Volume 15, Issue 2, 152410 (1-8)

International Journal of Industrial Chemistry (IJIC)

https://dx.doi.org/10.57647/j.ijic.2024.1502.10

Environmental assessment of bamboo-based multilayer composites: a life cycle analysis perspective

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Original Research

Received:
27 February 2024
Revised:
18 March 2024
Accepted:
23 March 2024
Published online:
30 June 2024

Abstract:

Bamboo-based multilayer composite materials are a new type of bio-composite material with high strength, wide applicability, and low cost. Based on the life cycle assessment (LCA) method, this paper analyzes the energy consumption and harmful substance emissions of producing $1m^3$ of this product using the basic data inventory provided by the material processing enterprises, GaBi 6.0 software, and the CML2016 method. Results show that in the production and manufacturing process of bamboo-based multilayer composite materials, the environmental impact category with the most significant influence is acidification (AP), accounting for 53.27%, followed by marine aquatic ecotoxicity (MAETP) and eutrophication (EP). In its production, the environmental load mainly comes from bamboo combustion (for energy) and rough planing (to remove bamboo green and bamboo yellow), which account for 74.59% and 6.93% of the total environmental load, respectively. The study also found that burning waste bamboo can meet the factory's energy selfsufficiency, and except for eutrophication (EP) and acidification (AP), all other environmental loads are less than that of coal and natural gas combustion. Based on the above analysis, bamboo-based multilayer composite materials possess low-carbon, energy-saving, and environmentally-friendly characteristics.

Keywords: Bamboo-based multilayer composite materials; Environmental benefits; Life cycle assessment; Environmental impact; New type of bio-composite material

1. Introduction

Life Cycle Assessment (LCA) was first proposed by the Society of Environmental Toxicology and Chemistry (SETAC) in 1990. Its aim is to evaluate the burden and impact a product or production pro-cess has on the environment by quantitatively analyzing the consumption of energy, raw materials, wastewater, waste gases, solid waste, and others. In other words, it assesses the potential environmental impacts of a product's entire inputs and outputs throughout its life cycle [1]. Currently, this tool is widely applied in areas like materials, environment, food, chemical engineering, and more. The evaluation process includes defining objectives and scope → inventory analysis → impact assessment → results interpretation. GaBi is a commonly used LCA assessment tool internationally. It contains databases for more than 1000 processes and is suitable for engineering fields, capable of calculating carbon foot-prints, aiding in analysis and decision-making, quantifying analyses, supporting cost analyses, and phase analysis[2, 3].

Since the 1990s, scholars have used the GaBi software to conduct environmental benefit assessments of various biomass materials and their products. Atish [4] compared wooden houses to houses made of other materials and found that wooden houses emit less carbon and are more environmentally friendly. Similarly, Richard [5] compared bamboo to stone materials in buildings and found that bamboo struc-tures have only half the environmental load of stone structures, suggesting that bamboo is a low-carbon, environmentally friendly material at every stage of its harvesting, transportation, and processing. Gerfried [6] also found that wooden structures in houses and floors have 40% less environmental load than reinforced concrete structures. Sara [7] found that nanocoatings containing silica aerogels are a cost-effective modification of exterior walls while reducing the thermal load requirements of buildings Pablo [8] believed that bamboo has low carbon emissions and is more convenient for product processing. Especially when used in its cylindrical form, its environmental benefits are several times greater than other materials. Silva [9] tailored the life cycle inventory for medium-density fiberboards, focusing on the environmental loads during its thermal pressing stage in the manufacturing process. Rivela [10] discussed the life cycle database for particleboards prepared based on urea-formaldehyde adhesive and derived the life cycle inventory data for particleboards and found that the main environmental harms were water pollution and dust pollution, primarily from sanding and chip planing stages. Urea-formaldehyde resin adhesives have many advantages, including high strength, good heat resistance and water resistance. Formaldehyde release is one of the main shortcomings of urea-formaldehyde resin, and it also has some shortcomings such as poor weather resistance and long curing time [11, 12], so its advantages and disadvantages should be considered comprehensively in practical application. Ead [13] reviewed the life cycle analysis of green composite materials and concluded that green composite materials have been proven to be a viable alternative to synthetic composite materials in many applications.Low production costs, wide availability, low environmental impact, and high specific strength and stiffness are just some of the advantages of green composites over traditional glass, carbon fiber, Kevlar, and other man-made composites. LCA helps quantify the environmental impact of products at the production, use, and end-of-life stages, but LCC studies should be used when analyzing the economic costs and benefits of a product or system.

Chinese scholar Yu Xiang [14] evaluated the life cycle of bamboo integrated materials and bamboo reconstituted bamboo materials. He found that the environmental load during the bamboo strip preparation process of bamboo integrated materials is the heaviest, consuming a lot of electricity, heat, and water resources, with significant wastewater discharge. The environmental load of reconstituted bamboo materials is most significant during the slab manufacturing phase. Overall, the environmental load of manufacturing reconstituted bamboo is 1.64 times that of bamboo integrated materials. Hu Jianpeng [15] studied the environmental effects of glue-free fiberboard manufacturing by setting the boundary system as the laboratory manufacturing link. He optimized high-energy-consuming processes such as enzyme synthesis and drying through quantitative analysis, proposing energy-saving strategies. Wang Aihua[16] took a particular bamboo flooring factory as an example and found that the environmental load of its products during the manufacturing process is ranked as: (production > transportation > use). Huang Dongmei [17] found that during the construction process of bamboo-structured houses, the environmental load contribution rates are as follows: (production 52.17% > resource mining 30.82% > construction 13.57% > transportation 3.42%), with phenolic resin adhesive contributing 15% of the environmental load. Dai Qian [18] evaluated the life cycle of integrated materials used in construction and concluded that the most significant environmental impact during its production process is global warming. The environmental loads of each process in order are: raw wood processing, lumber drying, milling, cross-cutting, planing, and board joining. Xu Peiyu [19] compared the environmental impact of bamboo building materials with other building structural materials, and the results showed that the environmental impact value of bamboo building materials was 0.098 standard human equivalent, which was significantly lower than that of other building materials. The importance of bamboo building materials to environmental improvement is explained. Xu Xiaoxiao [20] found that bamboo building materials had the largest carbon absorption in the planting stage and the largest carbon emission in the production stage.one cubic meter of bamboo assembled components can reduce 249.92 kg CO_2 from the atmosphere. Although LCA has made some progress in the field of biomass materials, there are still some issues, such as lack of reliability, vague boundary condition settings, and a gap in research on the environmental impact of new bamboo-based multilayer composite materials that have been widely used in construction, furniture, and other fields in recent years.

bamboo is a kind of natural renewable resources, the growth cycle is relatively short, with good renewability and sustainability. bamboo laminates prepared from bamboo have the characteristics of light weight and high strength [14]. In this study, the GaBi 6.0 LCA software is used, and the CML2016 evaluation method is adopted. The product manufacturing process is defined as the life cycle assessment boundary system. With the production of 1 m^3 of this product as the functional unit, the environ-mental effects of this product's manufacturing process, including electricity, heat, water, and other energy and resource consumption, as well as the quality of three wastes, are scientifically accounted for. This establishes an environmental effect assessment model for bamboo-based multilayer composite materials. The environmental load and environmental effect evaluation of each process in the boundary system during the material's production and manufacturing are analyzed. Quantitative analysis of the environmental load characterization results is performed, explanations for its environmental impact are provided, and several further energy-saving measures are proposed.

2. Environmental impact assessment of bamboo laminated timber based on LCA

2.1 Objective and scope

This study focuses on the manufacturing process of a common market construction-grade 4-layered 12 mm thick bamboo laminated timber made using cross-lamination. The production process encompasses stages like raw material preparation, preprocessing, hot pressing of lamination, and product shaping. These stages comprise 12 main procedures and include processes from the entry of raw materials to the in-factory transportation of raw materials, waste, semi-finished goods, and finished products. The boundary of this study is depicted in Figure 1.

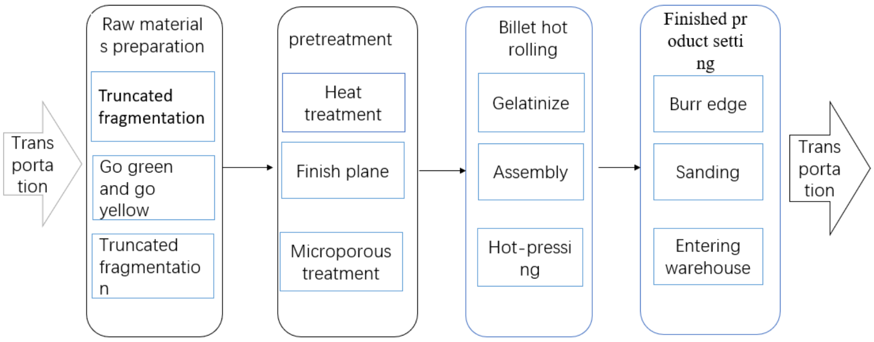

Figure 1. The boundary range of bamboo laminated lumber products.

2.2 Inventory analysis

The data for inventory analysis were sourced from the production lines of Fujian's leading bamboo enterprise, Youzhu bamboo Industry Co., Ltd. The input materials include bamboo strips and phenolic resin adhesive. Energy inputs comprise electricity, steam, and diesel, whereas outputs include waste and emissions from the combustion of leftover materials, steam, and exhaust from internal and external transportation vehicles.
Using the GaBi 6.0 software and the Ecoinvent database for China, as well as the production energy consumption data provided by the company, the material and emission inventory for producing 1 m^3 of bamboo laminated timber is shown in Table 1.

2.3 Composition and evaluation method of environmental load

This research utilizes the GaBi 6.0 LCA software developed by the German company PE-INTERNATIONAL, along with the CML2016 method. The primary environmental burdens identi-fied during the production process include: Resource Depletion (Abiotic Depletion, abbreviated as ADP), Acidification (Acidification Potential, abbreviated as AP), Eutrophication (Eutrophication Po-tential, abbreviated as EP), Global Warming (Global Warming Potential, abbreviated as GWP), Fresh-water Ecotoxicity (Freshwater Aquatic Ecotoxicity, abbreviated as FAETP), Human Toxicity (Human Toxicity Potential, abbreviated as HTP), Marine Ecotoxicity (Marine Aquatic Ecotoxicity Potential, abbreviated as MAETP), Terrestrial Ecotoxicity (Terrestrial Ecotoxicity Potential, abbreviated as TETP), and Ozone Layer Depletion (Ozone Layer Depletion Potential, abbreviated as ODP), totaling 9 categories. By considering nine different environmental impact categories, the study provides a com-prehensive assessment of the environmental impact of production processes. This kind of comprehen-sive assessment helps to understand the potential environmental impact of the production process more comprehensively, and provides an important basis for formulating environmental management strategies.The classification, characterization, normalization, and weighting factors of CML2016 in GaBi 6.0 are shown in Table 2.

Table 1. Environmental load inventory of producing 1 m^3 bamboo laminated lumber

	Inventory Name	Unit	Input/Output
Product	bamboo Laminated Timber	kg	720
Raw Material	bamboo (with a moisture content of 65%)	kg	5233
	Water	kg	3000
	Phenolic Resin Adhesive	kg	30
Energy	Electricity	MJ	1.86E+03
	Steam	MJ	7.90E+03
	Diesel	kg	24
Liquid Waste	Wastewater	kg	850
Solid Waste	Dust	kg	32
	bamboo offcuts	kg	3.39E+03
	Processed product offcuts (after gluing)	kg	74
	Ash after combustion	kg	211
Gaseous Waste	Water vapor	kg	3369
	NH_3	kg	140
	CO_2	kg	1120
	HCN	kg	16.9
	NO	kg	20.3
	NO_2	kg	6.29
	SO_2	kg	0.484

Table 2. The characteristic factor of CML2016 evaluation method [3].

Types of Environmental Impact	Equivalent Units	Weight
Abiotic Depletion Potential (ADP)	kg of Antimony (Sb)	6.4
Acidification Potential (AP)	kg of Sulfur Dioxide (SO_2)	6.1
Eutrophication Potential (EP)	kg of Phosphate (PO_{4-3})	6.6
Global Warming Potential (GWP)	kg of Carbon Dioxide (CO_2)	9.3
Freshwater Aquatic Ecotoxicity Potential (FAETP)	kg of Dichlorobenzene (DCB)	6.8
Marine Aquatic Ecotoxicity Potential (MAETP)	kg of Dichlorobenzene (DCB)	6.8
Terrestrial Ecotoxicity Potential (TETP)	kg of Dichlorobenzene (DCB)	6.8
Human Toxicity Potential (HTP)	kg of Dichlorobenzene (DCB)	7.1
Ozone Depletion Potential (ODP)	kg of Trichlorofluoromethane (R11)	6.2

3. Environmental impact assessment of bamboo laminated timber products

Throughout the assessment process, the collected data for each procedure is sequentially characterized, normalized, and weighted. Characterization analysis converts the environmental burdens of each procedure into some "equivalent", quantifying various types of burdens exerted on the environment. Normalization and weighting process the characterization results, comparing the proportions of different environmental impact categories and energy resource consumption in the overall environmental impact, thereby exploring the most significant influencing factors.

3.1 Characterization analysis

Based on the impact types listed in Table 3 and utilizing the GaBi 6.0 software and the CML2016 characterization model, the environmental impact characterization analysis of bamboo laminated timber product manufacturing technology is conducted. The results from the inventory analysis are standardized, converting them into unified environmental impact type parameters, as shown in Table 3.

3.2 Normalized analysis

To facilitate the comparison and analysis of various environmental impact factors, the characteristic values were standardized and weighted through the GABI6.0 software. The normalized environmental load results (CML2016) during the bamboo laminated lumber production process are shown in Table 4.

From the normalized results, it can be known that the environmental loads generated by producing 1m^3 of bamboo laminated lumber in this process are ranked as follows: Acidification (AP) > Marine Aquatic Ecotoxicity (MAETP) > Eutrophication (EP) > Human Toxicity (HTP) > Global Warming (GWP) > Terrestrial Ecotoxicity (TETP) > Freshwater Aquatic Ecotoxicity (FAETP) > Resource Depletion (ADP) > Ozone Depletion (ODP). Assuming a total load of 100%, the percentages of each load are shown in Figure 2, which in the aforementioned order are: 53.27%, 20.34%, 19.29%, 4.01%, 2.78%, 0.15%, 0.11%, 0.01%, and 0.001%.

From Figure 3, it can be seen that in each step, the environmental loads are ranked as: bamboo burning > rough planing (removing the green-yellow part of bamboo) > drying > fine planing > sanding > punching > heat treatment > hot pressing > slab cutting > cutting > slicing > oil refining > transport. Assuming a total load of 100%, the percentage of each step's impact on the environment is: 74.59%, 6.93%, 3.99%, 3.25%, 2.52%, 2.25%, 2.18%, 2.13%, 0.96%, 0.69%, 0.35%, 0.21%, and 0.10%.

3.3 Results interpretation

According to the CML2016 evaluation criteria, manufacturing 1m^3 of the new bamboo laminated lumber has minimal

Table 3. Environmental load characterization results of producing 1 m^3 bamboo laminated lumber.

	ADP	AP	EP	GWP	FAETP	MAETP	TETP	HTP	ODP
	Sb/kg	SO_2/kg	PO_{4-3}/kg	CO_2/kg	DCB/kg	DCB/kg	DCB/kg	DCB/kg	R11/kg
Transport	0.00E+00	1.72E-01	4.52E-02	3.18E+01	4.57E-04	9.10E-05	5.20E-05	3.23E-01	0.00E+00
Cutting	8.91E-07	8.24E-02	1.15E-02	1.78E+01	1.67E-01	2.34E+03	9.79E-02	4.35E+00	4.20E-14
Slicing	4.45E-07	4.11E-02	5.74E-03	8.91E+00	8.34E-02	1.17E+03	4.90E-02	2.18E+00	2.10E-14
Rough planing	7.44E-06	5.44E-01	4.23E-02	1.29E+02	1.24E+00	2.40E+04	1.04E+00	4.44E+01	4.48E-13
Drying	4.39E-06	3.34E-01	2.99E-02	7.81E+01	7.48E-01	1.37E+04	5.93E-01	2.55E+01	2.56E-13
Heat treatment	2.47E-06	1.96E-01	1.98E-02	4.50E+01	4.29E-01	7.48E+03	3.22E-01	1.39E+01	1.38E-13
Fine planing	3.61E-06	2.78E-01	2.57E-02	6.46E+01	6.18E-01	1.12E+04	4.83E-01	2.08E+01	2.08E-13
Punching	2.54E-06	2.01E-01	2.01E-02	4.62E+01	4.41E-01	7.72E+03	3.32E-01	1.43E+01	1.43E-13
Hot pressing	2.05E-05	2.57E-01	3.36E-02	9.98E+01	7.33E-01	6.83E+03	2.70E-01	1.43E+01	3.59E-13
Slab cutting	6.48E-07	6.48E-02	1.02E-02	1.36E+01	1.26E-01	1.54E+03	6.35E-02	2.91E+01	2.71E-14
Sanding	2.83E-06	2.22E-01	2.16E-02	5.12E+01	4.89E-01	8.67E+03	3.73E-01	1.61E+01	1.61E-13
Oil refining	1.26E-06	2.75E-02	2.08E-03	4.61E+00	3.21E-01	7.11E+02	9.27E-03	1.13E+00	2.67E-15
bamboo burning	0.00E+00	3.03E+02	6.72E+01	1.25E+03	0.00E+00	0.00E+00	0.00E+00	2.72E+01	0.00E+00

Table 4. Normalized Results of Environmental load of Producing 1m^3 bamboo Laminated Lumber

	ADP	AP	EP	GWP	FAETP	MAETP	TETP	HTP	ODP	TOTAL
	Sb/kg	SO_2/kg	PO_{4-3}/kg	CO_2/kg	DCB/kg	DCB/kg	DCB/kg	DCB/kg	R11/kg	
Transport	0.00E+00	4.39E-12	1.89E-12	7.02E-12	1.32E-15	3.18E-18	3.24E-16	8.90E-13	0.00E+00	1.42E-11
Cutting	1.58E-14	2.10E-12	4.80E-13	3.93E-12	4.81E-13	8.15E-11	6.11E-13	1.20E-11	1.15E-21	1.01E-10
Slicing	7.89E-15	1.05E-12	2.40E-13	1.96E-12	2.40E-13	4.07E-11	3.05E-13	5.99E-12	5.73E-22	5.05E-11
Rough planing	1.32E-13	1.39E-11	1.77E-12	2.85E-11	3.59E-12	8.35E-10	6.49E-12	1.22E-10	1.22E-20	1.01E-09
Drying	7.78E-14	8.53E-12	1.25E-12	1.72E-11	2.15E-12	4.79E-10	3.70E-12	7.01E-11	6.98E-21	5.82E-10
Heat treatment	4.38E-14	5.00E-12	8.26E-13	9.92E-12	1.24E-12	2.61E-10	2.01E-12	3.82E-11	3.78E-21	3.18E-10
Fine planing	6.40E-14	7.09E-12	1.07E-12	1.42E-11	1.78E-12	3.90E-10	3.01E-12	5.72E-11	5.68E-21	4.74E-10
Punching	4.50E-14	5.13E-12	8.39E-13	1.02E-11	1.27E-12	2.69E-10	2.07E-12	3.94E-11	3.90E-21	3.28E-10
Hot pressing	3.63E-13	6.57E-12	1.40E-12	2.20E-11	2.11E-12	2.38E-10	1.68E-12	3.93E-11	9.81E-21	3.11E-10
Slab cutting	1.15E-14	1.65E-12	4.26E-13	3.00E-12	3.64E-13	5.38E-11	3.96E-13	8.01E-11	7.41E-22	1.40E-10
Sanding	5.02E-14	5.66E-12	9.04E-13	1.13E-11	1.41E-12	3.02E-10	2.33E-12	4.43E-11	4.39E-21	3.68E-10
Oil refining	2.23E-14	7.01E-13	8.70E-14	1.02E-12	9.24E-13	2.48E-11	5.78E-14	3.10E-12	7.30E-23	3.07E-11
Burnt bamboo	0.00E+00	7.73E-09	2.81E-09	2.76E-10	0.00E+00	0.00E+00	0.00E+00	7.47E-11	0.00E+00	1.09E-08
Total	8.33E-13	7.79E-09	2.82E-09	4.06E-10	1.56E-11	2.97E-09	2.27E-11	5.87E-10	4.93E-20	

impact on resource depletion, ozone depletion, freshwater aquatic ecotoxicity, and terrestrial ecotoxicity. This suggests that the use of bamboo to produce laminated lumber and its production process have low energy and resource consumption characteristics. However, in this pro-duction process, because processes like bamboo drying and hot pressing require a large amount of steam as thermal energy, saturated steam obtained from burning waste bamboo is relied upon as a heat source. The burning of waste bamboo is the primary cause of environmental acidification, eutrophication, and global warming.

In this production process, a total of 3000 kg of saturated steam is theoretically consumed, equivalent to a total of 7900 MJ of heat. The amount of waste bamboo available for combustion and the heat it provides throughout the process are shown in Table 5. From the table, it's evident that the combustion of all waste bamboo from this production process (without considering the heat released from the evaporation of moisture within the bamboo during combustion) can produce 28500MJ of heat, leaving 20600 MJ of heat. In this environmental assessment, the emission conditions are at the highest combustion (300 °C). The waste materials generated from the cutting, slicing, rough planing, and fine planing processes are all burned, equivalent to the calorific value of 0.98 tons of standard coal or 730.78 m^3 of natural gas [21].

Based on GaBi6.0, the environmental impact of waste bamboo, standard coal, and natural gas producing the same heat value is shown in Table 6.

(Characteristic equivalent results of burning bamboo are marked as + values, while those of coal and natural gas are marked as - values.)

From the table, it is evident that under conditions producing equivalent heat, the environmental load from coal and natural gas is significantly higher than that from burning waste bamboo. Specifically, the acidification (AP) from burning coal is 6 times that of burning bamboo, global warming (GWP) is 34 times, and human toxicity (HTP) is 573 times; for natural gas, the global warming (GWP) is 25 times, and human toxicity (HTP) is 37 times that of burning bamboo. Additionally, it's found that the eutrophication (EP) from burning bamboo is 6/11 times that of coal and natural gas. This is mainly due to the residual ash from burning bamboo, which contains minerals like K, P, Ca, and Si. The acidification effect of natural gas is only 1/10 that of burning bamboo. Moreover, from a cost perspective, based on the current coal price of 650 yuan/t and natural gas at 1.8 yuan/m^3 in Fujian Province, producing 1 m^3 of this bamboo laminated product, subtracting the electricity costs of processing waste bamboo, labor, and bamboo material

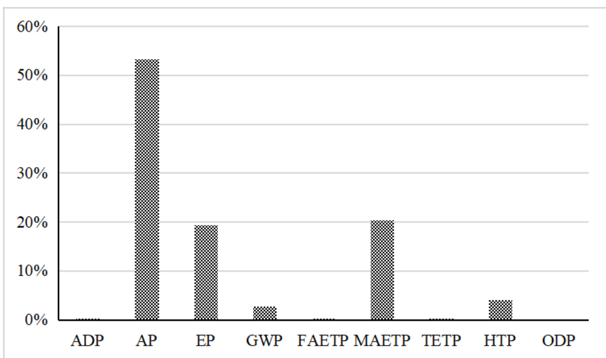

Figure 2. Various environmental load proportions.

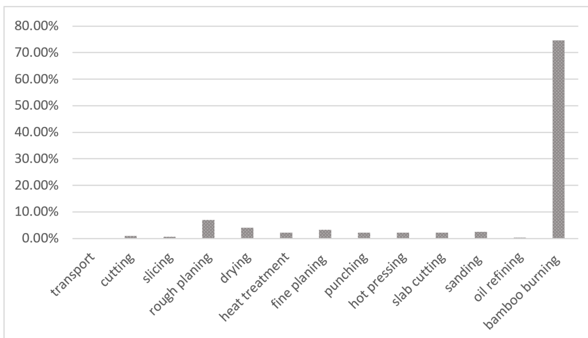

Figure 3. Various process proportion of environmental load.

Table 5. Provided waste bamboo and heat

Process	Waste bamboo mass (kg)	Moisture content (%)	Heat value (MJ)
Cutting	105	65	649.37
Slicing	410	65	2535.65
Rough Planing	2123	65	13129.70
Fine Planing	750	8	12192.30
Total			28500

costs, can save between 200-800 yuan, bringing considerable economic benefits to businesses.

In the production process of bamboo laminated lumber, besides the significant environmental load from bamboo burning, processes like rough planing, fine planing, and sanding also produce a significant environmental burden. For these steps, due to the high power of the equipment and longer processing time, they have a high electricity consumption. When modeling and analyzing with the GABI6.0 software, the environmental load from the power generation process is also accumulated into the environmental load of these steps.

During the drying and hot pressing steps, a large amount of saturated steam is required as a heat source. Under hydrothermal effects, bamboo and its products produce acetic acid and release trace amounts of phenols and aldehydes [22, 23], which are discharged with wastewater, thereby causing tox-icity to freshwater (FAETP), marine water (MAETP), terrestrial (TETP) ecosystems, and human health (HTP). During the hot pressing stage, due to the use of phenol-formaldehyde resin adhesive, there's also a certain level of resource consumption (ADP) and ozone depletion (ODP) risks. As this process uses a glue-coating technique with a glue amount of 150 g/m^2, it reduces the glue amount by 1/3 compared to other bamboo-based composites prepared using the immersion glue technique, such as bamboo bundle laminated lumber and bamboo curtain laminated lumber, and also eliminates the drying process after immersion, saving energy and reducing pollutant emissions. Moreover, in the hot pressing process, because this product is thin (12mm) and uses a "hot in, hot out" process, it significantly re-duces energy consumption compared to the "cold in, cold out" process of bamboo bundle laminated lumber and bamboo curtain laminated lumber.

4. Results and recommendations

With the boundary scope from the transportation of bamboo laminated material raw materials to product storage, according to the CML2016 evaluation method, the environmental load for producing 1m^3 bamboo laminated material in a pilot production line mainly comprises: Acidification (AP) 53.27% > Marine Ecotoxicity (MAETP) 20.34% > Eutrophication (EP) 19.29% > Human Toxicity (HTP) 4.01% > Global Warming Potential (GWP) 2.78% > Terrestrial Ecotoxicity (TETP) 0.11% > Freshwater Ecotoxicity (FAETP) 0.15% > Resource Consumption (ADP) 0.01% > Ozone Depletion (ODP) 0.001%.

The main environmental load in manufacturing this product comes from bamboo combustion (self-sufficient energy) and rough planing (removing bamboo green and yellow layer), accounting for 74.59% and 6.93% of the total environmental burden, respectively. Contributions from other processes are in the following order: Drying 3.99% > Fine Planing 3.25% > Sanding 2.52% > Hole Punching 2.25% > Heat Treatment 2.18% > Hot Pressing 2.13% > Panel Cutting 0.96% > Cutting 0.69% > Slicing 0.35% > Refining 0.21% > Transportation 0.10%.

Using waste bamboo for combustion can satisfy the factory's self-sufficient energy needs. Except for Eutrophication (EP) and Acidification (AP), all other environmental impacts are less than those from burning coal and natural gas. Moreover, the carbon footprint of products manufactured using this method is significantly superior to that of coal and natural gas. During the drying and hot pressing

Table 6. Environmental effects characterization analysis of coal and gas in burning waste bamboo of the same heat.

Environmental load and equivalent		Bamboo burning	Fire coal	Natural gas	Equivalent difference between coal burning and bamboo burning	Difference between gas and bamboo equivalent
ADP	Sb/kg	0.00E+00	-2.91E-02	-3.12E-01	-2.91E-02	-3.12E-01
AP	SO_2/kg	3.03E+02	-1.80E+03	-2.82E+01	-1.50E+03	2.75E+02
EP	PO_4^{-3}/kg	6.72E+01	-1.17E+01	-6.15E+00	5.55E+01	6.11E+01
GWP	CO_2/kg	1.25E+03	-4.30E+04	-3.18E+04	-4.18E+04	-3.06E+04
FAETP	DCB/kg	0.00E+00	-4.22E+02	-3.90E+01	-4.22E+02	-3.90E+01
MAETP	DCB/kg	0.00E+00	-7.70E+06	-9.47E+04	-7.70E+06	-9.47E+04
TETP	DCB/kg	0.00E+00	-3.67E+02	-1.31E+00	-3.67E+02	-1.31E+00
HTP	DCB/kg	2.72E+01	-1.56E+04	-1.03E+03	-1.56E+04	-1.00E+03
ODP	R11/kg	0.00E+00	-4.64E-10	-1.18E-10	-4.64E-10	-1.18E-10

processes, because the wastewater contains acetic acid, phenols, and aldehydes, it poses toxic threats to freshwater (FAETP), marine water (MAETP), terrestrial (TETP) ecosystems, and human health (HTP). Additionally, the use of phenol-formaldehyde resin adhesive introduces risks associated with resource consumption (ADP) and ozone depletion (ODP).

The newly developed bamboo laminated material in this study is a low-carbon, energy-saving multifunctional bamboo-based composite. The following recommendations are made regarding its environmental effects: (1)Since the heat produced by burning waste bamboo significantly exceeds the actual energy consumption for producing $1m^3$ of bamboo laminated material, this excess heat can be utilized for thermal treatment of bamboo, reducing electricity consumption. (2)For manufacturers, outdated equipment with high electricity consumption should be replaced or upgraded. Additionally, equipment utilization rates should be improved, production process routes optimized, labor productivity enhanced, and equipment operation times reduced. (3)For non-outdoor products, urea-formaldehyde resin adhesive can replace phenol-formaldehyde resin adhesive, which would lower the hot pressing temperature and reduce saturated steam consumption. (4)The ash produced from burning waste bamboo should be further processed into agricultural fertilizer, converting waste into wealth. (5)Promote green consumption and lifestyle: Through education and publicity, promote green consumption and lifestyle, reduce waste generation and emissions, and reduce the pressure on Marine ecosystems.

Authors Contributions
Authors were equally contributed in acquisition and analysing the data as well as preparing the paper.

Availability of Data and Materials
Data is available on request from the corresponding author, upon reasonable request.

Conflict of Interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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