Life cycle assessment of the artisanal bamboo pole (*Guadua angustifolia*) production in the Brazilian Amazon

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Abstract

The artisanal production of bamboo poles is an income alternative for small producers in countries in Africa, Asia, and Latin America. Despite the positive impact on climate change from the use of this renewable material for construction purposes, there is a gap in knowledge about the environmental footprint of this production system. This study assessed the potential environmental impacts of the artisanal production process of bamboo poles (*Guadua angustifolia*) in the Brazilian Amazon. A life cycle assessment (LCA) conducted within an artisanal production unit (PU) of bamboo poles, in the municipality of Rio Branco, state of Acre, in the Brazilian Amazon, encompassed the entire production chain, from bamboo planting to the chemically treated bamboo poles. The environmental impact category that prominently emerged was Human Carcinogenic Toxicity (HCT), achieving 93% of the total impact generated. Shaving and cutting waste and discarded poles accounted for 91% of the total impact generated by the artisanal bamboo production chain. The findings highlight the need to explore alternative methods for the chemical treatment of bamboo poles and to enhance the management of solid waste, emphasizing the optimization of water usage in the treatment process. Addressing these aspects is imperative for mitigating the environmental footprint associated with the artisanal bamboo production chain and promoting the bioeconomy in the Brazilian Amazon.

Keywords: production management, environmental management, environmental impact, health risks.

Avaliação do ciclo de vida da produção artesanal da vara de bambu (*Guadua angustifolia*) na Amazônia Brasileira

Resumo

A produção artesanal de varas de bambu é uma alternativa de renda para pequenos produtores em países da África, Ásia e América Latina. Apesar do impacto positivo nas mudanças climáticas pelo uso deste material renovável para fins de construção, existe uma lacuna no conhecimento sobre a pegada ambiental deste sistema de produção. O presente trabalho levantou os potenciais impactos ambientais do processo de produção artesanal de varas de bambu (*Guadua angustifolia*) na Amazônia brasileira. Uma avaliação do ciclo de vida (ACV) realizada em unidade de produção artesanal (UP) de varas de bambu, no município de Rio Branco, estado do Acre na Amazônia brasileira, abrangeu toda a cadeia produtiva, desde o plantio do bambu até as varas de bambu quimicamente tratadas. A categoria de impacto ambiental que se destacou foi a Toxicidade Carcinogênica Humana (TCH), atingindo 93% do impacto total gerado. Os resíduos de aparas e corte e as varas descartadas responderam por 91% do impacto total gerado pela cadeia produtiva artesanal do bambu. Os resultados reforçam a relevância de explorar métodos alternativos para o tratamento químico das varas de bambu e aprimorar a gestão de resíduos sólidos, enfatizando a otimização do uso da água no processo de tratamento. Abordar esses aspectos é imperativo para mitigar a pegada ambiental associada à cadeia produtiva do bambu artesanal e fomentar a bioeconomia na Amazônia brasileira.

Palavras-chave: gestão da produção, gestão ambiental, impacto ambiental, riscos à saúde.

1. Introduction

Urbanization has increased in the Brazilian Amazon in recent decades, particularly in the vicinity of the capitals of the states within the region (Araujo et al., 2022). In this context, the construction industry stands out as one of the most propelled sectors, albeit with significant environmental impacts, due to the consumption of both renewable and non-renewable materials, the utilization of energy resources, and the generation of waste, some of which is deemed environmentally hazardous.

In the Amazon, the ramifications of these impacts are accentuated by its geographical location, with specific regard to climate change. This heightened vulnerability is attributed to the reliance on imported civil construction materials, notably steel, sourced from other regions of Brazil. This dependency stems from the fact that roughly 85% of the yearly output of Brazilian steel, totaling 24 million tons, is predominantly concentrated in four states situated within the southeastern region of Brazil, among which São Paulo state holds significance, far from 3,000 to 4,000 km of Amazon states (BSE, 2023). This highlights the importance of considering viable alternatives sourced within the Amazon region to mitigate the environmental impact associated with construction materials and transportation.

In recent decades, the construction industry has endeavored to mitigate and offset its environmental footprint by incorporating bamboo, exploring various sustainable construction approaches (Xu et al., 2023). Moreover, bamboo's robust strength characteristics and mechanical properties position it as a viable alternative to traditional materials such as steel and wood (Escamilla et al., 2018), particularly for applications like beams and struts (Escamilla; Habert, 2014).

Various sectors, beyond construction, employ bamboo as raw material, spanning the production of furniture and handicrafts (Pieter; Utomo, 2023), textiles, and paper (Alexander, 2022). Additionally, there is considerable potential for bioenergy generation (Deshmukh; Pathan, 2024). The diverse applications of this biomaterial contribute to the expansion of the global bamboo market, which was valued at US$ 53 billion in 2020, with an anticipated annual growth rate of 5.7% from 2022 to 2028 (Neha; Aravendan, 2023).

The bamboo industry chain plays a pivotal role in job creation, spanning from the cultivation and management of the crop to the processing of harvested material. In India, around 8 million individuals rely on the bamboo-related industry chain, with approximately 2 million of them engaged as artisans (Alexander, 2022). Consequently, the bamboo chain presents itself as a viable option for poverty alleviation and income generation, particularly for rural communities, rooted in artisanal work and family-based production (Pieter; Utomo, 2023).

On the environmental front, bamboo forests exhibit favorable characteristics in providing habitat for wildlife, a carbon sink, and recovering degraded areas (Tambe et al., 2020). Consequently, the bamboo chain contributes to advancing various United Nations Sustainable Development Goals (SDGs) for 2030. These include SDG 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), 13 (Climate Action), and 15 (Life on Land – Protection and restoration of terrestrial ecosystems) (Alemayehu; Hido, 2023).

In the southwestern region of the Brazilian Amazon, bamboo encompasses an expanse of 121,000 km², equivalent to the land area of Portugal, with particular emphasis on the state of Acre. Within this state, bamboo forests occupy 62% of its territory, amounting to 94,600 km², thereby establishing it as one of the largest global reserves of this plant species (Bayma et al., 2023). These researchers estimated approximately 21.8 billion Guadua spp bamboo poles, equivalent to a total volume of 800 million m³ in the state of Acre alone. Despite these substantial quantities, the utilization of this material and its fibers in the Amazon region remains limited.

A pertinent concern within the bamboo production chain revolves around the environmental impacts of the generated materials (Xu et al., 2022). To address this issue, life cycle assessment (LCA) has been employed to gauge the environmental footprint within the construction industry (Gan et al., 2022). This methodology enables the analysis of the environmental performance of products and services through a comprehensive examination of the inventory, encompassing pertinent inputs and outputs of a system or product over its entire life cycle. LCA spans from the extraction of the raw material, its production, utilization, and ultimately, the disposal of its waste (Oliveira et al., 2022). Thus, LCA studies allow the identification and understanding of opportunities for mitigating environmental impacts, with a broad range of applications, including agricultural management (Costa et al., 2018) and solid waste management (Oliveira et al., 2022).

In the construction industry, LCA studies have assessed various construction types (Ryberg et al., 2021), strategies to minimize the generation of construction and demolition waste (Llatas et al., 2021), and the development of new materials (Alexander, 2022). Furthermore, these studies have involved the comparison of the environmental performance of construction materials (Zhang et al., 2023).

Nevertheless, there is a notable scarcity in the literature regarding the sustainability of the artisanal bamboo chain, particularly with regard to quantitative analyses that can substantiate decision-making in public policies aimed at supporting the production and commercialization of this biomaterial. This scarcity is primarily attributed to the insufficient data available for the formulation of inventories, particularly on an international scale and especially in Brazil. Such limitations add complexity and time-consuming aspects to the application of the life cycle assessment methodology.

From this perspective, this research aimed to estimate the environmental impacts of the artisanal bamboo chain by evaluating the life cycle within a Producing Unit (PU) in the Brazilian Amazon. To achieve this, a life cycle inventory of this PU and its potential environmental impacts was compiled, aiming to offer insights for the sustainable management of artisanal bamboo production in the Brazilian Amazon.

The emerging hypothesis of the present research points out that LCA allows the identification of the main environmental vulnerabilities of an artisanal bamboo production system, in the context of the Amazon

2. Materials and Methods

A case study was carried out on an artisanal bamboo production unit (PU) in the municipality of Rio Branco, in the Brazilian Amazon (Figure 1). This PU was selected because it is the main supplier of artisanal bamboo poles for furniture production and use in civil construction in the municipality of Rio Branco. In addition, it had a management system that recorded the inputs used in the artisanal process of producing bamboo poles. Data were collected and analyzed for the life cycle inventory (LCI), involving the identification of input and output material flows and the estimation of potential environmental impacts through life cycle assessment (LCA).

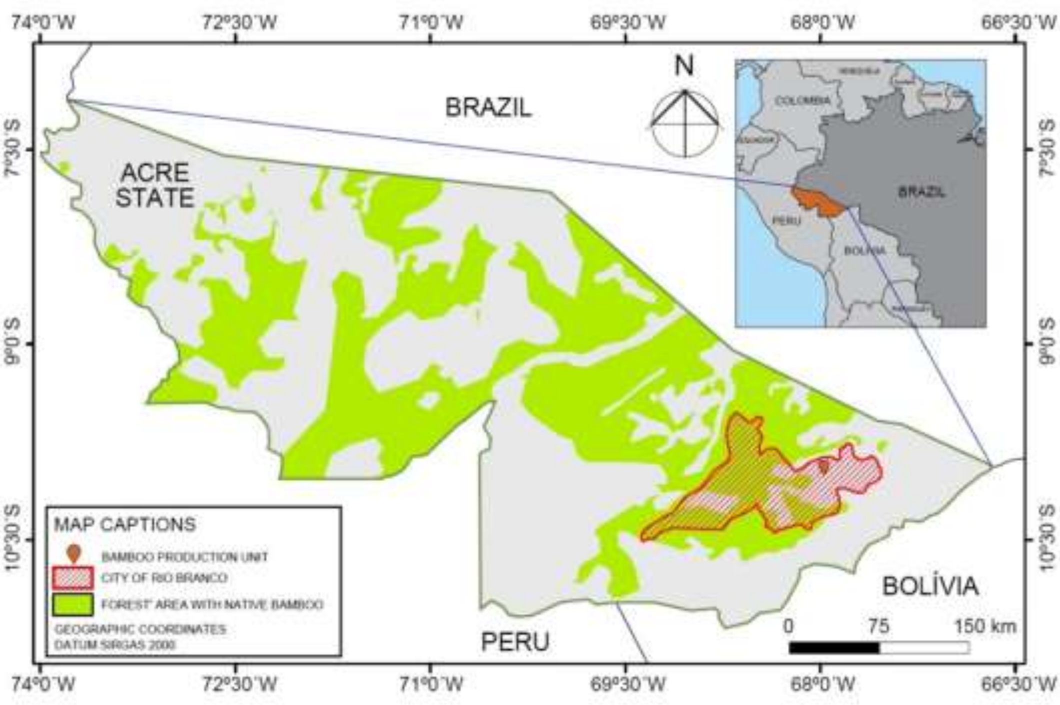

Figure 1. Bamboo Production Unit (PU) located in the rural area of the municipality of Rio Branco and the distribution of forests with native bamboo in the state of Acre, Brazilian Amazon. Source: Authors, 2025.

2.1 Description of the artisanal processing in bamboo Production Unit (PU)

PU is 13 kilometers from the commercial center of Rio Branco and is accessible by road. The proximity to the consumer market and the availability of road infrastructure are factors that can enhance the producer's involvement in the regional bamboo market, mitigating logistical costs (Alemayehu; Hido, 2023; Gelaw et al., 2023). Within this property, around 30 distinct bamboo species are cultivated across a 3-hectare expanse for use in civil construction, landscaping, furniture production, and the commercialization of seedlings. The production and treatment of bamboo poles for the civil construction market correspond to the Guadua angustifolia specie with an annual production of approximately 500 treated poles of 6 meters per hectare.

The production unit (PU) employs three workers, each earning a daily income of US$ 16.00 or a monthly salary of US$ 350.00, according to the PU manager. This amount exceeds the minimum wage practiced in Brazil in 2023 by 35% (US$ 260.00 per month) (Brasil, 2023).

2.2 Life cycle inventory (LCI)

The life cycle inventory (LCI) encompassed the following phases: planting and management of *Guadua angustifolia* bamboo, cultivated in an agroforestry system; harvesting and separation; and the subsequent chemical treatment of the bamboo poles, all conducted within the PU. The entire manual process, from planting to the chemical treatment of the bamboo poles, characterized the production system as artisanal. The data collection of the production process of bamboo poles, from planting to the chemically treated stick, was carried out during visits to the PU from September 2021 to January 2022. Specific assessments regarding waste and wastewater generation were conducted on October 10, 2021, and October 22, 2022. The phases and corresponding data collection are described below:

a) Manual planting and crop management: The necessary inputs were acquired for the manual planting, management, and harvesting of a clump of *Guadua angustifolia* bamboo, yielding 15 poles. For planting and soil tillage, a hole of 10m² per clump was dug. The inputs included 300 g of limestone and 50 g of NPK (nitrogen, phosphorus, and potassium) chemical fertilizer in the commercial formulation 15-15-15, based on on-site observation. During the bamboo growth period, no pesticides were applied, given the crop's hardiness and the region's mesoclimatic conditions, as reported by the producer. Additionally, the significant rainfall in the Amazon obviates the need for irrigation, a common practice in bamboo cultivation in China (Xu et al., 2022).

b) Manual harvesting and sorting: at this stage, field estimates based on visual observation corroborated information provided by the PU manager and indicated that 20% of the total biomass of the bamboo poles (leaves and part of the stem) corresponded to cutting wastes left on the soil, in the planting area, to mitigate water erosion. This result corroborates a review by Gan et al. (2022), where harvesting waste (leaves and branches) ranges from 20 % to 37 % of the total aboveground biomass in the bamboo farm. Such sorting is necessary to maintain the structural strength values of the selected poles, a requirement for their use in civil construction.

c) Chemical treatment of poles: the selected bamboo poles were immersed in 100 L of water containing 5 kg of borax (disodium tetraborate) and 5 kg of boric acid, a procedure observed and quantified using weighing in the treatment facility of these poles. This chemical treatment was also employed by artisanal producers for bamboo preservation in Africa (Mwanja et al., 2023) and South America (Escamilla & Habert, 2014). Following the chemical treatment, the poles were air-dried, a method similarly utilized by artisanal producers in Uganda (Mwanja et al., 2023). During the chemical treatment process, approximately 13% of the poles were discarded due to aesthetic issues or material damage, such as cracks. Post-chemical treatment, bamboo poles of the Guadua angustifolia species can be commercialized for construction purposes (Escamilla; Habert, 2014).

However, additional treatments can be performed for more valuable applications, such as the manufacturing of furniture, flooring, and panels. Figure 2 illustrates the selling prices of bamboo poles per linear meter, according to information provided by the PU manager, in the region of Rio Branco, Brazilian Amazon. *Guadua angustifolia* achieved the highest market value among other species in the region of Rio Branco, reaching US$ 2.20 m after treatment, attributable to its utilization in civil construction.

This is driven by the demand for high-quality materials suited to meet the structural requirements of construction projects (Pieter; Utomo, 2023). Sanding and varnishing the bamboo poles, after chemical treatment, led to an average selling price increase of 30% and 48%, respectively, according to information provided by the PU manager. In this study, the modeling of environmental impacts was confined to the treated bamboo pole, a stage preceding the subsequent treatments (sanding and varnishing).

2.3 Life cycle inventory modeling

In modeling the life cycle inventory of the artisanal production process of *Guadua angustifolia* species, a diagram depicting the inflow and outflow of matter and energy was generated, spanning from the planting of the seedling to the treated product (6 m bamboo pole) (Figure 3). In the flow diagram, the following aspects of bamboo production were considered: the quantity and formulation of fertilizers and lime in soil tillage; water usage during treatment and cleaning; the quantity of boric acid and borax in the treatment of the poles; and the estimation of the waste generated from the treated bamboo poles. Part of the data collection took place at the PU and was reviewed with the producer, facilitating the assessment of the operational phases of the material.

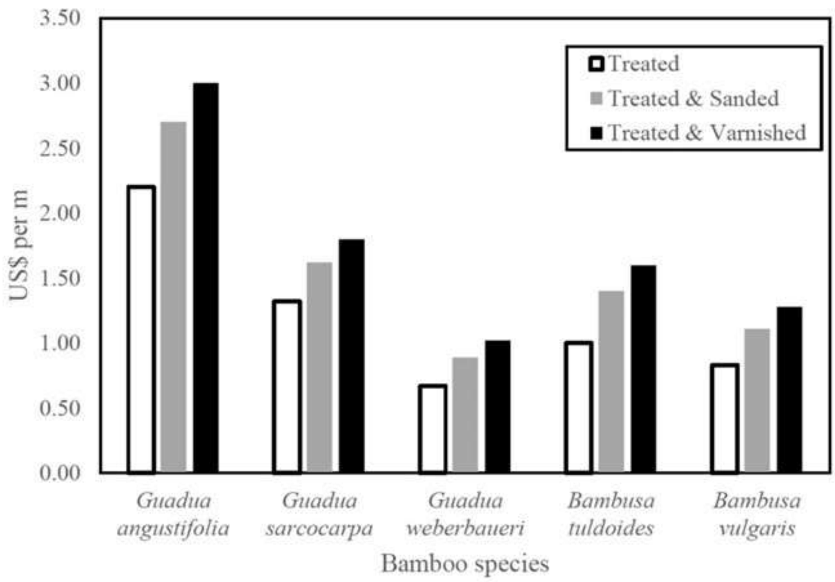

Figure 2. Price of bamboo pole, by species and linear meter, according to the type of treatment (treated, treated and sanded, treated and varnished), at the Production Unit (PU) in Rio Branco, Brazilian Amazon, in December 2023. Source: Authors, 2025.

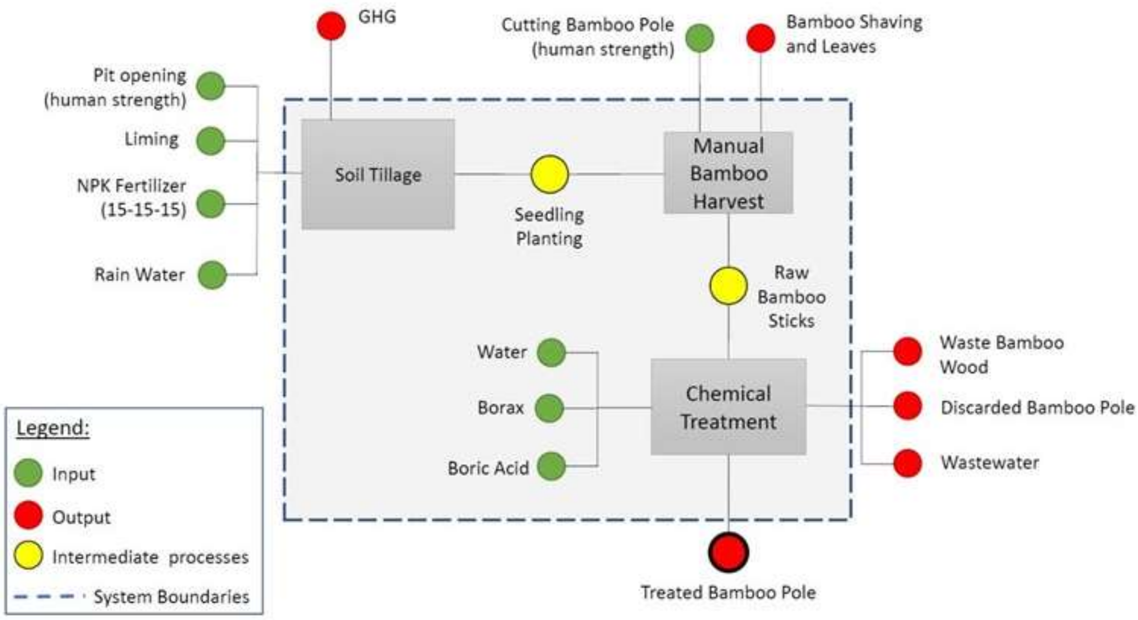

Figure 3. Schematic representation of the Product System comprising the artisanal production system of bamboo poles at the Production Unit in Rio Branco, Brazilian Amazon. Source: Authors, 2025.

These phases encompassed the selection and extraction of raw materials, cutting, cleaning, and finishing, culminating in their ultimate treatment. This process is characterized as a product system in an LCA study.

An inherent limitation to the elaboration of the life cycle inventory of an artisanal bamboo production system refers to seasonality, influenced by climatic variability throughout the year, skill and availability of labor, availability of inputs, variability of das espécies vegetais, and market prices (Bagheriehnajjar et al., 2024). Such variability is inherent in that observed in an agricultural production system, when compared to an industrial system (Costa et al., 2018). In addition, another relevant topic refers to the quality of data along the entire bamboo supply chain (Escamilla; Habert, 2014).

2.4 Objective and scope of the LCA

The current attributional life cycle assessment (LCA), from cradle to gate, aimed to assess the potential impacts generated in the artisanal production of bamboo for civil construction in the southwest region of the Brazilian Amazon. The LCA analysis was based on the model proposed by ISO 14040 (ISO, 2014a) and ISO 14044 (ISO, 2014b).

2.5 Functional unit

The functional unit corresponded to the assessment of potential environmental impacts for the "Artisanal production of 1 kg of treated *Guadua angustifolia* bamboo pole for use in civil construction".

2.6 Life cycle impact assessment

The SimaPro v9.1 software was utilized for estimating environmental impacts, a tool commonly employed in LCA research associated with bamboo applications in civil construction (Zhang et al., 2023; Chang et al., 2018). The ReCiPe 2016 Midpoint method was employed to assess life cycle environmental impacts (LCIA), aligning with a trend observed in studies on LCA of materials in the construction industry (Llantoy et al., 2020). Ecoinvent 3 database was employed in modeling, according to recommendations for LCA of bamboo-based products by Xu et al. (2022); Escamilla & Habert (2014).

3. Results

Table 1 presents the LCI for producing 1 kg of treated bamboo pole in Rio Branco, Brazilian Amazon. This Table underscores the generation of waste in the chemical treatment process of the harvested bamboo poles, signifying a loss of 25% of the raw material directed to the chemical treatment stage.

Table 1. Inventory of the artisanal production chain for producing 1 kg of treated bamboo pole in Rio Branco, state of Acre, Brazilian Amazon.

Input	Unity	Quantity
NPK Fertilizer (15-15-15)	kg	0.0003
Liming	kg	0.002
Water	L	0.67
Boric acid	kg	0.0003
Borax	kg	0.0003
Output	Unity	Quantity
Waste bamboo wood	kg	0.20
Discarded bamboo pole.	kg	0.13
Wastewater	L	0.07

Source: Authors, 2025.

In the production of bamboo materials for civil construction on an industrial scale, LCA studies predominantly emphasize categories of environmental impact associated with energy consumption (Xu et al., 2022; Zhang et al., 2023; Chang et al., 2018) and climate change (Escamilla et al., 2018), while in the dimension of human health, respiratory inorganics are highlighted (Chang et al., 2018). However, in the literature, there is a scarcity of life cycle assessment studies specifically focused on artisanal bamboo production processes, with Escamilla & Habert (2014) being a notable exception.

The significant impact of the construction industry on greenhouse gas emissions leads to a predominance of categories related to the phenomenon of global warming in LCA studies, such as Climate Change (Llantoy et al., 2020), Global Warming Potential (Gan et al., 2022; Llatas et al., 2021; Chang et al., 2018), Global Warming (Xu et al., 2022), and Carbon Footprint (Escamilla et al. 2018; Zhang et al., 2023). In addition to Global Warming, the following impact categories were selected in the present study, based on recommendations from the literature: Atmospheric Ozone Depletion (Xu et al., 2022; Ryberg et al., 2021); Particulate Matter Formation (Ryberg et al., 2021; Llantoy et al., 2020); Freshwater Eutrophication (Llatas et al., 2021; Llantoy et al., 2020); Human Carcinogenic Toxicity (Xu et al., 2022; Ryberg et al., 2021); Depletion of Mineral Resources (Ryberg et al., 2021); Water Use (Xu et al., 2022; Ryberg et al., 2021).

The results of the impact estimation for the selected categories in this study, using the ReCiPe midpoint (h) methodology, were normalized (millipoint) and presented in Table 2.

4. Discussion

The primary category of environmental impact observed, encompassing the entire production process from planting to chemical treatment, was Human and Carcinogenic Toxicity (HCT), accounting for approximately 93% of the total estimated environmental impact for artisanal bamboo pole production (Figure 4). The primary determinant of this outcome is attributed to the utilization of boric acid and borax in the chemical treatment process of bamboo poles. These chemicals are present in the residues of shavings and cuts, in the discarded bamboo poles, and in the wastewater generated. Contaminated bamboo waste (shaving + discarded poles) was responsible for 91% of the total impact of the artisanal pole production system. Wastewater constituted 10% of the total water used in the chemical treatment process, and it was subsequently discharged directly into the soil, thereby posing a threat to water resources, according to Xu et al. (2022).

Escamilla & Habert (2014) produced one of the rare references on life cycle assessment in artisanal production of bamboo poles intended for construction. The authors discovered that the primary potential impacts on artisanal bamboo production were associated with human health, stemming from the chemical treatment of bamboo poles. These findings are consistent with this study with the current research, wherein the HCT impact category was emphasized during the chemical treatment process of bamboo poles at the PU.

The limitations and health risks associated with the chemical treatment of bamboo poles raise questions about the sustainability of using this biomaterial to replace steel in reinforced concrete in the construction industry (Bayma et al., 2023). The ability of industries to mitigate waste generation in the production process of bio-based materials is a pivotal aspect for enhancing the environmental performance of the entire bamboo chain in Indonesia (Pieter; Utomo, 2023). Therefore, the management of waste and wastewater generated in the chemical treatment stage of the artisanal production process of bamboo-based materials should be prioritized to alleviate impacts associated with human health risks and advance a circular economy (Oliveira et al., 2022).

The second most prominent impact category relates to Freshwater Eutrophication (FE), accounting for 4% of the total impact. In this environmental impact category, the use of nitrogen, phosphorus, and potassium (NPK) chemical fertilization during planting stood out due to its potential to transport nutrients to water bodies, intensifying eutrophication. Although the environmental impact category Freshwater Eutrophication was not evaluated, Escamilla & Habert (2014) estimated that the contribution of the materials involved in the growth of the bamboo culm, including the use of fertilizers, represented less than 10% of the total impact of the bamboo pole production process.

Literature reports the use of manure during the planting phase, as observed in China (Xu et al., 2022) and Ethiopia (Alemayehu; Hido, 2023). The use of manure as a nutrient source for bamboo cultivation has the potential to increase carbon (C) and nitrogen (N) stocks in the soil, concurrently diminishing the reliance on chemical fertilizers and thereby mitigating the potential for greenhouse gas emissions (Leip et al., 2019).

Table 2. Environmental impacts of the artisanal bamboo production chain for the functional unit (1 kg of bamboo pole) at an artisanal production unit in Rio Branco, state of Acre, Brazilian Amazon.

Materials	Unity	Impact Categories						
		GW	SOD	PM	FE	HCT	MRS	WU
NPK fertilizer	mPt	$3.60x10^{-5}$	$7.56x10^{-5}$	$8.37x10^{-6}$	$1.02x10^{-5}$	$3.60x10^{-5}$	$2.85\ x10^{-8}$	$6.00x10^{-7}$
Liming	mPt	$3.55x10^{-6}$	$4.15x10^{-7}$	$2.16x10^{-6}$	$9.98x10^{-9}$	$2.47x10^{-6}$	$6.33x10^{-12}$	$7.50x10^{-6}$
Wastewater	mPt	$5.54x10^{-4}$	$2.95x10^{-5}$	$1.22x10^{-4}$	$4.10x10^{-6}$	$2.31x10^{-3}$	$4.64x10^{-9}$	$2.55x10^{-3}$
Boric acid	mPt	$3.91x10^{-5}$	$2.68x10^{-6}$	$5.68x10^{-5}$	$2.72x10^{-4}$	$5.54x10^{-3}$	$1.91x10^{-8}$	$3.16x10^{-5}$
Borax	mPt	$5.47x10^{-5}$	$2.94x10^{-6}$	$2.44x10^{-5}$	$2.42x10^{-4}$	$4.21x10^{-3}$	$4.68x10^{-9}$	$9.10x10^{-6}$
Waste bamboo wood	mPt	$6.58x10^{-4}$	$3.56x10^{-5}$	$4.67x10^{-4}$	$4.41x10^{-3}$	$7.42x10^{-2}$	$2.58x10^{-8}$	$1.33x10^{-4}$
Discarded bamboo pole	mPt	$1.53x10^{-4}$	$1.12x10^{-5}$	$7.91x10^{-5}$	$1.89x10^{-3}$	$7.31x10^{-2}$	$3.58x10^{-8}$	$7.67x10^{-5}$
Treated bamboo pole	mPt	$1.50x10^{-3}$	$1.58x10^{-4}$	$7.60x10^{-4}$	$6.83x10^{-3}$	$1.59x10^{-1}$	$1.19\ x10^{-7}$	$2.82x10^{-3}$

Note: The unit mPt represents millipoints, where: GW: Glogal Warming; SOD: Stratospheric Ozone Depletion; PM: Fine Particulate Matter Formation; FE: Freshwater Eutrophication; HCT: Human Carcinogenic Toxicity; MRS: Mineral Resources Scarcity; WU: Water Use. Source: Authors, 2025.

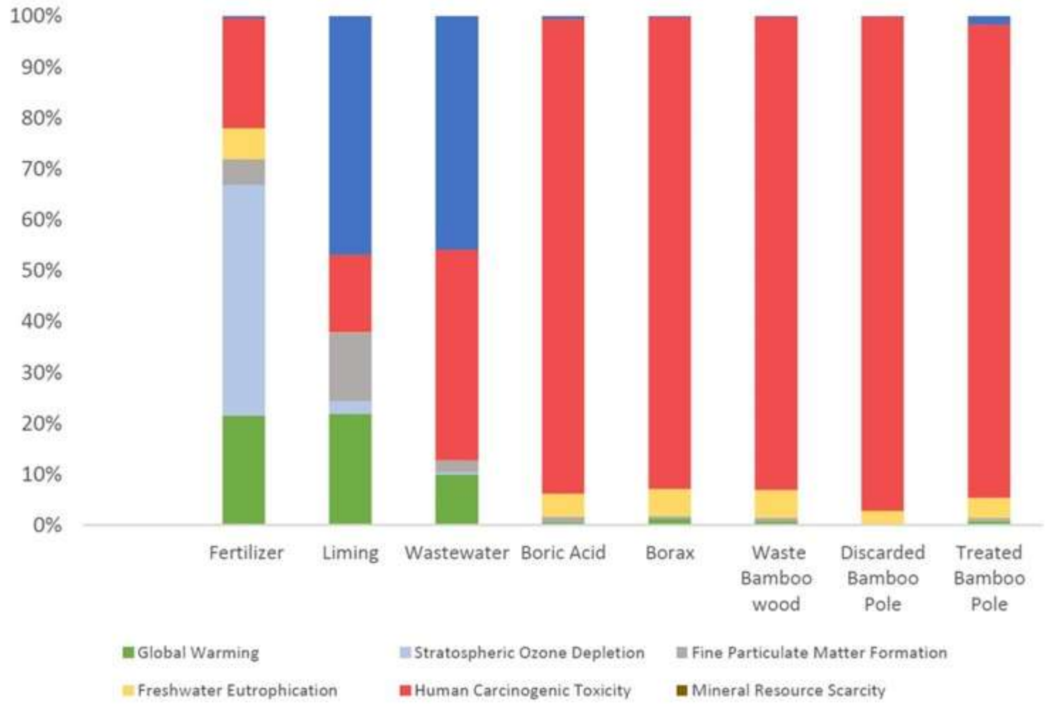

Figure 4. Relative contribution of each environmental aspect within the impact categories of the bamboo production chain in an Artisanal Production Unit in Rio Branco, state of Acre, Brazilian Amazon. Source: Authors, 2025.

The Water Use (WU) impact category was the third to stand out, representing 1.6% of the potential impacts of artisanal bamboo production. Bamboo is a crop that requires water during its growth and development, and irrigation is necessary for its cultivation in regions of China (Xu et al., 2022). However, in the Amazonian environment, the average rainfall exceeds 2,000 mm per year (Oliveira et al., 2022), fulfilling the water needs of this crop and eliminating the need for supplementary irrigation.

Research related to the industrial-scale production of bamboo-based materials indicates additional categories of potential environmental impacts. Chang et al. (2018) conducted a study of LCA in the industrial production chain of laminated bamboo in Taiwan. In this study, the greatest impacts were related to human health and resource depletion in the drying, pressing, and other processes involving water. Xu et al. (2022) determined that the primary environmental impact category in the production process of bamboo-based materials was ecotoxicity, accounting 86% of the total impact. According to these authors, the main factors contributing to this result are associated with the intricate production phase of bamboo materials and the lengthy transportation phase. The study considered logistics from the bamboo-producing area to the processing industry and from the industry to the distribution centers spread throughout the territory of China.

In the current investigation, employing a cradle-to-gate methodology effectively curbed the influence of soil tillage, air-drying of bamboo poles, and logistics on environmental impact categories such as ecotoxicity and climate change. Notably, the manual nature of planting and harvesting forestalled greenhouse gas emissions associated with agricultural mechanization, a significant environmental concern in Brazilian crop production (Costa et al., 2018). Additionally, the impacts associated with the air-drying method were disregarded due to minimal energy consumption, aligning with the prevailing trend in LCA studies on bamboo products (Gan et al., 2022). However, the evaluation of potential environmental impacts of this process becomes relevant only in LCA studies involving the use of natural gas (Escamilla; Habert, 2014; Chang et al., 2018), and electricity (Gan et al., 2022) for drying bamboo poles. This rationale underpins the marginal representation of the Global Warming category, amounting to a mere 0.9% of the overall potential environmental impacts attributed to artisanal bamboo production in the PU under evaluation within the Brazilian Amazon.

An important aspect of bamboo-based materials pertains to their carbon storage functions, contributing to the mitigation of impacts in the climate change category (Chang et al., 2018).

Gan et al. (2022) conducted a review of life cycle assessment (LCA) studies comparing the carbon footprint of bamboo-derived products with other construction materials (steel, plastic, and concrete). According to these authors, most bamboo products analyzed in LCA studies exhibited a significant advantage in reducing the carbon footprint throughout the life cycle, attributed to the carbon sink capacity of bamboo.

In a study conducted in Colombia, buildings constructed with bamboo produced lower greenhouse gas (GHG) emissions compared to those constructed with conventional materials, such as concrete and steel (Bayma et al., 2023). Therefore, bamboo and its industrialized materials contribute to mitigating the impacts of climate change, promoting the bioeconomy, and can support producing countries in achieving sustainable development goals in housing while contributing to global GHG reduction efforts (Isukuru et al., 2023).

Compared to other timber resources, bamboo is less susceptible to cutting and deforestation, as well as suitable for reforestation, making it a viable option for the recovery of degraded land (Bayma et al., 2023). This constitutes a pertinent consideration given that approximately 2.5 x 10^6 km² of Amazon forests are degraded by timber extraction, habitat fragmentation, fires, and drought (Lapola et al., 2023). The production unit (PU) examined in the current study is situated in the peri-urban region of the city of Rio Branco. Initially, this property was a degraded area that has since undergone restoration through the cultivation of bamboo.

Such characteristics may justify the magnitude of the environmental impact on the Mineral Resources Scarcity category, which is less than 0.001% of the total (Figure 4). The categories Stratospheric Ozone Depletion and Fine Particulate Matter Formation, together, represented about 0.5% of the total impact generated in the Production Unit evaluated.

In addition to the environmental aspect, it is imperative to underscore the socio-economic dimension inherent in the bamboo artisanal production chain. The increasing demand for bamboo in civil construction within the Amazon region is poised to instigate a proliferation of production units, thereby engendering a consequential expansion in local employment opportunities.

In the appraised Production Unit (PU), a singular employment opportunity was generated per hectare. This holds particular significance in the context of the Brazilian Amazon, where the unemployment rate escalated to 16.2%, surpassing the national average of 13.7%, as delineated by the Continuous National Household Sample Survey (PNAD) data from the Brazilian Institute of Geography and Statistics (IBGE) during the period from July to September 2023 (IBGE, 2023). This observation underscores the pertinence of the employment impact stemming from such production initiatives within the regional socio-economic landscape.

Local job creation was identified as one of the potential positive social impacts of expanding the bamboo chain in Nigeria (Isukuru et al., 2023), Uganda (Mwanja et al., 2023), and Indonesia (Ekawati et al., 2022). However, a significant portion of the jobs generated by the bamboo chain in Indonesia lack formal contractual agreements, placing workers in an informal and insecure work environment, particularly in rural areas, a challenge for developing countries (Pieter; Utomo, 2023).

The economic impact of the Production Unit is ascertainable by analyzing the annual income generated from the production of bamboo poles. This metric serves as a quantitative indicator for evaluating the financial implications and viability of the production process. The annual production within the Production Unit (PU) achieved 1,500 bamboo poles across a 3-hectare expanse, devoid of any agricultural mechanization and reliant solely on human labor. However, bamboo pole productivity varies depending on the species and crop management practices. For instance, mechanized and irrigated Moso bamboo (*Phyllostachys pubescens*) crops in China can achieve around 1,000 poles per hectare (Xu et al., 2022).

The bamboo pole market is contingent upon factors such as bamboo species and its intended use (construction, furniture, handicrafts), bamboo pole treatment, product quality and standardization, market location (urban or rural), and market infrastructure (logistics) (Alemayehu; Hido, 2023; Gelaw et al., 2023; Teshale et al., 2017). The proximity to the urban market of Rio Branco, accessibility via paved roads, the utilization of *Guadua angustifolia* species suitable for construction, and the treatment of bamboo poles contribute to an economic impact of this production, resulting in an annual gross income of approximately US$ 1,300.00 per hectare. In Ethiopia, smallholder farmers realized an annual gross cash income of US$ 162.00 per hectare from the sale of unprocessed bamboo (Gelaw et al., 2023). In this African nation, Type 1 bamboo poles, designated for civil construction and of superior quality, command US$ 9.41 in urban areas and US$ 4.81 in rural settings, inclusive of the value added through chemical treatment (Teshale et al., 2017). Accordingly, these authors underscore the significance of rural extension services to support farmers in bamboo production, harvesting, and marketing, to enhance the efficiency and efficacy of the bamboo artisanal chain in Ethiopia.

Hence, public and market policies directed towards incentivizing and enhancing the artisanal bamboo production chain would foster environmental performance, bolster the local economy, and facilitate a more efficacious transition to eco-efficiency within the construction industry and other sectors in the Amazonian environment. In this regard, actions have been compiled from the literature review to develop internal guidelines for managing processes in artisanal bamboo production units in the Amazon, based on the findings of this study. Additionally, policy guidelines have been proposed to foster the artisanal bamboo production market, aiming to serve various sectors of society, such as the construction industry (Figure 5).

Internally, at the farm level, it is imperative to enhance cultivation techniques and crop management to mitigate potential impacts of fertilizer use on the aquatic environment (Costa et al., 2018). Concurrently, advancements should be pursued in bamboo pole processing and preservation methods (Tambe et al., 2020; Gelaw et al., 2023). The notable impact of the Human Carcinogenic Toxicity category (comprising 93% of the entire estimated potential impact in the Production Unit, from cultivation to treated bamboo poles) underscores the imperative to substitute or diminish the products employed in the chemical treatment process of bamboo poles. For this proposal, techniques have been developed to reduce the impact of pesticide use on the preservation of bamboo poles, including heat treatment (Wang et al., 2019), optimized prophylactic treatment (Garcia. Morrell, 2010), and nanotechnology-based products (Fraceto et al., 2016). This necessitates minimizing waste and wastewater generation, thereby mitigating adverse effects on human health and the environment, while concurrently ensuring the production of bamboo poles of superior quality.

Addressing the farm level, research gaps were identified to promote the bamboo chain from cradle to gate, including the development of higher productivity species, cultivation techniques, and crop management, as well as cleaner processes for the treatment of bamboo poles, including water use, waste, and wastewater management. In addition to these issues, the expansion of databases related to artisanal bamboo production processes should be developed to improve life cycle inventories and the estimation of environmental impacts at the farm level.

Figure 5. Internal and external policy guidelines to reduce environmental impacts and promote artisanal bamboo production in the Brazilian Amazon. Source: Authors, 2025.

In external aspects, highlighting the benefits of bamboo over other materials (plastics, furniture, construction) through educating stakeholders is crucial (Xu et al., 2023). Improvements in public perception can be achieved through advertising campaigns, fairs, and exhibitions (Alexander, 2022). Government regulatory support aimed at sourcing bamboo raw materials from local artisanal producers is essential (Ekawati et al., 2022).

Establishing communication channels between producers and various types of buyers is crucial (Pieter; Utomo, 2023). Developing new markets for bamboo by promoting industries that support job creation and farmers' incomes is recommended (Tambe et al., 2020; Alemayehu; Hido, 2023; Hailemariam et al., 2023). Additionally, structuring the bamboo chain through technological development, innovation, and product eco-design is essential (Neha; Aravendan, 2023; Hailemariam et al., 2023), and extension support (Alemayehu; Hido, 2023; Teshale et al., 2017).

Therefore, the present study pointed out ways for governmental and industrial decision-makers to develop the artisanal bamboo production chain. Considering government policy decisions, the guidelines point to a process of awareness of the consumer market about the environmental and social benefits of bamboo-based products and bioeconomy; creation of regulatory measures to promote the artisanal bamboo production chain, such as tax incentives, certifications, and public notices to enhance research and innovation of bamboo-based products. In this context, it is possible to enhance an environment of innovation in the industrial environment by generating products and markets aimed at the use of bamboo in the Amazon.

5. Conclusions

The utilization of bamboo in the Amazon region holds the potential to significantly contribute to the bioeconomy and sustainability across various sectors, notably civil construction, fostering local economic stimulation through the cultivation of this adapted species in artisanal production units. However, the application of life cycle assessment techniques has led to the conclusion that the artisanal bamboo production process predominantly influences Human Toxicity and Carcinogenesis (93%).

This finding underscores the necessity for managing artisanal bamboo pole production for civil construction in the Brazilian Amazon by investigating alternatives to boric acid and borax, substances also utilized in African countries, posing risks to local workers. Additionally, there is a need to enhance solid waste management and optimize water usage during the chemical treatment of bamboo poles. Finally, the implementation of improved practices for fertilizer utilization during planting is deemed crucial. Managing these aspects should be a priority for guaranteeing the sustainability of artisanal bamboo production within the bamboo chain in the Amazon.

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7. Authors’ Contributions

The conceptualization and theoretical-methodological approach were developed by the 1st, 2nd, 3rd, and 4th authors. Data collection was conducted by the 1st author. The theoretical review was carried out by the 1st and 4th authors. All authors contributed to data analysis, writing, and final revision of the manuscript.

8. Conflicts of Interest

No conflicts of interest.

9. Ethics Approval

Not applicable.

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