Life-Cycle Assessment of Bicycles Based on Bamboo Bending Technology

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Abstract

Greenhouse gas emissions have increased significantly, driven by rising energy consumption and global population growth. The manufacturing sector is a major contributor to these emissions, emphasizing the importance of assessing carbon footprints across various production stages, including transportation. This study conducted a comprehensive life-cycle assessment to evaluate the environmental impacts of manufacturing bamboo bicycles using a specialized bamboo bending technology. Unlike conventional bamboo bicycles with tubular frames, this innovative model features frames constructed from curved bamboo panels produced by a dedicated bending machine. The assessment adhered to the publicly available specification 2050 framework, with a cradle-to-gate system boundary. Data were collected on site and analyzed using eFootprint software. Results show that manufacturing bamboo bicycles generates approximately 163.93 kg of CO_2 equivalent emissions, a 56.7 percent reduction compared with the 378.7 kg CO_2 equivalent emissions of traditional aluminum-frame bicycles. This highlights the low-carbon advantages of bamboo bicycles. These findings underscore the potential of bamboo bicycles as a sustainable alternative, providing valuable insights for optimizing production processes and promoting environmentally conscious consumption.

Since the Industrial Revolution, the rise of energy-intensive industries and widespread fossil fuel use have significantly increased atmospheric greenhouse gas (GHG) concentrations, further exacerbated by deforestation and population-driven resource demand (Goodwin et al. 2024). Energy, as the foundation of economic and social development, is the primary source of GHG emissions (Jackson et al. 2019, Peters et al. 2020). Climate change now poses one of the greatest global challenges (Zhang 2022). Addressing this issue requires promoting renewable energy, enhancing production efficiency, and advancing green development strategies. Sustainable production and consumption models aim to optimize resource use, reduce waste, and lower carbon footprints, supporting a transition to a low-carbon economy and a sustainable future. Achieving carbon neutrality necessitates reducing GHG emissions, aligning economic growth with environmental sustainability (Finkbeiner et al. 2010).

Bamboo, as a rapidly renewable resource, matures within 3 to 5 years (Hinkle et al. 2019), making it ideal for sustainable construction and furniture materials (van der Lugt et al. 2006). During its growth, bamboo absorbs significant amounts of CO_2 through photosynthesis, contributing to climate change mitigation (Juan et al. 2016). Its extensive root system prevents soil erosion, maintains soil quality (Nath et al. 2015), and supports biodiversity by providing habitats for various species. As a sustainable alternative, bamboo can replace nonrenewable materials like aluminum, reducing environmental degradation (Escamilla and Haber 2014).

Bamboo possesses high strength and flexibility, along with excellent impact resistance (Sharma and Vegte 2015), making it highly durable and adaptable for withstanding external forces in practical applications. The bamboo bending process uses a proprietary bending machine developed by the factory. On the basis of specific design blueprints, the dimensions of the bamboo strips are determined, and controlled heat and pressure are applied during the process. This technique effectively utilizes the unique properties of bamboo, including its high tensile strength and natural flexibility, to precisely bend the strips to the desired curvature (Ma et al. 2024). This technique allows for design flexibility and the creation of unique shapes, enhancing structural strength and aesthetic appeal (Lao et al. 2024). Moreover, it

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maximizes the efficient use of bamboo, reducing waste, maintaining lightweight properties, and facilitating transportation and installation.

Because of its accessibility, resilience, and natural aesthetic, bamboo is widely used across various aspects of daily life (Flander and Rovers 2009), including furniture, architecture, kitchenware, and household items. As society increasingly emphasizes environmental protection and ecological balance, bamboo's renewable nature makes it an ideal choice for sustainable development (Zhou et al. 2014). Bamboo is increasingly being used as a material for bicycle frames. These bicycles are lightweight, offer excellent shock absorption, and treated bamboo is resistant to moisture and decay, increasing their longevity (Zhang et al. 2017). The natural texture of bamboo gives these bicycles a distinctive appearance, adding a sense of individuality.

This study uses the "cradle-to-gate" approach outlined in the publicly available specification (PAS) 2050 assessment framework (Wang and Yang 2019) to delineate the production processes of bamboo bicycles on the basis of their system boundaries. The focus is on the bamboo bicycle produced by a company in Zhejiang, China that has developed the world's first rideable curved bamboo bicycle using its proprietary bamboo bending technology. Compared with conventional bicycles, the metal content in the bamboo bicycle frame is reduced by nearly 70 percent. A comprehensive analysis of relevant production data is conducted, and a life-cycle model is developed to calculate the life-cycle assessment (LCA) results. These results are then compared against various environmental impact indicators to evaluate the product's carbon footprint.

Objectives and Scope

Research objective

The main objective of this study was to assess the carbon footprint of a bicycle made of bamboo fiber throughout its life cycle. The data were obtained through an on-site survey of a company in Zhejiang known for its advanced bamboo bending technology and commitment to sustainable development. All data were cross-checked with production data provided by the company and verified through direct observation and interviews with the manufacturing team. The survey covered the entire production process, from material selection to final shaping. The results show that GHG emissions associated with the production life cycle of bamboo bicycles are significantly lower compared with traditional aluminum bicycles.

Functional unit

The carbon footprint calculation was based on the production of one bamboo bicycle as the functional unit (ISO 1997, 2006). The net weight of the bicycle is 16.3 kg, and its design is depicted in Figure 1.

Research scope

The PAS 2050 standard framework (British Standards Institution 2011) is an evaluation system based on LCA methodology (Vogtländer and van der Lugt 2015). It offers two approaches for evaluating products and services. The first is the cradle-to-gate model, also known as the business-to-business approach, which includes the carbon footprint from all production stages up until the product is delivered to another manufacturer. The second is the cradle-to-grave model, or business-to-consumer approach, which encompasses the entire product life cycle, including raw material extraction, manufacturing, distribution and retail, consumer use, and final disposal or recycling (Vogtländer et al. 2010, Weng et al. 2012).

Figure 1.—Bending bamboo-frame bicycle.

The bamboo involved in this study comes from sustainably managed plantations and is certified by well-known independent third-party organizations such as the Forest Stewardship Council (FSC) to prevent the destruction of natural and native forests. The system boundary starts from the planting and harvesting stage of bamboo and goes through a series of processing steps until the product is packaged. This definition is based on the cradle-to-gate approach. Because of the complexity and difficulty of quantifying carbon emissions during the use and disposal stages of products, this study focuses on carbon emissions from raw material acquisition to the manufacturing process. In addition, the carbon offset generated by bamboo growth is difficult to quantify accurately. Considering the characteristics of bamboo's rapid growth and carbon sequestration throughout its life cycle, it is usually assumed that the carbon absorbed during the growth process can offset the carbon emissions generated during the production process. Therefore, data from the planting and harvesting stages are not included in this assessment. The specific system boundary is shown in Figure 2.

System boundaries include the following stages:

1. Production and manufacturing of rough-planed bamboo strips: The raw bamboo undergoes selection, cutting, splitting, and rough-planing processes before it can be purchased and used by bamboo product manufacturers.
2. Production and manufacturing of bamboo composite panels: The rough-planed bamboo strips are processed through hydrothermal carbonization, drying, fine planing, sorting, gluing, and hot-pressing stages to form bamboo composite panels (Fang et al. 2018).
3. Production and manufacturing of bamboo bicycle components and finished products: The bamboo composite

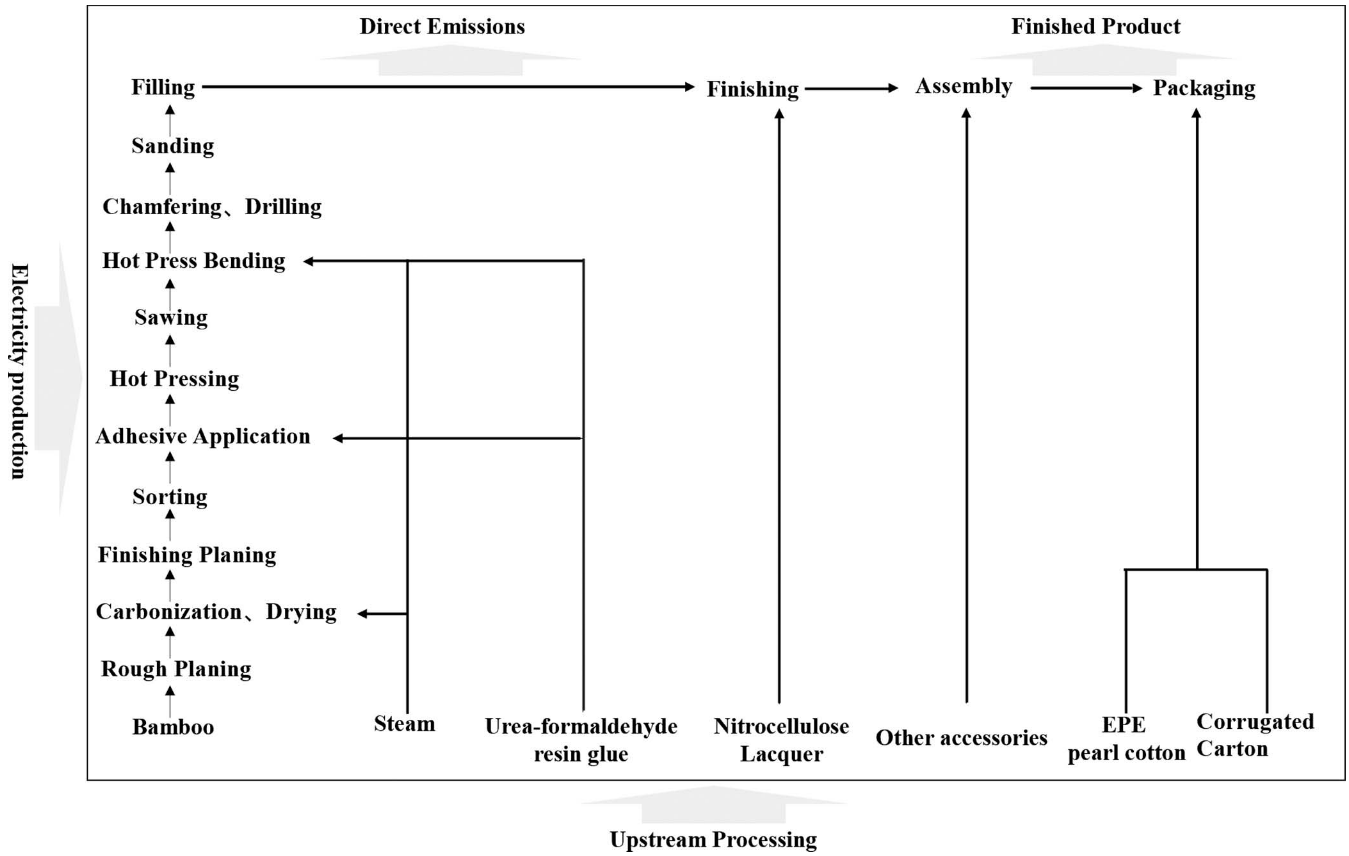

Figure 2.—System boundaries of the bamboo bicycle (cradle to gate).

panels are cut and subjected to hot-press bending (Huang et al. 2015) to create curved bamboo panels. These curved panels are then chamfered, drilled, sanded, filled, and coated to produce the required bamboo components. These components are assembled with metal parts, and the final bamboo bicycle is packaged using expanded polyethylene (EPE) foam and corrugated cardboard boxes.

Environmental impact types

The climate change indicator is based on CO_2 as the reference substance, with other GHGs assigned their respective CO_2 equivalent factors according to their potency (global warming potential [GWP]) in contributing to the greenhouse effect (State Forestry Administration of the People's Republic of China 2018). Therefore, the emissions of various GHGs throughout the product life cycle can be multiplied by their respective equivalency factors and summed to obtain the total climate change indicator (commonly referred to as the product carbon footprint), expressed in kg CO_2 equivalents. The indicators for environmental impact types are summarized in Table 1.

Inventory Analysis

Collection of on-site production data

Using the production of a curved bamboo bicycle as the functional unit, on-site data collection methods were used to gather production data from the enterprise. The specific data sources include product drawings, material analysis

Table 1.—Environmental impact type indicators.[a]

Environmental impact type indicator	Impact type indicator unit	Key inventory substances
Global warming potential	kg CO_2 eq.	CO_2, CH_4, N_2O, etc.
Primary energy demand	MJ	Hard coal, lignite, natural gas, etc.
Abiotic depletion potential	kg Sb eq.	Iron, manganese, copper, etc.
Water use	kg	Freshwater, surface water, groundwater, etc.
Acidification potential	kg SO_2 eq.	SO_2, NO_x, NH_3, etc.
Eutrophication potential	kg PO_4^{3-}eq.	NH_3, NH_4-N, COD, etc.
Respiratory inorganics	kg PM2.5 eq.	CO, PM10, PM2.5, etc.
Ozone depletion potential	kg CFC-11 eq.	CCl_4, $C_2H_3Cl_3$, CH_3Br, etc.
Photochemical ozone formation potential	kg NMVOC eq.	C_2H_6, C_2H_4, etc.

[a] eq. = equivalent; PM2.5 = particulate matter with diameter $\leq$ 2.5 μm; PM10 = particulate matter with diameter $\leq$ 10 μm; CFC-11 = trichlorofluoromethane; NMVOC = nonmethane volatile organic compound; COD = chemical oxygen demand.

sheets, processing methods, process parameters, equipment specifications, on-site monitoring, and company inspection reports. The relevant data inventory is presented in Table 2.

The resource utilization for producing a bicycle is categorized into three types: bamboo materials, coatings, and packaging materials (Leuenberger et al. 2010). The total amount of bamboo required is 9.2 kg, which is processed into several key bicycle components. The specific weights of these bamboo components are as follows: bamboo seat (0.38 kg), bamboo handle (0.33 kg), chain guard (0.34 kg), bottom bracket decorative plate (0.16 kg), bicycle frame (4.26 kg), fork decorative cover (0.12 kg), and mudguard (0.56 kg). In terms of coatings, the production process includes 0.25 kg of urea–formaldehyde (UF) resin adhesive and 0.1 kg of nitro-based paint. The packaging materials consist of 0.5 kg of EPE foam and 3 kg of corrugated cardboard. Energy utilization included the use of 1 kWh of electricity and 5 kg of steam. Throughout the entire production process of bamboo components, solid waste and bamboo powder amounted to 2 kg, whereas wastewater generated is 105 kg. The wastewater was collected by the factory and transferred to a professional treatment facility for processing.

Collection of upstream raw material production data

In addition to the on-site resources required for production, several upstream raw materials need to be purchased, included one seat support metal frame, one seat screw, two handlebar grips, two brake cables connected to the handlebars, one chain, one set of single crankset, one set of pedals, one set of bicycle bottom bracket, one front fork, one support leg, and two tires. The details of these purchased raw materials are presented in Table 3. Among these materials, the weight of the tires is 3.92 kg, the weight of metal components is 4.84 kg, the weight of rubber components is 0.42 kg, and the weight of plastic components is 0.32 kg.

Table 2.—Bamboo material data for bicycles

Item	Input quantity	Output quantity	Unit
Resource utilization			
Bamboo strips	9.2	/	kg
Bamboo seat		0.38	kg
Bamboo handle		0.33	kg
Chain guard		0.34	kg
Bottom bracket decorative plate		0.16	kg
Bicycle frame		4.26	kg
Fork decorative cover		0.12	kg
Mudguard		0.56	kg
Urea–formaldehyde resin Adhesive	0.25		kg
Nitro-based paint	0.1		kg
Expanded polyethylene (EPE) foam	0.5		kg
Corrugated carton	3		kg
Energy utilization			
Electricity	1		kwh
Steam	5		kg
Pollution emissions			
Solid waste and bamboo powder		2	kg
Waste gas			kg
Wastewater		105	kg

Table 3.—Purchased raw materials.

Name	Quantity	Unit	Unit material weight	Weight unit
Seat support Metal Frame	1	Piece	0.36	kg
Seat screw	1	Piece	0.48	kg
Handlebar grips	2	Pieces	0.12	kg
Brake cable Connected to handlebar	2	Pieces	0.3	kg
Chain	1	Piece	0.28	kg
Single crankset	1	Set	0.6	kg
Pedals	1	Set	0.32	kg
Bicycle bottom bracket	1	Set	1	kg
Front fork	1	Pair	1.84	kg
Support leg	1	Piece	0.28	kg
Tires	2	Pieces	3.92	kg

Software and databases

This study used the eFootprint software system to establish a life-cycle model for the curved bamboo bicycle (Liu et al. 2010) and to calculate the results of the LCA. The eFootprint software system is an online LCA analysis tool developed by Yike Environmental Technology Co., Ltd. It supports comprehensive analysis of the entire life-cycle processes and includes integrated databases such as the Chinese Life Cycle Database (CLCD), the European Life Cycle Database, and the Swiss Ecoinvent database. The CLCD, used during the research, is developed by Yike and is based on the industry average database derived from the core life-cycle model of China's foundational industrial systems. The CLCD encompasses inventory data sets for major domestic energy sources, transportation, and primary raw materials.

Unit Process Division

Bamboo strip processing stage

The bamboo strip processing stage involves cutting bamboo into specified lengths, followed by splitting the bamboo into strips. These strips undergo rough planing to achieve a smooth surface, resulting in long bamboo pieces with defined specifications and a rectangular cross-section. Subsequently the bamboo strips are bundled and placed in a carbonization furnace for carbonization and drying. After cooling, the strips are finely planed to meet standard size and aesthetic quality requirements.

The bamboo strip production process flow diagram delineates the inputs and outputs of raw materials and energy during this processing stage, as illustrated in Figure 3.

On the basis of the production process flow diagram, the bamboo strip production was primarily divided into the following steps:

1. Cutting: The production of bamboo strips begins with ensuring the quality of the raw materials. The bamboo used in this study comes from sustainably managed plantations certified by the FSC, ensuring that environmentally responsible practices are followed. The selected bamboo is at least 5 years old, with a diameter of over 10 cm and a wall thickness exceeding 7 mm. Younger bamboo has insufficient fiber lignification and a higher rate of drying shrinkage and wet swelling, which can adversely affect the structural

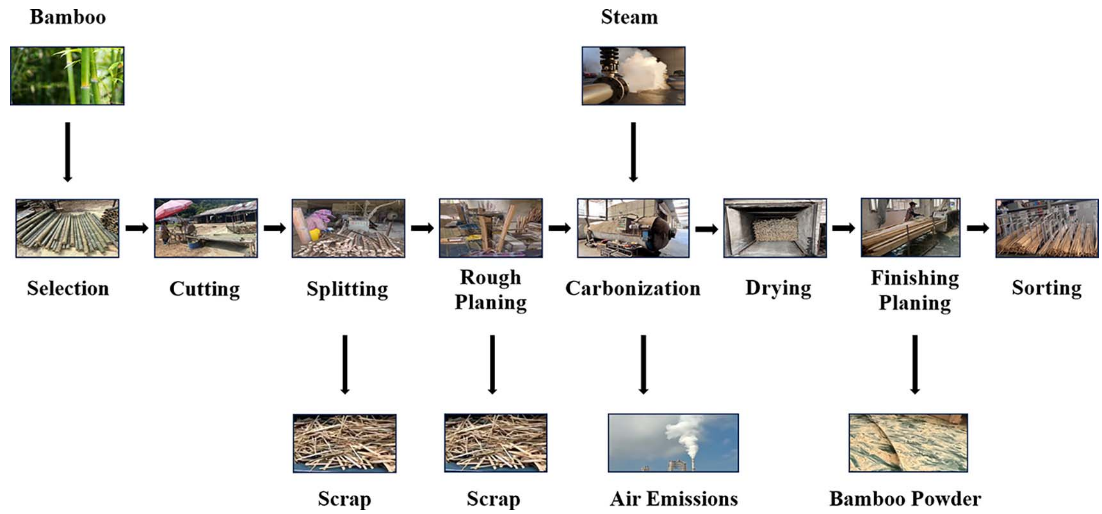

Figure 3.—Bamboo strip production process flow diagram.

strength of the bamboo products. The bamboo culms were cut to a length of 2 m after removing the roots, leaves, and branches.

2. Splitting: The cut bamboo culms were placed in a bamboo splitting machine for processing.
3. Rough planing: Since the green and yellow layers of bamboo can influence the viscosity of UF resin glue, it is customary to remove these layers before further processing. The bamboo strips were then planed using a rough planer to achieve a rectangular cross-section. The resulting bamboo strips generally measure 2 m in length, 2 cm in width, and 4 mm in thickness.
4. Carbonization (Zhang 2010): The rough-planed bamboo strips were bundled and placed in a high-temperature, high-humidity carbonization furnace. This process allows for the complete decomposition of organic compounds such as sugars and starches, making the bamboo less susceptible to pests. High-temperature carbonization also effectively eliminates any insects, eggs, and various bacteria adhering to the bamboo strips, serving a sterilization purpose.
5. Drying: Because of the significant amount of steam introduced during carbonization, the bamboo strips must be transferred to a designated drying chamber after carbonization. The drying process uses a kiln drying system, and the energy required to run the kiln is derived from the combustion of bamboo waste generated during the earlier processing stages, in line with the circular economy principle of using process by-products. The GHG emissions associated with the drying process are calculated on the basis of the carbon neutrality of biomass combustion, and the energy consumption of the process is fully accounted for in the total GHG emissions. This drying process evaporates moisture from the bamboo strips, preventing mold growth and reducing issues such as warping and cracking in subsequent production, thereby promoting structural stability.
6. Finishing planing: A finishing planer was used to remove rough surfaces from the bamboo strips, resulting in a smoother and flatter surface, which is advantageous for producing bamboo-laminated boards.
7. Sorting: An intelligent bamboo strip sorting machine was used to classify the bamboo strips that meet production requirements, providing high-quality strips for bamboo board manufacturing.

Throughout the entire process of producing usable bamboo strips from raw bamboo, energy consumption amounted to 1.23 kWh of electricity and 0.02 tons of steam, resulting in the generation of 3.98 kg of renewable waste bamboo powder. The specific process inventory data are presented in Table 4.

Bamboo strip bending technology in bicycle production

Production stage of laminated bamboo panels.—After the bamboo strips are processed, they undergo gluing, assembly, and hot pressing to form laminated bamboo panels.

Table 4.—Inventory data for bamboo strip production process.

Type	Inventory item	Quantity	Unit	Upstream data source[a]
Product output	Bamboo strips	9.2	kg	—
Raw materials/inputs	Raw bamboo	19.8	kg	Data unavailable
Energy	Electricity	1.23	kWh	CLCD China 0.9
Energy	Steam	4	kg	CLCD China 0.9
Renewable waste	Bamboo powder	3.98	kg	Data unavailable

[a] CLCD = Chinese Life-Cycle Database.

These panels are classified into two types: horizontally laminated bamboo panels and vertically laminated bamboo panels. Although both types follow the same processing method, they differ in their assembly orientation. Horizontally laminated panels are assembled with the grain running parallel to the flooring surface, whereas vertically laminated panels have the grain perpendicular to the surface, with edge-grain bonding. The laminated bamboo panels used in the production of the bamboo bending technology bicycles studied here include both types. The production process of these laminated bamboo panels, illustrated in Figure 4, details the material and energy inputs and outputs throughout this stage of manufacturing.

On the basis of the process flow diagram, the production of laminated bamboo panels could be divided into the following key steps:

1. Adhesive application: The adhesive used for this type of bamboo panel is a UF resin glue, characterized by low free formaldehyde content, which poses minimal health risks. After precision planing and sorting, the bamboo strips were evenly coated with an adequate amount of the UF resin glue before being assembled for hot pressing.
2. Assembly: After gluing, the bamboo strips were assembled into layers according to the required dimensions and structural specifications, forming a composite assembly.
3. Hot pressing: The assembled bamboo strips were promptly transferred to a hot press. The heat accelerates the curing of the UF resin glue, solidifying the bonds between the strips and completing the lamination process (Restrepo et al. 2016).
4. Sawing: The laminated bamboo panels were cut to the required dimensions according to design specifications.
5. Sanding: The pressed panels were sanded to remove surface burrs and impurities, improving the adhesion of subsequent coatings.
6. Panel lamination: Depending on the product requirements, individual bamboo layers were laminated to achieve the desired thickness of the laminated bamboo panels.

Production and assembly stage of main bamboo bicycle components.—This stage represents the final step in the production of bamboo-frame bicycles. Laminated bamboo panels are subjected to a specialized bending process and integrated with other components to create the finished bamboo bicycle (Agyekum et al. 2017). The process flow diagram for the bending and production of these bamboo panels provides a clear representation of the material and energy inputs and outputs at this stage, as illustrated in Figure 5.

On the basis of the process flow diagram, the production of the final product could be divided into the following steps:

1. Panel bending: After the formation of laminated bamboo panels, they needed to enter the bamboo bending workshop, where a specialized bamboo bending machine was used to perform the bending operations (Ji et al. 2023), ultimately producing customized bamboo components suitable for bicycles.
2. Trimming: Specific cutting tools were used to remove any irregular or uneven sections along the panel edges, ensuring straight and clean lines.
3. Drilling: The shaped bamboo components were drilled and tenoned according to the design specifications.
4. Sanding: Bamboo parts were finely processed using sanding machines and sandpaper, enhancing the precision and quality of the product.
5. Finishing: A coat of nitrocellulose lacquer was applied to the surface of the bamboo components using DISK electrostatic spray equipment, with one layer of primer followed by a topcoat.
6. Assembly: The finished bamboo components were combined with purchased metal, rubber, and plastic parts to

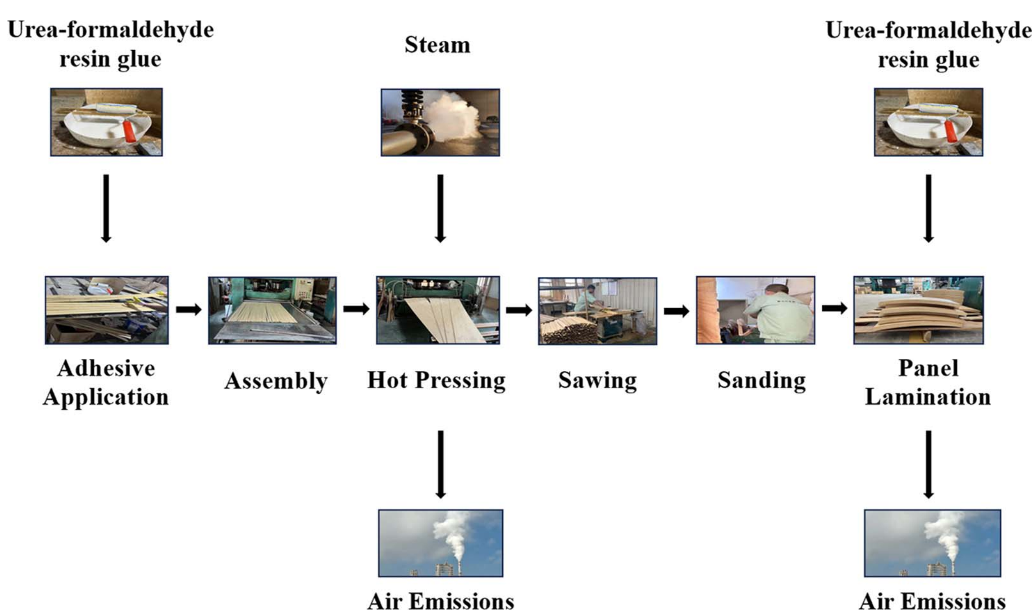

Figure 4.—Process flow diagram for laminated bamboo panel production.

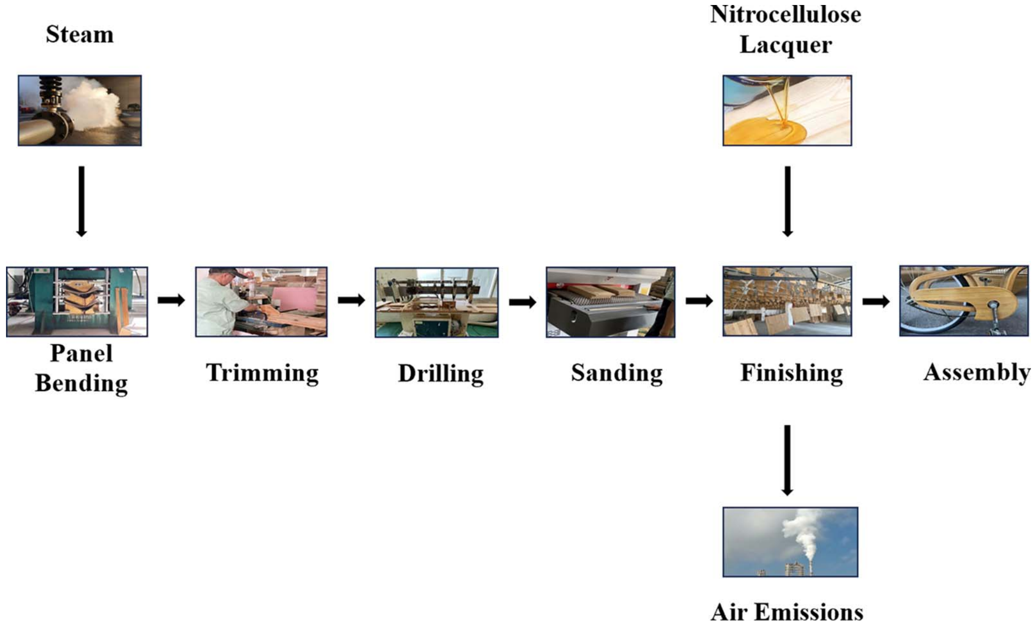

Figure 5.—Process flow diagram for laminated bamboo panel bending production.

assemble a semifinished bamboo bicycle, which is then packaged. The final assembly of the bicycle is completed by the consumer upon purchase.

Data on the input and output of raw materials, energy consumption, packaging use, environmental emissions, and renewable waste are provided in Table 5.

Transportation stage

The transportation process is divided into three stages. The first stage involves transporting raw bamboo to the rough-planed bamboo strip factory. As the two locations are adjacent, the transportation distance is negligible and does not significantly affect the LCA. The second stage involves transporting rough-planed bamboo strips to the finished product manufacturing plant, covering 2.5 km. The third stage consists of short-distance transfers within the manufacturing plant. Because of the minimal distances involved and their negligible environmental impact, these transfers are excluded from the LCA. Detailed transportation data from raw bamboo to finished products are presented in Table 6.

Impact Assessment

Analysis of computational results

The LCA of a bamboo bicycle was modeled and calculated using the eFootprint platform. The evaluation metrics included GWP, primary energy demand (PED), abiotic depletion potential (ADP), water use (WU), acidification potential (AP), eutrophication potential (EP), respiratory inorganics, ozone depletion potential, and photochemical ozone formation potential. The results are presented in Table 7.

On the basis of the data in Table 7, the production of a single bamboo bicycle resulted in approximately 163.93 kg of CO_2 equivalent emissions and consumed about 1,915.02 MJ of energy, with water consumption reaching 1,182.94 kg. Energy

Table 5.—Inventory data for the bicycle production process.

Type	Inventory name	Quantity	Unit	Upstream data source[a]
Product output	Curved bamboo bicycle	16.3	kg	—
Raw materials/items	Raw bamboo	19.8	kg	Real-time process data
Raw materials/items	urea–formaldehyde resin glue	0.25	kg	Real-time process data
Raw materials/items	Nitrocellulose-based paint	0.1	kg	Negligible: weight ratio <1%
Raw materials/items	Tires	3.92	kg	lcacontest-t-e31v@ike-global.com 1.0
Raw materials/items	Bicycle metal components	4.84	kg	Yike Database
Raw materials/items	Bicycle rubber accessories	0.42	kg	lcacontest-s-o20p@ike-global.com 1.0
Raw materials/items	Bicycle plastic accessories	0.32	kg	Yike Database
Energy	Electricity	1	kWh	CLCD China 0.9
Energy	Steam	5	kg	CLCD China 0.9
Packaging	Expanded polyethylene pearl cotton	0.5	kg	Yike Database
Packaging	Corrugated carton	3	kg	CLCD China 0.9
Environmental emission	Formaldehyde (emitted to atmosphere [unspecified type])	0.03	kg	
Waste to be disposed	Solid scraps and bamboo powder	5.98	kg	Yike Database
Renewable waste	Wastewater	105	kg	Yike Database

[a] CLCD = Chinese Life-Cycle Database.

Table 6.—Transportation process information.

Material name	Gross weight	Starting point	Destination	Transportation distance	Transportation type
Bamboo	19.8 kg	Bamboo rough planing facility	Product processing facility	2.5 km	Truck transport (2 t)–diesel

use was distributed across various production stages, with electricity for machinery operation and steam for the specialized bamboo-bending process representing key contributors. Water consumption was primarily associated with the bending process of irregular bamboo components. Because of variations in the thickness and bending angles of these components, each part required individual fabrication. Steam was used during the molding process, which was carried out manually by skilled workers under strict supervision, with drainage necessary at each step, leading to relatively high water consumption.

Cumulative process contribution analysis

Cumulative process contribution refers to the aggregated contributions of the direct production process along with all upstream processes. Since processes typically involve multiple inventory data sets, process contribution analysis entails accumulating the sensitivity of various inventory data. On the basis of the division of unit processes, the environmental impacts of the bamboo strip processing stage, bamboo laminated board production stage, and bamboo laminated board bending stage were decomposed, quantifying each process's contribution to the overall environmental impact. The specific results are shown in Table 8.

The results of the cumulative contribution analysis presented in Table 8 show that the environmental impact indicators associated with "other purchased parts" consistently represent the highest values in all categories. Therefore, it can be concluded that the main source of carbon emissions throughout the bicycle's life cycle comes from these other purchased parts, which include nonbamboo materials such as rubber, plastic, and metal. In addition, the production process related to bamboo contributes a measurable but much smaller contribution to the overall environmental impact. This contribution is mainly attributed to the use of chemical adhesives in the manufacturing process; however, the magnitude of this impact is much smaller than that of other purchased parts.

Table 7.—Life-cycle assessment (LCA) results for the bamboo bicycle.[a]

Environmental impact category	Unit	LCA results
Global warming potential	kg CO_2 eq.	163.93
Primary energy demand	MJ	1915.02
Abiotic depletion potential	kg Sb eq.	1.08×10^{-3}
Water use	kg	1,182.94
Acidification potential	kg SO_2 eq.	0.61
Eutrophication potential	kg PO_4^{3-} eq.	0.09
Respiratory inorganics	kg PM2.5 eq.	0.52
Ozone depletion potential	kg CFC-11 eq.	6.84×10^{-6}
Photochemical ozone formation potential	kg NMVOC eq.	0.49

[a] eq. = equivalent; PM2.5 = particulate matter with diameter $\leq$ 2.5 μm; CFC-11 = trichlorofluoromethane; NMVOC = nonmethane volatile organic compound.

Data interpretation and sensitivity analysis

Inventory data sensitivity refers to the degree to which a unit change in inventory data affects the corresponding impact indicators. By analyzing the sensitivity of inventory data to various indicators and combining this with an evaluation of improvement potential, the most effective improvement points can be identified. This study focuses on evaluating the environmental impacts of various materials and components used in the production of bamboo bicycles, including tires, metal fittings, corrugated cardboard boxes, bamboo, and UF resin adhesive. The specific results are presented in Figure 6.

Tires and metal components exhibit high values across multiple environmental impact categories, significantly contributing to global warming potential and demonstrating substantial energy consumption. The production of corrugated cardboard involves considerable water usage, further exacerbating its environmental burden. Additionally, the use of steam imposes a notable environmental load. In contrast, bamboo exhibits relatively low environmental impacts, characterized by minimal resource depletion and EP, underscoring its advantages in reducing GHG emissions and energy consumption.

Overall, the significant contributions of tires and metal components to GWP, energy consumption, and AP highlight them as key areas for improvement in designing more sustainable bicycles. In comparison, bamboo demonstrates superior performance across most environmental impact categories, establishing it as a more environmentally friendly material choice. These findings underscore the critical role of material selection in reducing the carbon footprint and resource consumption associated with bicycle production.

Comparative analysis of LCA results for bamboo and aluminum bicycles

The aluminum bicycle was selected as the comparison object for the LCA because of its widespread use as a high-performance and durable material in the bicycle industry, serving as a major alternative to bamboo. Comparing bamboo with aluminum helps evaluate the environmental benefits of bamboo. To ensure a fair comparison, a controlled variable approach was adopted, keeping all components identical except for the frame material. The selected aluminum bicycle weighs 11.5 kg. The LCA was conducted using eFootprint software and reliable databases such as the CLCD. Detailed results are presented in Table 9.

According to Table 9, the production of a single aluminum alloy bicycle results in approximately 378.7 kg of CO_2 equivalent emissions, with an energy consumption of 4,338.11 MJ and water consumption of 2,021.61 kg.

The bamboo bicycle outperforms the aluminum alloy bicycle in all environmental impact categories, demonstrating significant environmental benefits. Specifically, in the following categories, the bamboo bicycle reduces the GWP by approximately 57 percent, PED by about 55.8 percent, ADP

Table 8.—Cumulative contribution results for the bamboo bicycle life-cycle assessment (LCA).

Process name	Bicycle production	Bamboo strip production	Bamboo laminated board production	Bamboo laminated board bending	Other purchased parts
Global warming potential	163.9	3.90	0.23	0.46	159.34
Primary energy demand	1,915.02	45.59	2.68	5.36	1,861.74
Abiotic depletion potential	1.08×10^{-3}	2.57×10^{-5}	1.51×10^{-6}	3.02×10^{-6}	1.05×10^{-3}
Water use	1,182.94	28.16	1.66	3.31	1,150.03
Acidification potential	0.61	1.45×10^{-2}	8.54×10^{-4}	1.71×10^{-3}	0.59
Eutrophication potential	0.09	2.14×10^{-3}	1.26×10^{-4}	2.52×10^{-4}	8.75×10^{-2}
Respiratory inorganics	0.52	1.24×10^{-2}	7.28×10^{-4}	1.46×10^{-3}	0.51
Ozone depletion potential	6.84×10^{-6}	1.63×10^{-7}	9.58×10^{-9}	1.92×10^{-8}	6.65×10^{-6}
Photochemical ozone formation potential	0.49	1.17×10^{-2}	6.86×10^{-4}	1.37×10^{-3}	0.48

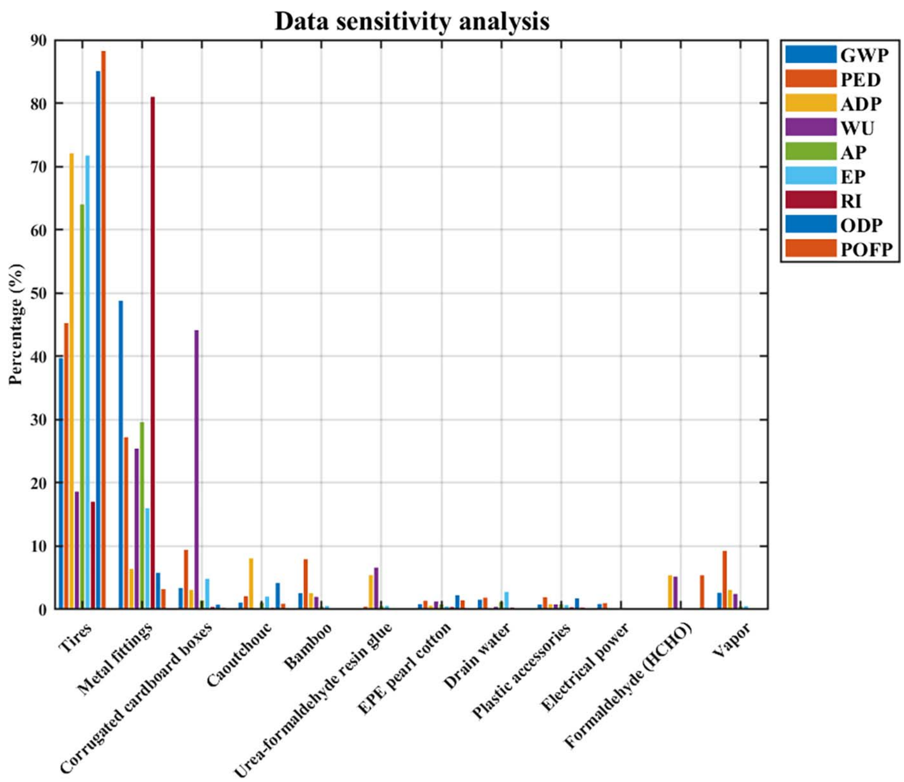

Figure 6.—Comparison of inventory data sensitivity. GWP = global warming potential; PED = primary energy demand; ADP = abiotic depletion potential; WU = water use; AP = acidification potential; EP = eutrophication potential; RI = respiratory inorganics; ODP = ozone depletion potential; POFP = photochemical ozone formation potential; EPE = expanded polyethylene.

Table 9.—Life-cycle assessment (LCA) results for the aluminum alloy bicycle.

Environmental impact category	Unit	LCA results
Global warming potential	kg CO_2 eq.	378.7
Primary energy demand	MJ	4,338.11
Abiotic depletion potential	kg Sb eq.	3.48×10^{-3}
Water use	kg	2,021.61
Acidification potential	kg SO_2 eq.	1.68
Eutrophication potential	kg PO_4^{3-}eq.	0.17
Respiratory inorganics	kg PM 2.5 eq.	0.88
Ozone depletion potential	kg CFC-11 eq.	8.67×10^{-6}
Photochemical ozone formation potential	kg NMVOC eq.	0.61

[a] eq. = equivalent; PM2.5 = particulate matter with diameter $\leq$ 2.5 μm; CFC-11 = trichlorofluoromethane; NMVOC = nonmethane volatile organic compound.

by 69 percent, WU by 41.5 percent, and AP by 63.7 percent. These data indicate that the bamboo bicycle excels in key indicators such as GHG emissions, energy consumption, and resource usage, making it an environmentally friendly alternative to the traditional aluminum alloy frame, particularly with respect to global warming and resource conservation.

Conclusion

Through a LCA of the bamboo bicycle, CO_2 equivalent emissions from its production were quantified and compared with those of an aluminum bicycle. The analysis underscores the significant advantage of bamboo in terms of carbon emissions. The results indicate that the carbon emissions from the production of a bamboo bicycle are substantially lower than those from an aluminum bicycle, with the primary emissions originating from the production of externally sourced plastic, metal, and rubber components. Additionally, the carbon content of bamboo, as a harvested wood product, serves as a carbon sink, offsetting part of the GHG emissions from the manufacturing process. On the basis of existing studies, the carbon content of bamboo is approximately 25 percent by dry weight. When this factor is considered, the environmental advantages of bamboo bicycles in terms of carbon emissions are further emphasized. Therefore, it is essential to fully explore the potential of bamboo, increase its utilization, and continuously optimize the sourcing of green alternatives for plastic, metal, and rubber components to further reduce carbon emissions. The full utilization of bamboo can help mitigate the environmental impact of manufacturing and decrease the carbon emissions associated with bicycle production, contributing positively to environmental GHG control.

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