Assessing the Environmental Impacts of Glued-Laminated Bamboo Based on a Life Cycle Assessment

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The bamboo industry plays a significant strategic role in the world's economy. Laminated bamboo, with increasing yearly yields, is the intermediate material for bamboo products such as furniture, floor board, and container floor. The trilaminar straight joint glued-laminated bamboo production line is the leading enterprise in Fujian Province, and it was used to conduct a load analysis of the data collected from a year's production, based on the life cycle assessment system. The results show that the processing of glued-laminated bamboo contributes notably to the acidification potential, eutrophication potential, global warming potential, and photochemical ozone creation potential, whereas resource depletion and ozone depletion are affected by the urea-formaldehyde resin adhesive, among which the urea contributes the most. As for processing, carbonization, desiccation, and thermo-compression, these have the greatest impacts on the environmental load, with a total contribution rate of greater than 67%, as the main source for the power depletion is from the processing of fossil fuel. In addition, the oxynitride, phosphide, sulfide, aromatic hydrocarbon, *etc*., that are discharged from the reaction intensify the eutrophication potential, the photochemical ozone creation potential, and the acidification potential.

Keywords: Glued-laminated bamboo; Life cycle assessment (LCA); Environmental impacts; Global warming potential

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INTRODUCTION

Bamboo is the most rapidly maturing plant in the world because of its ability to grow simultaneous vegetation at every joint, which is vastly different from other plants with apical meristems only at the vegetative part (Cho *et al*. 2011; Oyedun *et al*. 2013). Therefore, bamboo has become a very important replacement material for the correction of the problem surrounding wood supply and demand. Among bamboo plants, moso bamboo (*Phyllostachys pubescens*) is one of the best building raw materials because of its height, straightness, and hardness.

Bamboo is mainly distributed in the tropics, semi-tropics, and warm temperate zone between 46°N and 47°S. With the exception of Europe, local bamboo species are a global commodity after the Quaternary Glaciation (Du *et al*. 2010; Tamang *et al*. 2014). The distribution of global bamboo resources is shown in Fig. 1.

China is one of the main bamboo-producing countries, with a bamboo forest volume and bamboo production ranking first in the world. In China, the bamboo resources could be grouped according to 39 categories, which cover more than 500 species. Bamboo is primarily distributed in the provinces of Zhejiang, Sichuan, Fujian, Hunan, and Jiangxi. Among these, the Fujian province has the most abundant bamboo resources (998,000 hectares in total), with 78 counties and cities, making its bamboo forests the superior resource and regional characteristic. The most abundant species of bamboo in this region is the moso bamboo, which occupies approximately 904,667 hectares (Ying *et al*. 2010; Zhang *et al*. 2010).

Fig. 1. The distribution of global bamboo resources

Through photosynthesis, moso bamboo transforms carbon dioxide in the atmosphere into saccharides, oxygen, and organics to produce high-molecular weight compounds such as cellulose, hemicellulose, and lignin through matter energy conversion. This process provides renewable biologic materials. Thus, bamboo vegetation contributes to carbon sequestration (Wu *et al*. 2015; Yen 2015). After five or six years, the bamboo will enter into an aging period. Thus, it is recommended that the bamboo be cut for lamination prior to this aging period.

Laminated bamboo is a sheet material consisting of bamboo cane that is glued and laminated. In comparison with wood building materials, bamboo has a stable size, good rigidity, and is abrasion-resistant (Fuentes *et al*. 2015; Li *et al*. 2015; Sharma *et al*. 2015). Naturally, laminated bamboo has been recognized worldwide as a sustainable green building material and therefore is a very important material in promoting forest product transformation for the construction industries (Nath *et al*. 2015).

Because industrialization produces a large amount of waste that overwhelms the natural recycling capacity of nature, the utilization of life cycle assessment (LCA) could present an overall and comprehensive understanding of the resource depletion and environmental influence brought about by human activities (Gao *et al*. 2015).

Life cycle assessment has bridged the gap between scholars at home and abroad who have studied the potential influence of wood products and wastes on global warming. This method is used to assess not only the emission load of carbon dioxide, but also the effects of other greenhouse gases, such as methane and hydrogen fluoride. Furthermore, this assessment can evaluate the overall influence of wood product processing on the environment and conducts a comparative analysis of the carbon emissions of different methods.

The LCA method has been widely accepted worldwide and has become an important trend in current research and development (Rivela *et al*. 2006; García *et al*. 2011; Cambria and Pierangeli 2012). Some scholars have found that the global carbon reserve from wood products has an annual increase of about 40 million ton (40 Mt). Accordingly, the carbon emissions during the manufacturing process mirrors this annual increase and exceeds the reserves (Pingoud *et al*. 2001). Thus, the potential influence of wood processing and its effect on global warming is of great importance.

In this paper, trilaminar straight joint glued-laminated bamboo (TSJGLB) was used to establish an evaluation system based on the life cycle assessment (LCA) system, through the utilization of GaBi version 6.0 LCA software (Thinkstep Co., Germany), to analyze the resource depletion and environmental emission. The aim of this study was to provide scientific guidance for low-carbon material processing.

EXPERIMENTAL

Goal and Scope Definition

Laminated bamboo products have many potential applications in the industry, whose resource and energy depletion during manufacturing differs much from each other. Wood products manufactured from Fujian Ming Jiang Bamboo Craft Technical Co. Ltd, Liancheng Country, represent a typical model for this experiment. Trilaminar straight joint glued-laminated bamboo (TSJGLB) was analyzed for environmental cost effectiveness to provide a scientific basis for the optimization of the production line.

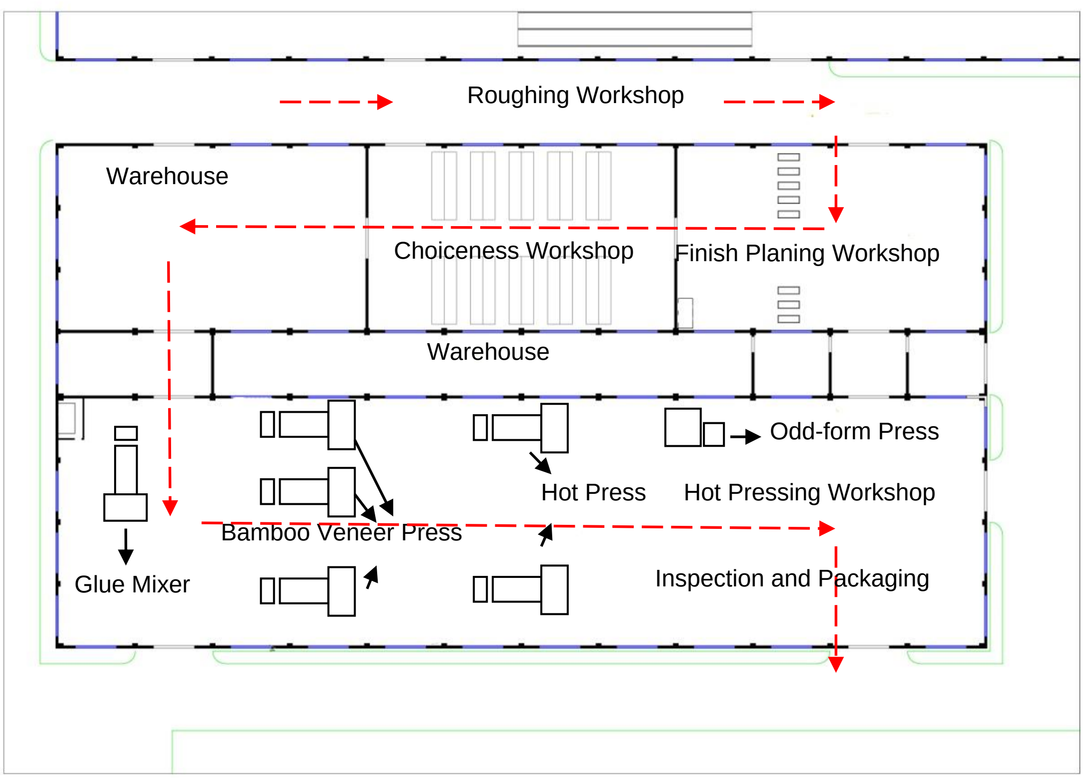

Fig. 2. Layout of the production line

The purpose of this study was to analyze and assess the energy depletion, material depletion, and environmental cost during the bamboo manufacturing process. The processing method of TSJGLB can be summarized as follows: carbonization, drying, roughing, finish planing, choiceness, gluing, hot pressing, inspection, and packaging. The purpose of the steps from the initial material collection to drying is to improve the rot resistance and stability of the bamboo. Furthermore, the steps from roughing to packaging are categorized as the production. The layout of the production line is shown in Fig. 2, with the arrows showing the operational path.

Functional Unit

Because the system is multi-functional, it is necessary to define the system according to the specific object and scope. The functional unit is a datum point of quantization for system input and output, which is the precondition for realizing the quantized contrastive analysis. Fresh bamboo prepared for this study was purchased from local farmers (Lvxi Ming Jiang Bamboo Factory, Liancheng Country), with a moisture content of approximately 100%. After steam drying, the moisture content was 7% to 9%. The variation in the data collected was attributed to the season. The mean density of TSJGLB in this study was 875 kg/m^3

Data Quality

Because the data quality determines the reliability of the assessment, the data collected were obtained from a full year of observation in the target enterprise, communication with the staff, and the production statement. The manufacturing of production commodities (bamboo, equipments, buildings, packaging film, *etc*.) and the transportation of energy and TSJGLB, as well as its depletion, was excluded from the system boundaries.

The assessment followed the 5% principle, where the environmental loads resulting from minor material flow consumed during production, *e.g*., lubricating oil for production means, the steam output for drying bamboo, or the water for glue mixing, were not taken into account.

Life Cycle Inventory Analysis

Life Cycle Inventory Analysis (LCIA) is a statistical quantization of the input and output resources and their energy depletion and environmental emissions (*e.g*., waste water, gas, and solid waste) during every process. Therefore, LCIA as the core of life cycle assessment is closely related to the boundary range and presents certain repeatability.

The boundary range definition of LCA and the output and input parameters are shown in Fig. 3.

The environmental loads during the processing stages of TSJGLB can be listed as follows:

1. The depletion of renewable resources, which refers to the damage occurring to bamboo during transportation (165 piece/m^3) and the loss during finish planing (410 g/m^3).
2. The depletion of non-renewable resources, including the depletion of diesel oil during transportation of bamboo (10.41 L/m^3) and adhesive (2.6 L/m^3), that of electricity

during carbonization (42.72 kWh/m^3), drying (39.72 kWh/m^3), finish planing (33.46 kWh/m^3), gluing (3.346 kWh/m^3), and hot pressing (46.7 kWh/m^3).

3. Solid waste, which refers to the depletion of adhesive (16.99 g/m^3).

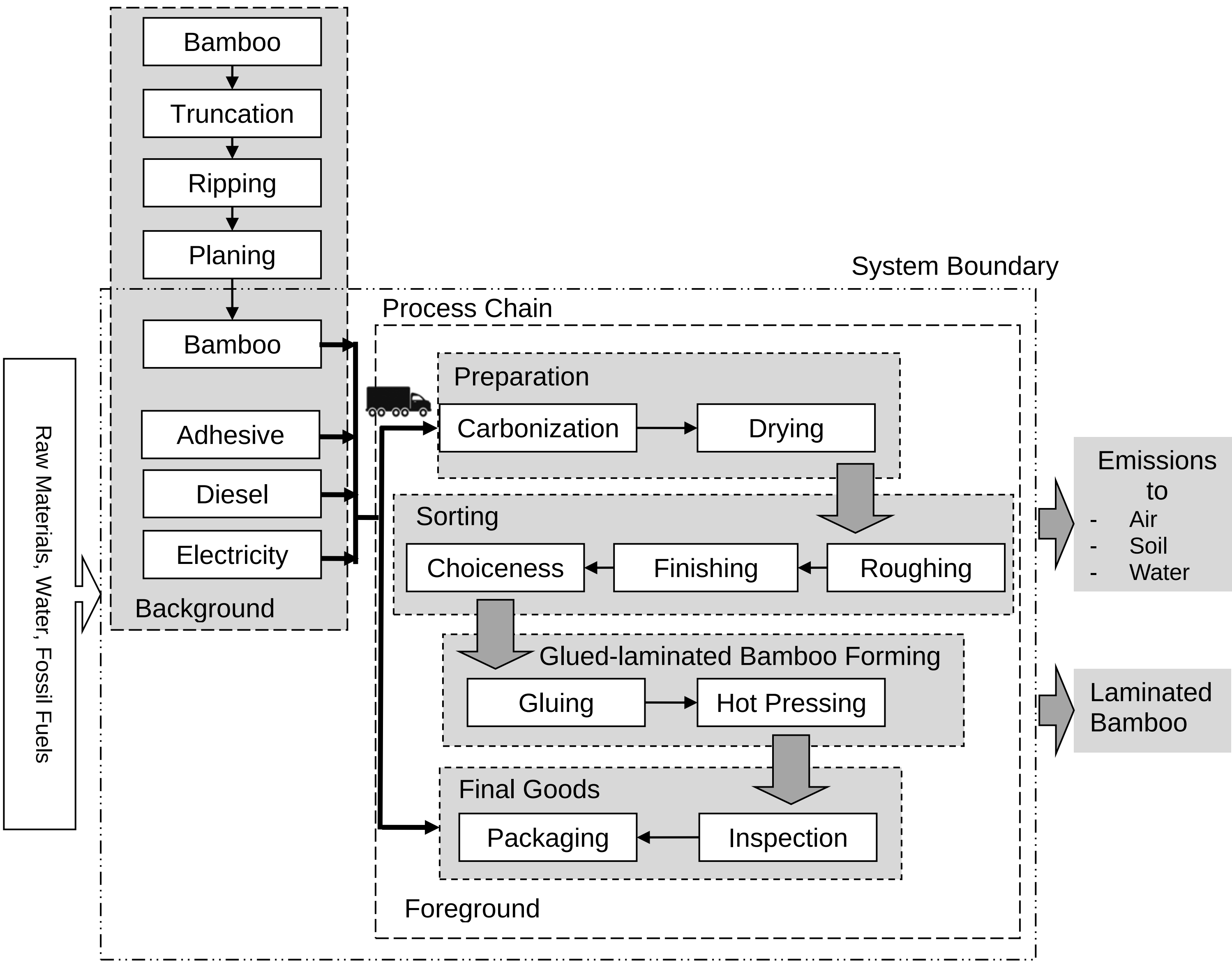

Fig. 3. Life cycle assessment system

The production of TSJGLB was divided into four subsystems: preparation, sorting, glued-laminated bamboo forming, and final goods. Because TSJGLB is an intermediate product, the inspection and packaging after hot pressing resulted in no energy or material loss, meaning no environmental load was generated. Thus, the quantification analysis primarily focused on the former three subsystems, and a comprehensive life cycle assessment of the environmental influence of the whole process chain was conducted.

RESULTS AND DISCUSSION

Analysis of Environmental Influence

A quantitative analysis of the six important environmental indexes in the CML2001 evaluation model which was put forward by Leiden University included: abiotic depletion (AD), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), and photochemical ozone creation potential (POCP). The results were characterized using GaBi version 6.0 software, and the life cycle assessment of TSJGLB was calculated as shown in Table 1. The values represented in bold are the indexes that demonstrated the greatest environmental effect (Table 1).

Table 1. Results of the Life Cycle Assessment of TSJGLB

Environmental Quantities	Preparation	Sorting	Glued-laminated Bamboo Forming
Abiotic Depletion (kg Sb-Equiv.)	1.454×10^{-7}	5.44×10^{-8}	**8.273×10^{-6}**
Acidification Potential (kg SO_2-Equiv.)	**0.70**	**0.262**	**0.433**
Eutrophication Potential (kg PO_4^{3-}-Equiv.)	**0.082**	**0.0307**	**0.0538**
Global Warming Potential (kg CO_2-Equiv.)	**100.8**	**37.7**	**71.9**
Ozone Layer Depletion Potential (kg R11-Equiv.)	8.98×10^{-12}	3.36×10^{-12}	**7.895×10^{-10}**
Photochemical Ozone Creation Potential (kg C_2H_4-Equiv.)	**0.056**	**0.0209**	**0.0349**

As shown in Table 1 by bold values, the aforementioned three subsystems influenced the AP, EP, GWP, and POCP indexes the most. In addition, the glued-laminated bamboo forming subsystem contributed greatly to the AD and ODP indexes. The bamboo forming subsystem composed of gluing and hot pressing was considered. It was observed from the original data that the preparation of adhesive during gluing influenced the AD and ODP indexes, instead of the hot pressing stage. The glue applied to TSJGLB was modified UF resin, and a characterized analysis of the results pertaining to the environmental effect is shown in Fig. 4.

The results showed that urea contributed the most to the environment effect, followed by the power consumption, and formaldehyde and melamine last. Thus, it can be inferred that reducing the consumption of urea would be one of the solutions for lowering the quantification index. However, its practical application would need to be evaluated together with the environmental load, among other factors.

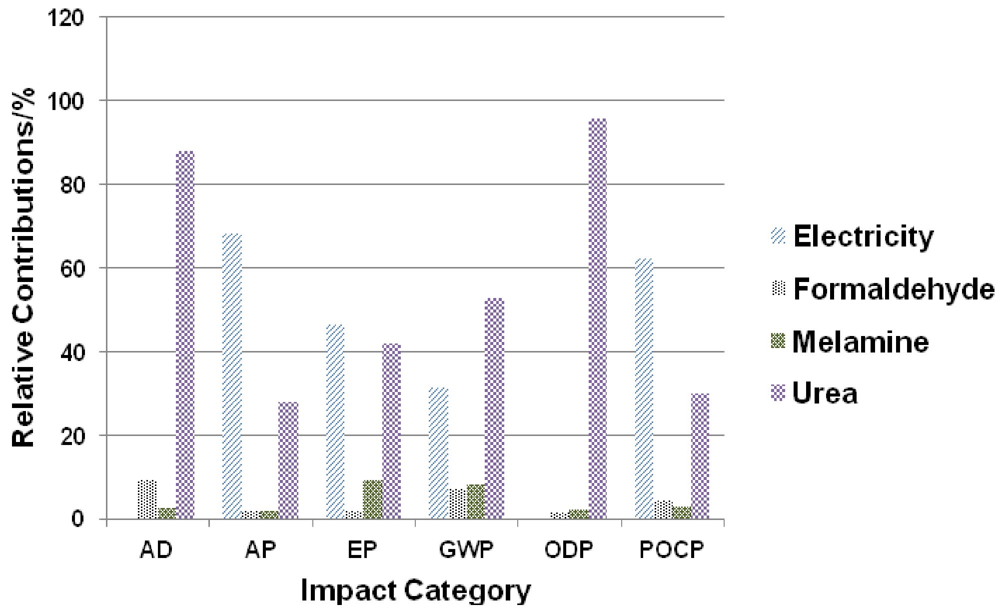

Fig. 4. Relative contributions (%) for each impact category in the preparation of UF resin

Normalized results for the environmental load during the production of TSJGLB were achieved through the standardization of the major environmental factors AP, EP, GWP, and POCP.

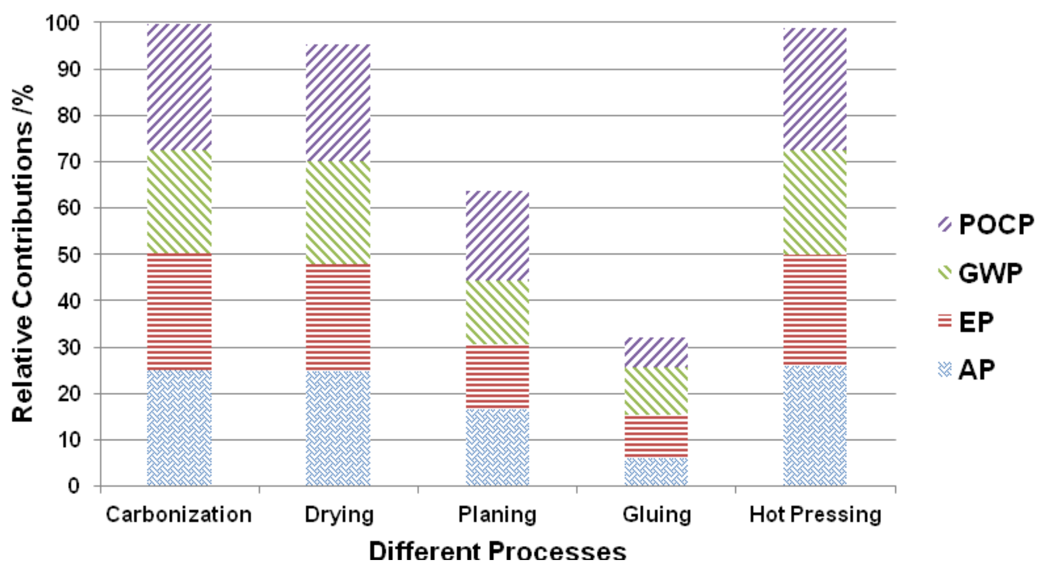

Fig. 5. Relative contribution of the different processes on the environment

Acidification

Acidification is primarily caused by the emission of NO_x and SO_x, which means that gluing minimally affects the acidification process (0.083 kg SO_2 Eq.). On the other hand, carbonization, drying, finish planing, and hot pressing contributed the greatest (over 90%). The effects of carbonization (0.355 kg SO_2 Eq.), drying (0.348 kg SO_2 Eq.), and hot pressing (0.365 kg SO_2 Eq.) were similar.

Eutrophication

Gluing contributed the least to eutrophication (0.016 kg PO_4^{3-} Eq.), followed by finish planing (0.024 kg PO_4^{3-} Eq). The effects of carbonization (0.042 kg PO_4^{3-} Eq.), drying (0.039 kg PO_4^{3-} Eq.), and hot pressing (0.041 kg PO_4^{3-} Eq.) were similar. The latter three contributed approximately 72% to the eutrophication process.

Global Warming

Gluing contributed the least to global warming (21.513 kg CO_2 Eq.), followed by finish planing (29.181 kg CO_2 Eq.). The effects of carbonization (47.925 kg CO_2 Eq.), drying (47.073 kg CO_2 Eq.), and hot pressing (48.138 kg CO_2 Eq.) were similar. The latter three contributed approximately 67% to global warming.

Photochemical Ozone Creation

Gluing contributed the least to photochemical ozone formation (0.0069 kg C_2H_4 Eq.), followed by finish planing (0.0209 kg C_2H_4 Eq.). The effects of carbonization (0.0293 kg C_2H_4 Eq.), drying (0.0273 kg C_2H_4 Eq.), and hot pressing (0.0282 kg C_2H_4 Eq.) were similar. The latter three contributed approximately 79% to the formation of photochemical ozone.

By analyzing the influence of carbonization, drying, gluing, and hot pressing on major environmental factors, the authors have found that gluing contributed the least, followed by finish planing, whereas, carbonization, drying, and hot pressing contributed the most. This was attributed to greater electrical power consumption of the later from fossil fuel. Furthermore, the consumption of fossil fuel is the leading contributor to the environmental load. Therefore, the core of low-carbon processing was to optimize the techniques and reduce power consumption.

Consequently, during the actual process, some small-molecule saccharides are emitted into the outdoor environment during the carbonization of bamboo. Therefore, these nitrogen and phosphorous compounds were predicted to exert acidification and eutrophication on the surroundings. For another, the bamboo dust post-planing is normally recycled and sold to the solid fuel processing plant. Thus, the environmental load caused by bamboo dust processing and burning was not discussed in this paper. Meanwhile, during the gluing process, the adhesive contained chemicals such as oxynitrides, VOCs, and arenes, meaning that the depletion of adhesive will intensify eutrophication and POCP and the following hot pressing will further accelerate the emission of small molecule compounds inside of the bamboo and the adhesive, which will further promote POCP.

CONCLUSIONS

1. The processing of trilaminar straight joint glued-laminated bamboo (TSJGLB) exhibits the greatest effect on acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), and photochemical ozone creation potential (POCP) indices, among which the preparation of modified UF resin exhibited the greatest influence on AD and ODP because of urea.

2. Carbonization, drying, and hot pressing were more influential factors to the environmental load than the other two phases during the production because of the consumption of electricity generated from fossil fuel. In addition, the emissions from oxynitrides, arenes, *etc*., during the manufacturing process intensified eutrophication, photochemical ozone generation, and acidification.

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