substitutes PVC glass holders with WPCs based on recycled polypropylene reinforced with 30 wt% bleached softwood kraft pulp (BSKP). This change is intended to decrease reliance on fossil-based resources, and promote material circularity, with WPCs assumed recoverable at the end of life.

Scenario 4 replaces Zamak handle (Zn-alloy based) with WPCs. The objective is to minimize environmental impacts associated with raw material extraction and processing.

Scenario 5 integrates all previous substitutions to achieve the greatest potential environmental benefits. It encompasses replacing aluminum cladding, PVC glass holders, and handle with WPCs based on recycled polypropylene reinforced with 30 wt% bleached softwood kraft

pulp (BSKP).

The selected substitution scenarios were based on the environmental relevance and material intensity of specific window frame components which represent fossil- or metal-intensive materials with potential for replacement through lighter biocomposite alternatives.

Life Cycle Inventory (LCI)

The baseline component masses presented in Table 2 were obtained from manufacturer-provided production and material inventory data for the reference wood-aluminum window system in Finland. The reported values therefore represent the actual material composition of the studied product configuration.

To operationalize the substitution scenarios, Table 3 summarizes the component-level masses per 1 m² of window that are replaced by the rPP + 30% BSKP biocomposite. The aluminum cladding (SC2), PVC glass holders (SC3), and Zamak handle (SC4) together account for 3.46 kg of conventional materials per functional unit. When substituted with the biocomposite, the required mass is reduced to 1.18 kg, representing a total mass reduction of 66.0%. These values form the basis of the inventory for the substitution scenarios (SC2–SC5) and are used in the subsequent results and discussion.

The data provided above reflects the standard composition of the window frame, primarily utilizing conventional materials (Fig. 2). The components are processed through various manufacturing steps, including cutting, surface treatment, glazing, and assembly.

The inventory data will serve as the basis for evaluating alternative scenarios that incorporate biocomposites, as discussed in the upcoming sections. The substitution masses presented in Table 3 were not derived assuming equal material volumes between conventional and biocomposite components. Instead, the substituted biocomposite quantities were estimated based on preliminary design adaptation considerations, material density differences, and the targeted structural and functional requirements of the respective window components. The selected biocomposite formulation had previously demonstrated suitable performance potential for the intended application within the broader material development activities of the project.

Life Cycle Impact Assessment (LCIA)

Environmental impacts were evaluated using the ReCiPe 2016 midpoint (H) method, which enables consistent assessment of multiple environmental impact pathways. The assessment covered global warming potential (GWP), acidification potential, Fossil resource Depletion, and human toxicity (non-cancer effects). All impact categories were assessed at the midpoint level to quantify potential environmental burdens associated with the different material substitution scenarios. The inclusion of fossil resource depletion is particularly relevant for comparing conventional fossil-based materials like PVC with biobased and recycled alternatives, as it captures the depletion of non-renewable resources across the life cycle. The LCIA results were analysed and compared across scenarios to evaluate the potential sustainability benefits of incorporating biocomposites into window frame design. Environmental impacts associated with raw material

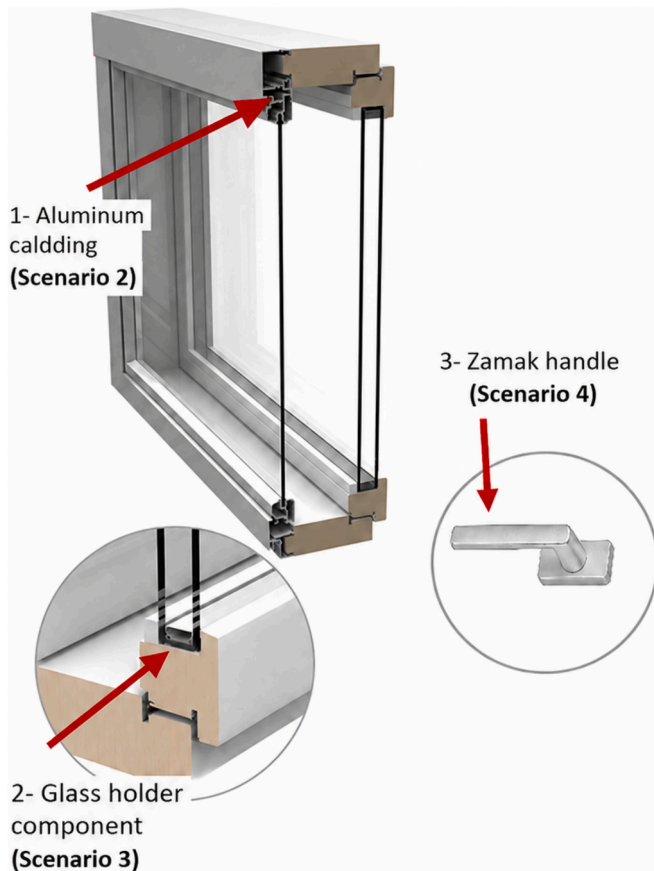


Fig. 2. Reference wood-aluminum clad window frame analysed in this study, used to define the baseline configuration (SC1) and the component substitutions evaluated in SC2–SC5.

Table 2

Baseline LCI for the reference window, reporting component masses for the original window size (1.23 m × 1.48 m) and normalized to the functional unit (1 m²).

Component	Mass (kg) per 1.23 m × 1.48 m window	Mass (kg) per 1 m ² of window
Glass	44.01	24.18
Wood	24.37	13.39
Aluminum	5.17	2.84
PVC	0.41	0.23
Steel	0.49	0.27
Paint	1.32	0.73
Seals	0.33	0.18
Silicone	0.13	0.07
Plastic parts	0.0003	0.0002
Total	76.23	41.87

Table 3

Component-level material substitutions modelled in the biocomposite scenarios, showing conventional material masses replaced by rPP + 30 wt% BSKP and the corresponding mass reduction per functional unit (1 m²).

Component Replacement	Conventional Material (kg)	rPP + 30% BSKP (kg)	Percentage of Mass Reduction (%)
Aluminum → rPP + 30% BSKP	2.84	0.97	65.8
PVC → rPP + 30% BSKP	0.23	0.15	34.8
Zamak → rPP + 30% BSKP	0.39	0.06	85.9
Total	3.46	1.18	66.0

production, manufacturing, transportation, and end-of-life management were calculated based on the aggregated contributions of the corresponding unit processes within the defined system boundary. Additional methodological details, modelling procedures, and calculation formulations are provided in the Supplementary Material file.

2.4. Sensitivity analysis

The sensitivity analysis was conducted to evaluate the influence of key material sourcing assumptions and future supply-chain variations on the robustness of the LCA results. Uncertainties related to the use of recycled versus virgin polymer matrices and the potential adoption of

low-carbon aluminum production pathways were examined, as these factors may affect the embodied environmental impacts of both the baseline and substitution scenarios. To address these uncertainties, two alternative scenarios were modelled. In the first scenario, virgin polypropylene was used as the matrix material instead of post-consumer recycled polypropylene (rPP) in the biocomposite formulation, allowing the influence of recycled polymer content on the environmental performance of the substitution scenarios to be assessed. In the second scenario, a low-carbon recycled aluminum pathway powered by renewable electricity was considered as an alternative to conventional primary aluminum production. This scenario reflects emerging industrial decarbonization practices and provides insight into the influence of future aluminum supply chains on the environmental performance of both the baseline and substitution scenarios.

To further evaluate the robustness of the results, additional sensitivity analyses were conducted to examine uncertainties associated with end-of-life modelling. These analyses included a scenario without heat and electricity recovery from waste incineration and a prospective mechanical recycling scenario for the PP-based biocomposite components. The former was introduced to assess the influence of future WM systems in which energy recovery may be reduced or unavailable, whereas the latter explored the potential environmental benefits of implementing circular recycling pathways for biocomposite materials. In addition, service life was recognized as a potential source of uncertainty. However, due to the lack of long-term durability data for the selected rPP + 30% BSKP biocomposite formulation and the exclusion of use-phase,

Table 4

LCIA results by life cycle stage (raw materials, manufacturing, and end-of-life) for the baseline (SC1) and substitution scenarios (SC2-SC5) across GWP, acidification, fossil depletion, and human toxicity (nc), reported per functional unit (1 m²). The reported stage contributions correspond to the system boundary defined in Fig. 1. Transportation impacts (Module A4) are included within the relevant life cycle stage results and are not presented separately.

Impact category (unit)	Scenario	Raw materials	Manufacturing	EoL	Total
GWP (kg CO ₂ -eq)	SC1	65.1	2.6	−20.1	47.5
	Baseline				
	SC2	36.5	7.4	−15.1	28.8
	Al replacement				
	SC3	64.7	2.4	−21.2	45.8
	PVC replacement				
	SC4	64.7	2.6	−20.6	46.7
	Zamak replacement				
	SC5	35.7	7.4	−14.6	28.5
	All replacements				
Acidification (kg SO ₂ -eq)	SC1	0.263	0.005	−0.099	0.168
	Baseline				
	SC2	0.198	0.022	−0.088	0.131
	Al replacement				
	SC3	0.262	0.005	−0.099	0.168
	PVC replacement				
	SC4	0.261	0.005	−0.098	0.168
	Zamak replacement				
	SC5	0.196	0.022	−0.086	0.131
	All replacements				
Fossil depletion (kg oil-eq)	SC1	20.7	4.5	−8.9	16.3
	Baseline				
	SC2	12	5.5	−8.3	9.3
	Al replacement				
	SC3	20.4	4.5	−9	16
	PVC replacement				
	SC4	20.5	4.5	−8.7	16.3
	Zamak replacement				
	SC5	11.5	5.5	−8.1	9
	All replacements				
Human toxicity, non-cancer (kg 1,4-dB-eq)	SC1	2.8	−0.8	−0.9	1.1
	Baseline				
	SC2	1.7	0.2	−0.8	1
	Al replacement				
	SC3	2.8	−0.8	−0.9	1.1
	PVC replacement				
	SC4	2.6	−0.8	−0.7	1.1
	Zamak replacement				
	SC5	1.4	0.2	−0.6	1
	All Replacements				

maintenance, and replacement activities from the system boundary, the influence of service-life variation was discussed qualitatively rather than assessed quantitatively.

3. Results

The life cycle impact assessment (LCIA) results for the baseline (SC1) and substitution scenarios (SC2-SC5) are presented across four categories: Global Warming Potential (GWP), Acidification, Fossil Depletion, and Human Toxicity (non-carcinogenic). All results are reported per functional unit of 1 m² of window and are separated into contributions from raw material production, manufacturing, and end-of-life (EoL) management (Table 4 and Fig. 3).

The baseline window resulted in a total GWP of 47.5 kg CO₂-eq per m², with raw material extraction contributing the largest share (65.1 kg CO₂-eq) followed by manufacturing (2.6 kg CO₂-eq). These burdens were partially offset by a significant EoL credit (−20.1 kg CO₂-eq) associated with aluminum recycling. This distribution highlights the dominant role of aluminum in shaping the carbon footprint of conventional wood-aluminum window frames.

The substitution scenarios consistently reduced overall GWP compared to the baseline. The most substantial reductions were achieved in scenarios involving aluminum replacement. In SC2 (aluminum cladding substitution), raw material burdens fell to 36.5 kg CO₂-eq, reflecting the high impact of aluminum avoided by the biocomposite substitution. Manufacturing impacts rose to 7.4 kg CO₂-eq because aluminum substitution removed the recycling credits normally obtained from aluminum waste during the manufacturing stage. In the baseline case, aluminum off-cuts are recycled and credited as avoided impacts, but this credit is absent in SC2 and SC5, leading to higher net

manufacturing impacts despite the lower material intensity of the biocomposites. The EoL credit declined to −15.1 kg CO₂-eq, as less aluminum was available for recycling. Nevertheless, the total GWP decreased to 28.8 kg CO₂-eq, representing a 39% reduction relative to SC1.

The combined substitution scenario (SC5) achieved the lowest total GWP at 28.5 kg CO₂-eq. Similar to SC2, raw material burdens decreased substantially (35.7 kg CO₂-eq), manufacturing increased (7.4 kg CO₂-eq), and the EoL credit was reduced (−14.6 kg CO₂-eq) because of lower recycling potential.

By contrast, scenarios targeting minor components had only marginal influence. SC3 (PVC replacement) achieved 45.8 kg CO₂-eq, while SC4 (Zamak replacement) resulted in 46.7 kg CO₂-eq. In both cases, raw material burdens remained above 64 kg CO₂-eq, dominated by aluminum. Improvements arose mainly from higher EoL credits (−21.2 and −20.6 kg CO₂-eq), as recovery of aluminum and glass offset burdens, along with minor changes in manufacturing emissions (2.4–2.6 kg CO₂-eq).

The same trend was observed in the other impact categories. For Acidification, the baseline (SC1) totaled 0.168 kg SO₂-eq, with raw materials contributing 0.263 kg SO₂-eq, partly offset by an EoL credit of −0.099 kg SO₂-eq. Aluminum substitution (SC2) achieved the largest reduction, lowering the total to 0.131 kg SO₂-eq by reducing raw materials to 0.198 kg SO₂-eq, though manufacturing rose to 0.022 kg SO₂-eq and EoL credits declined (−0.088 kg SO₂-eq). SC5 produced almost the same result, while PVC (SC3) and Zamak (SC4) substitutions showed almost no change from the baseline.

For Fossil Depletion, the baseline reached 16.3 kg oil-eq, driven by raw materials (20.7 kg oil-eq) and manufacturing (4.5 kg oil-eq), partly offset by an EoL credit of −8.9 kg oil-eq. SC2 and SC5 showed the

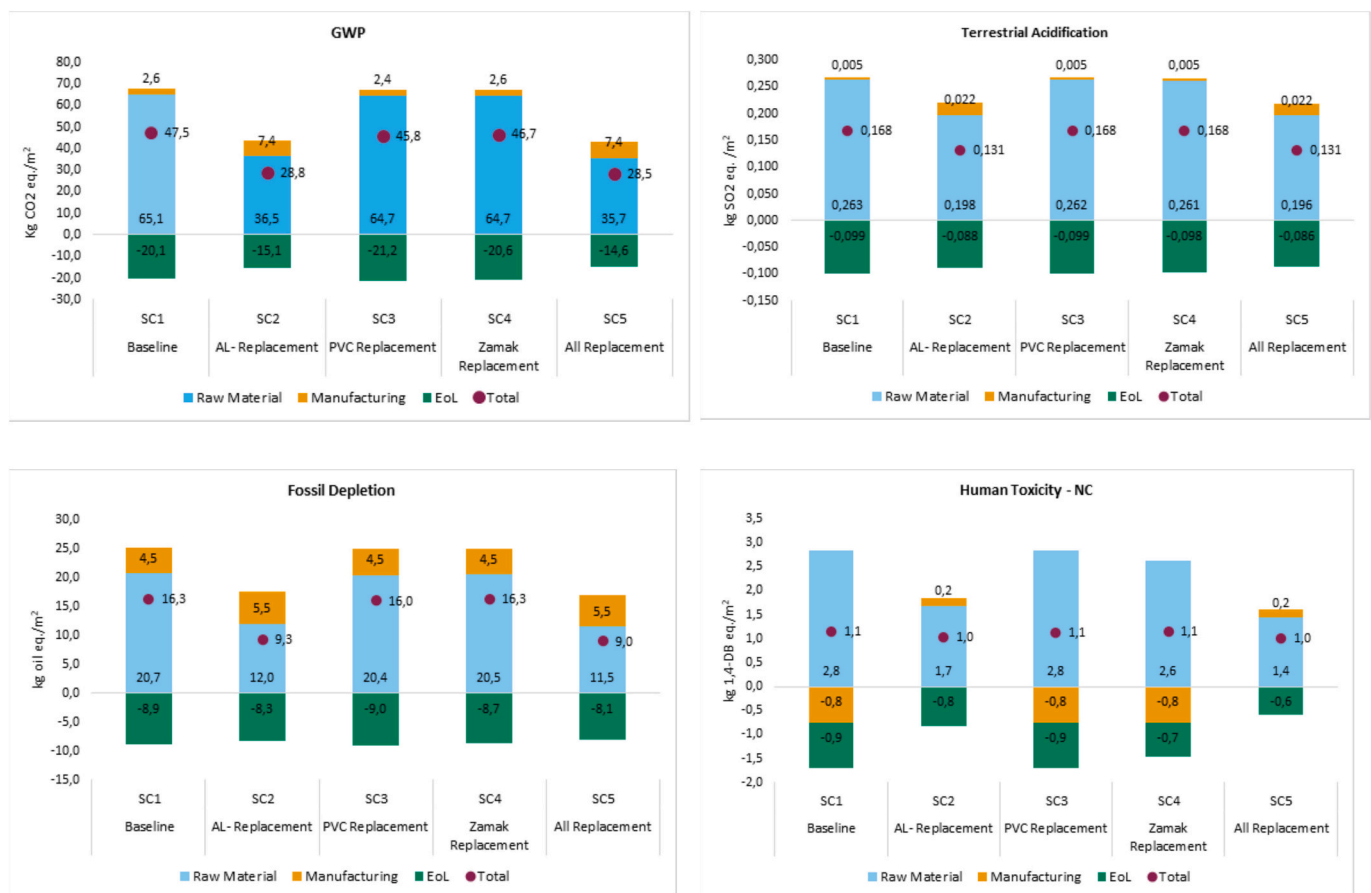


Fig. 3. Life cycle impact assessment (LCIA) results for the baseline (SC1) and substitution scenarios (SC2-SC5) across GWP, Acidification, fossil resource depletion, and human toxicity (nc), reported per functional unit (1 m²).

greatest improvements, reducing totals to 9.3 and 9.0 kg oil-eq, with raw materials dropping to 12 and 11.5 kg oil-eq, respectively. Manufacturing increased slightly (5.5 kg oil-eq), while EoL credits fell (−8.3 and −8.1 kg oil-eq). PVC and Zamak substitutions had negligible influence, with totals of 16.0 and 16.3 kg oil-eq.

For Human Toxicity, the baseline (SC1) resulted in 1.1 kg 1,4-dB eq, with raw materials at 2.8 kg 1,4-dB eq, partly offset by negative contributions from manufacturing (−0.8 kg 1,4-dB eq) and EoL (−0.9 kg 1,4-dB eq). Aluminum substitution (SC2) lowered raw materials to 1.7 kg 1,4-dB eq, reducing the total to 1.0 kg 1,4-dB eq, though manufacturing shifted to a small positive contribution (0.2 kg 1,4-dB eq). SC5 showed the same outcome, while PVC and Zamak substitutions remained essentially unchanged at 1.1 kg 1,4-dB eq.

Across all four impact categories, the combined substitution scenario (SC5) achieved the greatest overall reductions compared to the baseline, followed by aluminum cladding substitution alone (SC2). For example, SC5 reduced GWP by 40%, Fossil Depletion by 45%, and Acidification by 22%, whereas SC2 achieved reductions of 39%, 43%, and 22%, respectively. In both scenarios, the dominant improvements were linked to the substantial decrease in raw material impacts from avoiding aluminum production. By contrast, substituting PVC (SC3) and Zamak (SC4) individually led to negligible improvements, with GWP reductions of only 3.6% and 1.7%, respectively. This limited effect is explained by the very low mass of these components in the functional unit (0.23 kg of PVC and 0.39 kg of Zamak compared with 2.84 kg of aluminum), which restricts their overall contribution to the life cycle impacts. However, their influence becomes visible in SC5, when combined with aluminum substitution, PVC and Zamak replacements contributed to the lowest overall results across all categories. This confirms that while aluminum is clearly the dominant contributor to the environmental impacts of the baseline wood-aluminum window, the replacement of smaller components can still reinforce the overall environmental benefits when implemented together with major substitutions. Nevertheless, the evaluation of smaller component substitutions remains relevant from a circular design perspective, as such interventions may represent more feasible and incremental pathways for material transition in industrial manufacturing systems. In addition, although their individual contributions were limited, these substitutions reinforced the overall environmental benefits when combined within the integrated scenario (SC5).

3.1. Sensitivity analysis results

When virgin PP was used in the biocomposite instead of post-consumer recycled PP, the sensitivity analysis results shows that overall substitution benefits were reduced but not eliminated. (Table 5 and Fig. 4) For GWP, virgin PP increased emissions compared with recycled PP. SC2 reached 31.5 kg CO₂-eq, SC5 30.4 kg CO₂-eq, while SC3 and SC4 exceeded 46 kg CO₂-eq. SC2 and SC5 still improved over the baseline, but with weaker reductions, which highlights the importance of recycled polymers for climate benefits. Acidification was less affected by polymer sourcing, with SC2 at 0.134 kg SO₂-eq and SC5 at 0.135 kg SO₂-eq, both lower than the baseline, while SC3 and SC4 remained close to the baseline value of 0.168 kg SO₂-eq. Fossil Depletion rose markedly with

virgin PP, with SC2 and SC5 at about 11 kg oil-eq compared with 9 kg oil-eq for recycled PP, while SC3 and SC4 exceeded 16 kg oil-eq, close to the baseline. For Human Toxicity, SC2 at 1.20 kg 1,4-dB eq and SC5 at 1.22 kg 1,4-dB eq remained the lowest, though slightly higher than with recycled PP, while SC3 and SC4 stayed near the baseline at about 1.15 kg 1,4-dB eq.

When conventional primary aluminum was substituted with recycled aluminum produced using renewable electricity, notable improvements were observed across all categories, particularly in the baseline (SC1). For GWP, the baseline dropped from 47.5 to 35.3 kg CO₂-eq, representing a reduction of more than 25%. Substitution scenarios SC3 and SC4 showed similar decreases (around 35.1–35.6 kg CO₂-eq), reflecting the strong influence of low-carbon aluminum on climate performance. For Acidification, the baseline decreased to 0.158 kg SO₂-eq compared to 0.168 kg SO₂-eq with conventional aluminum. SC3 and SC4 showed nearly identical values (0.158 kg SO₂-eq). Fossil Depletion also improved markedly, with the baseline reduced from 16.3 to 12.4 kg oil-eq. Substitution scenarios SC3 and SC4 resulted in values around 12.3–12.5 kg oil-eq, again showing significant improvements linked to the decarbonized aluminum supply chain. For Human Toxicity, reductions were more modest but still visible. The baseline dropped slightly to 0.56 kg 1,4-dB eq compared to 1.1 kg 1,4-dB eq in the conventional case. SC3 and SC4 showed similar totals (−0.57 kg 1,4-dB eq). (Table 6 and Fig. 5).

An additional sensitivity analysis was conducted to assess the influence of energy recovery credits associated with waste incineration. In the baseline model, combustible materials, including PVC, wood, plastic components, and paint, were assumed to undergo incineration with heat and electricity recovery. To address uncertainty in future waste management systems, a sensitivity scenario was modelled in which energy recovery credits were excluded while maintaining the same recycling assumptions for aluminum, glass, steel, and Zamak components.

As shown in Table and Fig. 6, recycling (Glass, Aluminum, Steel, and Zamak) generated substantial environmental credits across all impact categories, whereas direct incineration contributed to positive environmental burdens. In the baseline scenario, energy recovery provided additional environmental credits, resulting in total end-of-life contributions of −14.6 kg CO₂-eq for GWP, −8.1 kg oil-eq for fossil depletion (FD), −8.6 dag SO₂-eq for acidification (TA), and −5.9 hg 1,4-dB-eq for human toxicity non-cancer (HTNC).

When energy recovery credits were removed, the end-of-life benefits decreased across all impact categories. The total EoL contribution increased from −14.6 to −7.66 kg CO₂-eq for GWP, from −8.1 to −6.15 kg oil-eq for FD, from −8.6 to −6.6 dag SO₂-eq for TA, and from −5.9 to −3.6 hg 1,4-dB-eq for HTNC (Table 7).

Consequently, the total impacts of SC5 increased from 28.5 to 35.4 kg CO₂-eq for GWP (+24.2%), from 9.0 to 10.9 kg oil-eq for FD (+21.3%), from 13.1 to 15.1 dag SO₂-eq for TA (+15.6%), and from 10.0 to 12.3 hg 1,4-dB-eq for HTNC (+23.4%). The largest relative increase was observed for GWP, while acidification showed the lowest sensitivity to the removal of energy recovery credits.

Despite these increases, SC5 remained environmentally preferable to the baseline window system across all assessed impact categories. For example, under the conservative assumption of no energy recovery, the

Table 5

Sensitivity analysis comparing LCIA results for substitution scenarios (SC2–SC5) modelled with recycled PP versus virgin PP as the biocomposite matrix, reported per functional unit (1 m²).

Scenario	*GWP (kg CO ₂ -eq)		Acidification (kg SO ₂ -eq)		Fossil depletion (kg oil-eq)		Human toxicity, non-cancer (kg 1,4-dB-eq)	
	Recycled PP	Virgin PP	Recycled PP	Virgin PP	Recycled PP	Virgin PP	Recycled PP	Virgin PP
SC2	28.8	31.5	0.131	0.134	9.3	10.9	1	1.2
SC3	45.8	46.3	0.168	0.169	16	16.3	1.1	1.15
SC4	46.7	46.8	0.168	0.168	16.3	16.4	1.1	1.15
SC5	28.5	30.4	0.131	0.135	9	11	1	1.22

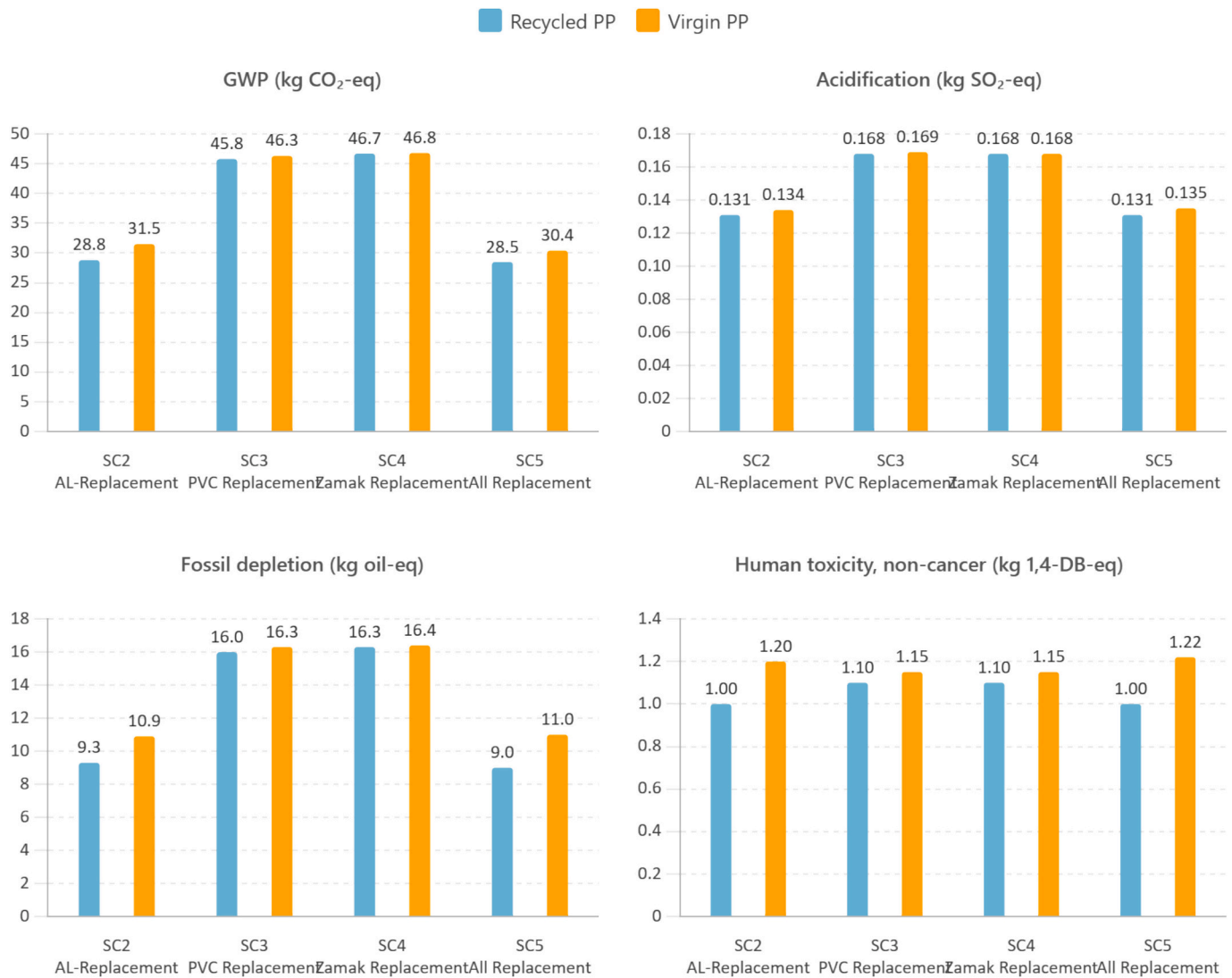


Fig. 4. Sensitivity analysis results comparing rPP and virgin PP as the biocomposite matrix material for substitution scenarios SC2–SC5 across the assessed impact categories.

Table 6

Sensitivity analysis comparing LCIA results for scenarios modelled with conventional primary aluminum versus recycled aluminum produced using renewable electricity, reported per functional unit (1 m²).

Scenario	GWP (kg CO ₂ -eq)		Acidification (kg SO ₂ -eq)		Fossil depletion (kg oil-eq)		Human toxicity, non-cancer (kg 1,4-DB-eq)	
	Conventional AL	Green AL	Conventional AL	Green AL	Conventional AL	Green AL	Conventional AL	Green AL
SC1	47.5	35.3	0.168	0.158	16.3	12.4	1.1	0.56
SC3	45.8	35.1	0.168	0.158	16	12.3	1.1	0.59
SC4	46.7	35.6	0.168	0.158	16.3	12.5	1.1	0.57

total GWP of SC5 (35.4 kg CO₂-eq) remained substantially lower than that of the baseline scenario (47.5 kg CO₂-eq).

A second end-of-life sensitivity analysis was conducted to evaluate the potential environmental benefits of mechanical recycling of the PP-based biocomposite components used in SC5. In the baseline model, the substituted biocomposite components were assumed to be incinerated with energy recovery, reflecting current WM practices for mixed polymeric materials in many European waste treatment systems. However, future developments in recycling technologies and collection infrastructure may enable more effective recovery of PP-based biocomposite materials. Therefore, an alternative scenario was modelled in which the

incineration route for the biocomposite components was replaced by mechanical recycling.

Mechanical recycling generated additional environmental benefits through the substitution of virgin polypropylene production, resulting in a more favorable end-of-life profile compared with incineration in SC5 (Table 8 and Fig. 7). The largest improvement was observed for GWP, where the EoL contribution improved from −14.6 to −19.2 kg CO₂-eq. Consequently, the total GWP of SC5 decreased from 28.5 to 23.9 kg CO₂-eq, corresponding to an approximately 16.1% reduction relative to the incineration scenario.

The influence of mechanical recycling varied across impact

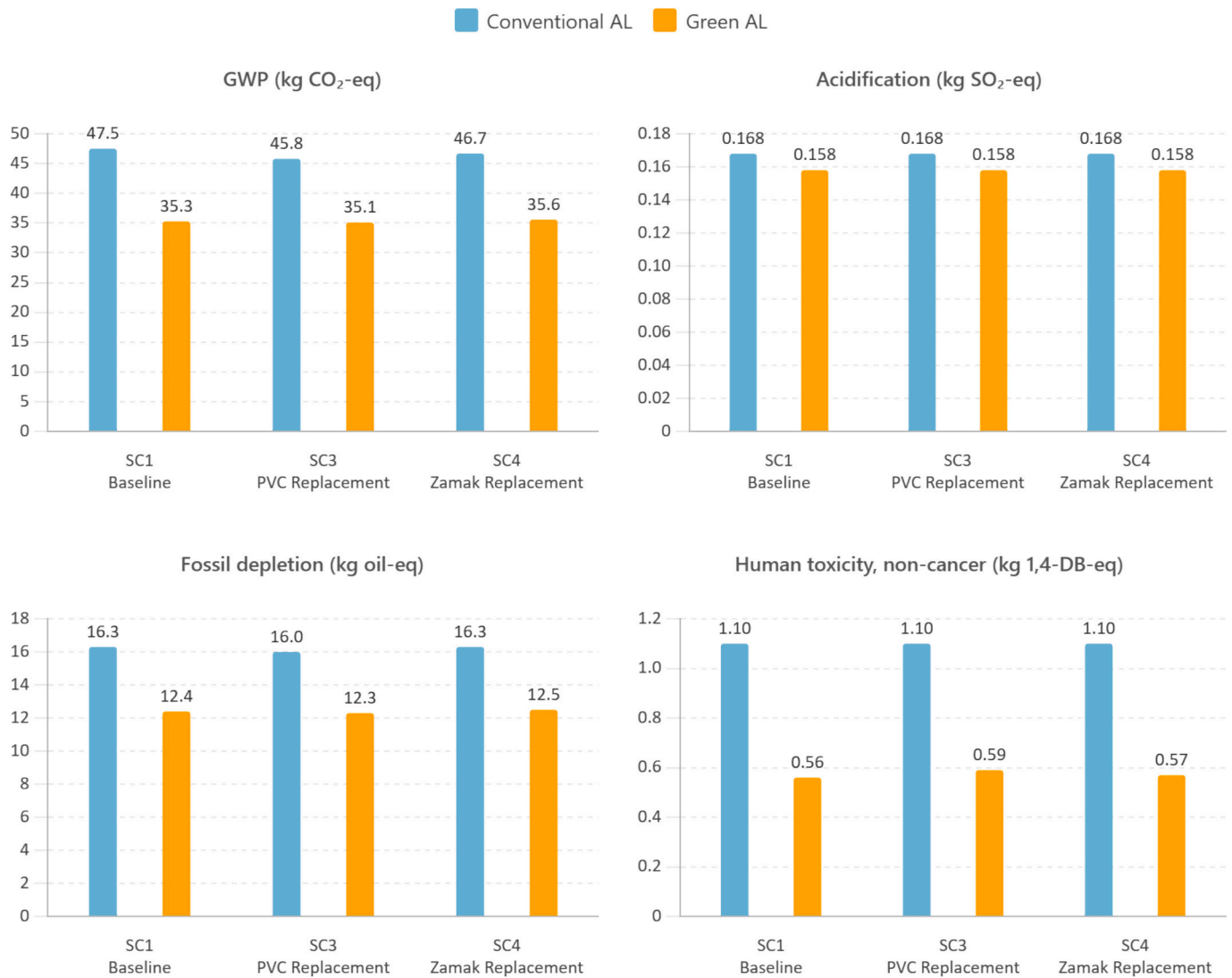


Fig. 5. Sensitivity analysis results for SC1, SC3, and SC4 using conventional primary aluminum and recycled low-carbon aluminum.

categories. For fossil depletion, a marginal improvement was observed, with the total impact decreasing from 9.0 to 8.91 kg oil-eq. In contrast, acidification increased slightly from 13.1 to 14.5 dag SO₂-eq, while human toxicity non-cancer (HTNC) changed only marginally from 10.0 to 10.1 hg 1,4-dB-eq. These results indicate that the environmental benefits of mechanical recycling are impact-category dependent and are primarily associated with climate change mitigation, whereas other impact categories exhibit either limited improvements or small increases.

The results demonstrate that recycling represents a promising future end-of-life pathway for PP-based biocomposite components. The scenario achieved the lowest GWP among all evaluated end-of-life options and provided a slight reduction in fossil depletion impacts. Although small increases were observed for acidification and HTNC, the overall environmental performance remained comparable to the incineration scenarios. These findings suggest that future implementation of recycling could further improve the environmental performance of biocomposite components in the construction industry, particularly from a climate change perspective. Therefore, recycling should be considered a prospective circularity strategy that may enhance the long-term sustainability of biocomposite-based construction components.

Although service life has been identified as a potential source of uncertainty in long-term building product assessments, it was not

quantitatively evaluated in the present study. The assessment focused exclusively on embodied environmental impacts, while operational performance, maintenance, and replacement activities were excluded from the system boundary. Furthermore, long-term durability data for the selected rPP + 30% BSKP biocomposite formulation are not yet available. Therefore, the substituted components were assumed to provide equivalent functionality throughout the assessed life cycle. Future studies should investigate the durability and service-life performance of biocomposite window components to determine whether differences in replacement frequency could influence the environmental benefits reported in this study.

4. Discussion

4.1. Component replacement and circular design implications

The substitution scenarios exemplify several Circular Design Strategies (CDS), particularly Design for Lightweighting, Design for Material Efficiency, and Design from Recycled and Renewable Resources [60,61,64]. Table 3 highlights the reductions in material mass achieved by replacing conventional components with rPP + 30% BSKP biocomposites, which directly reflect material efficiency gains. In the combined substitution scenario (SC5), these strategies collectively

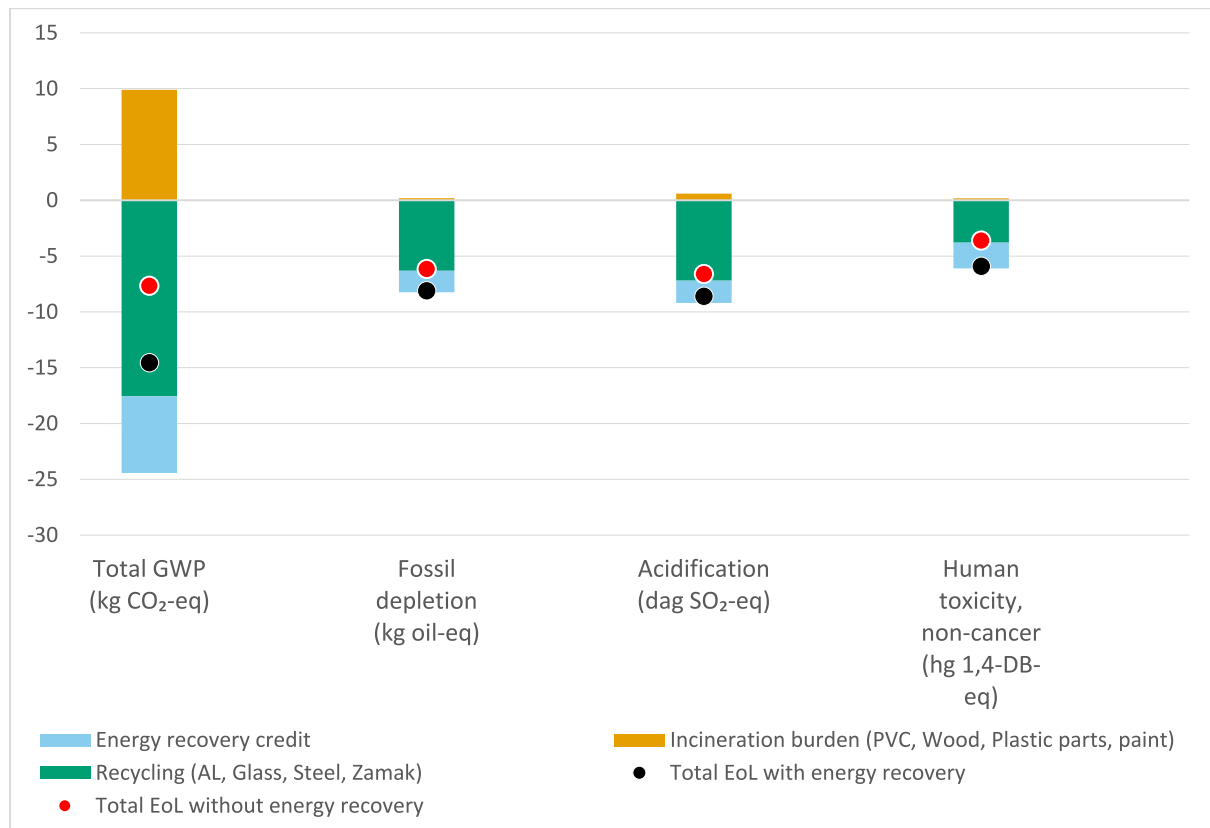


Fig. 6. End-of-life impact contributions of recycling, incineration, and energy recovery for SC5.

Table 7

Decomposition of SC5 end-of-life impacts with and without energy recovery from waste incineration.

Impact category	Recycling (AL, Glass, Steel, Zamak)	Incineration burden (PVC, Wood, Plastic parts, paint)	Energy recovery credit	Total EoL with energy recovery	Total EoL without energy recovery
Total GWP (kg CO ₂ -eq)	-17.55	9.89	-6.89	-14.6	-7.66
Fossil depletion (kg oil-eq)	-6.32	0.18	-1.92	-8.1	-6.15
Acidification (dag SO ₂ -eq)	-7.2	0.6	-2	-8.6	-6.6
Human toxicity, non-cancer (hg 1,4-DB-eq)	-3.8	-0.17	-2.3	-5.9	-3.6

reduced the mass of high-impact materials per functional unit by more than 66%, which translated into the strongest reductions across all impact categories. By lowering the demand for aluminum, PVC, and Zamak, the interventions directly reduced upstream impacts in the raw material production stage.

Aluminum substitution (SC2 and SC5) illustrates Design for Lightweighting and Design for Material Substitution and Innovation, where energy-intensive aluminum is replaced by a lighter biocomposite

incorporating both recycled PP and renewable BSKP fibres. This substitution substantially decreases the embodied energy of material production and reduces dependence on virgin non-renewable resources. PVC replacement (SC3 and SC5) demonstrates Design for Material Efficiency and Design from Renewable and Recycled Resources, as fossil-based PVC is partially displaced by biocomposites, lowering reliance on petrochemicals and enabling energy recovery at end-of-life. Zamak handle substitution (SC4 and SC5) highlights Design for Low-Impact Manufacturing and Lightweighting, since Zamak requires resource-intensive die-casting and machining. Its replacement with biocomposites reduces both the weight and the energy intensity of production.

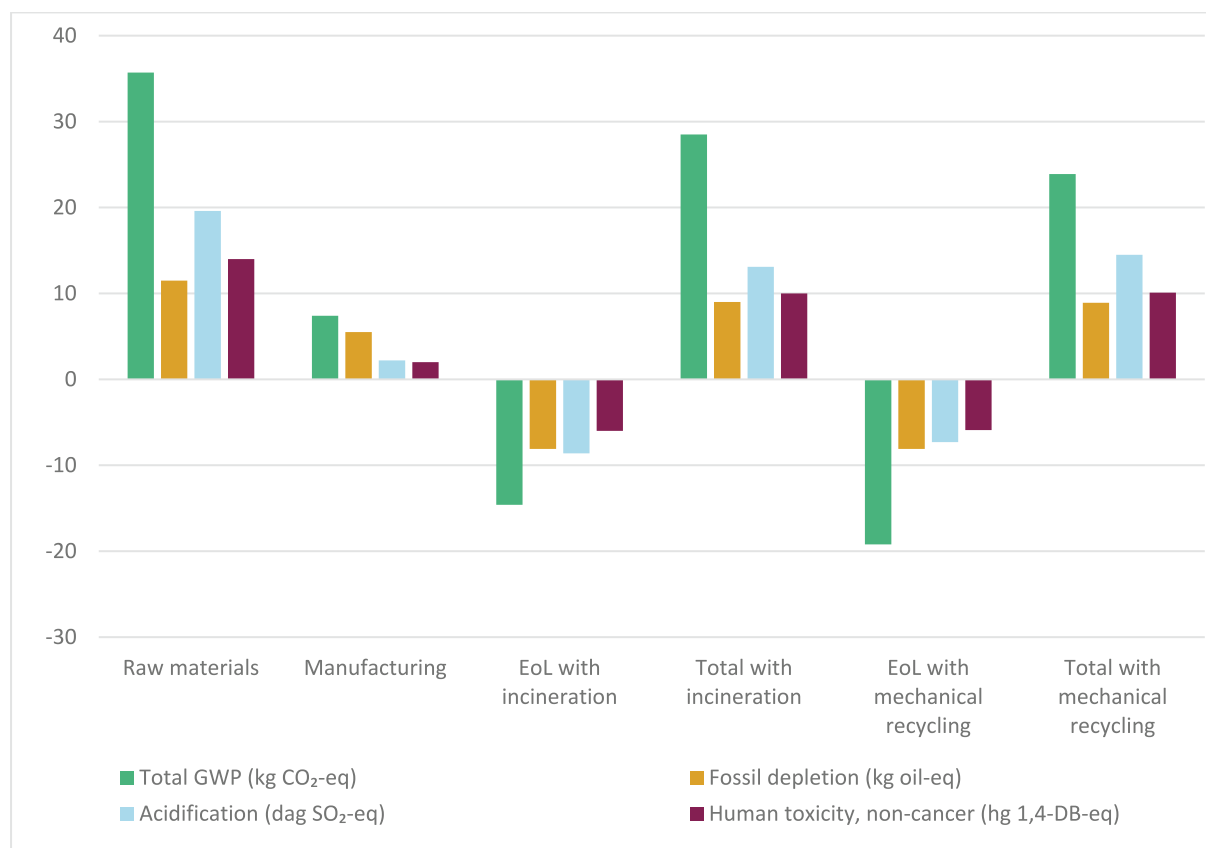
The implications of these findings should be considered in the broader context of building energy and carbon performance, particularly as operational energy demand is progressively reduced in low-energy and nearly zero-energy buildings (nZEB) [73,74]. Under these conditions, embodied emissions associated with building envelope components account for an increasing share of life-cycle impacts, making material selection an important lever for further emission reductions. [75] Window frames are relevant in this context because they represent material-intensive elements of the building envelope, and changes in their composition directly affect upstream environmental burdens and replacement-related impacts over the building lifespan [4,21]. The substantial reductions observed in scenarios involving aluminum substitution therefore represent immediate environmental benefits that are independent of assumptions about operational energy use. By focusing on component-level material substitution within an unchanged window system configuration, the results highlight how embodied impact reductions can complement operational energy efficiency strategies and support whole-building decarbonization pathways aligned with circular economy objectives [24,76].

The findings of this study are generally consistent with previous LCA studies reporting that aluminum is the dominant contributor to the

Table 8

Comparison of SC5 LCIA results under end-of-life incineration and mechanical recycling scenarios for PP-based biocomposite components.

Impact category	Raw materials	Manufacturing	EoL with incineration	Total with incineration	EoL with mechanical recycling	Total with mechanical recycling
Total GWP (kg CO ₂ -eq)	35.7	7.4	−14.6	28.5	−19.2	23.9
Fossil depletion (kg oil-eq)	11.5	5.5	−8.1	9	−8.09	8.91
Acidification (dag SO ₂ -eq)	19.6	2.2	−8.6	13.1	−7.3	14.5
Human toxicity, non-cancer (hg 1,4-DB-eq)	14	2	−6	10	−5.9	10.1

**Fig. 7.** Comparison of SC5 LCIA results for incineration and mechanical recycling end-of-life scenarios.

embodied environmental impacts of window systems due to the energy-intensive nature of aluminum production [33,37,52]. Similar to the observations of Sinha and Kutnar [19] and Kowalczyk et al. [23], the present study confirms that reducing aluminum content can substantially decrease GWP and fossil resource depletion. However, unlike earlier studies that mainly compared complete window frame materials such as wood, PVC, or aluminum systems, the present work focuses on component-level substitution strategies within an existing wood-aluminum window configuration. The results further demonstrate that targeted biocomposite substitution can significantly reduce the embodied environmental impacts of window systems, with the combined substitution scenario achieving approximately a 40% reduction in GWP compared with the baseline configuration. This observation is consistent with previous studies reporting that recycled and bio-based composite materials offer considerable potential for lowering embodied carbon by replacing conventional energy-intensive materials while maintaining the required functionality of construction products. Similar conclusions have been reported by Ahmad et al., Sinha and Kutnar, and Sečák et al., who highlighted the environmental benefits of renewable fibres, recycled polymers, and reduced dependence on virgin aluminum in building applications [19,31,40]. In addition, the study

integrates circular design strategies with LCA-based evaluation of biocomposite alternatives and examines the influence of recycled polymers and low-carbon aluminum pathways through sensitivity analysis.

Beyond the environmental reductions observed in the LCIA results, the assessed substitution strategies also align with broader circular economy and regulatory sustainability objectives in the building sector. The reduced reliance on virgin aluminum and fossil-based plastics supports current European sustainability directions emphasizing embodied carbon reduction, resource efficiency, increased recycled material utilization, and circular material flows in construction products [77,78]. In addition, the integration of recycled polymers and ligno-cellulosic reinforcement materials is consistent with life cycle thinking approaches promoted within environmental product declaration (EPD) frameworks and circular building assessment initiatives such as the EU Level(s) framework [76–80]. From a circular design perspective, the evaluated substitutions demonstrate how component-level material transitions can contribute to reducing resource consumption and supporting more circular building envelope systems without requiring complete redesign of the window assembly similar to a study by Bergmans et al. [81] that assessed the circular design implications in the building sector.

4.2. Manufacturing feasibility and design adaptation

Replacing aluminum cladding with a rPP + 30 wt% BSKP biocomposite requires careful assessment of both processing feasibility and design adjustments to ensure reliable performance. The proposed material was evaluated using extrusion and injection molding techniques. While both methods showed potential, extrusion was selected as the more suitable approach for producing long and continuous cladding profiles.

Extrusion is widely recognized as an effective method for producing continuous cladding profiles from thermoplastic composites. In this context, the biocomposite formulation appears suitable for extrusion-based manufacturing. However, potential challenges are anticipated, particularly in maintaining dimensional accuracy and controlling surface quality. These concerns are often reported in wood–plastic composite applications and are typically linked to the behaviour of natural fibres during thermal processing [82–85]. Although minor geometry adaptations may be required due to differences in material behaviour and processing characteristics between aluminum and biocomposites, the substituted components were designed to fulfil the same function and comparable structural requirements as the original components. The assessment therefore represents a material substitution within an equivalent design basis rather than a complete component redesign, ensuring a consistent comparison between the baseline and alternative scenarios. Reducing complexity can enhance manufacturability and reduce the risk of warping or uneven cooling. Additionally, post-processing methods such as milling could be employed where necessary to achieve precise dimensions and smoother finishes [86–89].

Among the technical challenges, thermal expansion of the biocomposite stands out as a critical concern. Natural fibre-reinforced polymers typically exhibit a higher coefficient of linear thermal expansion (CLTE) than metals. This means that under outdoor conditions, changes in temperature and humidity could lead to dimensional changes that affect the window's fit and function. Recent studies have reported CLTE values for WPCs ranging between 50 and $80 \times 10^{-6} / ^\circ\text{C}$, depending on the formulation and fibre load. These values are significantly higher than that of aluminum, which is around $22 \times 10^{-6} / ^\circ\text{C}$. [90] Recent findings on WPC durability demonstrate that composites made with higher plastic content display enhanced dimensional stability and mechanical strength [91].

Although this disparity presents a valid concern, it does not make the concept of biocomposite cladding impractical. Instead, it highlights the importance of accommodating this behaviour in the design phase. Strategies such as allowing tolerance for thermal movement, reinforcing the structure with stabilizing elements, or selecting installation techniques that minimize stress at joints can help mitigate deformation [92,93]. Ongoing material development efforts also show promise in reducing expansion by optimizing fibre–matrix interactions and improving interface adhesion [94–98]. In the context of circular design, even materials with performance trade-offs can be valuable when paired with thoughtful engineering and system-level integration.

Injection molding is another relevant manufacturing method, especially for parts requiring high dimensional precision, such as corner joints or end caps. While this technique is generally less suited for long profiles due to tooling limitations, it remains a viable option for specific components within a modular window design. This hybrid approach is consistent with industry practices in composite applications, where different processing methods are combined to meet functional and economic requirements [99,100].

Surface treatment is another key consideration. As polypropylene has low surface energy, achieving durable paint adhesion can be difficult. Instead of post-production painting, incorporating pigments into the material during compounding is recommended. This strategy offers better UV resistance, avoids delamination, and improves recyclability. Recent literature supports that integrated pigmentation enhances aesthetic durability while maintaining process efficiency [101,102].

Simplifying profiles and considering modular design supports both manufacturing and circularity goals. Modular systems allow damaged parts to be replaced without discarding entire assemblies, and simpler profiles reduce material waste and improve recyclability. These design decisions align with established circular design strategies in the construction industry that prioritize durability, reparability, and resource efficiency [103].

Nevertheless, the findings should be interpreted considering the study limitations related to the exclusion of operational performance variations and the absence of long-term experimental validation of the proposed biocomposite components. The environmental benefits reported here are conditional on the assumption that the substituted biocomposite components provide equivalent functional performance and service life to the conventional components. Future studies should therefore verify the long-term durability, weathering resistance, and maintenance requirements of the proposed biocomposite solutions under real operating conditions.

5. Conclusion

This study demonstrates that biocomposite substitution in wood–aluminum window frames can deliver significant environmental benefits, particularly when aluminum cladding is replaced. Regarding RQ1, the life cycle assessment identified aluminum as the dominant contributor to the environmental impacts of the baseline window system, confirming that it represents the primary environmental hotspot and the greatest opportunity for reducing embodied impacts. Aluminum substitution with a recycled polypropylene (rPP)–BSKP biocomposite achieved the largest reductions in global warming potential (GWP), fossil resource depletion, and acidification. The combined substitution scenario (SC5) provided the strongest overall environmental performance, reducing GWP from 47.5 to 28.5 kg CO₂-eq/m² and fossil resource depletion from 16.3 to 9.0 kg oil-eq/m² compared with the baseline scenario. By contrast, PVC and Zamak substitutions showed only limited individual improvements due to their relatively small contribution to the total material inventory.

Regarding RQ2, the results demonstrated that targeted component-level biocomposite substitutions can substantially improve the environmental performance of window systems while maintaining the existing window configuration. Sensitivity analyses further showed that the environmental performance of the substitution scenarios depends on the use of recycled polymers, whereas low-carbon aluminum pathways can significantly reduce the impacts of the baseline scenario. In addition, the environmental benefits of the proposed substitutions remained robust under alternative end-of-life waste management assumptions, and prospective mechanical recycling of PP-based biocomposites provided further reductions in GWP. These findings demonstrate that combining material substitution strategies with recycled feedstocks and decarbonized supply chains can effectively reduce the embodied environmental impacts of window systems.

Regarding RQ3, the study demonstrates that component-level biocomposite substitutions provide a practical pathway for implementing circular design strategies in building envelope systems. The evaluated substitutions support design for lightweighting, material efficiency, and the integration of recycled and renewable materials while reducing dependence on virgin aluminum and fossil-based plastics. Rather than requiring complete redesign of the window assembly, the proposed approach shows that targeted replacement of high-impact components can improve environmental performance and contribute to more resource-efficient and circular construction practices.

The novelty of this study lies in integrating circular design principles with component-level biocomposite substitutions and LCA-based evaluation within an existing wood–aluminum window system. By combining environmental hotspot identification, quantitative assessment of substitution scenarios, and evaluation through circular design strategies, the study provides a practical framework for prioritizing

material substitutions according to their environmental significance. However, the assessment focused on embodied environmental impacts and did not consider operational performance variations or long-term validation of the substituted biocomposite components. Future research should investigate durability, thermal performance, recyclability, and large-scale manufacturing feasibility under practical operating conditions.

CRediT authorship contribution statement

Amirmehrab Falsafi: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Amir Togiani:** Writing – review & editing, Supervision, Methodology. **Mariam Abdulkareem:** Writing – review & editing. **Jeremy Faludi:** Writing – review & editing. **Juha Varis:** Supervision. **Mika Horttanainen:** Writing – review & editing, Supervision.

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. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enbuild.2026.118074>.

Data availability

Data will be made available on request.

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