

## Article

# Carbon Retention Efficiency in Bamboo-Based Engineered Products: Linking Biomass Processing and Biogenic Carbon Retention

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## Abstract

Bamboo-based engineered products have attracted increasing attention because of their renewable origin and long-term carbon storage potential. However, conventional life cycle assessment (LCA) mainly evaluates greenhouse gas emissions and cannot quantify how efficiently biomass-derived carbon is retained during manufacturing. Therefore, this study proposes carbon transfer efficiency (CTE) as a complementary indicator for assessing retained biogenic carbon in bamboo-based engineered products. Based on plant-scale manufacturing data from a representative bamboo scrimber factory in China, CTE was quantified together with the cradle-to-gate carbon footprint. Carbon loss distribution among manufacturing stages and sensitivity to key process parameters were further analyzed. Results showed that 65–78% of the initial biogenic carbon was retained in the final product. Unit separation and secondary machining accounted for more than 70% of total carbon loss, whereas adhesive application and hot pressing dominated greenhouse gas emissions but caused little direct carbon loss. Material-loss-related parameters exhibited substantially greater influence on CTE than energy-related parameters. These findings demonstrate that carbon retention efficiency and greenhouse gas emissions characterize different dimensions of environmental performance. Integrating CTE with LCA provides a more comprehensive framework for evaluating carbon storage and low-carbon manufacturing of bamboo-based engineered products.

**Keywords:** bamboo-based engineered products; carbon transfer efficiency; biogenic carbon retention; life cycle assessment; manufacturing process; material loss



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## 1. Introduction

Bamboo has attracted increasing attention as a sustainable alternative to conventional construction materials because of its rapid growth, high biomass productivity, and excellent

mechanical properties. As a fast-renewable lignocellulosic resource, bamboo not only provides structural materials with favorable strength-to-weight ratios but also acts as an important temporary carbon reservoir by storing atmospheric carbon fixed through photosynthesis in long-lived products. Consequently, bamboo-based engineered products have been widely recognized as promising low-carbon materials that can contribute to climate change mitigation and sustainable construction, particularly under global carbon neutrality strategies and the transition toward bio-based economies [1,2].

Life cycle assessment (LCA) has become the most widely adopted method for evaluating the environmental performance of bamboo-based engineered products. Previous studies have quantified greenhouse gas emissions associated with bamboo harvesting, transportation, resin production, manufacturing, and product use, enabling the identification of major emission hotspots throughout the product life cycle [3]. These studies have substantially improved the understanding of the carbon footprint of engineered bamboo products and provided important guidance for low-carbon manufacturing. However, conventional LCA primarily evaluates greenhouse gas emissions and does not explicitly describe how efficiently the biogenic carbon originally stored in bamboo biomass is retained within final products during manufacturing [4–7].

For bio-based materials, environmental performance depends not only on emission reduction but also on the extent to which biomass-derived carbon is preserved in durable products. During bamboo processing, substantial biomass is removed through splitting, fiberization, trimming, sanding, and machining. These material losses directly reduce the amount of biogenic carbon retained in the final product, yet they are not explicitly represented in conventional emission-based assessment frameworks. Consequently, greenhouse gas emissions and retained biogenic carbon describe two different dimensions of environmental performance, indicating the need for an additional process-oriented indicator capable of tracking carbon retention throughout manufacturing.

Several studies have evaluated biomass utilization efficiency, material yield, harvested wood products, and carbon storage in bio-based materials. Although these approaches provide valuable information on resource efficiency or long-term carbon storage, they do not directly quantify the proportion of biomass-derived carbon transferred from raw materials into finished engineered products during manufacturing. Furthermore, the relative contributions of different processing stages, such as unit separation, adhesive impregnation, composite forming, and secondary machining, to retained biogenic carbon have rarely been quantified systematically. Therefore, an important methodological gap remains between conventional life cycle carbon assessment and process-level evaluation of retained biogenic carbon in bamboo manufacturing [8–10].

Compared with previous studies focusing on life cycle carbon emissions or biomass utilization efficiency, this study proposes carbon transfer efficiency (CTE) as a process-oriented indicator that explicitly links manufacturing behavior with retained biogenic carbon. The proposed framework integrates CTE with conventional life cycle assessment to simultaneously evaluate greenhouse gas emission intensity and carbon retention performance, thereby providing a new perspective for assessing the low-carbon manufacturing of bamboo-based engineered products [11–13]. Unlike traditional carbon footprint indicators, CTE focuses on the physical transfer and preservation of biogenic carbon within the manufacturing system, enabling the identification of carbon-loss hotspots that cannot be revealed by emission-based analyses alone [14–18].

The objectives of this study are therefore to (i) define and quantify carbon transfer efficiency for bamboo-based engineered products, (ii) identify key processing stages and parameters influencing carbon retention, and (iii) propose optimization strategies for improving carbon transfer efficiency and enhancing the carbon storage performance of

engineered bamboo materials. The findings aim to support process-level low-carbon manufacturing optimization and improve understanding of retained biogenic carbon behavior during bamboo processing. The framework links process-level manufacturing parameters to both greenhouse gas emissions and biogenic carbon retention, enabling integrated low-carbon optimization strategies.

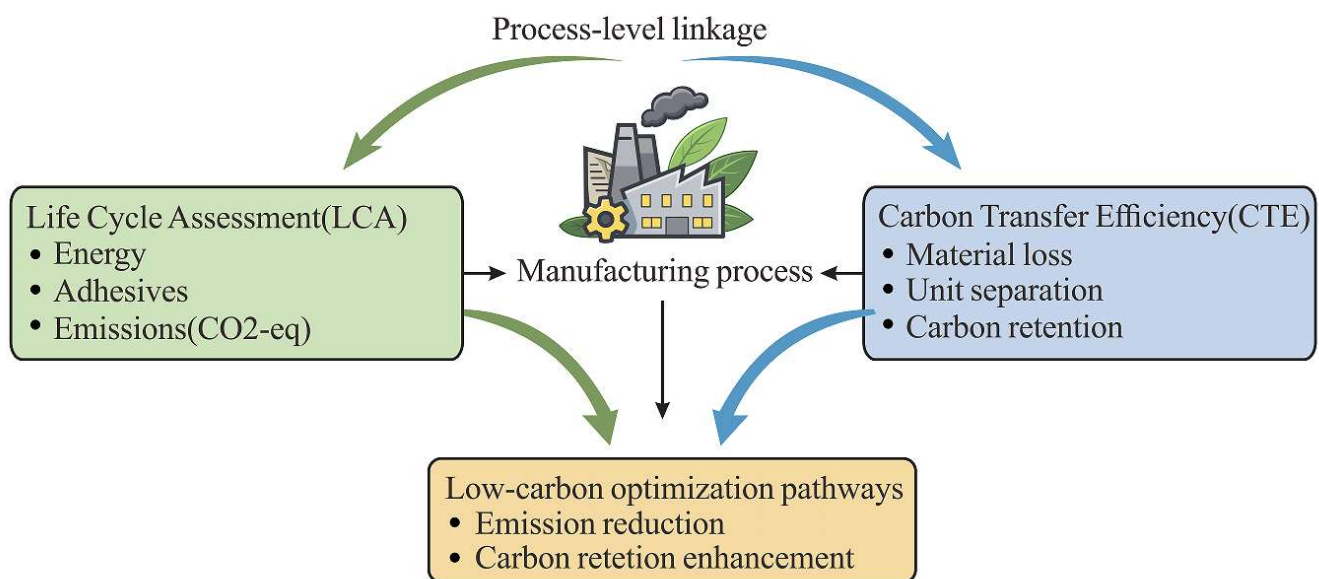
## 2. Materials and Methods

### 2.1. Definition and Quantification of Carbon Transfer Efficiency

Carbon transfer efficiency (CTE) is defined as the proportion of biogenic carbon originally fixed in raw bamboo biomass that is retained in the final engineered product after manufacturing. It is expressed as

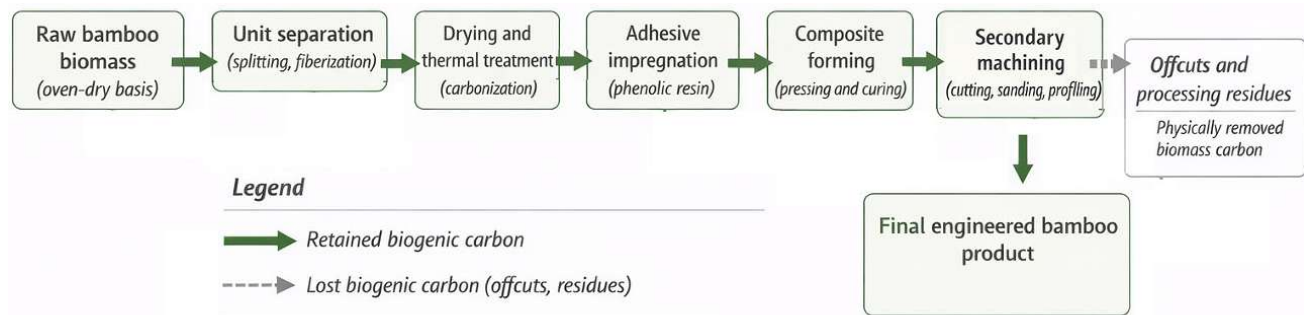
$$\text{CTE} = \frac{C_{\text{product}}}{C_{\text{raw}}} \quad (1)$$

where  $C_{\text{raw}}$  represents the biogenic carbon content of oven-dry bamboo effectively entering the manufacturing line as usable feedstock, excluding upstream harvesting residues and pre-processing losses, and  $C_{\text{product}}$  denotes the biogenic carbon retained in the finished bamboo-based engineered product at the factory gate, serving a structural or material function within the defined manufacturing system boundary (Figure 1).



**Figure 1.** Integrated analytical framework combining life cycle assessment (LCA) and carbon transfer efficiency (CTE) for bamboo-based engineered products. While LCA identifies greenhouse gas emission hotspots primarily driven by energy consumption and resin production, CTE reveals manufacturing stages responsible for biogenic carbon loss due to material removal. The framework highlights a fundamental process-level decoupling between emission intensity and carbon retention, enabling complementary low-carbon optimization strategies by linking process-level manufacturing parameters to both emission reduction and carbon storage performance. Green arrows indicate retained biogenic carbon, while blue arrows indicate process-level linkage.

Unlike conventional life cycle carbon footprint indicators, which focus on greenhouse gas emissions associated with energy and material inputs, CTE explicitly reflects material-based carbon retention performance, linking manufacturing behavior directly to biogenic carbon fate (Figure 2). Conceptually, this process-oriented indicator is consistent with previous discussions on material efficiency and carbon storage performance in sustainable manufacturing and bio-based product systems [11,19].



**Figure 2.** Conceptual framework and calculation boundary of carbon transfer efficiency (CTE) in bamboo-based engineered product manufacturing.

Figure 2 illustrates the conceptual framework of the proposed carbon transfer efficiency (CTE), which describes the transfer of biogenic carbon throughout the manufacturing process of bamboo-based engineered products. Unlike conventional life cycle assessment (LCA), which primarily focuses on greenhouse gas emissions associated with material production and energy consumption, the proposed CTE framework tracks the physical transfer of biogenic carbon from raw bamboo to the final engineered product.

As shown in Figure 2, the biogenic carbon flow consists of four components: (i) input carbon, representing the biogenic carbon entering the manufacturing system with raw bamboo; (ii) carbon loss during processing, resulting from trimming, cutting, sanding, machining, and other material removal operations; (iii) retained structural carbon, representing the carbon physically preserved in the final engineered bamboo product; and (iv) carbon transfer efficiency (CTE), defined as the ratio of retained structural carbon to the initial carbon input.

The proposed framework assumes that only carbon physically retained in durable engineered bamboo products contributes to long-term carbon storage. Therefore, carbon contained in processing residues, such as trimming waste, machining residues, sanding dust, and rejected bamboo units, is excluded from retained carbon because these materials are no longer incorporated into the final product system.

Similarly, biomass used for energy recovery is not included in the CTE calculation. Although energy recovery can partially substitute fossil fuels and thereby reduce greenhouse gas emissions, the biogenic carbon contained in the biomass is ultimately released to the atmosphere during combustion. Consequently, this carbon does not contribute to long-term structural carbon storage and should be assessed separately through conventional LCA rather than the CTE indicator.

Accordingly, the proposed CTE framework focuses exclusively on retained structural carbon, providing a process-oriented indicator of the manufacturing system's ability to preserve biogenic carbon in long-lived construction materials. This perspective complements conventional emission-based assessments by evaluating manufacturing performance from the standpoint of carbon retention.

The system boundary adopted in this study is conceptually consistent with the principles of ISO 14067 [20], which distinguish greenhouse gas emissions from biogenic carbon storage, and is also compatible with the carbon accounting approach for harvested wood products (HWPs), where carbon retained in durable products is accounted for separately from greenhouse gas emissions [21–25]. By integrating CTE with conventional LCA, Figure 2 establishes a unified framework for simultaneously evaluating greenhouse gas emissions and biogenic carbon retention during the manufacturing of bamboo-based engineered products.

## 2.2. Relationship Between CTE and Life Cycle Assessment

Life cycle assessment (LCA) and carbon transfer efficiency (CTE) evaluate different dimensions of environmental performance within bamboo-based engineered product systems. Conventional LCA primarily quantifies greenhouse gas emissions associated with energy consumption, material inputs, and manufacturing activities throughout the production process. In contrast, CTE focuses on the retention of biogenic carbon within the final engineered product, thereby reflecting the carbon preservation performance of the manufacturing system from a material-flow perspective.

The integration of LCA and CTE enables simultaneous evaluation of both emission intensity and carbon retention efficiency. Through this complementary analytical framework, environmental impacts associated with manufacturing emissions can be assessed together with the effectiveness of biomass-derived carbon preservation in durable material applications. Consequently, the combined use of LCA and CTE provides a more comprehensive understanding of the low-carbon performance of bamboo-based engineered product manufacturing systems.

## 2.3. Representative Manufacturing System

Plant-scale production data were obtained from a bamboo scrimber manufacturing enterprise located in Jiangxi Province, China. Jiangxi Province is one of the major bamboo-engineered-product manufacturing regions in China and represents a typical industrial cluster for bamboo scrimber production. The selected enterprise was chosen because it operates continuous industrial-scale manufacturing lines, its process route is representative of mainstream bamboo scrimber production technologies, and detailed production inventory data were available from previous peer-reviewed life cycle assessment (LCA) studies [26].

The selected product was a bamboo scrimber panel with a nominal thickness of 15 mm and an average density of approximately  $1100 \text{ kg}\cdot\text{m}^{-3}$ , representing mainstream industrial production technology in China. The manufacturing process included five major stages: (1) unit separation, (2) drying and thermal treatment, (3) adhesive impregnation, (4) composite forming, and (5) secondary machining.

Although the present case study was based on a single manufacturing facility, the selected production route is broadly representative of current industrial bamboo scrimber manufacturing systems in China. Nevertheless, regional and technological variability among manufacturers remains an important limitation.

## 2.4. Functional Unit and System Boundary

The functional unit was defined as  $1 \text{ m}^2$  of finished bamboo scrimber panel. The system boundary adopted a cradle-to-gate approach and included raw bamboo preparation, unit separation, drying and thermal treatment, adhesive application, composite forming, and secondary machining processes. Downstream use-phase and end-of-life scenarios were excluded from the present study.

Consistent with the objective of carbon transfer efficiency (CTE), removed residues and by-products generated during manufacturing were not allocated retained structural carbon value within the product system. The analysis therefore focused specifically on the proportion of biogenic carbon retained within the final engineered bamboo product serving structural or material functions.

## 2.5. Carbon Content Assumptions and Uncertainty

The carbon content of oven-dry bamboo biomass was assumed to be 50 wt.% based on commonly adopted values in bamboo- and wood-based LCA studies [8,10]. To evaluate

uncertainty associated with this assumption, an uncertainty range of 48–52 wt.% carbon content was additionally considered.

Sensitivity analysis indicated that variation in carbon content assumptions produced relatively minor changes in overall CTE values compared with material-loss-related parameters, suggesting that manufacturing-stage material losses exert a substantially greater influence on retained biogenic carbon performance.

## 2.6. Example Calculation of Carbon Transfer Efficiency

Accordingly, the initial biogenic carbon input per functional unit was calculated as

$$C_{\text{raw}} = 0.50 \times m_{\text{raw}} \quad (2)$$

where  $m_{\text{raw}}$  is the oven-dry bamboo mass entering the manufacturing system.

For the reference bamboo scrimber product, the oven-dry bamboo input was  $15.31 \text{ kg} \cdot \text{m}^{-2}$ , and the carbon content was assumed to be 50 wt.%. Accordingly, the initial biogenic carbon input was calculated as follows:

$$C_{\text{raw}} = 15.31 \times 0.50 = 7.66 \text{ kg C m}^{-2}$$

After manufacturing-stage processing losses, the retained bamboo mass was estimated to be approximately  $10.0\text{--}12.0 \text{ kg oven-dry equivalent} \cdot \text{m}^{-2}$ , corresponding to a retained carbon content of approximately  $5.0\text{--}6.0 \text{ kg C m}^{-2}$ . Therefore, the resulting CTE value was estimated as follows:

$$\text{CTE} = 5.0 - 6.0 / 7.66 = 0.65 - 0.78$$

This calculation framework provides a transparent process-level mass–carbon balance approach for evaluating retained biogenic carbon within engineered bamboo product manufacturing systems.

## 2.7. Sensitivity and Uncertainty Analysis

Sensitivity analysis was conducted to evaluate the influence of key manufacturing parameters on carbon transfer efficiency, including material loss rate, unit separation degree, adhesive dosage, and energy intensity. Parameter variations were evaluated using  $\pm 10\%$  perturbation relative to baseline conditions.

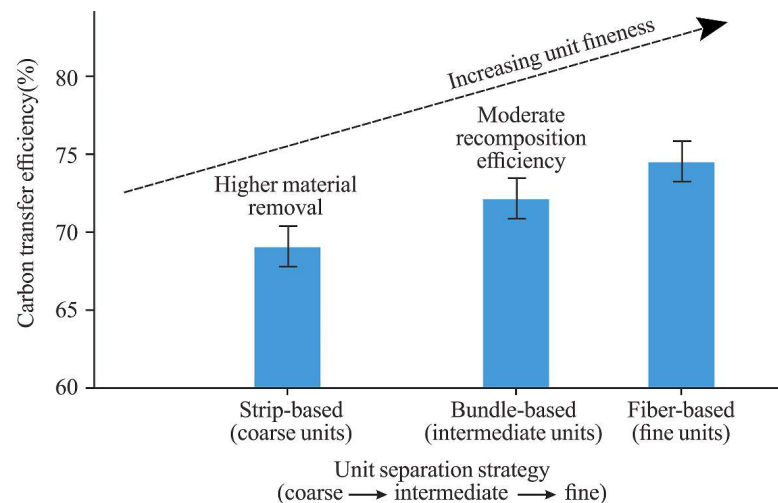
In addition, Pearson correlation analysis and standardized sensitivity coefficients were applied to compare the relative influence of individual parameters on the final CTE values.

# 3. Results

## 3.1. Carbon Transfer Efficiency of Bamboo-Based Engineered Products

The carbon transfer efficiency (CTE) of bamboo-based engineered products ranged from 65% to 78%, depending on the manufacturing route (Figure 3). Fiber-based products generally exhibited higher CTE values than strip-based products. The observed variation indicates that different manufacturing routes retain different proportions of the initial biogenic carbon in the final engineered products.

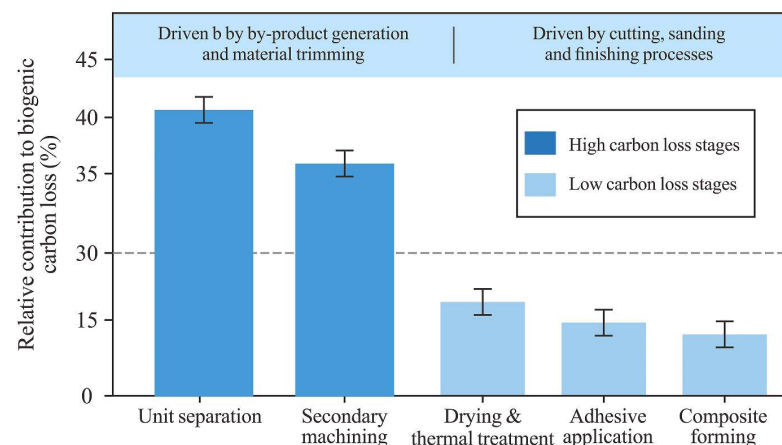
Overall, approximately two-thirds to three-quarters of the carbon initially fixed in raw bamboo biomass remained in the finished products after manufacturing.



**Figure 3.** Carbon transfer efficiency (CTE) of bamboo-based engineered products under different manufacturing routes. Error bars represent  $\pm$  one standard deviation based on batch-level production variability associated with material loss rates and minor process fluctuations observed in plant-scale manufacturing data.

### 3.2. Contribution of Manufacturing Stages to Biogenic Carbon Loss

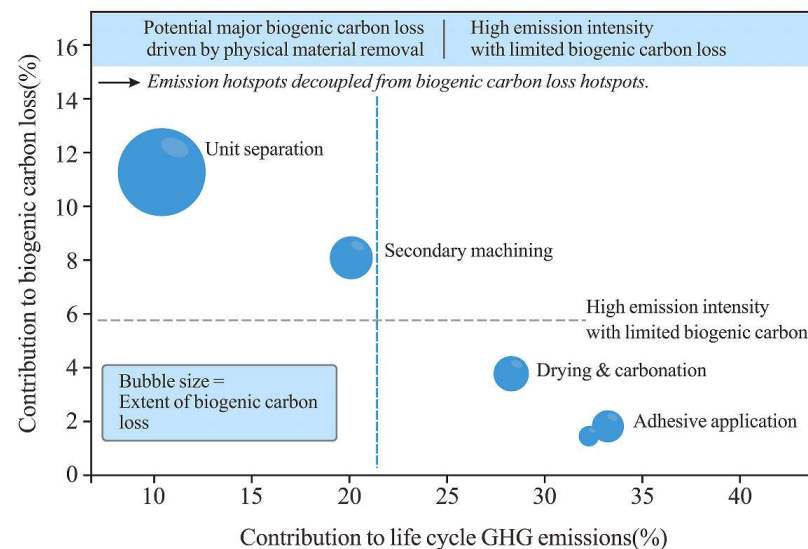
Unit separation and secondary machining accounted for more than 70% of the total biogenic carbon loss during manufacturing (Figure 4). Material removal during these stages represented the dominant source of retained carbon reduction. In contrast, drying, adhesive impregnation, and hot pressing contributed little direct carbon loss. Similar material-loss mechanisms during bamboo processing have also been reported in previous studies on bamboo scrimber and other engineered bamboo products [27–29].



**Figure 4.** Relative contribution of individual manufacturing stages to total biogenic carbon loss in bamboo-based engineered product manufacturing. Physical material removal processes, particularly unit separation and secondary machining, dominate biogenic carbon loss, accounting for more than 70% of total carbon removal, whereas energy-intensive processes contribute negligibly to direct carbon loss. The dashed horizontal line at 30% is included as a visual reference to distinguish relatively high and low contributions to total biogenic carbon loss.

### 3.3. Relationship Between Carbon Retention and Greenhouse Gas Emissions

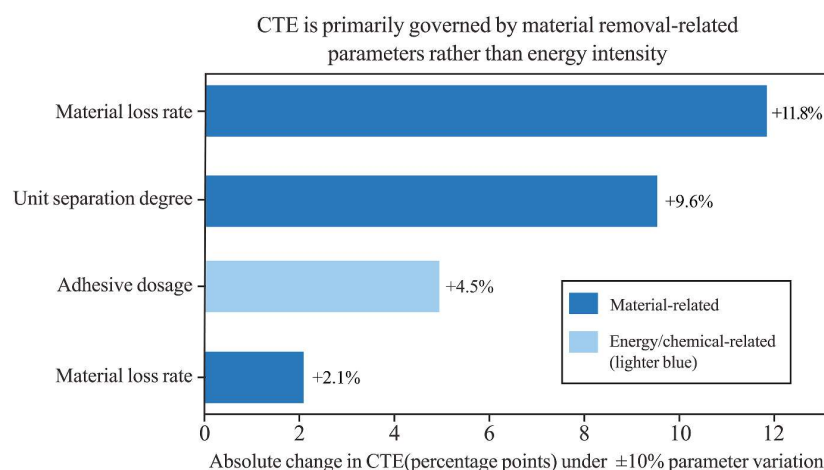
The cradle-to-gate carbon footprint of the reference bamboo scrimber product was  $3.11 \text{ kg CO}_2\text{-eq m}^{-2}$ . Manufacturing contributed 46.6% of total emissions. Figure 5 shows that manufacturing stages exhibiting high greenhouse gas emissions did not necessarily correspond to stages with high biogenic carbon loss.



**Figure 5.** Process-level decoupling between life cycle greenhouse gas emission contribution and biogenic carbon loss across key manufacturing stages of bamboo-based engineered products. Each point represents a major manufacturing stage positioned according to its relative contribution to cradle-to-gate greenhouse gas emissions (x-axis) and biogenic carbon loss (y-axis). The quadrant-based representation demonstrates that emission hotspots do not coincide with carbon loss hotspots, underscoring the necessity of combining emission-based and material-based indicators for low-carbon manufacturing optimization. The vertical dashed line separates relatively low and high contributions to life cycle greenhouse gas emissions, whereas the horizontal dashed line separates relatively low and high contributions to biogenic carbon loss. These lines are included as visual references for the quadrant-based comparison.

### 3.4. Sensitivity Analysis of Key Influencing Factors

Sensitivity analysis results presented in Figure 6 indicate that carbon transfer efficiency (CTE) is strongly governed by material-removal-related parameters. Increasing unit fineness from strip-based to fiber-based configurations leads to systematically higher CTE values due to improved recombination efficiency and reduced material removal.



**Figure 6.** Sensitivity of carbon transfer efficiency (CTE) to key manufacturing parameters relative to the baseline scenario. Bars represent the absolute change in CTE (percentage points) resulting from a  $\pm 10\%$  variation in each parameter. Material-removal-related parameters, particularly material loss rate and unit separation degree, exert a substantially stronger influence on CTE than energy- or chemical-related factors, highlighting yield-oriented process optimization as the most effective pathway for enhancing biogenic carbon retention.

Specifically, a 10 percentage-point reduction in material loss rate increases CTE by approximately 8–12% (absolute), representing the strongest influence among all parameters considered. Transitioning from coarse bamboo strips to finer fiber-based units further improves CTE by 10–15%. In contrast, varying adhesive dosage between 8 and 12 wt.% results in a relatively modest CTE change of 3–5%, primarily through substitution effects rather than direct carbon loss. A  $\pm 10\%$  variation in energy intensity produces only a marginal change in CTE (approximately 2.1%), reflecting the fact that energy-related parameters affect greenhouse gas emissions but do not directly govern the retention of biogenic carbon within the final product.

Pearson correlation analysis further confirmed that material-removal-related parameters exerted a substantially stronger influence on CTE than energy-related variables. Table 1 summarizes the correlation coefficients between key manufacturing parameters and CTE values.

**Table 1.** Pearson correlation coefficients between key manufacturing parameters and carbon transfer efficiency (CTE).

| Parameter              | Correlation Coefficient (r) | Influence on CTE |
|------------------------|-----------------------------|------------------|
| Material loss rate     | −0.82                       | Strong negative  |
| Unit separation degree | 0.71                        | Strong positive  |
| Adhesive dosage        | 0.31                        | Moderate         |
| Energy intensity       | −0.12                       | Weak             |

Overall, material loss rate emerges as the dominant controlling factor for carbon transfer efficiency, highlighting yield-oriented process optimization as the most effective strategy for enhancing biogenic carbon retention in bamboo-based engineered products.

4. Discussion

4.1. Interpretation of Carbon Transfer Efficiency

The results indicate that carbon transfer efficiency (CTE) of bamboo-based engineered products ranges from 65% to 78%, suggesting that a substantial proportion of the carbon initially fixed through photosynthesis can be retained within durable construction materials. Nevertheless, approximately 22–35% of the original biomass-derived carbon is removed during manufacturing, indicating that manufacturing yield remains one of the principal constraints on maximizing long-term carbon storage.

The observed variation in CTE is primarily associated with differences in manufacturing routes. Fiber-based engineered bamboo generally exhibits higher CTE because fiber bundles can be redistributed more uniformly during recomposition, reducing trimming losses and improving material utilization. In contrast, strip-based products usually require additional sizing, edge trimming, and dimensional adjustment during manufacturing, leading to greater biomass removal before final product formation. Consequently, the manufacturing route directly influences retained biogenic carbon through differences in material yield rather than greenhouse gas emissions.

Another important finding is that physical biomass flow rather than energy consumption governs retained carbon performance. Carbon transfer efficiency essentially reflects the proportion of biomass entering the manufacturing system that ultimately remains embedded within long-lived structural products. Therefore, any manufacturing process that removes bamboo material inevitably decreases retained carbon, regardless of its associated energy demand. This explains why material-removal-related parameters exert a substantially stronger influence on CTE than energy-related parameters [30].

#### 4.2. Transfer Efficiency as a Complementary Indicator to Life Cycle Assessment

Traditional life cycle assessment (LCA) provides a robust framework for quantifying greenhouse gas emissions associated with material production but offers limited insight into the fate of biogenic carbon embedded in biomass-based products. Carbon transfer efficiency complements LCA by explicitly tracking how effectively biomass-derived carbon is retained within long-lived material applications throughout manufacturing processes.

The results of this study reveal that emission hotspots and biogenic carbon loss hotspots do not necessarily coincide. Manufacturing stages such as adhesive application and hot pressing dominate life cycle emissions due to energy demand and resin production, yet they preserve most of the bamboo carbon within the final product. Conversely, unit separation and secondary machining exhibit relatively low emission intensity while accounting for the majority of biogenic carbon loss.

By linking process-level manufacturing decisions to carbon retention outcomes, CTE provides a process-oriented perspective that cannot be captured by emission-based indicators alone. The combined use of LCA and CTE therefore enables a more comprehensive evaluation of climate performance, distinguishing between energy-related emission efficiency and material-based carbon storage efficiency.

This complementary framework is particularly relevant for bio-based materials, where the climate mitigation potential depends not only on renewable feedstocks and low-energy processing but also on the degree to which biogenic carbon is preserved in durable products rather than prematurely released during manufacturing [11,19,30].

#### 4.3. Comparison with Previous Studies

Previous studies on bamboo-based engineered products have predominantly focused on life cycle greenhouse gas emissions, energy consumption, and environmental impacts. For example, Gan et al. [3] comprehensively reviewed life cycle assessment (LCA) studies of bamboo products and demonstrated that resin production and thermal energy consumption are the dominant contributors to greenhouse gas emissions. Similarly, Liu et al. [5] identified adhesive production and hot pressing as the principal emission hotspots in structural glued laminated bamboo manufacturing. These studies have substantially advanced understanding of emission reduction pathways but provide limited information regarding the fate of biomass-derived carbon during manufacturing.

The present study extends previous LCA research by introducing carbon transfer efficiency (CTE), which explicitly quantifies the proportion of biogenic carbon retained within finished products. Unlike conventional carbon footprint indicators, CTE tracks biomass-derived carbon throughout the manufacturing process and therefore identifies carbon-loss hotspots that cannot be detected using emission-based assessment alone.

The CTE values obtained in this study (65–78%) are also broadly comparable with material yields reported for engineered wood products such as cross-laminated timber (CLT), laminated veneer lumber (LVL), plywood, and oriented strand board (OSB). However, the mechanisms governing retained carbon differ between bamboo and wood products. Wood processing losses are primarily associated with sawing recovery and veneer peeling, whereas bamboo manufacturing additionally requires the removal of bamboo epidermis, nodes, irregular culms, and subsequent precision machining. Consequently, bamboo products generally experience greater processing-related biomass losses despite exhibiting comparable structural performance [31–33].

These findings demonstrate that retained biogenic carbon represents a complementary dimension of environmental performance that cannot be adequately characterized using greenhouse gas emissions alone. Integrating CTE with LCA therefore provides a

more comprehensive framework for evaluating low-carbon manufacturing of bio-based construction materials.

#### *4.4. Implications for Industrial Process Optimization*

The identification of material loss rate, unit separation degree, and adhesive dosage as dominant influencing factors provides actionable guidance for low-carbon industrial practice. Among these parameters, material loss rate exerts the strongest influence on carbon transfer efficiency, highlighting the importance of yield-oriented process optimization [34–36].

Reducing unnecessary trimming, optimizing unit geometry, improving recombination efficiency, and minimizing excessive secondary machining can significantly enhance carbon retention without increasing energy demand or production costs. Sensitivity analysis indicates that targeted, CTE-oriented process optimization can improve carbon transfer efficiency by more than 20%, demonstrating substantial potential for enhancing the carbon storage function of bamboo-based engineered products.

Importantly, these optimization strategies align well with existing industrial objectives, as improvements in material retention simultaneously enhance resource efficiency and economic performance. This synergy makes CTE-oriented optimization particularly attractive for manufacturers seeking to balance environmental performance with production efficiency.

#### *4.5. Limitations and Future Research Needs*

Several important limitations of the present study should be acknowledged. First, the analysis was based on data derived from a single manufacturing facility. Although the selected process route is representative of mainstream bamboo scrimber production technologies in China, substantial variability may still exist among industrial configurations, processing technologies, and regional manufacturing systems.

Second, the assumption of constant biomass carbon content simplifies natural variability in bamboo composition. Third, the downstream fate of removed residues and by-products was not incorporated into the present analysis. Consequently, CTE reflects retained structural carbon storage within the product system boundary rather than total biomass utilization efficiency.

Finally, the study does not incorporate ecosystem-scale carbon dynamics or land-use-related carbon allocation processes. Future studies should therefore integrate multi-facility comparative analysis, dynamic carbon flow assessment, and ecosystem-scale biomass-carbon modeling to further improve the robustness and applicability of retained biogenic carbon evaluation frameworks.

## **5. Conclusions**

This study introduces carbon transfer efficiency (CTE) as a process-oriented complementary indicator for evaluating retained biogenic carbon in bamboo-based engineered products. Unlike conventional emission-oriented indicators, CTE explicitly characterizes the retention behavior of biomass-derived carbon within durable material systems during manufacturing processes.

Based on plant-scale manufacturing data from a representative bamboo scrimber production system, the results indicate that approximately 65–78% of the initial biomass-derived carbon was ultimately retained within the final engineered bamboo product. Material-removal-related stages, particularly unit separation and secondary machining, were identified as the dominant contributors to retained carbon loss. In contrast, energy-intensive stages such as adhesive application and hot pressing contributed substantially

to greenhouse gas emissions while preserving most biomass-derived carbon within the product system. Consequently, emission hotspots and carbon-loss hotspots were found to represent fundamentally different manufacturing characteristics.

The results further suggest that process optimization strategies targeting material retention, including improved recomposition efficiency and reduced unnecessary material removal, may substantially enhance retained structural carbon storage performance in bamboo-based engineered products.

The combined application of carbon transfer efficiency and life cycle assessment (LCA) provides a complementary framework for simultaneously evaluating greenhouse gas emissions and retained biomass carbon within bio-based manufacturing systems. This integrated approach may contribute to a more comprehensive understanding of low-carbon manufacturing performance in engineered bamboo products.

Nevertheless, the broader applicability of the proposed framework beyond the analyzed manufacturing system remains to be further validated through multi-facility studies and cross-material comparisons.

**Author Contributions:** Conceptualization, Y.H. and G.W.; methodology, M.H.; software, H.H.; validation, Y.Z., X.H. and Z.X.; formal analysis, C.P.; investigation, M.A.; resources, Y.H.; data curation, J.Z.; writing—original draft preparation, M.H.; writing—review and editing, G.W.; visualization, M.A.; supervision, Y.H. and G.W.; project administration, Y.H.; funding acquisition, Y.H. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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**Conflicts of Interest:** Zhenhua Xiong is employed by Ganzhou Sentai Bamboo and Wood Co., Ltd. All the remaining authors declare no conflicts of interest.

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