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ADVANCED MATERIALS' LIFE CYCLE ASSESSMENTS: LCA OF ALTERNATIVE BINDERS FOR ENGINEERED WOOD PRODUCTS

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Abstract: Engineered wood products EWPs, seldom assess the off-site incorporation of glues, epoxy resins and binders. To address this gap, a life-cycle assessment (LCA via SimaPro) of four adhesives is presented: melamine-urea-formaldehyde (MUF); polyurethane (PUR); a hybrid PUR-Soy adhesive; and, an adhesive-free dowel-laminated timber (DLT) system. The functional unit of the amount of adhesive required for 1m³ of cross-laminated-timber CLT is adopted within a cradle-to-gate scope. Environmental impacts are quantified across the key indicators of: global warming potential; eutrophication; ozone depletion; and, fossil fuel depletion. Results are normalised and aggregated using a weighted eco-point framework informed by Western Australian practitioner feedback. Supplementary modelling provided by XLam extended the analysis, evaluating the influence of adhesives on end-of-life scenarios such as recycling, energy recovery, landfill and reuse. Results show that MUF exhibited the lowest eco-point score overall despite the partial organic material substitution in PUR-Soy; however, findings show that adhesives contribute only 1.7-2.2% of the environmental burden of a whole CLT product representing a negligible impact. Despite this relatively minor contribution during the off-site production phase, further cradle-to-cradle analysis revealed that end-of-life EoL disposal pathways have a critical influence on the overall environmental scores of the CLT products, with over 200% variation depending on the scenario chosen. If adhesives are found to directly restrict viable disposal options, then they will play a much more critical role in determining the environmental impacts of engineered wood products. This work recommends continued innovation in bio-based and mechanical bonding systems and development of specific legislation for the disposal of EWPs with regard to adhesive contents, to allow a clearer understanding of the full impacts of these advanced materials.

Keywords: Advanced-Materials; Life-Cycle-Assessment; Composite-Timber; Adhesives

1 INTRODUCTION

Sustainability is increasingly shaping the trajectory of design, material selection and policy in the construction industry. According to the International Energy Agency, the building sector is responsible for over one-third of global final energy consumption and contributes to nearly 40% of total carbon dioxide emissions (Duan et al., 2022). In light of the challenges posed by climate change, the materials chosen for construction play a pivotal role in reducing the environmental footprint of the construction industry.

Timber has emerged as a key material in the pursuit of sustainable construction, largely due to its renewability and carbon storage potential. Duan et al. (2022) demonstrated through a life cycle assessment (LCA) that cross-laminated timber (CLT) buildings account for approximately 15% fewer greenhouse gas emissions compared to their reinforced concrete counterparts. Furthermore, when sourced from sustainably managed forests, wood can act as a long-term carbon sink. Buchanan and Levine (1999) reported that a 17% increase in wood usage within the building sector could result in a 20% reduction in carbon emissions.

The growing awareness of environmental issues, coupled with advancements in engineered wood products, such as CLT and laminated veneer lumber (LVL), has driven global interest in timber-based construction. However, a potential limitation to the environmental performance of these systems lies in the synthetic adhesives used to bond the timber layers.

Petrochemical-based adhesives not only emit harmful volatile organic compounds (VOC's) during production and use but may also hinder the reusability and safe disposal of the products at the end of their life cycle (Taylor et al., 2005). Despite these concerns, traditional adhesives remain the industry standard, largely due to their well-established mechanical properties and availability.

Similar comparative LCA's of synthetic adhesives such as the one conducted by Messmer and Hellweg (2015) have recommended that measures such as reducing the amount of raw material or substituting the raw material with renewable materials could be considered to reduce the impacts from adhesives used in engineered wood products. Recent research has identified promising solutions, including soy protein-based adhesives (Mary et al. 2024) and dowel-laminated timber (DLT) systems that eliminate adhesive altogether (Han et al., 2023) but these have not been compared in an LCA format for the construction industry. These innovations represent important steps toward maximising the environmental benefits of timber construction while addressing the challenge associated with conventional binding methods. The following discussion seeks to explore these alternative binders further.

2 LITERATURE REVIEW

The construction sector is one of the largest contributors to global greenhouse gas emissions, accounting for approximately 40% of total CO2 emissions and 35% of global energy consumption (Younis and Dodoo, 2022). As urban populations grow to a projected 70% of the global total by 2050, the demand for infrastructure and housing is expected to rise sharply, placing even greater emphasis on the adoption of sustainable construction solutions (Duan et al., 2022).

Engineered wood products (EWPs) have emerged as prominent alternatives to traditional materials like concrete and steel. These timber-based solutions offer substantial environmental advantages, including carbon sequestration, lower embodied energy and improved thermal performance (Messmer and Hellweg, 2015; Guan et al., 2018). In Europe, where sustainability standards are particularly advanced, the consumption of glue-laminated timber (GLT) almost doubled in the early 21st century, reaching approximately 3 million cubic metres in 2012 (Messmer and Hellweg, 2015). The expansion of the EWP market is closely tied to advances in engineering, manufacturing processes and digital design tools that have enabled the use of timber in larger and more complex structures. Tehrani and Froese (2017) noted that these developments, coupled with growing environmental awareness, have facilitated a resurgence in wood construction, especially for mid to high-rise buildings. Cross-laminated timber (CLT), in particular has been instrumental in redefining timber's role in modern construction. Syahirah et al. (2025) report that the global production capacity of CLT stood at approximately 2.8 million cubic metres in 2020, with Europe contributing 48% and North America 43%. Projections suggested that this figure will rise to 4 million cubic metres by 2025, reflecting sustained international demand for timber-based construction solutions.

The momentum for usage of timber in construction was affirmed at the COP28 in 2023, where 17 countries, including Australia, committed to advancing the use of sustainably managed wood in the built environment. This supports what van Veelen and Knuth (2023) describe as a new 'urban age of timber', characterised by mass timber technologies, modularity and circular design principes.

In the Australian context, similar trends are evident, although the scale and pace of adoption differ. Langenberg et al. (2010) wrote that the government-led initiatives such as the Green Building Council's 'Green Star' rating system and the Victorian Government's '5 Star' energy rating scheme have promoted the use of energy-efficient technologies and environmentally friendly materials in both commercial and residential projects. Australia's construction industry is gradually aligning with global sustainability objectives. However, challenges remain in terms of mainstream adoption, regulatory adaptation and overcoming the entrenched use of traditional materials like concrete and steel. Nevertheless, the foundational frameworks and rising awareness of environmental issues place Australia in a favourable position to accelerate its transition towards low-carbon construction methods (Langenberg et al. 2010; Tehrani and Froese, 2017).

In the Australian context, a notable example of the use of EWPs is the Forte building in Melbourne, which stands as one of the world's first multi-storey residential buildings constructed primarily from cross-laminated timber (CLT). Completed in 2012, the 10-story structure represents a landmark achievement in sustainable design and construction, illustrating the feasibility of large-scale timber projects in urban environments. The building achieved a 22% reduction in global warming potential compared to an equivalent reinforced concrete structure, as reported by Sotayo et al. (2019). This reduction was attributed to several factors, including the carbon sequestration capacity of timber, the lower embodied energy associated with CLT production, and the efficiency of prefabrication and assembly processes that minimise on-site waste and construction time. The Forte building highlights the potential for EWPs to challenge conventional materials not only in environmental performance but also in structural capability, acoustic insulation and fire safety, areas once considered barriers to tall timber construction.

Duan et al. (2022) reports that adhesives and resin systems contribute significantly to the global warming potential (GWP) of mass timber structures. In a life cycle assessment study, he found that in LVL assemblies, phenol resorcinol-formaldehyde (PRF) resin, a more outdated adhesive system, accounted for approximately 20% of the total GWP. Even in cradle-to-gate assessment, which exclude emissions from the usage and disposal phases, the resin system still accounted for nearly one-third of environmental impacts, underscoring their substantial footprint (Duan et al., 2022).

Environmental performance data on adhesives, especially polyurethane PUR, remains relatively scarce. Although PUR is increasingly used in CLT and other EWP applications due to its favourable mechanical properties and low formaldehyde emissions, Messmer and Hellweg (2015), in their own LCA of these traditional adhesives, emphasise that comprehensive comparative LCA data is still lacking. Their analysis shows that PUR, MUF and PRF adhesives carry notable environmental and health risks, underscoring the need for more detailed evaluation and regulation. They also state that an option to improve the environmental performance of these adhesives would be to replace the petrochemical raw materials with renewable and sustainable materials. However, studies observing the feasibility of these renewable wood adhesives used in wood construction were nominal in literature.

Further life cycle concerns arise for these adhesives used in EWPs, particularly at the end-of-life (EOL) phase. Despite the growing deployment of mass timber systems such as CLT in construction, relatively few buildings have reached the end of their service lives. As Younis and Dodoo (2022) state, the limited availability of data from real EOL scenarios makes it challenging to evaluate how these materials perform post-demolition, especially in regard to reuse, recycling and energy recovery. However, existing knowledge on the material composition of EWPs and the adhesives points to several challenges. Glue-laminated products, particularly those using thermosetting adhesives, such as MUF and PRF, are not fit to be recycled due to the irreversible curing properties of the binders. Guan et al. (2018) supports this by highlighting that recycling is further complicated by the presence of adhesives and metallic fasteners in EWPs. These embedded components reduce the purity of recovered material streams and limit the options for secondary applications. In many cases, the default treatment becomes landfilling, which constitutes a direct emission to land and is inconsistent with circular economy principles. This is reinforced by Sotayo et al. (2020) who point out that these traditional adhesives compromise the overall reusability and recyclability of engineered timber, potentially reducing its sustainability credentials despite the benefits observed during the construction phase.

2.1 BINDERS

The growing environmental and health concerns related to synthetic adhesives have catalysed substantial research into sustainable alternative binding options for EWPs. Mary et al. (2024) explored a hybrid approach that blended soy protein directly into existing polyurethane (PUR) systems which produced promising results; however, many of these alterations still rely on synthetic bases which limits the adhesives classification as fully 'green' solutions (Balducci et al., 2020; Langenberg et al., 2010). In contrast, some researchers have sought to reduce or eliminate synthetic components entirely. Yauk et al. (2020) highlighted work by Li, which developed a cold-set soy-based adhesive for CLT panels. Mary et al. (2024) offered a complementary perspective, with a blended soy protein and PUR system. The soy-enhanced PUR formulations, specifically with a 20% soy substitution achieved the highest block shear strength, even compared to an untampered PUR test. These hybrid systems demonstrated improved setting time and better substrate penetration; factors directly correlated with enhanced mechanical adhesion. Such results suggest that while soy in its pure form may lack sufficient bonding strength, its role as a performance-enhancing additive in partially synthetic systems is promising.

In contrast to chemically bonded adhesives, mechanical fastening systems such as dowel-laminated timer (DLT) offers an adhesive free approach to wood assembly. DLT uses conditioned or compressed wood dowels to join timber lamellas, relying on moisture-induced swelling to achieve a tight, durable fit (Sotayo et al., 2019). This system draws from centuries-old woodworking traditions and was revitalised in the 1970s for use in modern engineered wood applications (Han et al., 2023).

Across these studies, a consistent trade-off emerges. Soy-based adhesives, especially when chemically enhanced, can offer mechanical performance which approaches and even in some cases surpasses traditional adhesives, whereas adhesive-free systems like DLT currently fall short in stiffness and peak load capacity. A key distinction is that the adhesive solutions, although environmentally motivated, still rely heavily on synthetic modifications such as PAE or PUR, thereby diluting their 'green' classification. Meanwhile, purely mechanical systems maintain ecological purity but must address issues such as stress relaxation, creep and load redistribution to become more competitive with traditional adhesive systems.

Balducci et al. (2020) notes, several commercial adhesive systems derived from soy protein bases, such as Soyad, Kymene and Soybaby, already in use in plywood, particleboard and structural flooring systems. Sotayo et al. (2019) reports that THOMA Holz100, a DLT system using beech dowels in a cross and diagonal-lamination patterns, already secures a European technical assessment and is in use in over 300 buildings worldwide. Similarly, StructureCraft's DowelLam, a dowel-laminated mass timber product manufactured in North America, recently became the first of its kind to receive ICC-ESR-4069 certification. This report confirms its compliance with several editions of the International Building Code and other major US and Canadian standards, marking a key milestone in North American regulatory recognition of DLT.

2.2 LIFE-CYCLE ASSESSMENT LCA

In a comparative life-cycle assessment LCA of structural flooring systems in Western Australia, Hahnel et al. (2021) employed an eco-point system informed by local practitioner input. This approach led to prioritisation of environmental values such as global warming potential, eutrophication, ozone depletion, fossil fuel depletion and mineral depletion. By contextualising environmental weighting to regional relevance, such methods offer a more practical guidance for material selection in localised building contexts. Indeed Whyte (2014) discussed the British Research Establishment's use of eco-points and eco-costs as a part of a broader decision-making framework in sustainable construction. These strategies highlight balancing scientific precision with communicative clarity, especially when engaging designers, engineers and clients.

3 METHODOLOGY

This methodology presents an LCA approach, conducted in accordance with ISO 14040/44, covering system boundaries, functional units, data sources and impact assessment methods. Together, these components provide a holistic framework for evaluating and comparing the binder systems. The 4 binders under examinations for engineered wood are:

MUF: a formaldehyde-based thermosetting resin commonly used in industry. It is synthesized through the condensation of formaldehyde, urea and melamine, resulting in a three-dimensional network of cross-linked polymers. The typical molar ratio used in production is 2.5:10:0.3 for the relative components mentioned, with a solid content around 60-65% (Messmer and Hellweg, 2015).

PUR adhesives: a two-component system of isocyanates (typically methylene diphenyl diisocyanates, MDI) and polyols, which react to form a durable urethane linkage. The typical industrial formulation contains approximately 60-70% MDI-based prepolymer and 30-40% polyester polyols (Messmer and Hellweg, 2015). The inclusion of PUR in this study reflects its growing market share and role as a formaldehyde-free synthetic baseline for comparison.

Soy-based: the adhesive properties of soy-protein-based adhesives derive from the reactivity of soy protein's amino acid side chains, which provide multiple bonding sites. However, native soy adhesives suffer from high viscosity, poor water resistance and low mechanical strength (Islam et al., 2022).

Dowel Lamintaed Timber DLT: DLT is a mass timber construction system that achieves structural bonding through purely mechanical means, without the use of adhesives or synthetic chemicals entirely. However, it does typically present structural limitations, with bending stiffness and flexural strength typically 50-70% lower than glued alternatives (Yeh and Yeh, 2024; Guan et al., 2018).

The life-cycle inventory LCI developed for each of the binder systems is simulated under the defined function unit of a 1m2 30cm thick (0.3m3) EWP panel as the system boundary, with data compiled from a combination of data found in literature, and online in published life cycle databases in SimaPro across the variables of: raw-materials; transport; and manufacturing. In this study, uncertainty analysis is conducted using Monte Carlo Simulation function within the life cycle database software of SimaPro. Feedback gathered from industry professionals, a leading engineered wood product manufacturer in Western Australia and an experienced chartered structural engineer informs and validates the interpretation of the life cycle assessment results and end-of-life treatment of engineered wood products.

4 RESULTS

The results below (table 1) indicate that MUF adhesives perform better than both PUR and PUR-Soy in three of the four impact categories: global warming, eutrophication and ozone depletion. However, it performs significantly worse in fossil fuel depletion. This reflects the inherent trade-offs between using highly processed petrochemical-based systems and those incorporating bio-based components.

Table 1: LCA outputs for adhesive systems required for 1m3 CLT

Indicator	MUF	PUR	PUR-Soy
Global Warming (kg CO2 eq)	5.3715	5.64318	5.98118
Eutrophication (kg N eq)	0.00184021	0.00701535	0.00793135
Ozone Depletion (kg CFC-11 eq)	0.000000141007	0.000000578623	0.000000760723
Fossil Fuel Depletion (MJ Surplus)	18.3163	13.4008	12.5998

A weighted analyses utilising the eco-point method outlined above is tabulated in table 2 below:

Table 2: Eco-point conversion of LCA outputs for adhesive systems required for 1m3 CLT

Indicator (Eco-Points)	MUF	PUR	PUR-Soy
Global Warming	0.012058047	0.012667919	0.013426668
Eutrophication	0.002375185	0.009054812	0.010237107
Ozone Depletion	0.00000780471	0.0000320267	0.0000421059
Fossil Fuel Depletion	0.008676609	0.006348089	0.005968647
Total	0.023117645	0.028102847	0.029674528

The total eco-point scores reveal that MUF (0.023) exhibits the lowest overall environmental impact from a cradle-to-cradle perspective, followed by PUR (0.028) and PUR-Soy (0.03).While this ranking suggests that the traditional MUF adhesive is the most sustainable option, the interpretation of weighted scores requires consideration of trade-offs between categories and subjective weighting priorities used. The following graphic (figure 1) describes the eco-point scores for adhesives production for a 1m3 CLT product.

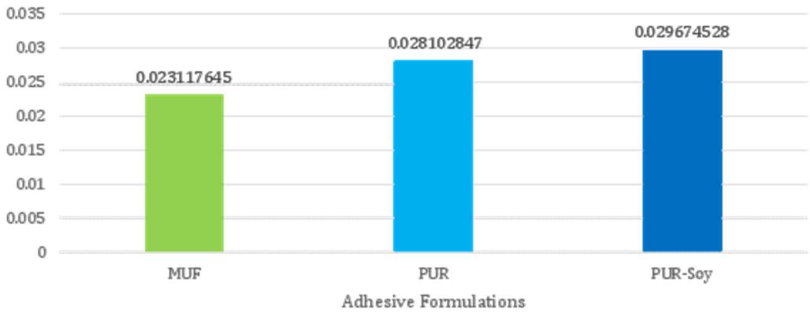
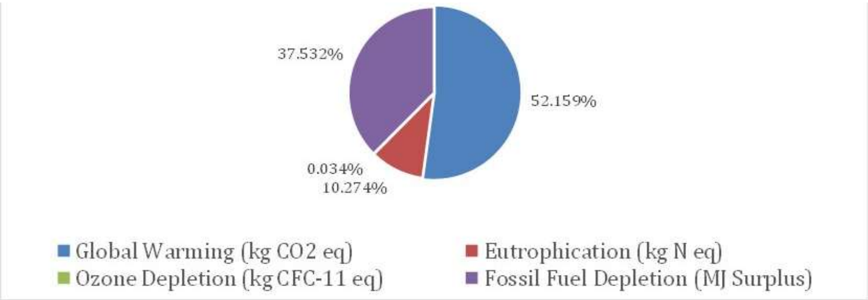


Figure 1: comparison of eco-point scores for the production of adhesives required for a 1m3 CLT product

The following graphics illustrate respectively, relative contributions of: MUF environmental indicators (figure 2); PUR adhesives (figure 3);



. Figure 2: contribution of environ. indicators to the overall eco-point score for MUF adhesive for 1m3 CLT

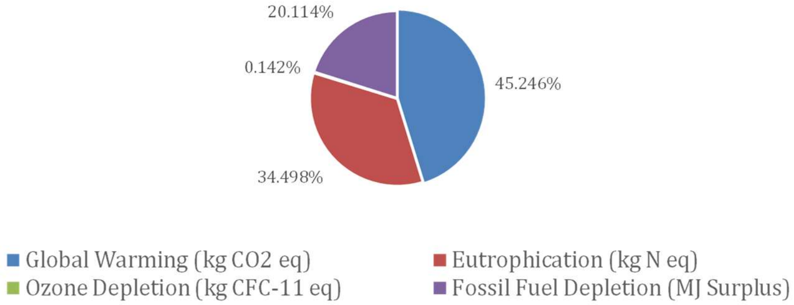


Figure 3: contribution of environ. Indictors to overall eco-point score for PUR-soy-adhesives for 1m3 CLT

As seen in figures 1, 2 & 3 above, global warming contributes the greatest share to the total Eco-Point scores for each adhesive, representing roughly 50% of the total weighted impact. This dominance highlights the central role of energy-related emissions in adhesive life cycles, consistent with global environmental priorities and with previous LCA findings by Messmer and Hellweg (2015), who identified greenhouse gas emissions as the primary driver of environmental damage in synthetic resin production.

In contrast, the ozone depletion potential contributes negligibly to the total scores, with values on the order of 10-5 Eco-Points, confirming that this impact category is relatively minor in the context of adhesive production. This low significance is consistent with the declining use of ozone-depleting substances in chemical production due to internation regulation, meaning that differences among adhesives in this category have minimal practicable relevance. Furthermore, the much higher eutrophication contribution observed in the PUR and PUR-Soy based systems significantly drives their overall scores upward and is a key reason for the discrepancy with MUF. This can be attributed to nutrient emission mechanisms involved in agricultural usage and polyurethane production processes.

Analyses were replicated for the remaining 2 adhesives, with the conclusions' discussions below summarising subsequent findings' comparisons. Relatedly, the end-of-life ecopoint comparison conducted for the proprietary EWP test-sample (of the engineered wood product XLAM by major Australian cross-laminated-timber CLT supplier) is shown below in figure 4, and shows how energy recovery and reuse offer the potential to turn these products into environmentally positive, carbon-offsetting/ recyclate materials.

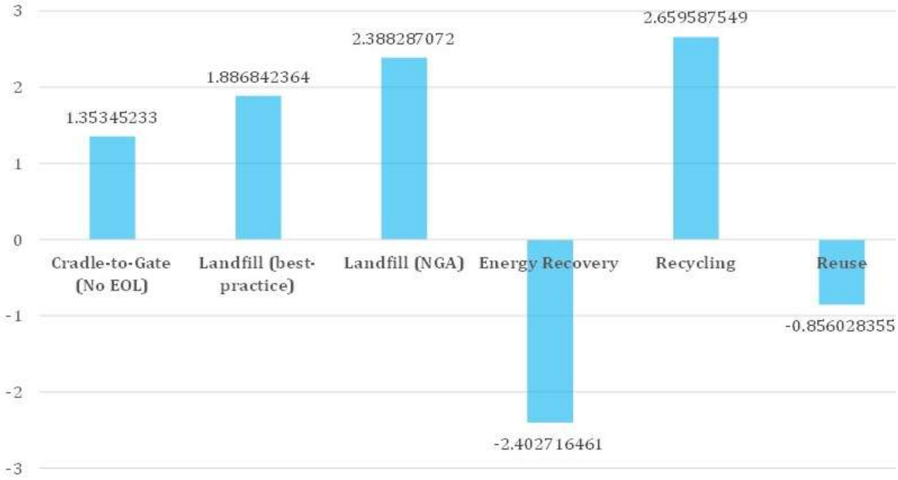


Figure 4: XLAM CLT end-of-life Eco-point comparison

5 CONCLUSIONS

Based on the analysis of the results, several key conclusions can be drawn regarding the environmental performance of adhesive systems in engineered wood products, particularly in CLT panels.

From a cradle-to-gate perspective, the comparison of eco-point scores for MUF, PUR and PUR-Soy adhesives reveal slight differences across impact categories. The total adhesive eco-point scores were 0.023 for MUF, 0.028 for PUR and 0.030 for PUR-Soy. This indicates that MUF has the lowest overall environmental impact among the adhesives, followed by PUR and then PUR-Soy. The differences between these adhesives finds that MUF performs 21% better than PUR, and 28% better than PUR-Soy environmentally. This comparison highlights the trade-offs inherent in adhesive selection: while bio-based or hybrid systems like PUR-Soy reduce fossil fuel depletion, they tend to increase impacts in global warming, eutrophication, and ozone depletion due to additional agricultural inputs, and introduce further energy-intensive processing requirements.

Despite these differences, the contribution of adhesives to the total environmental impact of a CLT product remains relatively minor. When the adhesive eco-points are compared to the total eco-points of a 1m³ CLT panel, the adhesives contribute between 1.7% (MUF) and 2.2% (PUR-Soy) to the overall product score. This indicates that while adhesives are chemically intensive, the bulk of the environmental burden originates from the extraction, production and manufacturing of the timber itself, which dominates across all impact categories, particularly global warming and fossil fuel depletion. The relatively small proportional contribution of adhesives underscores that optimising timber sourcing and manufacturing efficiency is more influential than adhesive selection for reducing the overall environmental footprint of CLT products.

However, the analysis of end-of-life scenarios introduces a critical point of difference. The eco-point modelling shows that different disposal and recovery pathways of energy recovery, reuse, recycling and landfill, can dramatically alter the environmental performance of the CLT panels. While the adhesives themselves contribute minimally to cradle-to-gate impacts, their chemical composition and bonding characteristics may significantly affect the feasibility of certain EoL strategies in a cradle-to-cradle perspective. Thermoset adhesives, for example, make mechanical recycling difficult by binding lamellae permanently, which reduces fibre quality and forces downcycling. Due to potentially toxic VOC's (formaldehyde and isocyanates) during combustion of these adhesives, high-temperature gas retention energy-to-waste facilities must be designed, which are expensive and potentially politically divisive. Similarly, high-strength adhesives can also impede the careful dismantling needed for high-value reuse, limiting the practical recovery potential of CLT panels.

These findings imply that the true environmental influence of adhesives may be far more significant when considering cradle-to-cradle perspectives. If adhesive chemistry constrains reuse, combustion or recycling, it could become one of the most critical factors in determining the long-term sustainability of engineered wood products. Compared to the cradle-to-gate eco-points based on production of a CLT product (+1.35 eco-points), the variation in eco-points across end-of-life scenarios, ranging from a net benefit under energy recovery (-3.76 eco-points) to substantial net burdens under recycling (+1.31 eco-points) or landfill (+0.53 to +1.03 eco-points), illustrates the potential scale of this effect. Consequently, while adhesives currently represent a small portion of total product impacts, their effect on material circularity and end-of-life viability could have disproportionately large consequences for the overall environmental performance of CLT and similar engineered wood products.

In conclusion, the study has partially achieved its objectives. It has clearly identified and compared the environmental performance of alternative adhesive systems and quantified their relatively minor contribution to total CLT impacts, fully addressing the cradle-to-gate objectives. However, the extent to which these adhesives and other systems such as DLT influence end-of-life management remains only partially resolved. While the results discussion indicate that adhesives may restrict recycling, reuse or energy recovery pathways, the precise mechanisms and degree of impact are still somewhat unknown.

6 RECOMMENDATIONS

Based on the conclusions of this study, several recommendations can be made to advance both research and industry practice regarding adhesives and engineered wood products.

Firstly, the continual development of bio-based and other novel adhesives such as adhesive-free DLT presents both opportunities and challenges. The perception that bio-adhesives, which offer a partial substitution of petrochemical substances with organic materials, offer improved environmental performance is not substantial. Rather than partial substitution, development of bio-adhesives should be focused on ensuring that the bulk of materials used are organic, or even seek complete removal of petrochemicals to truly see the environmental benefits which have been claimed. As mentioned, Yauk et al. (2020) highlight a cold-set soy-based adhesive for CLT panels that is proposed to eliminate any petrochemical elements. This adhesive has since been commercialised and patented by Solenis as Soyad®, with production processes and formulation details protected by IP rights, restricting further access to critical LCI information.

This leads to the next recommendation regarding the lack of transparency in environmental product declarations EPDs and LCA publications provided by companies; this limits researchers' ability to conduct comprehensive comparative LCAs and therefore constrains the promotion and validation of such bio-based innovations in sustainability frameworks. To address these challenges, companies might provide a more detailed disclosure of LCI inputs, assumptions and methodological choices used for declarations of their products. Such transparency would allow replication, verification and further investigation of environmental performance using tools such as SimaPro, improving the credibility of assessments and supporting informed, objective decision-making by manufacturers and designers. Regulatory or government-led requirements for detailed product breakdowns could therefore play a key role in ensuring that sustainability claims are verifiable and that innovative adhesives are appropriately evaluated across their full life-cycle.

There is also a clear need to better understand the extent to which adhesives affect end-of-life disposal capabilities of EWPs. While the results suggest that adhesives may restrict certain recovery pathways such as recycling, energy recovery or high-value reuse, there is a lack of existing standards and regulations in industry. This needs to be developed further as it is the critical component concerning the extent to which adhesives may impact engineered wood products over whole life-cycles. Future research should focus on quantifying how different adhesive chemistries and bonding methods influence the feasibility of disassembly, material separation and recycling efficiency. Such studies could inform practical guidelines for product design, waste management and policy, helping to ensure that adhesives do not inadvertently constrain circularity. Designing binders that enable easier separation of panels or components would facilitate reuse and recycling, reduce energy requirements and improve the overall environmental performance of the product across a full life-cycle. This approach, combined with transparent LCA reporting and careful end-of-life planning, would help maximise sustainability, support circular material flows and guide policy and industry practices toward more environmentally responsible engineered wood products.

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