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Comparative study of conventional and emerging façade systems: Pathways to reducing embodied carbon and enhancing circularity in buildings

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ABSTRACT

Façade systems play a critical role in building environmental performance, contributing substantially to embodied carbon due to their material intensity, exposure-driven replacement cycles, and complex assemblies. As operational energy demand decreases under increasingly stringent energy regulations, embodied impacts associated with facades are becoming a dominant component of whole-life building emissions. Conventional façade systems typically follow linear end-of-life pathways, resulting in limited material recovery and significant waste generation. Circular economy (CE) principles offer a pathway to address these challenges through durability, design for disassembly, reuse, and high-value recycling; however, comparative assessments integrating environmental performance and circularity across façade typologies remain limited. This study evaluates the whole-life environmental and circularity performance of six façade systems—three conventional and three emerging—within the contemporary Australian construction context, using a combined Life Cycle Assessment (LCA), with global warming potential (GWP) as the primary environmental indicator, and a circularity assessment. The analysis covers all life-cycle stages, enabling consistent comparison across contrasting material compositions and assembly strategies. The results reveal clear trade-offs between embodied carbon and circularity. Conventional systems such as Concrete Masonry Units (CMU) exhibited 446 $kgCO_2e$ per façade module, whereas Rammed Earth achieved 285 $kgCO_2e$, and Hempcrete–CLT reached net negative emissions of −268 $kgCO_2e$ when accounting for biogenic carbon storage. Circularity scores ranged from 21 to 28% for conventional systems to 35–77% for bio-based alternatives, with Rammed Earth achieving the highest circularity (77%). Dry-assembled systems such as Brick Slip Timber Frame further improved circularity performance (39%) through mechanically reversible connections. Overall, the findings highlight that façade circularity is shaped by system-level design decisions rather than material choice alone, underscoring the importance of integrating environmental and circularity considerations during early façade design stages.

1. Introduction

Facades play a critical role in the environmental performance of buildings. They constitute the external vertical elements of the building envelope, mediating exchanges between interior spaces and the external environment [1]. As the primary interface between indoor and outdoor environments, facades affect daylighting, ventilation, thermal regulation, moisture control, and insulation performance [2]. Together, these functions account for a substantial share of total building energy consumption [3,4].

Improvements in façade performance can significantly reduce operational energy use. However, these improvements often increase material intensity and embodied carbon. This is particularly evident in façade systems that rely on carbon-intensive materials or require frequent replacement over the building's lifespan [5–7].

As operational energy demand decreases due to stricter energy regulations, embodied carbon associated with façade systems represents an increasingly dominant share of total life-cycle emissions [7]. In parallel, emerging policy frameworks are increasingly targeting embodied carbon in the built environment. The EU Taxonomy for sustainable activities (EU 2020/852) and the Corporate Sustainability Reporting Directive (CSRD) are introducing sustainability disclosure requirements

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that influence investment decisions, corporate reporting, and material selection in the construction sector [8,9]. In addition, recent policy developments such as the recast Energy Performance of Buildings Directive (EPBD) are introducing requirements for whole-life carbon assessment and national embodied-carbon benchmarks for buildings, further increasing the importance of evaluating material-related emissions in building envelopes [10,11]. Similar policy initiatives are also emerging at national levels, for example in New Zealand where whole-of-life embodied carbon reduction frameworks have been introduced to support the national net-zero carbon target by 2050 [12]. Embodied emissions from façade materials and construction can account for approximately 20–30% of a building's total embodied carbon, depending on façade typology and material composition [13,14]. This shift highlights the importance of early façade design decisions. Material selection, assembly logic, and system durability can lock in environmental impacts for several decades. Previous studies show that façade configuration and material choice can lead to markedly different embodied carbon outcomes, depending on material type, façade area, and interactions with operational performance [15].

In response to these challenges, circular economy (CE) principles have gained attention as a pathway to reduce resource consumption, waste generation, and environmental impacts across building life cycles [16,17]. When applied to facades, CE focuses on durability, design for disassembly, reuse, and high-value recycling [18]. The objective is to maintain material value over time rather than treating façade systems as disposable elements. However, façade systems are often multi-layered, which can complicate end-of-life recovery [16,18,19].

This study focuses on façade systems commonly used in low- and mid-rise buildings within the contemporary Australian construction context [20,21]. Six façade typologies were selected to represent a spectrum of conventional and emerging opaque façade assemblies. Conventional systems include Brick Veneer with Steel Stud Framing (BV–SF), Cast-in-Situ Concrete (CIC), and Concrete Masonry Unit (CMU), while emerging systems include Brick Slips with Timber Frames (BS–TF), Rammed Earth (RE), and Hempcrete Blocks with Cross-Laminated Timber (HC–CLT). Curtain wall systems were excluded because they belong to the glazed façade category and are primarily associated with high-rise commercial buildings rather than the low- and mid-rise building stock examined in this study [22,23].

Life cycle assessment (LCA) is widely used to quantify the environmental impacts of façade systems. However, many LCA studies simplify or exclude end-of-life scenarios. As a result, the circularity potential of façade systems is often underrepresented. This limits the usefulness of LCA as a decision-support tool during early design stages [24,25]. Previous studies have explored the integration of environmental performance and circularity considerations in the built environment, particularly through design for deconstruction methodologies and circularity assessment tools [26,27]. However, these approaches have primarily focused on building-scale assessments or conceptual frameworks, and there remains limited research that systematically compares façade systems using both life-cycle environmental indicators and circularity metrics within a consistent and controlled methodological framework. Despite growing research on embodied carbon and circular design, few studies have undertaken controlled, system-level comparisons of conventional and emerging façade assemblies under aligned assumptions. This study addresses these limitations by comparing the environmental and circularity performance of selected conventional and emerging façade systems using a whole-life perspective. The objectives are to:

- quantify and compare the global warming potential (GWP) of six façade systems, normalised to one equivalent 3.84 m^2 façade module, across all relevant life-cycle stages;
- assess and compare the relative circularity potential of different façade typologies; and
- identify façade design strategies that improve both environmental and circularity outcomes.

This study does not propose a new LCA or circularity method. Instead, its contribution lies in a controlled, system-level comparison that reveals how façade assembly logic and connection strategies govern embodied carbon and circularity outcomes, often more strongly than material choice alone. By applying consistent functional units, system boundaries, and end-of-life assumptions across six façade typologies, the study exposes trade-offs that are not visible in material-focused assessments.

2. Literature review

2.1. Environmental performance of façade systems

Several studies have quantified the contribution of facades to operational energy use and embodied carbon. Recent life-cycle assessments report façade embodied carbon values ranging from approximately 160 to 520 $kgCO_2e/m^2$, depending on façade typology, material composition, and construction configuration [28]. This variation reflects differences in structural systems, glazing ratios, material intensity, and exposure-driven replacement cycles across façade assemblies (Teng & Pan, 2019; [7]). Conventional façade systems—including brick veneer, concrete, and masonry walls—remain widely used due to their durability and structural performance [29,30]. However, these systems are frequently associated with high embodied carbon resulting from cement production, steel reinforcement, and energy-intensive manufacturing processes [31–33].

Brick veneer systems supported by steel framing are among the most common residential façade typologies. Studies indicate that the combined brick–steel assembly can account for a substantial share of total embodied carbon, with non-structural elements such as brick and insulation contributing the majority of impacts [33]. For example, envelope-level assessments report exterior wall systems contributing up to 34% of total building embodied carbon, highlighting the significant influence of façade materials on whole-building environmental performance [34]. Although these systems exhibit long service lives, their reliance on mortar-bonded construction limits material recovery and reuse at end-of-life, resulting in predominantly downcycled or landfilled outputs [35,36].

Cast-in-situ concrete (CIC) and Concrete Masonry Unit (CMU) facades represent another dominant category of conventional construction. While valued for durability, fire resistance, and structural integration, these systems are characterised by high embodied carbon due to cement-intensive materials and reinforcement steel [31,37]. In addition, their monolithic construction typically results in high volumes of construction and demolition waste, with limited potential for high-quality recycling [38,39].

Emerging façade systems—including lightweight cladding, mechanically fixed assemblies, and bio-based materials—are increasingly proposed as lower-carbon alternatives. Brick slip façades, for example, reduce material volume compared to full masonry systems and have been shown to achieve meaningful reductions in embodied carbon, particularly when reclaimed materials are used [40,41]. Timber-based systems further contribute to lower embodied impacts through renewable material sourcing and biogenic carbon storage [42,43]. Reported environmental performance varies significantly across studies, reflecting differences in system configuration, material sourcing, and modelling assumptions. For instance, timber-based façade systems have been shown to achieve up to 49% lower embodied carbon than comparable aluminium-intensive façade systems [44].

2.2. Circularity constraints in façade systems

Recent studies have examined circular strategies in façade systems, particularly in relation to disassembly, reuse, and recycling [16,19]. Several studies identify circularity challenges in façade systems, particularly due to multi-layered construction, permanent connections, and differing component service lives. These characteristics often result in demolition-dominated end-of-life scenarios and material downcycling [36,45].

Conventional masonry and concrete facades generally exhibit limited circularity. Mortar-bonded construction and structural integration hinder disassembly and restrict reuse potential, even where materials such as steel reinforcement exhibit high recyclability [38,46]. Although theoretical circularity potentials for bricks and masonry elements have been reported, practical recovery rates remain low due to contamination and separation challenges [36].

In contrast, mechanically fixed and timber-based façade systems are frequently highlighted for their improved circular potential. Dry connections, modular substructures, and renewable materials can facilitate disassembly and higher-value material recovery at end-of-life [47,48]. Brick slip facades mechanically fixed to timber frames exemplify this approach, combining reduced material mass with improved recoverability [49]. Nevertheless, these systems may introduce additional metal substructures, such as aluminium rails, which increase upfront embodied carbon while improving recycling potential at end-of-life.

Bio-based façade systems, including rammed earth and hempcrete-based assemblies, align strongly with circular economy principles through local material sourcing, low processing energy, and biogenic carbon storage [50,51]. Rammed earth construction generates minimal waste and enables material reuse or re-compaction at end-of-life, particularly where dry assembly techniques are employed [52]. Hempcrete and hybrid hempcrete–timber systems similarly demonstrate low embodied carbon and high renewable content. However, end-of-life pathways for composite bio-based materials remain poorly defined, with limited evidence of scalable reuse or recycling routes [25,53].

2.3. Circularity assessment in façade systems

A growing body of research has sought to quantify circular economy performance in the built environment through the development of circularity assessment methods and indicators. Circular economy approaches aim to retain the value of building materials, reduce construction waste, and enable material recovery through reuse and recycling strategies [54]. However, the literature indicates that no single standardised framework currently exists for evaluating circularity in building systems, including façades. Instead, multiple approaches have been proposed that differ in scope, system boundaries, and data requirements, resulting in fragmented assessment practices and limited comparability across studies [55–57]. Several authors further highlight the lack of consensus on circularity metrics and the challenges associated with applying them consistently in real construction projects [58–60].

Existing circularity assessment methods generally fall into three broad categories. The first includes material-flow–based approaches, such as Material Flow Analysis (MFA), which tracks material stocks and flows throughout the building life cycle [61](104;105). Extensions of these methods include Carbon Flow Analysis (CFA), which integrates material flow tracking with life-cycle assessment to evaluate both circularity and embodied carbon in construction systems [61]. Other indicators, such as the Urban Mining Index, have been proposed to estimate the recovery potential of building materials at end-of-life [62].

A second group of approaches focuses on circularity index-based frameworks, which combine multiple indicators into composite metrics. Among these, the Material Circularity Indicator (MCI) is one of the most widely used tools for evaluating restorative material flows at the product level [63]. However, MCI has recognised limitations, as it primarily assesses circularity at the material or product scale and may not fully capture system-level design characteristics or environmental impacts [56,63]. To address these limitations, several studies have proposed building-scale adaptations, such as the Building Circularity Indicator (BCI), which incorporates additional parameters related to disassembly potential, embodied impacts, and lifecycle performance [63–65]. While BCI provides a broader system perspective, the literature notes that these indicators remain insufficiently standardised and can produce inconsistent results depending on modelling assumptions [63].

A third category of methods emphasises design-oriented circularity indicators, which evaluate aspects such as design for disassembly, adaptability, and component reuse potential [66,67]. In façade research specifically, these indicators are often linked to strategies such as reversible connections, modular construction, and material passports that facilitate reuse and high-value recycling [68,69]. Scenario-based analyses further demonstrate that reuse-oriented façade strategies can reduce environmental impacts by 7–57% compared with conventional demolition pathways, highlighting the importance of design decisions in enabling circular material flows [70].

While several frameworks have been proposed to support circular economy implementation in the built environment, their application to façade systems remains limited. Initiatives such as the Ellen MacArthur Foundation framework provide overarching circular economy principles but offer limited operational guidance for façade components and assemblies [71]. Similarly, the Buildings as Material Banks (BAMB) project introduced tools such as material passports and reversible design protocols to facilitate material reuse, although these were primarily developed at the whole-building scale rather than for façade-specific systems [72]. Other studies emphasise that building envelopes should be considered as continuous elements within the building lifecycle rather than isolated architectural components, highlighting the importance of lifecycle-oriented design strategies for façades [73]. Frameworks such as CIRCuIT further classify circular strategies across materials, parts, and components throughout the lifecycle (Cartwright, 2021[74]). However, despite these conceptual advances, many existing frameworks lack façade-specific indicators capable of measuring design attributes such as disassembly potential, modularity, and reuse pathways. This limitation reflects a broader challenge in translating circular economy principles into measurable performance indicators for façade assemblies.

Given the diversity of circularity indicators and the absence of methodological consensus, several authors emphasise the need for tools capable of integrating circularity metrics with life-cycle assessment to ensure consistent and comparable evaluation of building systems [56,58–60]. In response to this challenge, this study employs the circularity module implemented in One Click LCA, which operationalises widely used circularity indicators derived from approaches such as MCI and BCI within an integrated LCA workflow [64,65]. By combining material flow data, embodied carbon calculations, and circularity indicators within a single platform, the tool enables consistent comparison of alternative façade assemblies while reducing reliance on subjective modelling assumptions [56,63]. This integration makes it particularly suitable for evaluating the circularity potential of façade systems during early design stages. This approach enables a consistent comparison of circularity potential across the six façade typologies assessed in this study.

3. Methodology

3.1. Life cycle assessment framework

LCA was applied to evaluate and compare the environmental and circularity performance of six façade systems across their whole-life cycle. The assessment covers the following life-cycle modules in accordance with EN 15978: Product stage (A1–A3), Construction stage (A4–A5), Use stage (B4), End-of-life stage (C1–C4), and benefits beyond the system boundary (Module D) (CEN, 2011). These modules encompass material extraction and processing, product manufacturing, transportation, installation, maintenance and replacement, end-of-life processes, and potential recovery benefits [75]. LCA is widely used to support design decision-making by quantifying environmental impacts associated with material selection and construction systems. In the context of façade design, it provides a structured approach for comparing alternative assemblies and identifying trade-offs between environmental performance and material use [75,76]. The study examines three conventional façade systems—Brick Veneer with Steel Stud Framing (BV–SF), Cast-in-Situ Concrete (CIC), and Concrete Masonry Unit (CMU) wall—and three emerging systems—Brick Slips with Timber Frames (BS–TF), Rammed Earth (RE), and Hempcrete Blocks with Cross-Laminated Timber (HC–CLT). These façade systems were selected to represent opaque façade assemblies commonly used in low- and mid-rise residential and commercial buildings within the contemporary Australian construction context. The assessment follows the EN 15978 standard, which defines the framework, requirements, and calculation procedures for conducting building-level life cycle assessments. In addition to environmental impacts, circularity aspects were evaluated by analysing material flows and selected circularity indicators. This combined approach recognises that improvements in circularity do not necessarily correspond to reduced environmental impacts, and that trade-offs may arise between material recoverability, durability, and embodied carbon [60,77].

To ensure comparability between façade systems, a consistent functional unit was applied for all configurations. The thermal performance of each façade assembly was evaluated by calculating the overall U-value (W/m^{2}K) based on the thermal conductivity and thickness of the individual material layers. Thermal conductivity values were obtained from the NCC material database and Environmental Product Declarations. The resulting U-values ranged from 0.18 to 0.69 W/m^{2}K, depending on the façade configuration, and are reported in **Appendix A (Table A1)**. Façade systems were not normalised to a common U-value, as doing so would require adjusting insulation thickness and thereby modifying the original construction build-ups. Instead, façade assemblies were evaluated as defined build-ups, where insulation thickness, material composition, and layering are treated as part of the façade design. This approach is consistent with previous comparative façade life-cycle assessment studies, which assess façade assemblies based on their actual material configuration rather than aligning thermal performance across systems [78–80]. Across these studies, insulation type and thickness are recognised as key drivers of environmental performance and are therefore evaluated as part of the façade build-up [5,79,81]. Methodological research further highlights that modifying façade configurations to achieve uniform thermal performance can introduce additional modelling assumptions and reduce comparability between systems [82,83]. Accordingly, this study adopts a system-based comparison in which façade build-ups are assessed as designed, using a consistent functional unit while preserving differences in insulation levels and thermal performance as part of the design characteristics of each assembly. As operational energy use (Module B6) is excluded from the system boundary, variations in U-value do not influence the assessed environmental impact categories and are therefore not normalised across façade typologies.

3.2. Functional unit

The functional unit selected for this study is one façade panel with an area of 3.84 m^2, comprising 67% opaque elements and 33% glazed area. This configuration represents a typical façade module that integrates solid wall components and window openings within a single, repeatable assembly. Defining the functional unit at the panel level reflects how façade systems are designed, manufactured, installed, and replaced in practice, and supports consistent comparison across different façade typologies.

Façade life cycle assessments conventionally adopt 1 m^2 of façade area as the functional unit. However, recent studies indicate that embodied carbon impacts in façades are often non-linear and strongly influenced by discrete components, interfaces, and replacement cycles, rather than by surface area alone [78,84,85]. Area-based functional units may therefore distort results by averaging impacts that, in practice, occur at the level of repeatable façade modules. Industry analyses, including Arup's Carbon Footprint of Facades, further demonstrate that component-level contributions and replacement logic are more accurately captured when façade systems are assessed at a modular scale rather than per square metre [86].

In response to these limitations, this study adopts a panel-based functional unit, corresponding to a representative floor-to-floor façade module. This approach improves design realism, as circular façade strategies—such as design for disassembly, modularisation, and component reuse—are typically applied at the panel or assembly level rather than per unit area. It also enhances system completeness, ensuring that fixings, subframes, interfaces, and secondary elements are explicitly included in the assessment, rather than being implicitly averaged or excluded.

International standards, including ISO 14040 and ISO 14044, define the functional unit as a quantified description of the performance of a product system, rather than a purely material quantity ([87]Standardization & ISO, 2006). While 1 m^2 is commonly used as a declared unit for façade elements, these standards explicitly allow alternative functional units where functional equivalence—such as structural capacity, thermal performance, durability, and service life—is more appropriately represented at an assembly or module scale [88,89]. ISO 14044 (§4.2.3.1) permits any functional unit, provided that it reflects the same service function and enables meaningful comparison between alternatives (Standardization & ISO, 2006).

This interpretation is further supported by Product Category Rules (PCRs) developed under frameworks such as EPD International, which allow functional or declared units to be defined in a manner that reflects how products are designed and used in practice [89–91]. While façade products are often reported per 1 m^2 for comparability, PCRs permit alternative units—including assemblies, modules, or performance-based units—where these better represent the functional performance of the system, provided that functional equivalence is maintained [78,92].

A 40-year reference study period (RSP) was adopted for the assessment. This duration was selected to represent a single façade service cycle, consistent with multiple building and envelope LCA studies that adopt 40-year lifespans when evaluating façade systems and prefabricated envelope elements [93–95]. While façade service lives vary depending on material and exposure conditions, literature indicates typical ranges of 40–60 years for many cladding and envelope systems [96–98]. No full façade replacement was modelled during this period; however, part-and-materials-level replacements were included where service lives were shorter than the RSP (Module B4). This façade-focused reference period enables consistent comparison across systems while avoiding long-term forecasting uncertainty associated with extended building lifespans.

3.3. System boundaries

The system boundaries for this study were defined in accordance with EN 15978, which provides a standardised framework for structuring life cycle assessment in the building sector [99]. The system boundary and included life-cycle modules are illustrated in Fig. 1. The life cycle of the façade systems was modelled across the following modules:

- Product Stage (A1–A3): raw material extraction, transportation, and manufacturing.
- Construction Stage (A4–A5): transport to the construction site and on-site installation.
- Use Stage (B4): limited to materials replacement of façade elements with service lives shorter than the reference study period.
- End-of-Life Stage (C1–C4): including deconstruction, waste processing, and final disposal.

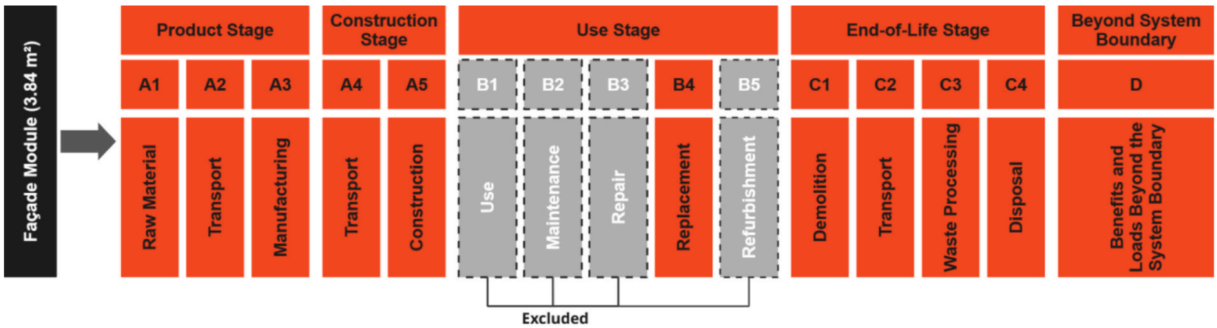

Fig. 1. System boundary and life-cycle modules considered in the assessment for one 3.84 m^2 façade module, structured in accordance with EN 15978. Operational stage modules (B1–B3) were excluded.

- Beyond System Boundary (D): considering potential benefits from recycling, reuse, and energy recovery processes.

All end-of-life modules (C1–C4) were included in the LCA modelling. However, the contribution of C1 (deconstruction/demolition) was found to be negligible relative to other life-cycle stages across all façade systems and is therefore omitted from graphical presentation for clarity.

Modules B1–B3 (use, maintenance, and repair) were excluded from the assessment. Façade systems typically do not generate direct operational emissions, and use-stage impacts are either negligible or highly uncertain due to limited data availability and strong dependence on project-specific maintenance regimes and user behaviour. Previous studies have similarly noted that façade LCAs often exclude B1–B3 due to this uncertainty and their limited contribution to overall impacts [82,100]. Module B4 (replacement) was included to account for the replacement of façade components with service lives shorter than the 40-year reference study period (RSP). Materials such as sealants, gaskets (e.g., EPDM), spacer bars, and glazing elements were modelled based on defined service lives, with replacement impacts calculated accordingly. Service life assumptions are summarised in **Appendix B**. Module B5 (refurbishment) was excluded, as no full façade replacement or major refurbishment was assumed within the 40-year reference study period. This reflects the assumption of a single façade lifecycle and avoids introducing additional uncertainty associated with long-term building-level interventions. Operational energy (Module B6) was excluded, as thermal performance was assumed to be functionally equivalent across façade systems. The study focuses specifically on embodied carbon and circularity impacts associated with material composition and assembly logic, enabling a controlled comparison without introducing variability related to building operation or user behaviour.

While EN 15978 defines life-cycle stage categorisation, it does not prescribe detailed methods for decomposing building assemblies into systems and components. In this study, façade assemblies were therefore modelled at the component, parts, and materials levels, ensuring transparent accounting of material flows and consistent comparison across all systems assessed [99].

3.4. Case study description

All six façade systems share a comparable scale and configuration; each modelled at a representative wall bay with identical overall dimensions and an equal distribution of openings—66% opaque area and 33% window area. The window systems are functionally equivalent across all cases, maintaining consistency in size, glazing ratio, and frame integration to isolate the effects of material and assembly differences. Each façade is site-built and non-loadbearing, connected to the primary structure through mechanical anchors, straps, or brackets that transfer self-weight and environmental loads while maintaining weathertightness and enclosure continuity. The systems differ in material composition and assembly logic. The masonry pair includes a Brick Veneer with Steel Frame (BV–SF), where the brick cladding is tied to a steel frame, and a Brick Slip with Timber Frame (BS–TF), which substitutes aluminium with timber framing and employs mechanical rails for modular brick slips [101,102]. The block-based pair contrasts a Concrete Masonry Unit Wall (CMU)—a conventional cement-based enclosure—with a Hempcrete Block with CLT Frame (HC–CLT), which replaces mineral aggregates with bio-based hemp and timber composites [103,104]. The monolithic pair compares a Cast-in-situ Concrete (CIC)—a continuous mineral mass—with a Rammed Earth (RE) façade constructed from compacted earth layers as a natural alternative [105,106]. All systems operate under comparable Australian National Construction Code (NCC) classifications (Classes 1–9), ensuring that observed differences reflect design and material choices rather than regulatory or structural discrepancies (see **Appendix A,** Table A1) (Australian Building Codes, 2019[107]).

At the part and material scale, all six façade cases follow a consistent three-level composition—inner layer, window system, and outer layer—but differ markedly in material logic and end-of-life potential. The masonry pair (BV–SF and BS–TF) shares a layered logic yet diverges in framing and insulation. The BV–SF comprises plasterboard, steel studs, glass-wool insulation, and a ventilated brick skin mechanically tied with steel angles, representing a conventional mineral-dominant assembly [102]. In contrast, the BS–TF replaces the steel substructure with timber studs and hemp-fiber insulation, improving renewability and reducing embodied carbon while retaining a ventilated outer skin fixed via aluminium profiles and rails (Fig. 2) ([108]DCA, 2024). The block-based pair (CMU and HC–CLT) transitions from traditional to hybrid bio-based construction. The CMU employs reinforced concrete blocks and plaster finishes, forming a dense façade optimised for durability and fire performance [109]. The HC–CLT replaces mineral aggregates with a hemp block's mechanical fix to a CLT substrate, creating a vapour-permeable, carbon-sequestering assembly that moderates humidity and improves insulation depth (Fig. 3) [110]. The monolithic pair (CIC and RE) reflects contrasting mineral and earthen paradigms. The CIC represents a fully mineral enclosure with integrated reinforcement steel and extruded polystyrene (XPS) insulation for thermal continuity. The RE, by comparison, substitutes cementitious mass with compacted local soils stabilised by lime and layered with straw-core insulation, achieving high thermal mass and low embodied energy while offering potential for on-site disassembly (Fig. 4) [111]. Comprehensive material specifications, including material densities, component service lives, and end-of-life (EoL) assumptions for each façade assembly, are provided in **Appendix B** (Tables B1–B6**)**. Together, these datasets enable transparent evaluation of material intensity, recyclability, and end-of-life pathways, forming the foundation for comparative circularity assessment across systems.

Across all façade systems, assemblies depend on mechanical or bonded joints to integrate materials, parts, and components, yet their reversibility and contamination potential vary significantly. BV–SF relies on mortar bedding and steel ties, forming predominantly bonded

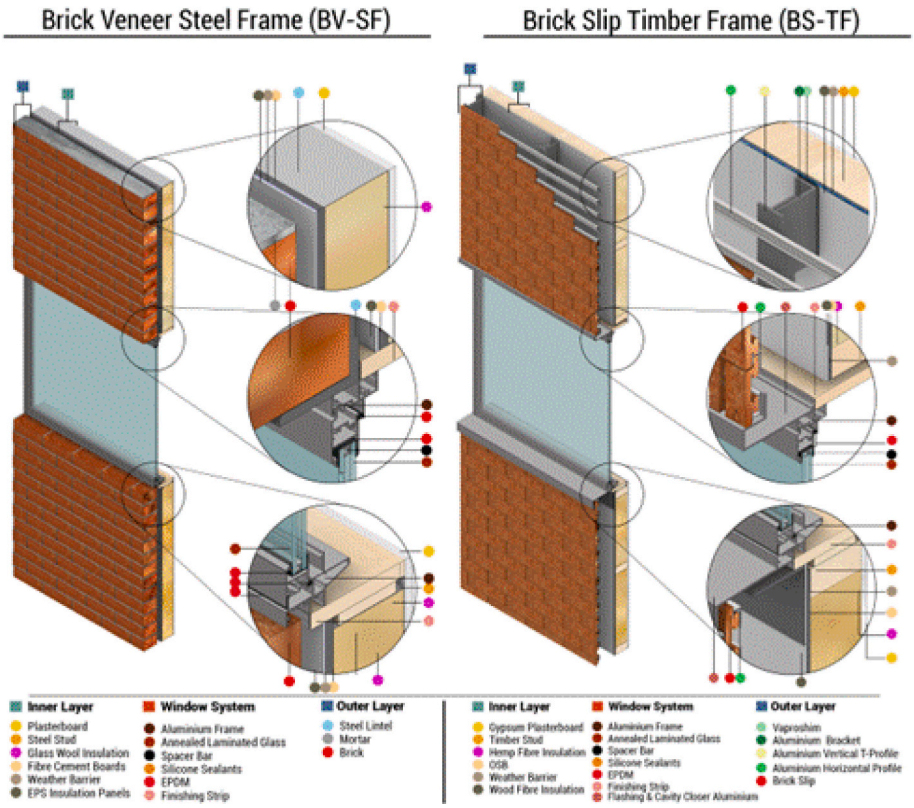

Fig. 2. Details of Brick Veneer with Steel Frame (BV–SF) and Brick Slip with Timber Frame (BS–TF) Systems.

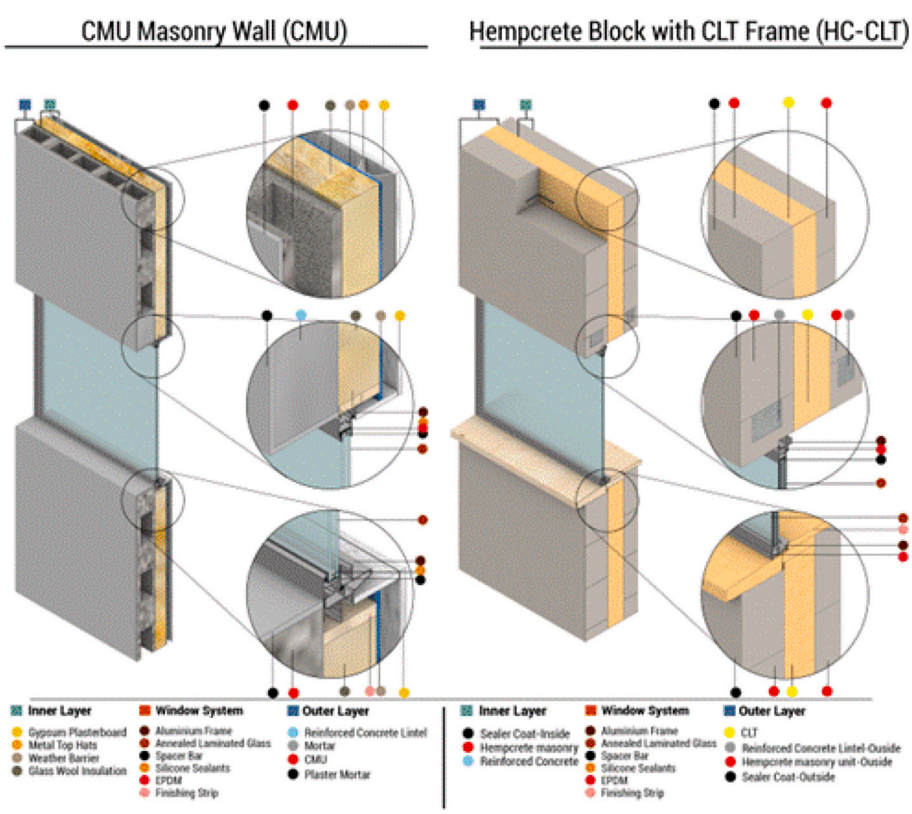

Fig. 3. Assembly Details of CMU Masonry Wall and Hempcrete Block with CLT Frame (HC–CLT) Systems.

connections between the brick skin, steel frame, and insulation layers. This ensures structural anchorage but limits recovery at end-of-life due to adhesive residues and composite interfaces. In contrast, BS–TF incorporates screws, aluminium brackets, and T-profiles to mechanically

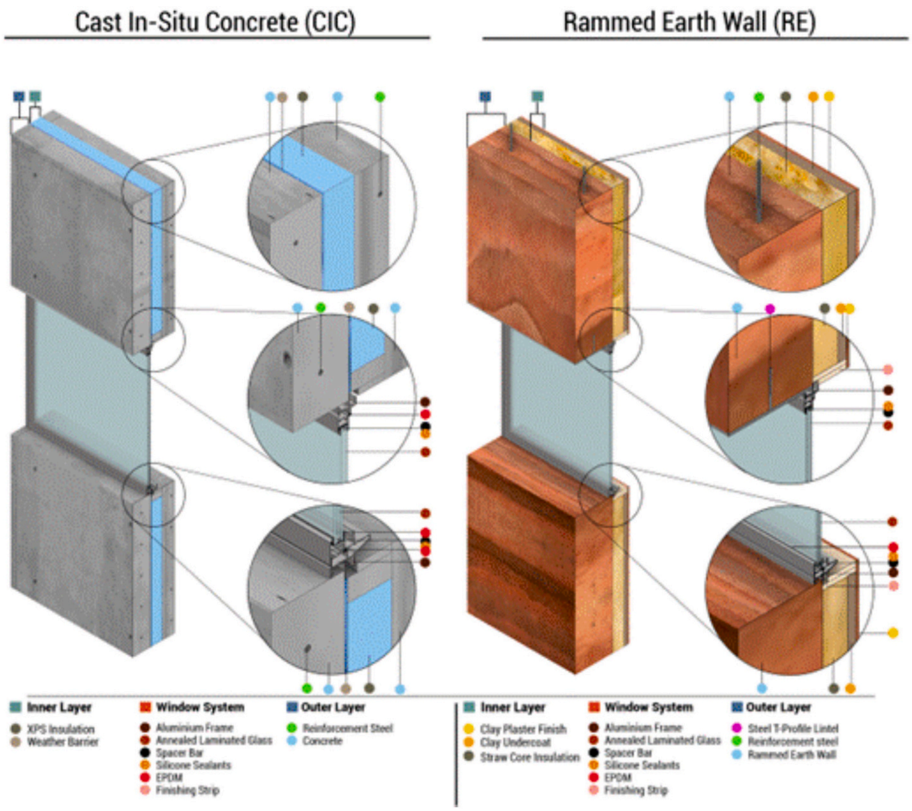

Fig. 4. Assembly Details of Cast-in-situ concrete (CIC) and Rammed Earth (RE) Façade Systems.

attach the slip cladding to the subframe, reducing reliance on wet bonds and improving disassembly potential between timber, insulation, and brick elements.

CMU employs continuous mortar joints and steel anchor straps, creating rigid monolithic connections that hinder material separation but ensure durability and fire integrity. HC–CLT adopts a hybrid interface logic, using bolts, brackets, and breathable sealant coatings to connect hemp-lime blocks with the CLT frame, allowing selective detachment and reducing cross-contamination between bio-based and mineral-based elements. CIC integrates reinforcement bars and cast interfaces, achieving structural continuity at the expense of reversibility, as steel–concrete composites are inseparable without destruction. Conversely, RE demonstrates a more circular assembly logic through dry mechanical lintels, steel ties, and clay-based plasters, enabling partial repair, localised replacement, and potential material reuse.

3.5. Data sources and tools

The environmental assessment was conducted using OneClick LCA (https://oneclicklca.com/), a web-based life cycle assessment (LCA) platform developed for the construction sector. The software has been independently verified for compliance with relevant ISO and EN standards and is commonly applied in building-level environmental assessments. Environmental data for materials and processes were primarily sourced from the OneClick LCA database and verified Environmental Product Declarations (EPDs). Where multiple datasets were available, preference was given to product-specific or regionally representative data. Additional information on material densities, service life assumptions, and end-of-life scenarios was incorporated to reflect Australian construction practices, based on available regional data and industry norms. Material inventories and façade assembly configurations were modelled to represent realistic construction methods for each system, consistent with the functional unit and system boundaries defined in Sections 3.2 and 3.3. This approach ensured that both primary materials and secondary components, such as fixings and substructures, were included consistently across all façade systems. The environmental impact assessment focused on global warming potential (GWP), expressed in kg CO_2e, and was evaluated across the full life cycle of each façade system.

3.6. Biogenic carbon accounting approach

Biogenic carbon associated with bio-based materials was accounted for following the framework of EN 15804 + A2 (CEN, 2011). The study adopts a $-1/+1$ biogenic carbon accounting approach, in which carbon uptake during biomass growth is reported as a negative emission in the product stage (modules A1–A3), representing the temporary storage of atmospheric CO_2 within the material [112]. At the end-of-life stage (modules C3–C4), biogenic carbon is assumed to be partially released depending on the disposal scenario. For bio-based materials such as hemp-based masonry units, straw insulation, timber products, and plant-based insulation materials, carbon sequestration during biomass growth was quantified using the carbon content of the material and reported as GWP-biogenic in A1–A3 [113]. Biogenic carbon storage was calculated based on the carbon content of the biomass, assuming that 1 kg of stored biogenic carbon corresponds to 3.67 kg CO_2 equivalent [113]. End-of-life scenarios assumed landfill disposal for most timber and bio-based materials, while OSB panels were assumed to undergo incineration with energy recovery. Under landfill conditions, only a portion of the stored biogenic carbon is released through degradation processes during the considered time horizon, while the remaining fraction remains stored in the landfill [114–116]. Consequently, a partial release of biogenic carbon was modelled at the end-of-life stage according to material-specific release fractions derived from Environmental Product Declarations (EPDs) and literature sources. Table 1 summarises the end-of-life scenarios and biogenic carbon release fractions applied to the bio-based materials included in the façade assemblies. Consistent with EN 15804 + A2, biogenic carbon flows are

Table 1
Biogenic carbon storage and end-of-life release assumptions for bio-based materials included in the façade systems. Release fractions represent the proportion of stored biogenic carbon assumed to be emitted during end-of-life processes (modules C3–C4), while the remaining fraction is assumed to remain stored in landfill.

Material	EOL scenario	Release fraction	Source
Hempcrete masonry unit	Landfill	15%	[117, 118, 119]
CLT	Landfill	0.15%	[115, 120]
Straw insulation	Landfill	100%	[121]
Timber stud	Landfill	0.10%	(Jordeson Timber., 2022; Limited & FWPA, 2017)
Hemp fiber insulation	Landfill	20%	[122, 123]
Wood fiber insulation	Landfill	0.10%	[115]
OSB	Energy recovery	100%	([124]; KOUS, 2023)

reported separately from fossil greenhouse gas emissions, and Module D includes only benefits associated with material recovery and recycling, without including additional credits for biogenic carbon storage (CEN, 2011).

However, it is important to note that this approach reflects current Australian LCA practice, where a variation of the −1/+1 method (often referred to as −1/+1*) assumes partial release of biogenic carbon in landfill conditions [114,115]. In contrast, the standard −1/+1 approach recommended by EN 15804 + A2, commonly applied in European Environmental Product Declarations (EPDs), assumes full release of biogenic carbon at the end-of-life regardless of disposal pathway ([125] CEN, 2011; [115]). As highlighted in previous studies, this difference in methodological treatment can significantly influence the reported embodied carbon results of bio-based materials, particularly timber systems, with the 1/+1* approach potentially leading to lower net emissions due to assumed carbon storage in landfill. This distinction should be considered when interpreting the results and comparing them with studies based on alternative biogenic carbon accounting approaches.

3.7. Circularity assessment approach

Circularity assessment was conducted using the OneClick Building Circularity tool, which provides a material-based evaluation of circularity performance across the building life cycle, with particular emphasis on end-of-life (EoL) recovery pathways. The tool calculates a Building Circularity Index (BCI), expressed as a percentage, based on the proportion of materials recovered, reused, recycled, or returned to productive use at the end of the system's life [60,126,127]. Accordingly, the OneClick Building Circularity results are interpreted strictly as indicators of circularity potential under controlled modelling assumptions, rather than predictions of real-world recovery outcomes.

The selected approach enables material-specific circularity assessment, distinguishing between virgin, renewable, recycled, and reused material inputs. Users define material quantities, service life assumptions, and circularity weighting factors, while default EoL processes are assigned to each material category. These assumptions directly influence the resulting circularity score and allow consistent comparison across façade systems under equivalent boundary conditions [60,126,127]. This material-flow-based logic aligns with the component-level modelling adopted in this study and supports comparative evaluation of façade assemblies as integrated systems.

A key reason for selecting the OneClick Building Circularity tool is its integration of circularity assessment with life cycle assessment (LCA) within a single platform. This allows circularity outcomes to be evaluated alongside environmental impacts using aligned data structures, system boundaries, and material inventories. Such integration is not commonly available in other circularity assessment tools, which often operate independently from LCA or require parallel modelling approaches [60].

The tool relies on third-party-verified datasets, including Environmental Product Declarations (EPDs), and is aligned with multiple standards and frameworks, such as ISO 14044, EN 15804, and NS 3720, as well as policy-oriented circularity requirements. This standards alignment supports transparency and consistency while enabling the inclusion of qualitative inputs, which is particularly relevant during early design stages when detailed future-use data may be unavailable [60,126,127].

The OneClick Building Circularity tool also includes qualitative indicators related to design for disassembly (DfD) and design for adaptability (DfA). These aspects are currently incorporated as binary indicators and do not directly influence the circularity score. While this represents a limitation in capturing design intent quantitatively, the approach enables structured consideration of circular strategies alongside material recovery metrics.

Overall, the tool was selected because it provides a standardised, sector-specific, and material-oriented approach to circularity assessment that is compatible with LCA-based comparison, supports façade-level analysis, and enables transparent evaluation of circularity potential under consistent assumptions. Accordingly, the OneClick Building Circularity results are interpreted strictly as indicators of relative circularity potential under controlled modelling assumptions, rather than predictions of real-world recovery outcomes.

Circularity calculations were performed using the circularity module implemented in One Click LCA, which operationalises indicators derived from frameworks such as the Material Circularity Indicator (MCI) and related building-scale adaptations. Recyclability and recovery rates were derived from Environmental Product Declarations (EPDs), industry datasets, and default recovery pathways included in the One Click LCA database, representing current construction waste management practices. While these indicators provide a consistent basis for comparing façade typologies, they primarily evaluate material flows and may not fully capture recovery challenges associated with composite or multilayer façade assemblies.

4. Results

4.1. Global warming potential (system level)

Fig. 5 compares the global warming potential (GWP) of the six façade systems, highlighting the influence of material composition, assembly strategy, and biogenic carbon storage. Results are presented comparatively to emphasise relative performance differences rather than absolute values.

Mineral-based façade systems—Brick Veneer with Steel Frame (BV-SF), Cast-in-Situ Concrete (CIC), and Concrete Masonry Unit (CMU) Walls—exhibit consistently higher embodied carbon than bio-based alternatives. These systems cluster within a similar range of GWP values, with net impacts of 546 kg CO_2e for BV-SF, 559 kg CO_2e for CIC, and 446 kg CO_2e for CMU, reflecting their reliance on cement-based materials, steel reinforcement, and energy-intensive manufacturing processes. Compared with the highest-impact system in this group (BS-TF at 615 kg CO_2e), CMU shows a 27% lower climate impact, while BV-SF and CIC reduce impacts by approximately 11% and 9%, respectively. Differences between these systems are primarily driven by material intensity and structural integration rather than façade typology alone.

Brick-based systems demonstrate the importance of assembly logic. Although both employ similar facing materials, the mechanically fixed Brick Slip with Timber Frame (BS-TF) system shows higher embodied impacts (615 kg CO_2e) than the bonded brick veneer system (546 kg CO_2e). This represents an increase of approximately 13%, attributable to additional substructure elements including aluminium rails, brackets,

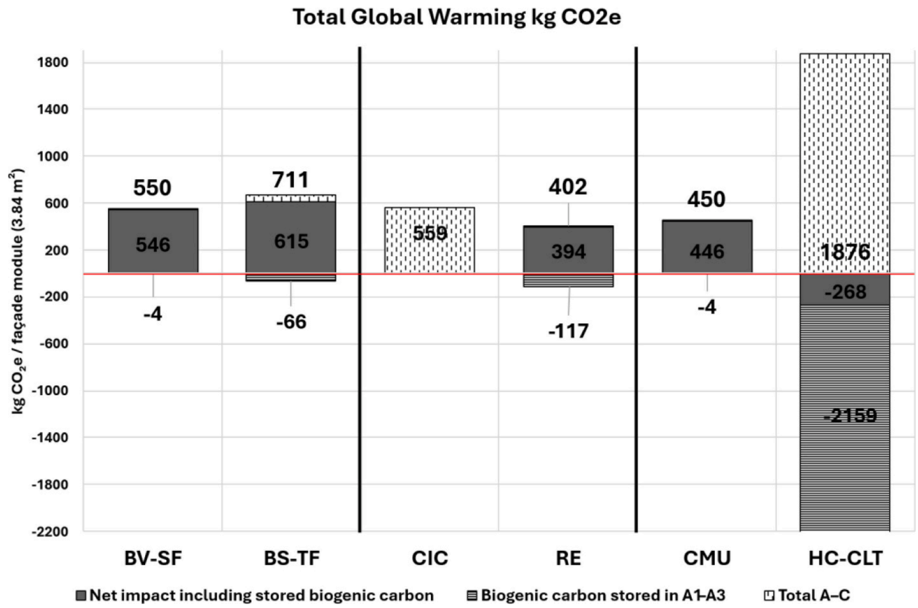

Fig. 5. Global Warming Potential (GWP) of Façade Systems at the System Level (A1–C4).

and multi-layer insulation, which offset the material efficiency gained from thinner brick components. This comparison illustrates that material substitution alone does not necessarily reduce GWP if it is accompanied by increased system complexity.

Among the alternative systems, the rammed earth façade achieves the lowest positive life-cycle impact (394 kg CO_2e), representing a 36% reduction relative to the BS-TF system, largely due to the lower embodied carbon of earth-based materials and reduced reliance on high-energy structural components.

The hempcrete block façade with CLT frame (HC-CLT) shows a net negative climate impact (−268 kg CO_2e) at the system level. This result reflects substantial biogenic carbon storage in hemp-based materials and timber components during the production stage (A1–A3). When this stored carbon is included, the total life-cycle balance becomes negative despite the relatively high production-stage emissions (1876 kg CO_2e across modules A–C). End-of-life modelling assumes that only a fraction of this stored carbon is released during disposal processes (C3–C4), while the remaining carbon remains stored within the system boundary according to the 1/+1 biogenic carbon accounting approach described in the methodology. However, it is important to note that this net-negative result is strongly influenced by the inclusion of biogenic carbon storage. When biogenic carbon is excluded, the HC–CLT system exhibits the highest production-stage impacts among all façade systems, reaching 1413 kg CO_2e in modules A1–A3. This highlights a significant trade-off between upfront embodied emissions and carbon storage effects, and indicates that the perceived environmental advantage of bio-

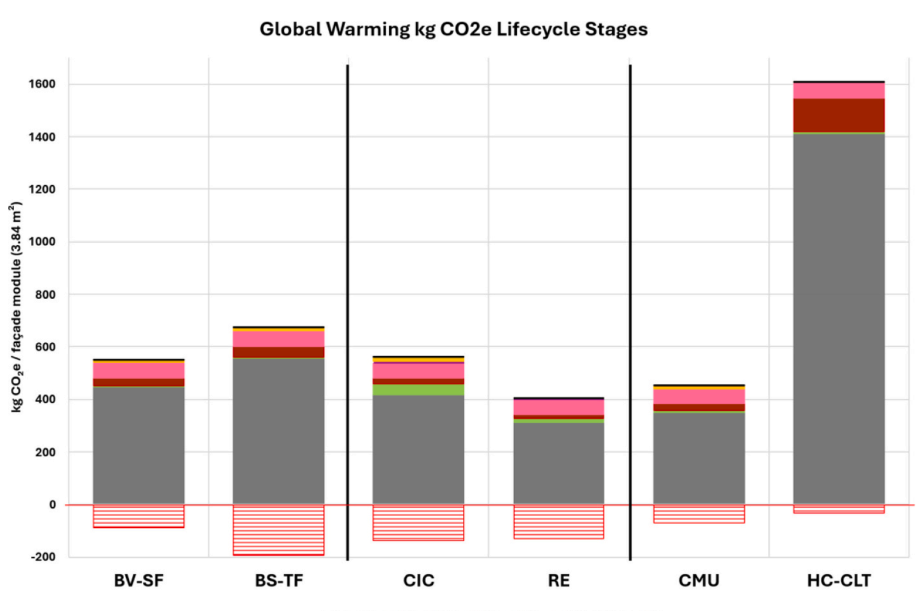

Fig. 6. Contribution of life-cycle stages to global warming potential (GWP) for the six façade systems, including production (A1–A3), construction (A4–A5), replacement (B4), end-of-life (C2–C4), and benefits beyond the system boundary (Module D). Module C1 (deconstruction/demolition) is excluded as its contribution was found to be negligible across all systems. Results are presented comparatively to illustrate dominant stages and relative differences between façade typologies. Production-stage impacts dominate across all systems, while end-of-life and Module D contributions vary according to assembly logic, material recoverability, and treatment of biogenic carbon.

based systems is highly dependent on the chosen accounting method and end-of-life assumptions.

Overall, the results indicate that façade GWP is governed not only by material choice but also by construction strategy and system integration. Bio-based systems benefit from carbon storage effects, while mineral-based systems remain dominated by production-stage emissions. Mechanically complex assemblies tend to increase embodied impacts regardless of material efficiency, reinforcing the importance of holistic system-level evaluation in early façade design.

4.2. GWP breakdown by lifecycle stage

Fig. 6 Contribution of life-cycle stages to global warming potential (GWP) for the six façade systems, including production (A1–A3), construction (A4–A5), replacement (B4), end-of-life (C2–C4), and benefits beyond the system boundary (Module D). Module C1 (deconstruction/demolition) is excluded as its contribution was negligible across all systems. The numerical GWP contributions for each façade system by life-cycle module are summarised in Table 2.

Across all façade typologies, the production stage (A1–A3) is the primary contributor to total GWP. Production-stage emissions range from 313 kg CO_2e for the Rammed Earth (RE) system to 1413 kg CO_2e for the Hempcrete Block with CLT Frame (HC–CLT) system prior to accounting for biogenic carbon storage. Mineral-based systems exhibit relatively high A1–A3 impacts due to cement manufacture, steel reinforcement, and energy-intensive masonry processing. Brick-based systems further reflect the influence of fired clay production, while Rammed Earth (RE) shows markedly lower A1–A3 impacts due to minimal processing and local material sourcing.

Assembly strategy strongly influences production-stage performance. Although Brick Slip with Timber Frame (BS–TF) systems reduce facing material thickness, their mechanically fixed configuration results in higher A1–A3 impacts (557 kg CO_2e) than bonded Brick Veneer with Steel Frame (BV–SF) systems (446 kg CO_2e), representing an increase of approximately 25%. This increase is primarily associated with aluminium sub-framing and additional insulation layers, reinforcing that reduced material mass does not necessarily translate to lower embodied carbon when system complexity increases.

Bio-based systems display contrasting behaviour depending on the treatment of biogenic carbon. The Hempcrete Block with CLT Frame (HC–CLT) system exhibits substantial biogenic carbon storage during production (−2159 kg CO_2e in A1–A3), reflecting carbon uptake during timber growth and hemp cultivation. When this stored carbon is accounted for, the production-stage balance becomes negative despite relatively high manufacturing emissions associated with lime binders and prefabrication processes. Partial release of stored carbon occurs at end-of-life, with 283 kg CO_2e released in modules C3–C4 according to the material-specific release fractions defined in the methodology. The magnitude of biogenic carbon storage and subsequent release is illustrated in Fig. 7, which shows the balance between carbon uptake during production (A1–A3) and partial release during end-of-life processes (C3–C4) for the bio-based façade systems. Despite the substantial biogenic carbon storage observed in the HC–CLT system, its production-stage impacts remain significantly higher than all other façade typologies when biogenic carbon is excluded. At 1413 kg CO_2e in A1–A3, this value is approximately three times higher than systems such as CMU (351 kg CO_2e) and RE (313 kg CO_2e). This elevated impact is primarily driven by the use of lime-based binders in hempcrete and the material intensity of cross-laminated timber production. When compared to conventional systems such as brick veneer (BV–SF), which exhibit lower production-stage impacts and more stable life-cycle performance, the HC–CLT system may not consistently provide a lower embodied carbon solution when biogenic carbon is reported separately. In such cases, the high upfront emissions of HC–CLT may dominate comparative assessments, particularly where biogenic carbon benefits are excluded or reported separately from total GWP. These findings highlight the importance of considering both accounting conventions and end-of-life scenarios when evaluating the environmental effectiveness of bio-based façade systems in practice.

End-of-life stages (C2–C4) and benefits beyond the system boundary (Module D) contribute less to total GWP but introduce greater variability between façade systems. Mineral-based systems show relatively small end-of-life impacts, generally below 10 kg CO_2e, reflecting inert material behaviour and limited degradation. In contrast, bio-based systems exhibit higher variability due to biogenic carbon release during disposal processes, including 109 kg CO_2e for the RE system and 283 kg CO_2e for HC–CLT. Module D benefits are primarily driven by metal recovery, particularly aluminium and steel in mechanically fixed assemblies, while bio-based systems show more limited credits due to constrained recovery pathways. Taken together, these results indicate that, from a practical perspective, the environmental effectiveness of bio-based façade systems depends not only on material selection but also on accounting methods and end-of-life strategies. Without improved reuse or recovery pathways, and particularly where biogenic carbon is reported

Table 2
Global warming potential (GWP) results by life-cycle module for the six façade systems (kg CO_2e per façade module). Results include production (A1–A3), construction (A4–A5), replacement (B4), end-of-life processes (C2–C4), and benefits beyond the system boundary (Module D). Biogenic carbon storage and release are reported separately following the EN 15804 + A2–1/+1 accounting approach.

Module	BV-SF		BS-TF		CIC		RE		CMU		HC-CLT	
	GWP (kg CO_2e)	Bio.c (kg CO_2e bio)	GWP (kg CO_2e)	Bio.c (kg CO_2e bio)	GWP (kg CO_2e)	Bio.c (kg CO_2e bio)	GWP (kg CO_2e)	Bio.c (kg CO_2e bio)	GWP (kg CO_2e)	Bio.c (kg CO_2e bio)	GWP (kg CO_2e)	Bio.c (kg CO_2e bio)
A1–A3	446.4	−4.5	556.9	−65.6	416.8	0.0	313.0	−117.3	350.9	−4.5	1413.2	−2159.3
A4	6.0	0.0	2.3	0.0	42.4	0.0	15.9	0.0	5.7	0.0	7.0	0.0
A5	30.1	0.0	42.2	0.0	22.9	0.0	13.6	0.0	26.5	0.0	124.7	0.0
B4	55.2	0.0	59.6	0.0	55.2	0.0	55.2	0.0	55.2	0.0	60.2	0.0
C2	3.6	0.0	1.9	0.0	6.5	0.0	3.0	0.0	2.4	0.0	1.5	0.0
C3	9.0	0.0	8.5	7.1	15.1	0.0	1.2	109.0	9.5	0.0	0.0	0.0
C4	0.1	0.0	0.2	1.7	0.1	0.0	0.6	0.0	0.1	0.0	1.5	283.4
Total A–C	550.5	n/a	671.6	n/a	559.0	n/a	402.5	n/a	450.2	n/a	1608.3	n/a
Biogenic carbon stored in A1–A3	n/a	−4.5	n/a	−65.6	n/a	0.0	n/a	−117.3	n/a	−4.5	n/a	−2159.3
Biogenic carbon released at end-of-life (C3–C4)	n/a	0.0	n/a	8.8	n/a	0.0	n/a	109.0	n/a	0.0	n/a	283.4
Net impact including stored biogenic carbon	546.0	−4.5	614.9	−56.7	559.0	0.0	394.2	−8.3	445.8	−4.5	−267.6	−1875.9
Module D	−88.6	n/a	−193.7	n/a	−137.0	n/a	−128.6	n/a	−69.2	n/a	−30.8	n/a

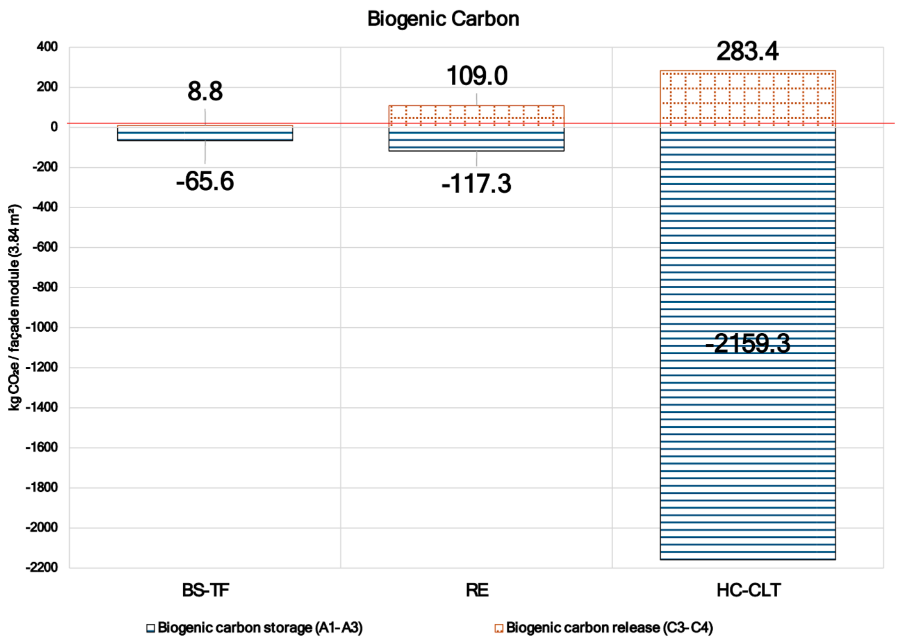

Fig. 7. Biogenic carbon flows in the façade systems: storage during production (A1–A3) and release at end-of-life (C3–C4).

separately from total GWP, the benefits of biogenic carbon storage may not translate into consistent lifecycle advantages compared to lower-impact mineral-based systems.

4.3. GWP breakdown by parts and materials

To identify the main drivers of embodied carbon within each façade typology, global warming potential (GWP) results were disaggregated into inner layer, outer layer, and window system parts (Figs. 8–13). This breakdown highlights how a limited number of materials and sub-assemblies dominate system-level impacts.

Across all façade systems, the window system represents a relatively consistent contribution to embodied carbon, with a baseline impact of approximately 189 kg CO₂e. Aluminium frames (~89 kg CO₂e) and laminated glass (~77 kg CO₂e) are the primary contributors, reflecting the energy intensity of aluminium production and glass manufacturing. In mechanically fixed systems, additional aluminium cavity closures and interface elements increase window-related impacts to approximately 200–240 kg CO₂e, indicating the sensitivity of component-level emissions to interface detailing rather than glazing alone.

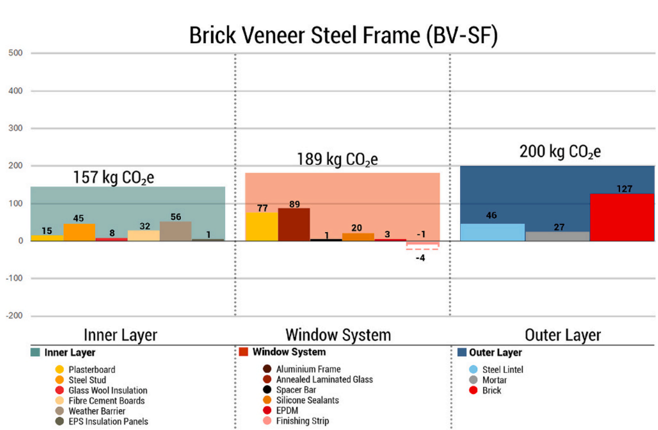

Fig. 8. GWP breakdown by part and material for the Brick Veneer with Steel Frame system (BV–SF).

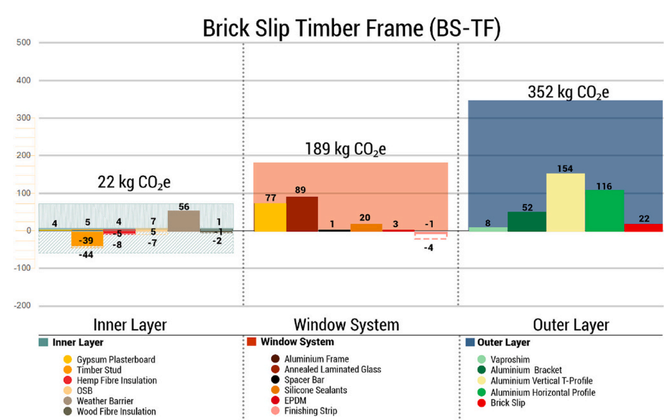

Fig. 9. GWP breakdown by part and material for the Brick Slip with Timber Frame system (BS–TF).

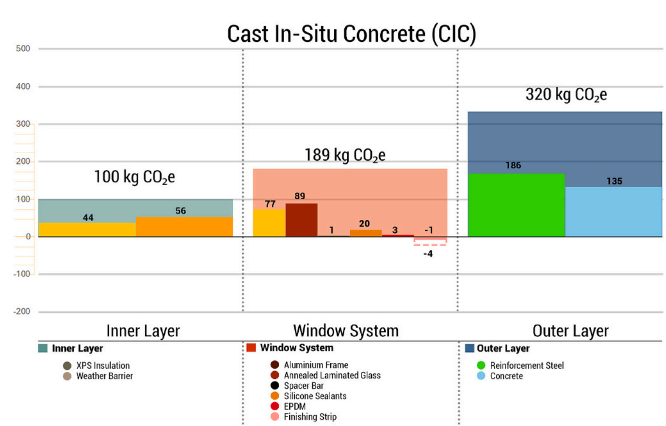

Fig. 10. GWP breakdown by part and material for the Cast-in-situ concrete system (CIC).

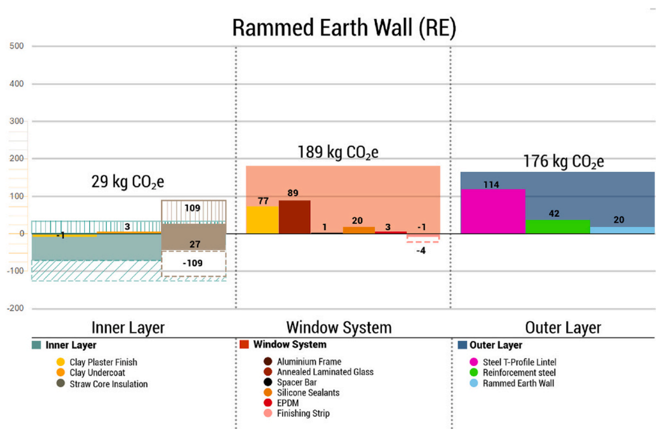

Fig. 11. GWP breakdown by part and material for the Rammed Earth Wall system (RE).

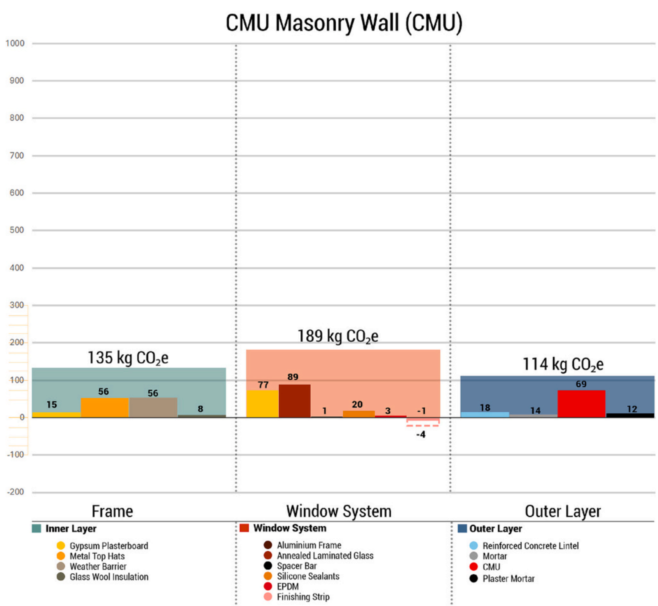

Fig. 12. GWP breakdown by part and material for the CMU Masonry Wall system (CMU).

The inner layer shows substantial variation between façade typologies. Mineral-based systems exhibit positive inner-layer emissions in the range of 100–157 kg CO₂e, driven by insulation materials, weather barriers, and metal framing elements. For example, the Brick Veneer Steel Frame (BV–SF) system records 157 kg CO₂e, while the Cast-in-Situ Concrete (CIC) system reaches approximately 100 kg CO₂e. In contrast, bio-based systems achieve markedly lower inner-layer impacts. The Rammed Earth (RE) system records approximately 29 kg CO₂e, while the Hempcrete–CLT assembly shows −147 kg CO₂e, reflecting substantial biogenic carbon storage in hemp-based materials and timber components. These values reflect carbon uptake during biomass growth in accordance with the biogenic carbon accounting approach described in the methodology.

The outer layer is the dominant contributor to system-level GWP in most façade typologies, although the underlying drivers differ significantly. In conventional masonry and concrete systems, outer-layer emissions typically range between 114 and 320 kg CO₂e. The Cast-in-Situ Concrete façade shows the highest value (∼320 kg CO₂e) due to the combined contribution of reinforced concrete (∼135 kg CO₂e) and steel reinforcement (∼186 kg CO₂e). Similarly, the Brick Veneer Steel

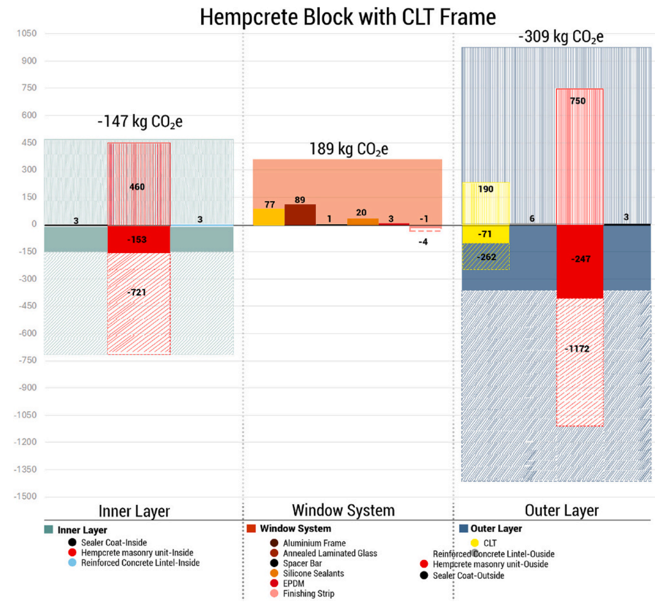

Fig. 13. GWP breakdown by part and material for the Hempcrete Block with CLT Frame system (HC–CLT).

Frame system records approximately 200 kg CO₂e, driven primarily by fired clay brick production (∼127 kg CO₂e) and associated steel lintels (∼46 kg CO₂e).

In mechanically fixed Brick Slip with Timber Frame (BS–TF) systems, aluminium substructures emerge as the dominant contributors. Aluminium vertical profiles (∼154 kg CO₂e), brackets (∼52 kg CO₂e), and horizontal rails (∼116 kg CO₂e) collectively increase outer-layer impacts to approximately 352 kg CO₂e, outweighing emissions from the brick slips themselves (∼22 kg CO₂e). This demonstrates that mechanically complex assemblies may increase embodied carbon despite reduced masonry thickness.

Bio-based façade systems display contrasting outer-layer behaviour. Rammed Earth walls exhibit relatively moderate outer-layer emissions of approximately 176 kg CO₂e, with steel lintels (∼114 kg CO₂e) and reinforcement (∼42 kg CO₂e) remaining the principal contributors. In contrast, the Hempcrete–CLT façade achieves net-negative outer-layer emissions of approximately −309 kg CO₂e due to substantial biogenic carbon storage in hempcrete (−1172 kg CO₂e) and CLT (−262 kg CO₂e) components. However, this result should be interpreted alongside the high embodied impacts of supporting materials, particularly lime-based binders and timber processing, which contribute significantly to the overall A1–A3 emissions. End-of-life modelling assumes partial release of this stored carbon according to material-specific release fractions, including approximately 15% for hemp-based materials and 0.15% for CLT, as defined in the methodology.

Overall, the part- and material-level analysis confirms that system-level GWP is shaped by a small number of high-impact materials and components—particularly cement-based materials, aluminium substructures, steel reinforcement, and fired clay products. Bio-based materials can significantly reduce or offset embodied carbon when their integration avoids reliance on emission-intensive supporting elements. This demonstrates the value of disaggregated analysis for identifying targeted façade design interventions at the material and assembly level.

4.4. Circularity assessment results

The circularity performance of the six façade systems was evaluated by assessing both material recovery at input and material return at end-of-life, as illustrated in Fig. 14. The results reveal clear contrasts between conventional mineral-based systems and emerging bio-based or modular

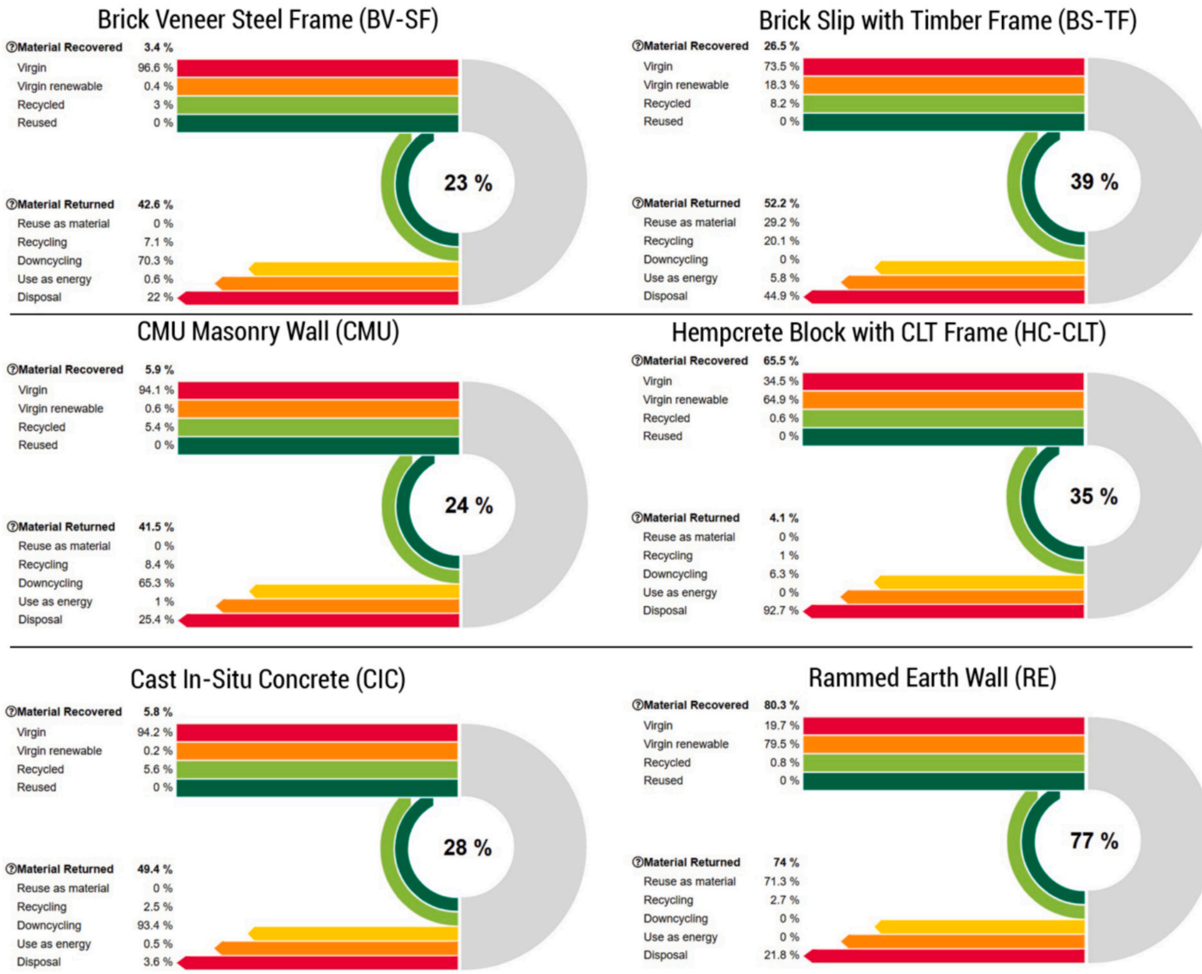

Fig. 14. Circularity results for all façade systems, showing total scores, recovered inputs, and end-of-life recovery. Higher circularity scores—particularly for rammed earth—reflect assumptions of low material processing and high direct reuse potential under harmonised modelling conditions.

assemblies.

Among conventional façade typologies, BV–SF and CMU systems exhibit the lowest circularity performance, with overall circularity scores of approximately 20–25%. These systems are dominated by virgin mineral materials and rely primarily on downcycling and disposal at end-of-life. Although isolated steel elements achieve high recycling rates, the prevalence of bonded masonry and cement-based materials limits meaningful reuse or closed-loop recovery.

The CIC system demonstrates a moderate circularity score of approximately 28%, reflecting high rates of material return in mass terms. However, this return is overwhelmingly achieved through downcycling, rather than reuse or high-quality recycling. As a result, the apparent circularity performance does not translate into retained material value, highlighting a limitation of monolithic concrete systems despite their recyclability claims.

In contrast, the BS–TF system achieves a higher circularity score of approximately 40%, driven by a combination of renewable timber components, increased recycled content, and mechanically fixed assemblies. The system benefits from higher reuse and recycling potential at end-of-life, although extensive aluminium sub-framing introduces trade-offs by increasing reliance on emission-intensive materials despite good recyclability.

The RE system demonstrates the highest circularity performance, with an overall score of approximately 77%. Minimal reliance on composite materials and the recoverability of earth-based components enable a substantially lower landfill fraction compared to all other systems.

The HC–CLT system exhibits a mixed circularity profile, achieving a moderate score of approximately 35%. While the system contains a high share of renewable materials at input, its end-of-life performance is constrained by the limited availability of recycling or reuse pathways for composite bio-based assemblies. As a result, a large proportion of materials are currently directed to landfill despite their biogenic origin. This combination of moderate circularity and high production-stage impacts suggests that, despite its renewable material composition, the HC–CLT system may not achieve optimal environmental performance without improved end-of-life recovery strategies.

Overall, the results indicate that material renewability alone does not guarantee circularity. Instead, circular performance is strongly influenced by assembly logic, material separability, and the availability of end-of-life pathways. Systems designed for disassembly and reuse consistently outperform those relying on monolithic or bonded construction, regardless of material type.

5. Discussion

5.1. Integrated environmental and circularity performance of façade systems

The comparative analysis demonstrates that assembly logic and material separability are decisive drivers of both environmental and circularity performance across façade systems. Systems relying on wet-bonded, monolithic construction consistently exhibit lower circularity outcomes and limited end-of-life value retention, regardless of material durability or structural performance. A key factor enabling material separability in façade systems is the application of design-for-disassembly (DfD) principles. These strategies rely on reversible mechanical connections, modular component layouts, and clear separation between façade layers, allowing materials to be removed without destructive processes during maintenance, replacement, or end-of-life recovery [144,145]. Mechanical fastening systems such as bolts, screws, and interlocking joints avoid adhesives and welded connections, enabling non-destructive retrieval of façade panels, brackets, glazing components, and insulation layers [146]. Accessibility of connections and a planned disassembly sequence are also recognised as critical factors influencing the practical recoverability of façade elements [147].

The comparison between Brick Veneer with Steel Frame (BV–SF) and Brick Slip with Timber Frame (BS–TF) illustrates this relationship clearly. Although BS–TF introduces additional aluminium sub-framing that increases upfront embodied carbon, its mechanically fixed assembly enables substantially higher material recovery and reuse potential, resulting in a markedly higher circularity score. The dry assembly strategy enhances end-of-life separation and improves the effectiveness of recycling pathways, particularly for aluminium components, whereas BV–SF remains constrained by mortar-bonded brickwork that limits disassembly and reuse. This comparison highlights a recurring trade-off between initial embodied impacts and long-term circular performance, reinforcing the importance of evaluating façade systems beyond production-stage emissions alone.

The contrast between mechanical and bonded construction methods further explains these differences in circular performance. Mechanical fastening systems—including screws, bolts, and reclosable connectors—allow façade components to be removed intact, preserving material quality and enabling reuse or high-quality recycling [148,149]. In contrast, bonded systems using adhesives, mortar, or sealants create hybrid material interfaces that prevent separation of layers and significantly reduce recyclability [3,149]. Such irreversible connections often result in composite waste streams that are difficult to recover and are therefore more likely to be downcycled or disposed of in landfill [149]. Simplifying façade assemblies through reduced bonded layers and compatible materials can therefore improve end-of-life recovery potential and support more effective circular material flows [45,150].

A similar contrast emerges between Cast-in-situ concrete (CIC) and Rammed earth (RE) facades. CIC exhibits higher embodied carbon during production and achieves material return predominantly through downcycling, resulting in a moderate circularity score despite high mass recovery. In contrast, the RE system combines low-processed renewable materials with dry compaction techniques, enabling extensive material reuse at end-of-life and achieving the highest circularity performance among the systems studied. This comparison demonstrates that the quality of material recovery is more critical than the quantity of material returned, particularly when recovery pathways preserve material value.

The comparison between Concrete Masonry Unit (CMU) and Hempcrete Block with CLT Frame (HC–CLT) further illustrates the distinction between material renewability and practical circularity. While HC–CLT incorporates a high proportion of bio-based materials and substantial biogenic carbon storage, its circularity performance remains constrained by the limited availability of recycling and reuse pathways for composite bio-based assemblies. As a result, landfill disposal remains a dominant end-of-life route despite high renewable input. CMU systems, by contrast, rely heavily on mineral materials and downcycling, achieving similarly limited circularity outcomes through different mechanisms. This highlights that renewable material content alone does not guarantee circular performance in the absence of compatible recovery infrastructure. In addition, the relatively high production-stage impacts of bio-based assemblies such as HC–CLT highlight that renewable material use does not necessarily correspond to lower embodied carbon when manufacturing processes are emission-intensive. While HC–CLT incorporates substantial biogenic carbon storage through timber and hemp-based materials, this storage represents temporary atmospheric carbon sequestration during the façade service life. Its long-term climate benefit therefore depends on end-of-life pathways and degradation behaviour.

Across all façade typologies, steel and aluminium components consistently provide meaningful environmental credits through recycling, particularly when used within mechanically fixed assemblies. However, these benefits cannot compensate for the structural limitations imposed by bonded construction methods. Overall, the findings indicate that construction technique, connection strategy, and end-of-life infrastructure maturity are at least as influential as material selection in determining combined environmental and circularity performance.

From a design perspective, these results suggest that achieving circular façade systems requires a system-level approach that integrates material choice with reversible connections, simplified layering, and realistic end-of-life pathways. Façade circularity should therefore be addressed as a design problem rather than a material substitution exercise, with early design decisions playing a critical role in locking in long-term environmental and circular outcomes.

5.2. Interpretation in light of existing studies

The findings of this study align closely with existing research demonstrating that façade design strategies play a decisive role in shaping both environmental and circularity performance. In particular, systems that apply design-for-disassembly (DfD) principles—such as mechanically fixed Brick Slip facades and dry-compacted Rammed Earth walls—consistently exhibit higher material recovery and reuse potential at end-of-life. These outcomes support prior studies showing that mechanical connections facilitate layer separation, reduce material contamination, and simplify dismantling processes, thereby enabling more effective circular strategies [151,152].

Material efficiency emerges as a key factor influencing both embodied carbon and circularity outcomes. The Brick Slip system demonstrates that reducing material volume through lightweight cladding can lower resource demand compared to full masonry facades, confirming earlier findings on material-efficient solutions [151]. However, the introduction of aluminium-intensive substructures increases upfront embodied carbon, illustrating a common trade-off identified in the literature between initial carbon impacts and improved end-of-life recovery. The higher recyclability of aluminium components contributes to increased Module D benefits, reinforcing observations that circular recovery potential may offset, but not eliminate, higher production-stage emissions [153].

Bio-based materials—including timber, hempcrete, and straw insulation—exhibited high renewable content and substantial biogenic carbon storage, consistent with previous research on their role in low-carbon construction [154]. Nevertheless, the results also confirm that the environmental benefits of biogenic carbon are highly sensitive to end-of-life scenarios. Biogenic carbon storage in bio-based materials represents temporary atmospheric carbon sequestration during the façade service life, and the ultimate climate benefit depends on the end-of-life pathway. Reuse can delay carbon release by extending the service life of materials, while landfill or incineration may lead to partial or full emissions depending on degradation behaviour and waste treatment conditions. This finding reinforces the need for full life-cycle consideration when assessing bio-based façade systems, as highlighted in recent studies [155].

Durability and service-life considerations also influence the circular performance of façade systems. Durable materials can support multiple reuse cycles when combined with accessible mechanical connections and planned maintenance strategies [156,157]. However, durability alone does not guarantee circularity; highly durable components may still become unrecoverable when incorporated into irreversible bonded assemblies [156]. Effective circular façade design therefore requires balancing material durability, service-life planning, and disassembly potential, ensuring that components can be replaced, refurbished, or reused without damaging surrounding layers [157–159].

For mineral- and cement-based façade systems, such as Concrete Masonry Unit (CMU) systems and Cast-in-situ Concrete (CIC) façades, the results are consistent with established literature identifying persistent circularity limitations. High embodied carbon from cement production, reliance on downcycling, and difficulties in producing high-quality recycled aggregates continue to constrain circular performance [160,161]. While reinforcement steel offers meaningful recycling benefits, these gains are insufficient to overcome the structural constraints imposed by monolithic, bonded construction methods.

Finally, the findings reinforce existing evidence that material complexity and assembly logic strongly influence circular outcomes. Façade systems with simplified layering, dry connections, and reduced reliance on adhesives or wet bonding consistently demonstrate higher recovery potential. This supports prior research emphasising that meaningful circularity gains require the co-optimisation of both material selection and construction technique, rather than material substitution alone [153].

The circularity scores presented in this study should be interpreted as relative indicators derived under harmonised modelling assumptions, rather than as predictions of real-world recovery rates or future circular performance. Actual circular outcomes will depend on the availability of recovery infrastructure, regulatory frameworks, market demand, and future industry practices, which are inherently uncertain and lie beyond the scope of this study.

The findings of this study are also consistent with emerging policy frameworks supporting circular construction. The European Level(s) framework provides a common methodology for assessing lifecycle performance and circularity indicators in buildings, including material inventories, service-life planning, and construction waste recovery pathways [162,163]. Complementary EU circular construction tools translate these principles into practical design and procurement requirements, encouraging strategies such as reversible connections, modular façade systems, and recoverable material assemblies in building envelopes [164,165]. These initiatives highlight the growing importance of integrating circular design principles into façade systems during early design stages.

5.3. Limitations, gaps, and future research directions

This study is subject to several limitations related to data availability, modelling assumptions, and the capabilities of current LCA and circularity assessment tools. One key limitation concerns the treatment of bio-based materials at end-of-life. Existing LCA tools do not fully capture the degradation behaviour of certain bio-based materials such as hempcrete in landfill environments. To address this limitation, material-specific release fractions derived from Environmental Product Declarations and literature were applied to estimate the proportion of stored biogenic carbon released during end-of-life stages (C3–C4). While this approach improves representativeness, uncertainty remains regarding degradation rates and landfill conditions.

A further limitation arises from the handling of biogenic carbon storage. In OneClick LCA, biogenic carbon is reported separately from total GWP, requiring external post-processing to estimate sequestration benefits for systems incorporating hempcrete and cross-laminated timber. Although this separation is consistent with current standards, it complicates direct comparison between bio-based and mineral-based façade systems and highlights the need for improved integration of biogenic carbon accounting within LCA workflows.

Constraints are also evident in the circularity assessment methodology. The Building Circularity v2 tool applies single end-of-life pathways for each material, which restricts the ability to model mixed recovery strategies that combine reuse, recycling, and downcycling within the same system. As façade components often follow multiple recovery routes in practice, this simplification limits the accuracy of circularity estimates. Similar limitations have been identified in previous research, indicating a broader need for more flexible and transparent circularity modelling approaches for building assemblies [166].

A further limitation relates to the use of a single end-of-life (EoL) scenario based on current Australian construction practices. While this reflects prevailing industry conditions and provides a realistic baseline for comparison, alternative EoL pathways—such as increased material reuse, higher recycling rates, or improved recovery systems—were not explicitly modelled in this study. These alternative scenarios could significantly influence both embodied carbon and circularity outcomes. For instance, bio-based systems such as the HC–CLT façade currently show partial release of stored biogenic carbon at end-of-life, contributing 283 kg CO_2e in modules C3–C4. Increased reuse of timber or hemp-based components could delay or avoid this carbon release, thereby improving net life-cycle performance. Similarly, systems such as BS–TF, which already benefit from high recyclability of aluminium components, may achieve greater Module D benefits under higher recycling rates. In contrast, mineral-based systems such as CMU and CIC, which currently exhibit low end-of-life impacts due to inert material behaviour, may show limited improvement under alternative scenarios due to constraints in high-quality recycling pathways. These observations suggest that the relative performance of façade systems is sensitive to end-of-life assumptions, particularly for bio-based and mechanically assembled systems. Therefore, the results presented should be interpreted as representative of current practice rather than optimal future scenarios. Future research should explore the sensitivity of façade system performance to different end-of-life pathways to better support decision-making and encourage circular design strategies.

More generally, standardised circularity metrics for façade systems remain underdeveloped, particularly with respect to incorporating design-for-disassembly (DfD) strategies, material quality loss during recycling, and multi-pathway end-of-life scenarios. These gaps constrain the ability of current tools to fully reflect the design decisions that influence real-world circular performance.

A further limitation relates to the system boundary adopted in this study. The analysis focuses on embodied carbon and circularity of façade systems and does not account for operational energy impacts (Module B6). However, façade design directly influences building energy performance through thermal properties such as U-values, solar heat gain, and air tightness. Variations in façade configuration may therefore lead to different operational energy demands over the building lifecycle. As a result, a whole-of-life assessment at the building scale—integrating both embodied and operational impacts—is likely to yield different comparative outcomes between façade systems. Future research should incorporate building energy modelling to evaluate these interactions and provide a more comprehensive assessment of façade performance.

A further limitation relates to the treatment of biogenic carbon at end-of-life. The study adopts an approach consistent with Australian practice, which assumes partial release of biogenic carbon in landfill conditions [114,115]. However, internationally, the standard $-1/+1$ method—commonly applied in European Environmental Product Declarations (EPDs)—assumes full release of biogenic carbon at the end-of-life (CEN, 2011; [115]). As a result, the findings related to bio-based façade systems, particularly those incorporating cross-laminated timber (CLT), are most applicable to Australian-sourced materials and may not be directly transferable to contexts where alternative accounting methods are applied. This methodological variation has been shown to significantly influence LCA results and highlights the need for greater consistency in biogenic carbon accounting approaches across regions.

Future research should build on the comparative framework presented in this study by expanding the range of façade typologies examined. In particular, prefabricated and modular façade systems—such as unitised curtain walls—warrant further investigation to assess how off-site manufacturing, standardised components, and repeatable connection geometries influence both environmental impacts and circularity outcomes. Prefabricated façade modules manufactured under controlled factory conditions may also reduce construction waste and improve lifecycle environmental performance while enabling potential reuse of façade components in future projects [73,167].

6. Conclusion

This study does not propose a new life cycle assessment or circularity method. Instead, it provides a controlled, system-level comparison of six façade typologies that reveals how assembly logic and connection strategies govern embodied carbon and circularity outcomes, often more strongly than material choice alone. By applying consistent functional units, system boundaries, biogenic carbon accounting assumptions, and end-of-life pathways.

This study presented a comparative life cycle and circularity assessment of six façade systems, including three conventional systems (Brick Veneer with Steel Frame, Cast-in-Situ Concrete, and Concrete Masonry Unit Wall) and three emerging alternatives (Brick Slip with Timber Frame, Rammed Earth, and Hempcrete Block with CLT Frame). By integrating full life-cycle stages (A1–C4 + D), part-level material breakdowns, and end-of-life pathways, this work provides a comprehensive comparative evaluation of façade environmental and circularity performance.

The results indicate that conventional façade systems are consistently associated with higher embodied carbon emissions and lower circularity performance. These outcomes are primarily driven by cement-intensive materials, wet-bonded construction techniques, and limited material separability at end-of-life. Although recyclable metal components such as steel and aluminium provide some environmental benefits, these gains are insufficient to offset the structural constraints that favour downcycling and landfill disposal.

In contrast, emerging façade systems demonstrate improved circularity outcomes through the use of renewable materials, dry assembly strategies, and modular construction approaches. The Brick Slip with Timber Frame system achieves higher recovery potential through mechanically fixed assemblies and recyclable substructures. Rammed Earth facades combine low material processing with high reuse potential, resulting in the strongest circularity performance among the systems studied. The Hempcrete Block with CLT Frame system exhibits substantial temporary biogenic carbon storage during the façade service life; however, its overall circularity performance remains constrained by the limited availability of end-of-life recovery pathways for composite bio-based materials.

Across all systems, this study highlights that construction method, material bonding, and assembly logic are as influential as material selection in determining both environmental and circularity outcomes. Façade systems that minimise permanent bonding, simplify material layering, and enable mechanical disassembly consistently perform better in circularity terms, while cement-intensive and monolithic systems remain limited by prevailing downcycling practices.

From a practical perspective, this work demonstrates that integrating environmental and circularity metrics at the façade design stage enables a more holistic evaluation of performance trade-offs and supports more informed system selection. Combining renewable materials with recyclable metals and modular assembly strategies can significantly enhance recovery potential while reducing long-term environmental impacts.

Overall, this study contributes to façade sustainability research by providing a detailed, system-level comparison of environmental impacts and circularity potential using part-level life cycle data and recovery benefits (Module D). While limitations remain—particularly regarding data availability, tool flexibility, and the modelling of mixed end-of-life pathways—the findings offer robust comparative insights to support circular façade design. The circularity results presented in this study should be interpreted as relative indicators under harmonised assumptions, rather than as predictions of real-world recovery rates or future circular performance.

From a design perspective, façade systems intended to support circularity should prioritise mechanically fixed assemblies, reversible connections, and simplified material layering to enable future disassembly and material recovery. Avoiding permanently bonded interfaces and designing façade layers that can be separated independently can significantly improve reuse and recycling potential at end-of-life.

Future research should extend this work by including prefabricated and unitised façade systems to explore differences between on-site and off-site construction methods. Further development of circularity indicators that integrate recovery efficiency, disassembly potential, and whole-life environmental performance will be essential to support more effective decision-making in circular façade design.

CRediT authorship contribution statement

Hamad Alabdulrazzaq: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Eugenia Gasparri:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Shady Attia:** Writing – review & editing, Supervision, Methodology. **Arianna Brambilla:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

Appendix A. Appendices

Table A1
Input data summary for case studies (geometry, materials, and connection features).

	Façade System	*Conventional vs. Emerging*	*Building Types*	*Construction Method*	*Material Type*	*Connection Component*	*Connection Parts*	*U-Value*
Masonry System	**BV–SF**	Conventional	Detached Houses, Townhouses, Apartments	On-Site Assembly	Brick, Steel	Bonded	Mix	0.18
	BS–TF	Emerging (Alternative)	Detached Houses, Townhouses, Apartments	On-Site Assembly	Brick Slip, Timber	Mechanical	Mechanical	0.32
Block-Based System	**CMU**	Conventional	Residential, Care Facilities, Hospitals	On-Site Assembly	Concrete	Bonded	Bonded	0.36
	HC–CLT	Emerging (Innovative)	Eco-Housing, Community Housing, Small Hostels	On-Site Assembly	Hempcrete, Timber	Mechanical	Mechanical	0.18
Monolithic System	**CIC**	Conventional	Clinics, Hospitals, Mixed-Use	On-Site Assembly	Concrete	Bonded	Bonded	0.36

(*continued on next page*)

Table A1 (*continued*)

	Façade System	Conventional vs. Emerging	Building Types	Construction Method	Material Type	Connection Component	Connection Parts	U-Value
	RE	Emerging (Alternative)	Rural Housing, Lodges, Community Facilities	On-Site Assembly	Earth-Based Material	Mechanical Compression	Mechanical Compression	0.69

Appendix B. Appendix B -table material specification and lifecycle data

Table B1
Material specifications for Brick Veneer with Steel Frame (BV–SF) façade system, including volume, density, end-of-life scenarios, and data sources for each layer and component.

BV–SF	Material	Volume	Density	Weight (kg)	Lifespan (years)	EOL**	Source
Inner Layer	Plasterboard	0.03	700	18	50	RCY	OneClick, [168]
	Steel Studes	0.0015	7850	12	60	RCY	OneClick, ([169]EAPL, 2024)
	Glass Wool Insulation	0.23	12	3	50	LF	OneClick, [170])
	Fiber Cement Board	0.02	1300	30	50	DCY	OneClick, (JHAPL, 2023)
	Breather Membrane	0.02	289	4	40	INC-ER	OneClick, [171,172])
	EPS Insulation	0.01	30	0.23	50	INC-ER	OneClick, [173]
Window System	Powder-Coated Aluminium Frame	0.0022	2700	6	60	RCY	OneClick, ([132,133])
	Double Glazing	0.01	2500	26	30	LF	OneClick,[134,135] [136])
	Spacer Bar	0.00013	527	0.07	30	LF	OneClick, ([137])
	Silicone Sealant	0.00037	1200	0.46	25–30	LF	OneClick, [138,139]
	EPDM Gasket	0.00037	1800	1	30	LF	OneClick, ([140];[141]
	Finishing Strip	0.01	528	3	60	LF	OneClick, ([142,143]
Outer Layer	Galvanised Steel Lintel	0.002	1976	16	50	RCY	OneClick, [174]
	Mortar	0.04	2200	91	50	DCY	OneClick, [175]
	Brick	0.24	7850	475	100	DCY	OneClick, ([176]; [177]

** End-of-life scenarios: REU – Reuse; RCY – Recycling; DCY – Downcycling; INC-ER – Incineration with energy recovery; LF – Landfilling.

Table B3
Material specifications for Brick Slip with Timber Frame (BS–TF) façade system, including volume, density, end-of-life scenarios, and data sources for each layer and component.

BS–TF	Material	Volume	Density	Weight (kg)	Lifespan (years)	EOL**	Source
Inner Layer	Gypsum Board	0.03	590	15	40	RCY	OneClick, [178]
	Timber Studes	0.05	528	27	60	LF	OneClick, ([142,143]
	Hemp Fiber Insulation	0.18	35	6	100	LF	OneClick, ([179])
	OSB	0.02	610	9	60	INC-ER	OneClick, [180]
	Breather Membrane	0.02	289	4	50	INC-ER	OneClick, [171,172]
	Wood Fiber Insulation	0.01	170	1	50	LF	OneClick, [181]
Window System	Powder-Coated Aluminium Frame	0.0022	2700	6	60	RCY	OneClick, ([132,133]
	Double Glazing	0.01	2500	26	30	LF	OneClick, [134,135] [136])
	Spacer Bar	0.00013	527	0.07	30	LF	OneClick, ([137])
	Silicone Sealant	0.00037	1200	0.46	25–30	LF	OneClick, [138,139]
	EPDM Gasket	0.00037	1800	1	30	LF	OneClick, ([140]; [141]
	Finishing Strip	0.01	528	3	60	LF	OneClick, ([142,143]
Outer Layer	Flashing & Cavity Closer Aluminium	0.0015	2700	4	60	RCY	OneClick, ([132,133]
	Vaproshim	0.0003	1200	0.36	30	LF	OneClick, [182]
	Aluminium Bracket aluminium	0.0017	2700	4	60	RCY	OneClick, ([132]; SA., 2023)
	Aluminium Vertical T-Profile	0.0043	2700	12	60	RCY	OneClick, ([165]; SA., 2023)
	Aluminium Horizontal Profile	0.0032	2700	9	60	RCY	OneClick, ([132]; SA., 2023)
	Brick Slips	0.041	1976	82	80	REU	OneClick, [183]

** End-of-life scenarios: REU – Reuse; RCY – Recycling; DCY – Downcycling; INC-ER – Incineration with energy recovery; LF – Landfilling.

Table B4
Material specifications for Cast-in-situ concrete (CIC) façade system, including volume, density, end-of-life scenarios, and data sources for each layer and component.

CIC	Material	Volume	Density	Weight (kg)	Lifespan (years)	EOL**	Source
Inner Layer	XPS Insulation	0.22	31	7	50	INC-ER	OneClick, [184]
	Breather Membrane	0.02	289	4	40	INC-ER	OneClick, [140,172])
Window System	Powder-Coated Aluminium Frame	0.0022	2700	6	60	RCY	OneClick, ([132,133]
	Double Glazing	0.01	2500	26	30	LF	OneClick, [134,135] [136])
	Spacer Bar	0.00013	527	0.07	30	LF	OneClick, ([137])
	Silicone Sealant	0.00037	1200	0.46	25–30	LF	OneClick, [138,139]
	EPDM Gasket	0.00037	1800	1	30	LF	OneClick, ([140]; [141]
	Finishing Strip	0.01	528	3	60	LF	OneClick, ([142]; [143]
Outer Layer	Concrete	0.66	2400	1578	40	DCY	OneClick, ([129]; [130]; [131])
	Steel Reinforcement Bars	0.005	7850	40	40	RCY	OneClick[129]

** End-of-life scenarios: REU – Reuse; RCY – Recycling; DCY – Downcycling; INC-ER – Incineration with energy recovery; LF – Landfilling.

Table B5
Material specifications for Rammed Earth (RE) façade system, including volume, density, end-of-life scenarios, and data sources for each layer and component.

RE	Material	Volume	Density	Weight (kg)	Lifespan (years)	EOL**	Source
Inner Layer	Clay Plaster Finish	0.03	1800	46	60	LF	OneClick, ([185–187]
	Clay Undercoat	0.08	1800	135	60	LF	OneClick,[186]
	Durra Panel Insulation	0.22	370	81	70	LF	OneClick, [121]
Window System	Powder-Coated Aluminium Frame	0.0022	2700	6	60	RCY	OneClick,([132,133])
	Double Glazing	0.01	2500	26	30	LF	OneClick, [134,135]; [136])
	Spacer Bar	0.00013	527	0.07	30	LF	OneClick, ([137])
	Silicone Sealant	0.00037	1200	0.46	25–30	LF	OneClick, ([138,139])
	EPDM Gasket	0.00037	1800	1	30	LF	OneClick, ([140]; [141]
	Finishing Strip	0.01	528	3	60	LF	OneClick, ([142,143]
Outer Layer	Steel T-Profile Lintel	0.01	7850	40	50	REU	OneClick, [174]
	Steel Reinforcement Bars	0.0011	7850	9	50	RCY	OneClick, [129]
	Rammed Earth Wall	0.77	2000	40	100	RCY	OneClick, [188]

** End-of-life scenarios: REU – Reuse; RCY – Recycling; DCY – Downcycling; INC-ER – Incineration with energy recovery; LF – Landfilling.

Table B6
Material specifications for Concrete Masonry Unit (CMU) façade system, including volume, density, end-of-life scenarios, and data sources for each layer and component.

CMU	Material	Volume	Density	Weight (kg)	Lifespan (years)	EOL**	Source
Inner Layer	Plasterboard	0.03	700	19	50	RCY	OneClick, [189]
	Metal top hats	0.0018	7850	15	60	RCY	OneClick, [190]
	Breather Membrane	0.02	289	4.5	50	INC-ER	OneClick, [176]; [177])
	Glass Wool Insulation	0.23	12	2.7	50	LF	OneClick, [170])
Window System	Powder-Coated Aluminium Frame	0.0022	2700	6	60	RCY	OneClick, ([165]; [190]
	Double Glazing	0.01	2500	26	30	LF	OneClick, [134]; [135] [136])
	Spacer Bar	0.00013	527	0.07	30	LF	OneClick, ([137])
	Silicone Sealant	0.00037	1200	0.46	25–30	LF	OneClick, ([137,138])
	EPDM Gasket	0.00037	1800	1	30	LF	OneClick, ([140]; [141]
	Finishing Strip	0.01	528	3	60	LF	OneClick, ([142]; [143])
Outer Layer	Reinforced Concrete Lintel	0.04	2386	89	40	DCY	OneClick, ([129]; [130]; [131])
	Mortar	0.02	2200	47	50	DCY	OneClick, [175]
	CMU	0.28	644	197	40	DCY	OneClick, [191]
	Plaster Morter	0.03	1000	31	50	DCY	OneClick, [181]

** End-of-life scenarios: REU – Reuse; RCY – Recycling; DCY – Downcycling; INC-ER – Incineration with energy recovery; LF – Landfilling.

Table B7
Material specifications for Hempcrete Block with CLT Frame (HC–CLT) façade system, including volume, density, end-of-life scenarios, and data sources for each layer and component.

HC–CLT	Material	Volume	Density	Weight (kg)	Lifespan (years)	EOL**	Source
Inner Layer	Sealer Coat			0.38	10	LF	OneClick, [128]
	Hemp Block 12 cm	0.3	330	99	100	DCY	OneClick, [118]
	Concrete Lintel	0.006	2386	15	50	LF	OneClick, ([129]; [130]; [131])
Window System	Powder-Coated Aluminium Frame	0.0022	2700	6	60	RCY	OneClick, ([132,133])
	Double Glazing	0.01	2500	26	30	LF	OneClick, ([134]; [135]; [136])
	Spacer Bar	0.00013	527	0.07	30	LF	OneClick, [137]
	Silicone Sealant	0.00037	1200	0.46	25–30	LF	OneClick, ([138]; [139])
	EPDM Gasket	0.00037	1800	1	30	LF	OneClick, ([140]; [141])
	Finishing Strip	0.01	528	3	60	LF	OneClick, ([142]; [143])
Outer Layer	Cross-Laminated Timber	0.35	480	170	60	LF	OneClick, [120]
	Concrete Lintel	0.011	2386	28	50	DCY	OneClick, ([129]; [130]; [131])
	Hemp Block 20 cm	0.488	330	161	100	LF	OneClick, [118]
	Sealer Coat			0.38	10	LF	OneClick, [128]

** End-of-life scenarios: REU – Reuse; RCY – Recycling; DCY – Downcycling; INC-ER – Incineration with energy recovery; LF – Landfilling.

Data availability

Data will be made available on request.

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