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Cold-Press Manufacturing of Laminated Bamboo and Bamboo–Timber Composites for Sustainable Construction: A Life-Cycle Carbon Assessment

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Abstract

This study examines a cold-press manufacturing method for laminated bamboo and bamboo-timber composites, together with a cradle-to-gate carbon footprint analysis of the produced materials. The proposed material systems are assessed as alternatives to conventional engineered bamboo and to widely used construction materials such as structural steel, concrete, and aluminum. Existing engineered bamboo products are typically manufactured using hot pressing and formaldehyde-based adhesives, both of which contribute to their environmental burden. The present work, therefore, considers a more practical and environmentally responsible route based on lower-energy processing and lower-emission adhesive systems. Following a cradle-to-gate carbon footprint analysis of the produced materials, the embodied carbon values obtained for the four systems are 404.8, 310.8, 264.8, and 197.5 kg CO_2e/m^3 for BBE, BPA, CBE, and CPA specimens, respectively. Relative to conventional hot-pressed laminated bamboo, these values correspond to embodied-carbon reductions of 32.0%, 47.8%, 55.5%, and 66.8%. When the biogenic carbon stored in the bamboo and pine biomass is included, the net carbon balances become −484.0, −619.0, −646.1, and −631.2 kg CO_2e/m^3. These results show that the proposed engineered bamboo and bamboo-timber composites offer a feasible low-carbon option for construction applications.

Keywords: cold-press manufacturing; laminated bamboo; bamboo–timber composites; engineered bamboo; sustainable manufacturing; life-cycle assessment (LCA); embodied carbon; bio-based materials

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1. Introduction

Bamboo is a naturally renewable resource with a rapid growth cycle which reaches maturity within three to five years, compared to several decades for most timber species [1]. Bamboo offers a superior strength-to-weight ratio and favourable mechanical performance, which makes it an attractive material for construction applications [2]. Bamboo can reduce dependence on traditional timber and less sustainable construction materials. Despite these advantages, natural bamboo has limitations that restrict its widespread structural use. Bamboo's mechanical properties vary with species, culm region, age, preparation method, and moisture content [2–5]. In addition, the hollow geometry of bamboo makes it vulnerable to splitting and buckling under load [6,7]. For these reasons, raw bamboo is often considered less reliable for demanding structural applications.

To address these limitations, bamboo has increasingly been used in engineered forms produced through processes such as resin impregnation and hot pressing [8]. These methods improve dimensional stability, reduce variability, and enhance structural performance. However, the performance of engineered bamboo depends strongly on adhesives and pressing conditions. Pressing temperature, applied pressure level, and duration influence density, fibre bonding, and mechanical properties [9,11]. In engineered laminated bamboo, weak adhesive layers may lead to premature bond-line failure, whereas in scrimber products, deeper resin penetration can improve fracture resistance and overall structural efficiency [4,10]. The strong dependence on processing conditions means that the sustainability and reliability of engineered bamboo cannot be assessed solely through material properties but must also be examined through the manufacturing route itself.

1.1. Research Gaps in Engineered Bamboo Materials

Several gaps remain in the existing literature related to engineered bamboo materials. For example, studies on bamboo–timber hybrid composites are still limited, even though partial replacement of timber with bamboo could reduce wood consumption in engineered renewable materials [11]. In such hybrids, incompatibilities in hygroscopic and thermal behaviour between bamboo and timber may generate warping, internal stresses, and cracking, yet studies on hygrothermal effects in these systems remain scarce [12]. Another important issue is adhesive sustainability. Many engineered bamboo products currently in use still depend on petrochemical adhesive systems, particularly phenol–formaldehyde (PF) and urea-formaldehyde (UF) or melamine–urea–formaldehyde (MUF) resins, which raise environmental concerns due to their fossil-based origin and potential formaldehyde (HCHO) emissions [13].

Another limitation is the scarcity of long-term durability data under realistic service conditions. Only a small number of studies have investigated the effects of moisture cycling, thermal ageing, or fungal exposure, and the available results are often difficult to interpret because the exposure conditions vary considerably and control specimens are not always included [2,11,14]. Standardization remains an additional challenge. The use of different specimen sizes, loading directions, and test standards, including ASTM D143 [15], ISO 22157 [16], and GB 50005 [17], has made direct comparison between studies difficult and has slowed the development of reliable databases for engineered bamboo systems [14].

1.2. Research Gaps in Engineered Bamboo Manufacturing

Methodological limitations in the literature are not confined to testing standards alone. The reliability of engineered bamboo depends heavily on adhesive performance, yet important parameters such as solid content, spread rate, and curing profile are frequently not reported. Likewise, microscopic assessment of bond-line quality and careful monitoring of failure modes are seldom included, even though both are essential for evaluating the effectiveness of the adhesive system. Most available studies also remain limited to controlled uniaxial laboratory tests, while validation at the field scale under realistic mechanical and environmental conditions is still scarce. As a result, meaningful comparison between different manufacturing routes remains difficult, particularly when sustainability must be considered together with structural behaviour [14]. Within this context, there is a clear need for engineered bamboo systems that reduce energy demand during production while maintaining adequate bonding quality, dimensional stability, and fabrication consistency. The manufacturing process developed in this study was conceived with this need in mind.

1.3. Life-Cycle Carbon Assessment of Engineered Bamboo

Studies that assess the environmental suitability of engineered bamboo through life-cycle assessment are still limited, especially when renewable or low-emission adhesive systems are involved. Although engineered bamboo is widely regarded as a sustainable material, relatively few studies have examined its environmental suitability through life-cycle assessment, particularly in relation to renewable or low-emission adhesive systems. Van der Lugt et al. [18], for example, reported that bamboo-based construction materials can achieve negative life-cycle carbon balances when biogenic carbon storage is taken into account. Li et al. [19] quantified the energy demand associated with hot pressing in glued laminated bamboo, while Liu et al. [20] further showed that bamboo materials can store substantial amounts of carbon in their biomass, in some cases exceeding the emissions generated during the manufacturing of engineered bamboo. This is important because existing engineered bamboo products continue to rely largely on petrochemical binders such as PF, UF or MUF resins, which introduce a clear sustainability trade-off [11].

While the development of cold-press laminated bamboo and bamboo–timber composites may help address the need for lower-emission manufacturing, process innovation alone may not be sufficient to establish environmental suitability. Engineered bamboo is often regarded as a sustainable material because of its renewable origin, yet the overall climate benefit of the final product depends not only on the bio-based carbon retained in the bamboo and timber phases, but also on the emissions associated with adhesive production and specimen fabrication. This distinction is particularly important for engineered bamboo systems, where the choice of resin and the manufacturing route can substantially influence the environmental balance of the material. Although existing products are commonly manufactured through resin impregnation and hot pressing, which require substantial energy input, the present study adopts a cold-press route specifically to reduce this burden. A life-cycle carbon assessment is therefore needed to determine whether the reduction in processing energy, together with the use of alternative adhesive systems, translates into a measurable embodied-carbon advantage. Such an assessment also makes it possible to examine the extent to which the stored biogenic carbon in the composite offsets the emissions generated during production, thereby providing a more complete basis for evaluating the sustainability of the proposed manufacturing approach.

The primary objective of this study is to establish a low-emission and low-energy manufacturing framework for laminated bamboo and bamboo–timber composites that can support future structural applications. While the broader study also considers mechanical behaviour and numerical modelling, the present paper focuses on the manufacturing process itself, including adhesive selection, strip preparation, layup configuration, moisture-related considerations, and the elimination of hot pressing as a sustainability measure, in addition to a cradle-to-gate carbon footprint analysis. In this way, the work responds to the need for more sustainable adhesive systems, improved fabrication consistency, and less energy-intensive processing routes for engineered bamboo composites. Because the environmental suitability of engineered bamboo depends not only on renewable feedstock but also on the emissions associated with adhesives and manufacturing, the study further incorporates a screening-level cradle-to-gate life-cycle assessment. This makes it possible to evaluate whether the proposed cold-press route provides a meaningful embodied-carbon advantage and to assess the balance between production-related emissions and the biogenic carbon stored in the composite system.

2. Materials and Manufacturing of Engineered Bamboo Specimens

A total of 36 innovative samples of laminated bamboo and bamboo-timber composites using the cold hydraulic press process were designed and manufactured. Among the innovative samples, unprecedented hybrid composite samples of bamboo-timber composite materials were developed by combining bamboo and pinewood strips in an alternating format. The specimen matrix was designed to study both the effect of the adhesive type and the effect of the material composition (Table 1). Four main cross-sectional configurations, BBE, BPA, CBE, and CPA, were compared to study both the influence of the adhesive type and the effect of the material composition.

Table 1. Production matrix of engineered bamboo and hybrid bamboo-timber composite specimens.

Group ID	Specimen Type	Specimen Dimensions (mm)
BBE	Laminated bamboo using bio-epoxy adhesive	40 × 40 × 155
BPA	Laminated bamboo using Polyvinyl Acetate (PVA) adhesive	40 × 40 × 155

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Group ID	Specimen Type	Specimen Dimensions (mm)
CBE	Hybrid composite bamboo-timber using bio-epoxy adhesive	40 × 40 × 155
CPA	Hybrid composite bamboo-timber using PVA adhesive	40 × 40 × 155

2.1. Composite Configuration

As mentioned earlier, four main cross-sectional configurations were manufactured. These configurations were BBE, BPA, CBE, and CPA. The BBE configuration represents bamboo bonded using bio-epoxy, while BPA represents bamboo bonded using PVA. Similarly, the CBE configuration represents composite bamboo-timber bonded using bio-epoxy, while CPA represents composite bamboo-timber bonded with PVA.

The development of composite members using an alternating bamboo-timber configuration introduces a balanced structural design that enhances stress transfer and dimensional stability. In existing bamboo-timber designs, differences in hygroscopic expansion, shrinkage, and swelling lead to undesirable internal stress development, delamination, or surface cracking. By alternating bamboo and timber strips throughout the cross-section, these dimensional variations are balanced layer by layer, which leads to more uniform stress distribution and improved dimensional stability. The proposed hybrid layup distributes mechanical and thermal stresses more evenly across the interface, which can improve bond quality, stress transfer efficiency, and long-term structural reliability.

The raw materials used in this study were selected to support the development of laminated bamboo and bamboo–timber composites produced through a cold-press manufacturing route. The selected constituents included bamboo and timber strips as the main structural phases, along with two adhesive systems used to evaluate the influence of bonding type on specimen fabrication. The raw materials used to produce the proposed engineered bamboo specimens are described in this section.

2.2. Bamboo and Timber

Caramelized Moso bamboo and pinewood timber were used to manufacture the specimens. A total of thirty-six specimens were manufactured using a novel combination of bamboo and pinewood strips to verify the manufacturing consistency of the specimens. Among these samples, 18 unprecedented hybrid bamboo-timber composite specimens were developed by integrating both bamboo strips and pinewood timber in an alternating layered format. Through integrating timber and bamboo, these proposed specimens were expected to improve bonding strength, stability, and load transfer between bamboo and timber, while also providing hygroscopic benefits by possibly reducing differential swelling and shrinkage, and thereby limiting warping, interfacial stresses, and surface cracks.

All specimens were stored under normal laboratory conditions at room temperature. Dedicated specimens for moisture content testing were weighed to obtain their initial wet mass and then dried in a ventilated oven at 103 ± 2 °C until fully dried. The measured moisture content of all specimens was calculated based on ISO 22157. BBE and BPA showed average values around 9.3%, while CBE and CPA had slightly lower values, between 7% and 9%. The individual bamboo and pinewood strips used in lamination also showed similar moisture levels, ranging from 9% to 11%, which indicates that all samples were well-conditioned.

2.3. Resins

To evaluate the impact of adhesives, two different types of adhesives were used to prepare different samples. The two adhesives are:

- Bio-Epoxy Resin, a two-part bio-based epoxy (resin/hardener = 2:1 by weight). This resin has 30% bio-based content that makes it more sustainable, renewable, and environmentally responsible compared to existing synthetic counterparts. Bio-based epoxy resins are considered sustainable because the bio-based epichlorohydrin is produced from glycerol, which is a by-product of biodiesel manufacturing. This major bio-component replaces the commonly used fossil-based epichlorohydrin, made mainly from propene, in the production process. The two components of bio-epoxy were mixed for about two minutes until consistency was achieved. The mixture had a working time of roughly 25–30 minutes at room temperature. Approximately 140 g of mixed resin was applied to every three specimens, equivalent to about 46–47 g per specimen.
- PVA, a single-component water-based adhesive commonly used in manufacturing engineered bamboo and timber, was used as the control adhesive.

The adhesive content of the manufactured specimens was determined by comparing the mass of each cured specimen with the combined mass of the dry bamboo and timber strips before bonding. The measured adhesive contents were 20.90% for the BBE group, 19.88% for the BPA group, 14.43% for the CBE group, and 15.03% for the CPA group.

2.4. Strip Preparation

To manufacture the specimens, the caramelized Moso bamboo was cut into accurate measurements of 8 mm × 8 mm × 155 mm using a precise laser cutter to ensure precision (Figure1a). This method ensured that there was minimal error in cutting the materials while maintaining length tolerance within 0.2 mm. After cutting, the strips were sanded and air-blown to achieve strong adhesive bonding. The same procedure was followed for pine strips to ensure that the surface preparation was the same for the Moso bamboo and pine.

After the bamboo and timber strips were cut to the desired size, the strips were prepared for installation in a specially designed steel mould. For the hybrid specimens, bamboo and pinewood strips were combined in an alternating format. Adhesives were then applied to the strips to provide a strong bond. To spread the adhesive in uniform thin layers, 1-inch trim brushes were used to apply the adhesive to all surfaces (Figure 1b).

The specimens were manufactured under controlled laboratory conditions using two types of adhesives, bio-epoxy and PVA. As mentioned earlier, two different categories of specimens were manufactured: engineered bamboo specimens using eco-friendly resins with Moso bamboo strips; and hybrid bamboo–timber composites developed using an innovative arrangement of Moso bamboo and pine strips combined with bio-based, low-emission resins and an energy-efficient fabrication process.

(a) (b)

Figure 1. Specimen preparation: a) laser cutting of Moso bamboo strips to the required dimensions; b) application of adhesive to bamboo and timber strips, and assembly in the mould.

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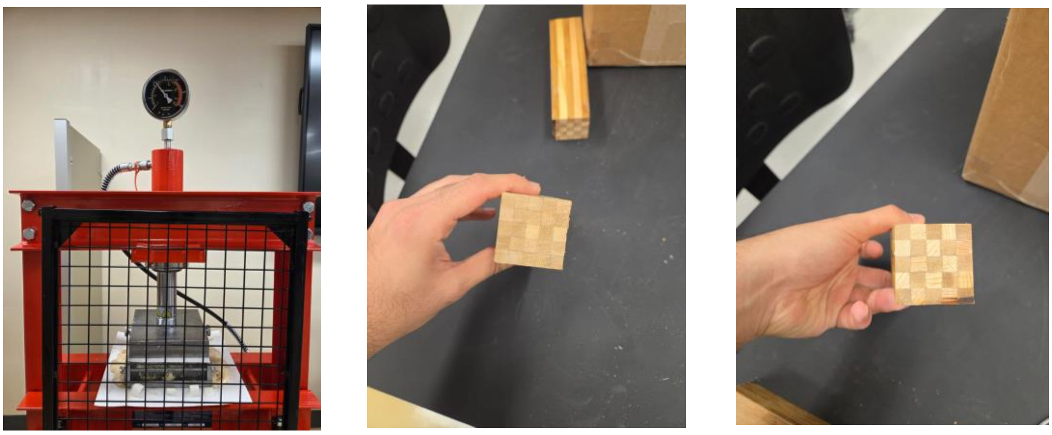
2.5. Cold-Press Manufacturing

Cold-pressing was performed using a 20-ton hydraulic press for 16 hours at room temperature, during which a constant uniform load of 98 kN was applied to a steel plate placed on top of the steel mould (Figure 2a). The manufacturing process is similar to the practice in industry, except that the hot-pressing stage was avoided as a sustainability measure to make the process less energy-intensive. Engineered bamboo composites are commonly manufactured through hot-press moulding. Production of engineered bamboo products such as laminated bamboo, bamboo scrimber, and hybrid composites typically involves resin impregnation followed by hot pressing, which requires considerable energy input. This research, however, introduces a novel and sustainable design strategy that employs a cold-press lamination method that eliminates the need for heat curing, leading to a reduction in energy consumption while maintaining the quality of samples (Figure 2b-c).



(a) (b) (c)

Figure 2. Specimen manufacturing: (a) cold-press lamination of the specimens under hydraulic loading, (b) cross-sectional view of the laminated bamboo specimen, BPA, and (c) cross-sectional view of the hybrid bamboo-timber specimen, CPA.

3. Embodied Carbon Assessment of Cold-Press Engineered Bamboo

3.1. Embodied Carbon Assessment

Life cycle assessment (LCA) is widely used to evaluate the environmental impacts of construction materials, particularly the greenhouse gas emissions associated with extraction, processing, manufacturing, and transportation. Bamboo-based construction materials have attracted increasing attention in recent years because of their rapid renewability and their capacity to retain substantial amounts of atmospheric carbon in structural applications.

On this basis, a screening-level cradle-to-gate carbon assessment was carried out to evaluate the proposed cold-press laminated bamboo and bamboo-timber composites against conventional hot-pressed laminated bamboo bonded with PF resin. The assessment was expressed in terms of global warming potential, reported as kg CO_2e/m^3 of finished material, which is the standard functional unit commonly adopted in construction-material LCAs. Calculations were performed in Microsoft Excel using a spreadsheet-based carbon accounting model. Emission factors for the adhesive systems were taken from publicly available Environmental Product Declarations (EPDs) and published LCA sources [18–20]. The electricity factor was selected to represent carbon-intensive, oil-based electricity generation.

The proposed composite materials were manufactured using cold hydraulic pressing at room temperature, thereby eliminating the thermal curing step typically associated with engineered bamboo production. For the developed specimens, the assessment was based on the measured adhesive contents and specimen-specific densities obtained from the experimental program rather than assumed generic values. For the hot-pressed laminated bamboo reference, the pressing-stage energy demand was taken as 46.7 kWh/m³ from published LCA inventories, e.g. [19]. The corresponding carbon burden was calculated using the selected electricity emission factor of 0.309 kg CO_2e/kWh, adopted from Department for Business, Energy and Industrial Strategy (BEIS) data [21].

The reported embodied-carbon values were derived on a sample-specific basis using the measured adhesive contents and specimen densities obtained from the experimental program, together with published cradle-to-gate carbon factors for the adhesive systems and the hot-press reference process. First, the density of each specimen group was calculated from the measured specimen mass and the known specimen volume. Second, the mass fraction of adhesive in each group was taken from the measured adhesive contents. The gross embodied carbon per cubic meter (EC_{gross}) was then obtained by multiplying the density of the composite by the adhesive mass fraction and the selected adhesive emission factor, with the manufacturing-energy contribution added where relevant (Eq. 1).

Product system	Gross embodied carbon (kg CO_2e/m³)
Cold-press laminated bamboo, bio-epoxy (BBE)	404.8
Cold-press bamboo-pine composite, bio-epoxy (CBE)	264.8
Cold-press laminated bamboo, PVA (BPA)	310.8
Cold-press bamboo-pine composite, PVA (CPA)	197.5
Hot-pressed laminated bamboo, PF resin as reference	595.6

$$EC_{gross} = \rho \times w_{adh} \times EF_{adh} + EC_{mfg} \tag{1}$$

where ρ is the specimen density (kg/m³), w_{adh} is the adhesive mass fraction, EF_{adh} is the adhesive emission factor (kg CO_2e/kg), and EC_{mfg} is the manufacturing-energy contribution (kg CO_2e/m³). For the bio-epoxy system used in the present study, an EF_{adh} value of 3.160 kg CO_2e/kg was taken from the environmental product declaration of liquid epoxy resin based on renewable epichlorohydrin [23]. For the hot-pressed laminated bamboo reference, the phenol-formaldehyde resin factor was taken as 4.56 kg CO_2e/kg from a published product carbon report [24]. An EF_{adh} value of 2.47 kg CO_2e/kg for PVA is adopted from the published life-cycle assessment of Kuraray Poval™ [25].

The resulting cradle-to-gate embodied carbon values are summarized in Table 2. The cold-press laminated bamboo system bonded with bio-epoxy yielded an embodied carbon of 449.6 kg CO_2e/m³, while the corresponding bamboo-pine composite yielded 294.1 kg CO_2e/m³. For comparison, the conventional hot-pressed laminated bamboo bonded with PF resin was calculated at 597.7 kg CO_2e/m³.

For the hot-pressed reference, the EC_{mfg} was converted to carbon dioxide equivalent (kg CO_2e/m³) using the selected oil-based electricity factor. To this end, the EC_{mfg} for the hot-pressing manufacturing process was calculated as 11.4 kg CO_2e/m³, while the remaining 584.2 kg CO_2e/m³ of the overall EC_{gross} was the contribution of the PF resin. For the cold-press systems, EC_{mfg} was not included because no thermal curing stage was used. The results suggest that, within the present system boundary, adhesive selection is more influential than the manufacturing process in determining embodied carbon. The difference between cold pressing and hot pressing is not negligible, but it is small compared with the contribution of the resin system.

Table 2. Cradle-to-gate embodied carbon of the evaluated bamboo systems.

Compared with conventional hot-pressed laminated bamboo with PF resin, the proposed laminated bamboo systems BBE and BPA and the bamboo-pine composite systems CBE and CPA exhibit 32.0%, 47.8%, 55.5%, and 66.8% lower embodied carbon, respectively.

3.2. Net Carbon Balance Comparison with Conventional Construction Materials

Apart from manufacturing-related emissions, bamboo- and timber-based materials retain biogenic carbon absorbed from the atmosphere during plant growth. Through photosynthesis, atmospheric carbon dioxide is converted into biomass and remains stored in the material throughout its service life [18].

Using Eq. 2, the biogenic carbon stored ($CO_{2,stored}$) in the bamboo and pine phases was calculated from the biomass fraction of the composite, based on a carbon content of 50% of dry biomass [18,22] and converting carbon to equivalent CO_2 using the molecular weight ratio 44/12 (Eq. 2).

$$CO_{2,stored} = \rho \times w_{bio} \times 0.50 \times 44/12 \quad (2)$$

where w_{bio} is the biomass fraction of the composite, 0.50 is the assumed carbon fraction of dry biomass, and 44/12 converts element carbon to equivalent carbon dioxide. It should be noted that the biogenic carbon stored values slightly differ among the developed systems because they were calculated from the specimen-specific densities and biomass fractions of each material. As a result, differences in adhesive content and final composite density led to slightly different amounts of stored biogenic carbon per cubic meter for each specimen.

In the next step, the net carbon balance (EC_{net}) was obtained by subtracting the stored biogenic CO_2 from the cradle-to-gate embodied carbon (Eq. 3).

$$EC_{net} = EC_{gross} - CO_{2,stored} \quad (3)$$

Using the relation defined above for EC_{net}, the cold-press laminated bamboo systems yielded net carbon balances of −484.0 kg CO_2e/m^3 for BBE and −619.0 kg CO_2e/m^3 for BPA, while the cold-press bamboo-pine composite systems yielded −646.1 kg CO_2e/m^3 for CBE and −631.2 kg CO_2e/m^3 for CPA (Table 2). These values indicate that, once biogenic carbon storage is taken into account, all four developed systems store substantially more carbon than is emitted during the manufacturing process.

For consistency, the same method was applied to softwood lumber, Laminated Veneer Lumber (LVL), and Parallel Strand Lumber (PSL). Based on published cradle-to-gate data, softwood lumber has gross emissions of 63.1 kg CO_2e/m^3. Assuming a carbon fraction of 50% of dry biomass, the corresponding biogenic carbon stored in the material is 843.3 kg CO_2/m^3, which results in a net carbon balance of −780.2 kg CO_2e/m^3. Similarly, published cradle-to-gate data [26] show that LVL has gross emissions of 361.45 kg CO_2e/m^3 and a net carbon balance of −636.86 kg CO_2e/m^3. For PSL, using a strand-based structural composite lumber proxy, the corresponding values for gross and net carbon balance are 310.28 kg CO_2e/m^3 and −667.17 kg CO_2e/m^3, respectively. The carbon values of the proposed engineered bamboo materials are close to those of engineered timber products such as LVL and PSL, while the bamboo-based systems offer the additional advantage of much faster renewability.

To place the developed materials more in context, Table 3 also compares the net carbon balance of the proposed systems with those of selected conventional construction materials. As mentioned earlier, all developed bamboo-based systems remain carbon negative when biogenic storage is taken into account, with the bamboo-pine composite exhibiting the more favourable net carbon balance.

Table 3. Carbon comparison of the proposed materials and selected conventional construction materials.

Material	Gross emissions (kg CO_2e/m^3)	Biogenic carbon stored (kg CO_2/m^3)	Net carbon balance (kg CO_2e/m^3)
Cold-press laminated bamboo, bio-epoxy (BBE)	404.8	888.8	−484.0
Cold-press bamboo-pine composite, bio-epoxy (CBE)	264.8	910.9	−646.1
Cold-press laminated bamboo, PVA (BPA)	310.8	929.8	-619.0
Cold-press bamboo-pine composite, PVA (CPA)	197.5	828.7	-631.2
Hot-pressed laminated bamboo, PF resin	595.6	888.8	−293.2

Material	Gross emissions (kg CO_2e/m^3)	Biogenic carbon stored (kg CO_2/m^3)	Net carbon balance (kg CO_2e/m^3)
Softwood lumber	63.1*	843.3	−780.2
Laminated Veneer Lumber (LVL)	361.5**	998.3	−636.8
Parallel Strand Lumber (PSL)	310.3	977.5	-667.2
Structural concrete	215.0*	0	215.0
Structural steel	15,857.0***	0	15,857.0
Aluminum	18,333.0***	0	18,333.0

* Single comparison values shown as midpoint value adopted from a broader range. ** North American laminated veneer lumber: Environmental product declaration [26] *** Van der Lugt et al. [18].

3.3. Discussion and Implications

Several observations can be drawn from the results of this screening-level cradle-to-gate LCA:

First, softwood lumber retains the lowest net carbon footprint among the materials considered, largely because it requires relatively little processing and contains no synthetic adhesive system. Meanwhile, the bamboo-based composites developed in this study remain strongly carbon negative after manufacturing emissions are included. Given the modest difference in net carbon balance between sawn lumber and the proposed engineered bamboo systems (Table 3), together with bamboo's much faster rate of renewability, engineered bamboo can reasonably be viewed as a competitive, sustainable construction material to sawn lumber.

Second, the cold-press manufacturing process provides a clear carbon advantage over conventional hot-pressed laminated bamboo. For example, the gross embodied carbon of the least carbon-efficient proposed laminated bamboo, i.e., BBE, was calculated as 404.8 kg CO_2e/m^3, compared with 595.6 kg CO_2e/m^3 for the hot-pressed PF-bonded reference, corresponding to a reduction of 32.0%. This difference is only slightly associated with the elimination of thermal curing and is primarily related to the lower adhesive emission factor of the bio-epoxy resin with respect to the PF resin reference.

Third, the material configuration also influences carbon performance. The cold-press bamboo-pine composite exhibited a lower embodied carbon than the laminated bamboo system and also showed a more favourable net carbon balance of the two developed systems.

Finally, when compared with concrete, steel and aluminum, the difference in net embodied carbon remains substantial. This highlights the potential of engineered bamboo composites and bamboo-timber hybrid systems as scalable, carbon-storing materials for low-carbon construction applications.

4. Conclusions

This paper examined the proposed cold-press manufacturing of laminated bamboo and bamboo-timber composites and assessed their environmental performance through a screening-level cradle-to-gate life-cycle carbon assessment.

From the results of this study, the following conclusions can be drawn:

- Adhesive selection had a greater influence on embodied carbon than the difference between cold pressing and hot pressing. Within the adopted system boundary, the resin system accounted for most of the gross embodied carbon, while the contribution of manufacturing energy was comparatively minor.
- Although softwood lumber showed the lowest net carbon footprint among the materials considered, the developed bamboo-based systems also remained strongly carbon negative.

- The carbon performance of the proposed engineered bamboo materials is comparable to that of established engineered timber products such as LVL and PSL, with the added benefit that bamboo is renewed far more rapidly.
- Given the relatively modest difference in net carbon balance of sawn lumber, LVL, and PSL with those of the proposed systems, together with bamboo's much faster renewability, engineered bamboo can be regarded as a competitive, comparably sustainable alternative to sawn lumber and engineered timber solutions.
- The cold-press systems showed a clear carbon advantage over conventional hot-pressed laminated bamboo, as reflected by gross embodied-carbon reductions of 32.0% for BBE, 47.8% for BPA, 55.5% for CBE, and 66.8% for CPA.
- The bamboo-pine composite systems exhibited lower embodied carbon and more favourable net carbon balances than the laminated bamboo systems, while all developed materials remained far lower in carbon impact than structural concrete, steel, and aluminum.
- These results support the use of engineered bamboo composites and bamboo-timber hybrids as promising low-carbon materials for construction.

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