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Life cycle assessment of non-timber forest products production systems

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Abstract: Non-wood forest products are any commodities obtained from the forest without cutting down trees. The role of Non-Timber Forest Products (NTFPs) production in minimizing threats to forest sustainability has been investigated. Life Cycle Assessment (LCA) can be used to measure the environmental performance and sustainability of the products. The objective of this study is to provide a narrative literature review of previous research on the LCA of NTFPs, such as chemicals, silk, honey, rubber, bamboo, and cork, and to compare them to their substitute products. The system boundary used in each product is varied, dominated by cradle to grave and cradle to gate. In addition, global warming is the most common environmental impact evaluated by all studies. Furthermore, acidification and eutrophication are commonly investigated in the production of chemical, silk, and cork products. Besides, eco-toxicity and human toxicity are considered in fiber and silk products.The results showed that in chemical products, such as volatile oil, bioactive compounds, tannins, and phenolics obtained from resin or bark on trees, the extraction phase tends to have the largest environmental impact caused by the solvent used. The manufacturing process is the main contributor to the environmental impact of silk, honey, rubber, and cork products, mainly in the raw material production and harvesting process. Furthermore, these products require electricity to operate process equipment that produces the most significant environmental impact. Energy consumption in bamboo processing and product transportation tends to have large environmental impacts for bamboo products. Moreover, the LCA results also considered other environmental impacts to determine the hotspots and overall environmental profile of the production systems. The comparisons to their substitute products are presented and briefly discussed.

Keywords: Life cycle assessment (LCA), environmental impact, non-timber forest products (NTFPs).

1. Introduction

Non-Timber Forest Products (NTFPs) are all goods of biological origin, excluding wood, derived from forests, other wooded land, and trees outside forests [1]. NTFPs are offered as an alternative to large-scale wood harvesting, forest land conversion, and destructive forest exploitation in other forms. Furthermore, they also provide many economic benefits for forest society [2]. NTFPs are categorized into four major products types, namely (1) culinary, for instance, honey, mushroom, fruits, (2) wood-based that used for fuel, furniture, and forage, (3) medicines and plant protection, and (4) aromatics, dyes, and oilseeds including chemicals and essential oils [3].

In general, NTFPs play an essential role in maintaining human well-being by supporting rural livelihoods, culture, and business through income diversification from formal and informal forest sectors to maintain financial security during difficult times [4-5]. Moreover, the extraction of NTFPs is generally thought to reduce threats to forest sustainability, though in some cases, inappropriate harvesting practices can disrupt the natural regeneration process [5]. The interest in NTFPs management has increased broadly due to its contribution in supporting sustainable development [4].

However, currently, there have not been many studies to ensure sustainable management and utilization of NTFPs [6], especially compared to other similar products. Therefore, increased research on the sustainability of NTFPs, including their ecological impacts, is important [6].

Regarding the ecological impacts, Life Cycle Assessment (LCA) is a tool that considers the life cycle phase from raw materials to intermediate and final products, depending on their system boundaries. It is required to support claims of positive environmental qualifications, particularly when compared to non-renewable materials. The LCA methodology is commonly described in ISO 14040 [7] and ISO 14044 [8]. Furthermore, the important result from LCA study is the identification of hotspots, or parts of a process related to the major environmental burdens, where there will be process improvements that will lead to environmental benefits [9].

Due to these considerations, the objective of this study is to review the LCA results conducted on the major NTFPs [1] such as chemicals, fiber and silk, cork, rubber, and bamboo. Furthermore, the environmental impacts, comparison to other substitute products, and recommendations for future works are described. The results of this study are expected to enrich the discussion on the sustainability of NTFPs, especially regarding the environmental impacts caused by their production processes.

2. Methods

This literature review implements a narrative literature review methodology, which identifies the objectives of previous research, formulates key concepts, and summarizes results in research. The goal is to access and select articles that provide information about the LCA of production processes in NTFPs. This study investigates the LCA of NTFPs from articles published in various publicly available databases, including ScienceDirect, ResearchGate, RSC Publishing Home, and Semantic Scholar in English language during 2008 and 2022. LCA studies of some major NTFPs that have been found in the article databases such as chemicals, fiber and silk, honey, cork, rubber, and bamboo. The substitute products are also performed using the same method. The LCA review in this study focuses on environmental impacts and hotspot identification in each production process. Furthermore, environmental profiles from NTFPs and their substitute products are explained in detail through appropriate tables and figures.

Figure 1 depicts forty articles published on LCA of NTFPs each year since 2008. The number of published articles has not increased consistently over time, even though the interest in NTFPs management has increased extensively. Based on Figure 2, the LCA of bamboo comprises 30% of the total number of published articles among NTFPs considered in this study. Most LCA studies of cork, chemicals, and honey are from Europe, whereas Asia dominates on rubber, bamboo, fiber, and silk products (Figure 3).

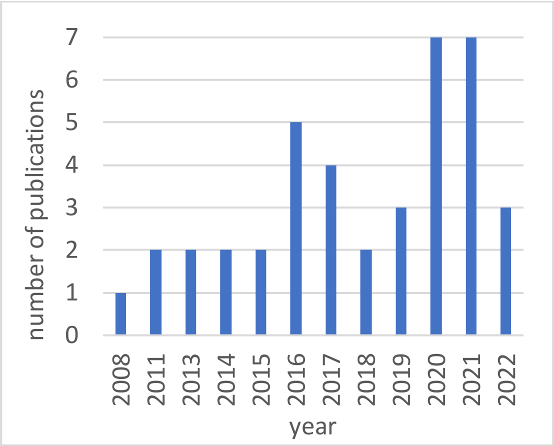


Figure 1. Publication trends in the world over the years.

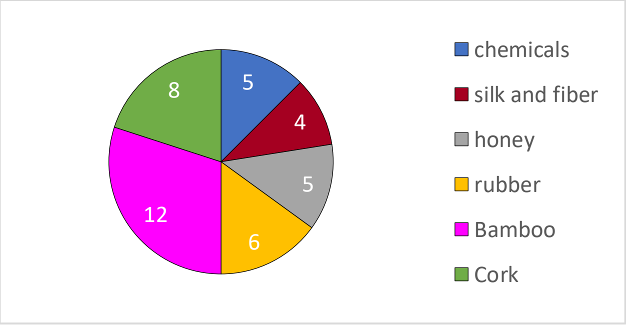


Figure 2. Publication on LCA of NTFPs during 2008 – 2022.

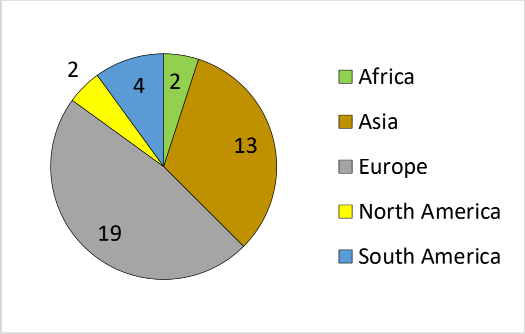


Figure 3. Publications on LCA of NTFPs based on regions.

3. Results and discussion

The LCAs of selected NTFPs: chemicals, fiber and silk, honey, cork, rubber, and bamboo have been summarized. This review covered the existing LCA studies and comparison with substitute products. The life cycle stage of each product is expressed in the form of a table representing the general production process in each research. Important discussions on each product are described below. Each product category is discussed with future recommendations. LCI data includes both primary and secondary data collected on-site as well as OpenLCA, Simapro, national, or regional databases related to the production of materials, emission factors and the reference system.

3.1 Chemicals

Chemical compounds can be obtained from bark and seeds. The bark is an essential part of trees for protection against fire, fungal diseases, frost, and animal attacks. It can provide high-value chemicals for various applications, including pharmaceutical and bioactive natural compounds, green polymers, and bio-based materials. Previous research on the life cycle assessment of chemical products from NTFPs that has been conducted around the world is presented in Table 1. The system boundary used for environmental assessment on this product varies, however, it is dominated by cradle to gate and cradle to grave, with functional units based on product mass of the final product produced.

Tannins are polyphenolic biomolecules that protect plants from herbivores, insects, fungi, and bacteria attacks [10]. Tannins can be used for adhesives, food additives, leather manufacturing, or medical and pharmaceutical applications [11]. The advantages of tannin extraction from bark are its availability and abundance in nature, and it can be done with simple hot-water extraction processes without chemicals.

In general, tannin production from bark involves forest cultivation, which includes fertilizing and harvesting from the forest as well as transportation to the sawmill, preparation treatment, which includes debarking and bark milling, followed by extraction and post extraction treatment, including evaporation, spray drying, ultrafiltration, adsorption, cationization, centrifugation, and pressing.

Table 1. The previous research on LCA of NTFPs chemicals.

Study	Products	Location	Functional Unit	System boundary
Ding et al. [10]	Tannin from spruce bark	Europe	1 kg tannin	Cradle-to-gate
Carlqvist et al. [11]	Tannin from spruce bark	Europe	1 kg of dried cationized tannins	Cradle-to-gate
Carlqvist et al. [12]	Phenolic compounds from spruce bark	Europe	1 kg phenolic	Cradle-to-gate
Arias et al. [13]	Tannin from pine bark	Europe	1 kg of bio-adhesive	Cradle-to-gate
Murugan et al. [14]	Bioactive compounds from *Darcyodes rostrata* seed	Asia	104.6 mg of extracted polyphenols	Cradle-to-grave

Table 2. The unit process from existing literature for chemicals.

Ref	A1	A2	B1	B2	B3	C1	C2	C3	C4	C5	C6	C7	C8
Ding et al. [10]	✓	✓	✓	-	✓	✓	✓	✓	-	-	✓	-	-
Carlqvist et al. [11]	✓	✓	✓	-	✓	✓	✓	-	✓	✓	✓	-	-
Carlqvist et al. [12]	✓	✓	✓	-	✓	✓	-	-	-	-	-	-	✓
Arias et al. [13]	✓	✓	✓	✓	✓	-	-	-	-	-	-	-	-
Murugan et al. [14]	-	-	-	✓	✓	✓	-	-	-	-	✓	✓	-

Note: The unit processes for chemicals products are defined in Figure 4.

Ding et al. [10] conducted an LCA study on the tannin production of Norway spruce (Picea abies Karst.) bark while its application as flocculants in wastewater treatment was investigated by Carlqvist et al. [11]. Other spruce bark research was conducted by the same researchers Carlqvist et al. [12], while the extraction of tannins from pine bark was conducted by Arias et al. [13]. Research on the extraction of polyphenols in Dacryodes rostrata was carried out by Murugan et al. [14]. D. rostrata is an underutilized indigenous fruit rich in several chemical contents, one of which is total phenolic content (TPC) with a significant amount. Life cycle stages and production processes for each study are depicted in Figure 4 and Table 2.

Forest cultivation A	Preparation and extraction B	Post extraction C
1. Fertilizer 2. Harvesting	1. Sawmill, debarking, peeling 2. Solvent preparation and feedstock conditioning 3. Extraction	1. Evaporation I 2. Spray drying 3. Ultrafiltration 4. Adsorption 5. Cationization 6. Evaporation II 7. Centrifugation 8. Pressing

Figure 4. Life cycle stages of NTFPs chemicals.

Extracting tannins and phenolic compounds use hot water as a solvent at atmospheric pressure and under the boiling point in mass production [10-13]. Research by Murugan et al. [14] used the conventional solid-liquid extraction (SLE) method, which is the extraction of soluble components in the form of phenolic compounds taken from solids (bark) by comparing two different types of solvents, namely ethanol and Deep Eutectic Solvent (DES). The preparation process for DES solvent is performed by mixing choline chloride and ethylene glycol and seed preparation consisting of freeze drying, grinding, and sieving. Then, post-extraction treatment is carried out by a double process of a rotary evaporator. On the other hand, the extraction of phenolic compounds [12] do not require feedstock preparation and used evaporation and pressing as post-extraction treatment.

3.1.1 Environmental impacts

Due to the high energy intensity of evaporation, this stage is the largest contributor to the environmental profile of tannin production [10]. Similar results were found on phenolic extraction of *Dacryodes rostrata* seed [14], where electricity contributed significantly to environmental impacts, especially global warming for feedstock and solvent preparation, including drying, cooling, mixing, and storage processes. Moreover, the additional heating in the extraction step to produce phenolic compounds from seed also contributed significantly to the environmental impacts [14]. On the other hand, the use of electricity for tannin production from Norway spruce bark has a relatively low impact in Nordic countries because 95% of electricity in Nordic countries is generated from nuclear and renewable sources. Because most equipment was powered by electricity, it impacted the stages of evaporation, hot water extraction, spray drying, and ultrafiltration [12].

In addition, transportation could add high environmental impacts to the production process depending on the carrying distance of the raw materials or products. The overall production process of bioactive compounds from *Darcyodes rostrata* seed transport activities had a high global warming [14]. It was due to the raw fruits being transported by airmail and truck over distances of approximately 1000 km and 100 km, respectively, which significantly affected the greenhouse gas emissions.

It is observed that solvent type can affect environmental impacts. Murugan et al. [14] used DES as an environmentally friendly green solvent that can reduce toxic air emissions rather than releasing them into the environment. In contrast, the results demonstrated that it had a greater environmental impact than ethanol due to the extraction time and efficiency, with ethanol solvent extracting three times faster than DES.

As the extraction time increases, more electricity is required, contributing to significant environmental impacts. However, the use of DES, which has the characteristic of capturing toxic air, its preparation had an ecotoxic air impact reduction of 20%. Besides the production process time, the size of the equipment also affects energy requirements; a smaller reactor requires more energy per kg cationized tannin produced, such as heat and electricity for agitation. Furthermore, improving the environmental profile of the chemicals used in the cationization step is the most important strategy to enhance the system's environmental performance [11]. The LCA study of phenolic compounds from spruce bark [12] that compared three technologies, namely ultrasound-assisted extraction (UAE), hot water extraction (HWE), and supercritical fluid extraction (SFE), concluded that a simpler process with a lower yield, less chemical use, and less solvent processing could be better for the environment compared to a more complex process with a greater product yield [12].

3.1.2 Challenges

The production scale can be challenging in LCA studies of NTFPs chemicals, i.e., using data from the lab scale to represent big commercial production systems based on new technology [12]. Therefore, experimental upscaling studies up to at least prototype are required to understand the possible scale-up effects. Moreover, the inclusion of environmental considerations in process design is another major challenge in developing sustainable processes.

3.1.3 The comparison of tannin bio-adhesives to fossil adhesives

One of the chemical products that is compared to other products is tannin. Tannin is naturally found in plants' bark, leaves, and fruits and has been widely used in ~~to~~ adhesive manufacture. Tannin extraction can be performed under different methods and influences tannin extracts' adhesive properties. Pine tannin-based bio-adhesive includes the processes of condensed tannin production and tannin-based bio-adhesive production. The production process includes forest activities and the extraction stage, involving solvent, energy, and water production. Compared to the tannin as bio-adhesive, there are petroleum-based adhesives which are derived from the co-products of petroleum processing and formaldehyde-based adhesives are currently used for the production of wooden flooring, such as urea-formaldehyde (UF), phenol formaldehyde (PF) and melamine-urea formaldehyde (MF). The use of these adhesives is supported by several advantages, such as low curing temperatures, excellent adhesion properties, water resistance, and low price [13].

In this case, fossil adhesives used for comparison are from wooden flooring production, including urea-formaldehyde and, phenol-formaldehyde [15], melamine formaldehyde [13]. These adhesives have formaldehyde emissions produced during the production process. The environmental comparison is based on the ReCiPe 2016 midpoint and endpoint methods (see Table 3).

The analysis of the endpoints level includes three categories to define the environmental damage, namely human health, ecosystem quality, and resource scarcity [13].

In all adhesives, fossil resources in their background systems contribute to GHG emissions. In tannin products, the production of bark chips, including diesel usage for forest equipment, especially harvesters, is the major contributor to all impact categories. In addition, the environmental impacts in tannin production are contributed by the mixing of bark chips with hot water and extractive chemicals in a container, the following evaporation step to concentrate the extract, and the final spray-drying. The endpoint score of tannin production is higher than almost all formaldehyde-based adhesives. This is due to the high ecosystem quality score associated with renewable feedstock usage, which impacts ecosystem degradation [13].

On the other hand, fossil-based adhesives have higher terrestrial acidification linked to raw material production, including urea and phenol [16]. Moreover, formaldehyde-based adhesives may possibly emit free formaldehyde during each processing phase. The release of free formaldehyde and power consumption significantly affected the environment. The use of formaldehyde resin contributed significantly to human toxicity and ozone depletion that are included in the human health category, and terrestrial acidification and mineral resources in the ecosystem quality category [17].

3.2 Fiber and silk

Silk is a natural material made from the protein fibroin produced by the silkworm *Bombyx mori* which consumes mulberry leaves as food. In general, the raw silk manufacturing process includes mulberry cultivation, silkworm rearing, and cocoon drying, where cocoons are dried with hot air, killing the pupae, and avoiding the eclosion of the moth. The following process is cocoon reeling which requires hot water to soften the cocoon shell. Several cocoon filament ends are connected to a reeling machine and unraveled onto spools [18]. While the *Eucalyptus* bark panel production [19] includes the biomass supply chain, namely forest management, transportation, wood chip production, and panel manufacturing, as depicted in Figure 5 and Table 4. Several studies on LCA of fiber and silk have been conducted around the world, such as fiber from South America [19] and silk from India [18, 20]. A case study by Sultan [21] was on a particular brand of dental floss made of silk from India, produced in Italy, and used in Germany. The cradle to gate system dominates on fiber and silk production; however, there is also a cradle to grave system [20], all with a mass-based functional unit for both fiber panels and silk, except silk dental floss, which has the length of dental floss as a functional unit.

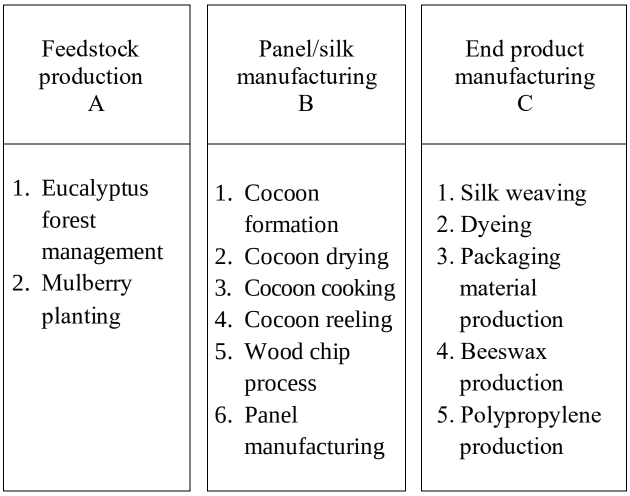


Figure 5. Life cycle stages of panel and silk products.

3.2.1 Environmental impacts

According to Astudillo et al. [18], the cocoon production phase in the raw silk production section generated the biggest environmental impact. It is influenced by inefficiencies in agricultural infrastructure, particularly power supply and irrigation.

This result is similar to silk dental floss production in which the raw silk production contributed significantly to all impact indicators because of high energy and water demand on the raw material production. In addition, the dental floss coating using beeswax and packaging also greatly impacts the production stage [21].

In eucalyptus panel production, the manufacture of the panel caused the largest portion that contributed to global warming, where the most significant contributors were related to natural gas combustion and the biomass waste generated during milling, refining, and sizing stages [19].

Table 3. The comparison of tannin to various fossil adhesives.

Environmental impacts/ kg adhesives	Unit	Tannin [13]	Melamine-urea formaldehyde [15]	Urea-formaldehyde [15]	Phenol formaldehyde [13]
Global Warming	kg CO_2-eq	2.97	4.54	2.64	-
Stratospheric Ozone Depletion	mg CFC11-eq	1.45	0.65	0.42	-
Terrestrial Acidification	g SO_2-eq	11.62	131.2	64.87	-
Endpoint scores [13]	mPt	46	33	41	56

Table 4. Life cycle process from existing literatures for panel and silk.

Reference	A1	A2	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5
Astudillo et al. [18]	-	✓	✓	✓	✓	✓	-	-	-	-	-	-	-
Casas-Ledón et al. [19]	✓	-	-	-	-	-	✓	✓	-	-	-	-	-
Bhalla et al. [20]	-	✓	✓	-	-	✓	-	-	✓	✓	-	-	-
Sultan [21]	-	-	-	-	-	✓	-	-	-	-	✓	✓	✓

Note: The unit processes for panel and silk are defined in Figure 5.

Table 5. The environmental impacts of silk and its substitutes.

Category	Silk [20]	Silk [18]	Cotton fiber [18]	Nylon 66 [18]	Sheep wool [18]
Global warming (kg CO_2-eq/kg)	10.019	80.9	3.4	8	18.5
Renewable cumulative energy demand (MJ/kg)	355	1613.6	19.7	1.3	81.7
Non-renewable cumulative energy demand (MJ/kg)		244.4	0.1	7×10^{-4}	0.1
Ecotoxicity (CTUe/kg)	-	1043.1	71.2	6×10^{-4}	3.4
Agricultural land occupation (m^2a/kg)	-	35.6	7.8	2×10^{-4}	53.5
Freshwater eutrophication (g P-eq/kg)	15.966	7	0.8	0.3	0.5

The mulberry feedstock cultivation is the major contributor to the environmental impacts as it causes harmful emissions into the air due to resources and fossil fuels consumption for fertilizers and herbicides [20]. Moreover, the use of pesticides and fuel consumption also affects the acidification and ecotoxicity due to the sulfur content in diesel, combustion efficiency, and steam generation both in the forest management of panel manufacturing and mulberry cultivation in silk production [19-20]

In addition, forest management is crucial in panel production, where forest management contributes around 36% of GHG emissions through forestry machinery and the N_2O emitted from the nitrogen-based fertilizers application. This stage also contributes almost 70% to eutrophication. This significant contribution is related to diesel combustion in forestry machinery and fertilizers and pesticides consumption. Moreover, biomass transportation from forests also contributes significantly to the environmental profile due to the considerable distance traveled for forest management and raw material transportation by truck [19].

3.2.2 Challenges

In the panel industry, forest management including biomass transportation from forest causes a significant effect on many environmental impact categories. It is affected by the physical characteristics of the biomass, its moisture content, the distance between the biomass conversion system and the field, and modes of transportation. As a result, biomass transportation is still an issue for the forest-based composite industry [19].

In silk production, it is necessary to have technical and economic factors for reducing macronutrient inputs that cause field emissions from fertilization yet still maintaining high-quality cocoon production. In silkworm rearing, the development of mulberry and silkworm varieties is important to produce high yield and quality and low fertilization and disinfection to produce minimal environmental impact [20].

3.2.3 Product comparison to other fabrics

The environmental damage comparison of 1 kg silk to other alternative fabrics is presented on Table 5, expressed as global warming, renewable cumulative energy demand, non-renewable cumulative energy demand, ecotoxicity, agricultural land occupation, freshwater eutrophication. The results from Bhalla et al. [20] showed lower global warming potential (GWP) results than Casas-Ledon et al. [19] because the system boundary excludes the background processes such as coal and diesel for electricity production, detergent in the use phase, and polyester resin in garment processing. As a result, the environmental impacts, particularly GWP, are minimal. Bhalla et al. [20] assessed handloom Indian silk with the system boundary of cradle to grave which includes silk production, transportation, garment processing, use phase, until the end of life of the product. It demonstrated higher eutrophication due to detergent consumption in the use phase, as much as 74% of the total emissions. On the other hand, the power loom Indian woven silk study with a boundary of cradle to gate system evaluated by Astudillo et al. [18] showed higher global warming impact (Table 5).

Compared to silk, there are Chinese cotton, Nylon 6.6, and wool from Ecoinvent database using a similar scope. The results showed that silk had the highest environmental impact in most categories. Several factors that contributed to the high environmental effects are identified, such as agricultural infrastructure inefficiencies and cocoon production, which are influenced by the electricity supply, irrigation, and use of fertilizers. Compared to other animal fibers, e.g., wool, silk is a natural filament fiber that requires more complex processing, especially in off-farm processing, including cocoon drying, cooking, and reeling. In general, animal fibers need higher inputs than fiber plant production and produce more co-products, such as unfed leaves, silkworm litter, pupae, and unreelable silk. Therefore, the challenges in the silk industry are the efficient valorization of these co-products, the improvement of quality and yield through fertilization and disinfection procedures, and the development of high-yielding varieties of mulberry and silkworm [18].

3.3 Honey

Several LCA studies on honey products have been conducted in America [22-23] and Europe [24-26]. The most critical phases of the life cycle of orange-blossom honey with a glass jar packaging were identified by [24]. The researches by [22-23, 26] aimed to calculate the carbon footprint of honey and evaluated greenhouse gas emissions throughout the life cycle stages in Europe, the US, and Argentina, respectively. Sillman et al. [25] assessed the environmental impacts of beekeeping while including pollination services and protein-containing by-products. The system boundaries used for environmental assessment on honey vary yet tend to be dominated by cradle to grave with mass-based functional unit of a kilogram of the product or honey mass that can be accommodated in a jar.

The honey production process begins with hive placement and construction, hive management, and pollination. Hive placement and construction requires input in the form of hive equipment, queen bees, and bee colonies. Feeding, medication, and pest control are needed for hive management, while transportation and fuels are required for pollination. It is followed by the honey production stage which consists of uncapping the hives, centrifugation, filtration, honey decanting, and extraction. The last stage is product packaging and distribution. Apart from honey, there are co-products from honey production which are also considered in the system boundary, including beeswax, drone brood, bee pollen, and pollination service. The honey production process is depicted in Figure 6.

Beekeeping A	Honey production B	Packaging and distribution C	Co-products D
1. Hive placement & construction 2. Hive management 3. Pollination trip	1. Uncapping 2. Centrifugation 3. Filtration 4. Decanting 5. Extraction	1. Honey packaging 2. Co-products packaging 3. Distribution	1. Beeswax 2. Drone brood 3. Bee pollen 4. Pollination service

Figure 6. Life cycle stages of honey.

Table 6. Life cycle processes from existing literatures for honey.

Reference	A1	A2	A3	B1-5	C1	C2	C3	D1	D2	D3	D4
Kendall et al. [22]	-	✓	✓	✓	-	-	-	-	-	-	✓
Mujica et al. [23]	-	✓	✓	✓	-	-	✓	-	-	-	-
Arzoumanidis et al. [24]	✓	✓	-	✓	✓	-	✓	-	-	-	✓
Sillman et al. [25]	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pignagnoli et al. [26]	✓	✓	-	✓	-	-	-	✓	-	-	✓

Note: The unit processes for honey production are defined in Figure 6.

3.3.1 Environmental impacts

Table 6 represents the life cycle stages of each existing research. Arzoumanidis et al. [24] conducted an LCA analysis of honey while accounting for pollination services. The results showed that the production stage had the greatest impact on most environmental categories due to electricity consumption during the storage of supers in refrigerated rooms and the use of glass for final product packaging. This is similar to the findings of [23] and [26] who discovered that electricity was primarily used to power the extraction machines for the honey extraction stage and bulk honey processing.

In addition, transportation activities play a role in contributing to high environmental impacts in honey production. According to Pignagnoli et al. [26], honey has a higher carbon footprint for migratory beekeeping systems because transportation will add to the environmental burden. Truck transport of bees for pollination service is the major contributor to both GHG emissions and pollutants in raw honey production. Transportation activities for product delivery using air freight are also indicated to have a significant environmental impact in the distribution stages [24].

3.3.2 Allocation

Allocation is critical in honey production. Allocation could be avoided by separating multifunctional processes and calculating and assigning environmental flows to specific co-products such as beeswax, drone brood, bee pollen, and pollination service. Differences in reported values revealed that the carbon footprint of honey was highly dependent on the allocation method used, as well as the production practices and honey beekeeping chain characteristics [23]. Several researchers [23-24] used the subdivision method to determine emissions, allowing them to trace the burden of each stage of the manufacturing process, which aided in the identification of additional measures that could reduce the carbon footprint of the beekeeping chain.

In the case of honey production, economic allocation may favor honey production because emissions from honey-related activities, such as extraction, are excluded. It was because honey production accounts for less than half of the annual beekeeping income, whereas subdivision would allocate 100% of the income to honey production [22]. Moreover, the findings revealed that emissions calculated using the subdivision method show higher results than economic allocations in both America and Argentina [23-24].

3.3.3 Pollination services

Pollination service is an additional function of beekeeping which is essential for ecosystem and agriculture [24]. Pollination services in the honey industry could be considered as co-products. Several studies have considered beekeeping and pollination services [23–26]. Pollination services with beekeeping cause less land occupation and greenhouse gas emissions than beekeeping alone. In LCA implementation of a beekeeping system, the pollination service could be considered as one of the functions of a multifunctional system that affects the various environmental impacts. The modeling of this system should be cautiously considered using several available approaches based on ISO 14040:2006 [7]. Because pollination service is not a physical material, economic allocation can be employed using its economic value in a multifunctional process. The implementation of economic allocation affects the environmental impact reduction because a part of the impact is allocated to the pollination service [24].

Pollination releases air emissions and requires materials and energy, contributing to environmental impacts. In contrast, it is a service that profits the ecosystem and agriculture. These two points could provide a trade-off between energy consumption and ecological benefit. In addition, the bee colonies' movement to produce honey is the main contributor to air emissions [22].

Therefore, when pollinating services are considered, the impact reductions are significant [25]. In large-scale commercial beekeeping operations, bees are moved to different places for pollination and honey production [22].

3.3.4 Challenges

The most challenging aspect in beekeeping is defining hive management, which benefits honey production and pollination services. There are numerous interactions between honey production, pollination services, increased disease and pest exposure, and supplemental feeding demand [22]. Related to the allocation method, future developments could include the implementation of economic allocation for other honey production to draw valid conclusions about these methodological hypotheses [24]. Furthermore, future developments may focus on analyzing the capacity of land around farms and selecting the best-performing vegetation based on the number of bees, climate conditions, and soil properties [26].

3.3.5 Comparison to other sweeteners

The comparison of honey to selected sweeteners that used as ingredients in chewing gum production, is presented in Table 7. For the production of 1 kg honey, the highest global warming was obtained by [23] of 2.5 kg CO_2-eq with system boundary cradle to grave, including hive management until transportation for imported products. The greatest contributor is the electricity consumption in the extraction process, as much as 90%, and freight transportation for product imports contributed almost 2%. Meanwhile, for non-migratory beekeeping, where beekeepers did not move the hives for pollination, the GWP produced were 0.4 kg CO_2-eq [22], 0.380 to 0.48 kg CO_2-eq [26] and 0.65 kg CO_2-eq [25]. Similar results to Mujica et al. [23], electricity requirements for extraction machines and refrigerators at the extraction phase are indicated as the major environmental impact contributor.

Table 7. Honey and alternative sweeteners comparison.

Study	Product	GWP (kg CO_2-eq/kg product)	Scope
Kendall et al. [22]	honey	0.67 - 0.92	cradle to gate
Mujica et al. [23]	honey	2.5	cradle to grave
Sillman et al.[25]	honey	0.65	cradle to gate
Pignagnoli et al. [26]	honey	0.38 - 2.2	cradle to gate
Shaji et al.[27]	xylitol	1.807	cradle to gate
Hafyan et al. [28]	xylitol	3.83	gate to gate
Akmalina et al.[29]	sorbitol	3.551	gate to gate

In migration pollination, the transportation of beehives showed the greatest contribution to the environment. Besides honey, xylitol [27-28] and sorbitol [29] have been evaluated for their environmental impacts. Xylitol is a sweetener obtained by biotechnological or chemical processes of lignocellulosic biomass. In these cases, xylitol was produced using the fermentation of sugarcane bagasse [27] and palm empty fruit bunch through the hydrogenation process [28]. It is reported that the primary process in xylitol production, namely fermentation and chemical hydrogenation followed by the purification process, is the major GWP contributor because of the energy requirements for aeration in the fermenter and heating in the reactor, as well as the chemicals required for the purification process. GWP in bagasse fermentation is lower because electricity is produced from bagasse in the sugar mill [27].

In comparison, sorbitol is produced from the hydrogenation of glucose syrup. The results showed that using glucose syrup as a raw material is the greatest contributor to GWP, followed by energy consumption, including electricity and steam [29]. In general, xylitol and sorbitol have a higher potential for global warming than honey because of the energy and chemicals requirements for the production process.

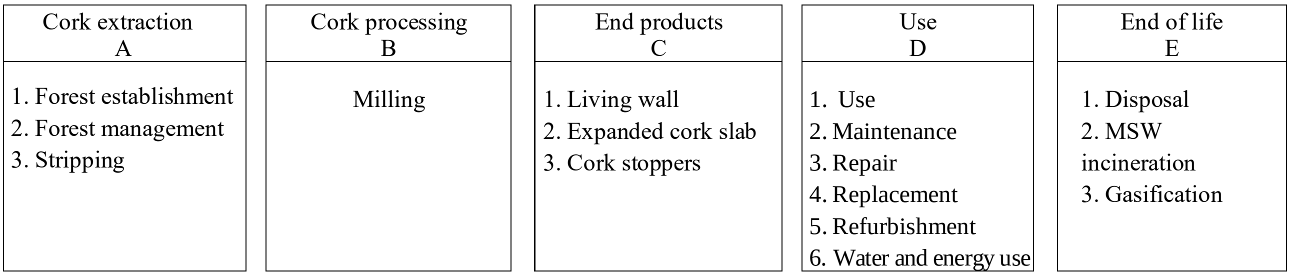
In a comparative study, the functional unit should consider differences in the product's properties or use phase. If the properties and performance of each analyzed system are the same, the systems can be compared on an individual basis [30]. Moreover, the function should represent the goals of the study, be end-used based, and include quantity, quality, and duration aspects [31]. In this study, a comparison of the sweeteners' environmental profiles was analyzed from several individual products in available research articles with a single functional unit in the form of an output of a kilogram of material. It must be noted here that a kilogram of each may not be the most relevant for comparison since a kilogram of honey, for example, may not substitute exactly one kilogram of xylitol or sorbitol. Also, foodstuffs frequently serve more than one function. They are commonly both a source of nutrition and pleasure. When defining a product's functional unit with multiple functions, the substitution should be used to define an abstract multifunction in which one functional unit of one product alternative is a real substitute for one functional unit of another product alternative. If more than one function was chosen for the LCA comparison, a multifunctional unit must be defined [32]. Therefore, the environmental profiles comparison of honey, sorbitol, and xylitol in this case should consider the nutrients contained in the product. For instance, honey contains various vitamins and minerals, amino acids, proteins, phenol antioxidants, and micronutrients, making it a highly nutritious food [33]. Sorbitol can be used for diet foods, as a laxative, as well as a thickener and humectant in cosmetics and low-moisture foods. On the other hand, xylitol is a sweetener commonly found in dietary supplements, drugs, toothpaste, and chewing gum [34].

3.4 Cork

The cork oak (*Quercus suber L.)* is a type of perennial oak in the *Fagaceae* family. It stands between 15-20 meters tall on average. The outer bark, known as cork, is composed of elastic, impermeable, and good thermal insulating tissue composed of dead cells with impermeable walls due to a chemical compound known as suberin [35]. The majority of cork oak forests are found in Portugal and Spain, resulting in a significant cork industry with significant economic importance [36]. The cork extraction is known as stripping, and it is usually harvested once every nine to fourteen years. It has no effect on the tree, and new bark begins to form behind the newly exposed trunk surface. Cork has two qualities; the low quality obtained from the first two extractions and the best quality for industrial purposes, which is called the reproduction cork, obtained from the third extraction onwards. The reproduction cork also has the highest market value [35].

There are four stages of cork production considering all the processes involved, namely forest establishment with oak planting, forest management, cork stripping, and milling. The various end products of cork include cork stoppers, cork slabs, and living walls. The end-of-life stages of cork from these cork products include landfill disposal, MSW incineration, and gasification.

The life cycle stages and processes from previous studies are illustrated in Figure 7 and Table 8. Most of the studies used cradle to gate and cradle to grave as the system boundaries with functional units based on the mass of products or the number of final product entities produced. Research on Portuguese cork was conducted by [35-42] with a cradle-to-gate system boundary, while the end-of-life of cork was conducted by Demertzi et al. [36], which is a waste management strategy for natural cork stoppers. In addition, several environmental assessments regarding product variations from cork have also been conducted previously, including expanded cork slabs and granules [36], gasification of cork waste [39], and cork-based modular living walls [37].



Cork extraction A	Cork processing B	End products C	Use D	End of life E
1. Forest establishment 2. Forest management 3. Stripping	Milling	1. Living wall 2. Expanded cork slab 3. Cork stoppers	1. Use 2. Maintenance 3. Repair 4. Replacement 5. Refurbishment 6. Water and energy use	1. Disposal 2. MSW incineration 3. Gasification

Figure 7. Life cycle stages of cork products.

Table 8. Life cycle processes from existing literatures for cork.

Ref	A1-2	A3	B	C1	C2	C3	D1-6	E1	E2	E3
González-García et al. [35]	✓	✓	-	-	-	✓	-	-	-	-
Demertzi et al. [36]	-	-	-	-	-	✓	-	✓	✓	-
Cortês et al. [37]	✓	✓	✓	✓	-	-	✓	✓	-	-
Demertzi et al. [38]	-	✓	✓	-	✓	-	-	-	-	-
Ramos et al. [39]	-	-	-	-	-	-	-	-	-	✓
Santos et al. [40]	-	✓	✓	-	-	✓	-	✓	-	-
Boschmonart [41]	✓	✓	✓	-	-	✓	-	-	-	-
PricewaterhouseCoopers and Ecobilan [42]	✓	✓	✓	-	-	✓	✓	✓	-	-

Note: The unit processes of cork production are defined in Figure 7.

Table 10 Life cycle processes from existing literatures for rubber.

Ref	A1	A2	A3	B1	B2	B3	B4	B5	B6	B7	B8	B9	C1	C2
Dunuwila et al. [43]	-	-	-	✓	-	-	-	-	-	-	-	-	-	-
Kumara et al. [44]	✓	✓	✓	✓	-	-	✓	-	-	-	-	-	-	-
Maulina et al. [45]	-	-	-	-	-	-	-	-	-	✓	-	✓	-	-
Pyay et al. [46]	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	-	-	-
Monteiro et al.[47]	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓
Soratana et al.[48]	✓	✓	✓	-	-	-	-	✓	-	-	-	-	-	-

Note: The unit processes of rubber production are defined in Figure 8.

3.4.1 Environmental impacts

According to Santos et al. [40], the occupation and transformation of land as part of forest management in the raw materials' extraction stage is the most critical life cycle stage. Cork stripping is usually conducted manually and included in the raw material stage. It is identified as the highest contribution to the environmental impacts due to the cork transportation from tree to the meeting point by lorry [41], also the cleaning and pruning processes [35, 41]. On the other hand, the most critical flows in the products' manufacturing stage are natural gas consumption and the emissions into the air from natural gas combustion [40].

3.4.2 Challenges

Cork production involves relevant stakeholders in the forest establishment and management activities. Communicating forest management improvement actions to cork producers might be challenging. Moreover, management activities depend on each region's climatological and edaphological conditions; thus, the forest stage may vary significantly [38].

3.4.3 Comparison to other materials

PwC/Ecobilan [42] compared the environmental impacts of various wine stoppers made of cork (Portugal), aluminum (France), and plastic (Belgium). The functional unit was the production of 1000 stoppers for sealing standard 750 ml of wine bottles with a general production process including raw material production until finishing, stoppers transportation to the bottling centers, bottling process with PVC covers, and end of life. The landfill portion for cork, aluminum and plastic stoppers are 100, 68 and 81%, respectively, with the remaining wastes processed in the recycle site. Mass allocation procedures were employed in this study. The environmental impact results can be seen in Table 9.

Compared to aluminum and plastic, the cork stopper has the lowest value for most environmental damages. On the contrary, cork closures have a worse environmental impact than the aluminum in terms of water consumption due to the cultivation in raw material production. The bottling process is similar for all types of closures. This process is identified as having the highest environmental impact due to the PVC cover. Transportation represents a minor impact on total emissions for all types of closures. Regarding the end-of-life phase, the recycling for both aluminum and plastic closures show beneficial impacts corresponding to the avoided virgin plastics and recycled aluminum usage for secondary packaging material.

3.5 Rubber

Rubber is a perennial plant that requires much water to grow. The natural rubber industry has an important role in the economies of many developing countries, especially in Asia [43]. Studies on environmental sustainability in various rubber products have been conducted, such as crepe rubber [43-44], crumb rubber [45], and intermediate rubber products, namely ribbed smoked sheets (RSS) [44, 46], ribbed smoked sheets bales (RSSB), block rubber (Standard Thai Rubber, STR 20), concentrated latex, and lumber AB [46] in Asia, and road-safety barrier in Europe [47].

In general, the natural rubber production process consists of seedling, cultivation, and tapping. The natural rubber is then processed into a final product with different treatments. Most of the system boundaries used in the previous studies are cradle to gate. The functional unit used is based on the mass of the product or the raw rubber input or the area used to produce the final product. The life cycle stages and processes from previous studies can be seen in Figure 8 and Table 10.

Table 9. The environmental impacts of selected cork materials [42].

Environmental impacts	Unit	Cork stopper	Aluminium stopper	Plastic stopper
Greenhouse gases emissions	kg CO_2-eq	1.53	37.17	14.83
Acidification	g H+-eq	1.35	8.30	2.08
Photochemical oxidants formation	g C_2H_4-eq	3.45	13.96	5.10
Eutrophication	g P-eq	0.61	0.67	0.92
Water consumption	m^3	25.64	13.48	41.31
Non-renewable energy consumption	MJ	102.02	441.92	496.75
Solid waste generation	kg	3.72	7.39	5.84

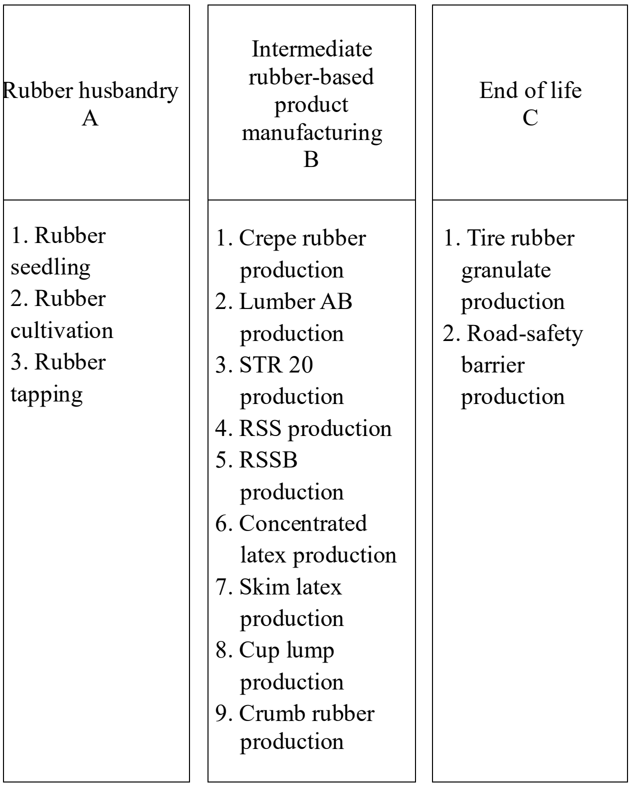


Figure 8. Life cycle stages of rubber.

3.5.1 Environmental impacts

In the production of crepe rubber, electricity generation by using old machinery and lights in the factories is the main contributor to GWP, as much as 89% of 0.3 MT CO_2-eq/ha per year [43]. This is similar to Kumara et al. [44] that showed global warming of crepe rubber processing was mainly based on electric power-based machinery, i.e., 2.08 MT CO_2-eq/ha [44]. Across all the production systems of intermediate rubber products (RSS, RSSB, STR 20, concentrated latex, and lumber AB) analyzed by Pyay et al. [46], human toxicity (cancer effects) was found to have one of the major significant impacts across all products. It was due to the production of chemicals, including urea, pesticides, potassium chloride, glyphosate, sulfuric acid, diammonium phosphate, and polyethylene bags used in cultivation and rubber seedlings. On the other hand, the use of diesel, organic and inorganic chemicals in the lumber AB production was also a major contributor to particulate matter and to ozone depletion impact [46].

3.5.2 Challenges

The crepe rubber manufacturing industry is challenged by low productivity, rising production costs, and environmental concerns [43]. On the other hand, the drying process that uses firewood combustion for some production processes, namely RSS, is inefficient and emits much pollution. To address these issues, it is recommended that renewable energy sources, such as solar energy, be used for electricity generation and solar power [43].

3.5.3 Comparison to synthetic and rubber wood

A study by Soratana et al. [48] compared Hevea natural rubber to synthetic rubber using the functional unit of 1 kg rubber, as presented in Table 11. In this case, the production process of Hevea rubber consists of agriculture, processing, and transportation stages, where nitrogen and phosphorus fertilizers are used in the agriculture stage and ammonia, electricity, and liquefied petroleum gas (LPG) in processing. The results showed that synthetic rubber has a lower global warming and acidification than Hevea natural rubber. Around 66% of the acidification value of synthetic rubber production is produced by SO_2 emissions from H_2SO_4 production used in the vulcanization process. On the other hand, 84% of the global warming of Hevea rubber is generated by LPG usage for drying at the rubber milling process. Furthermore, the use of LPG also affects the amount of acidification by up to 96%. Whereas most of the ozone depletion contribution is contributed using urea fertilizer at the agriculture stage.

Pyay et al. [46] compared the primary products of Hevea rubber based on the European Product Environmental Footprint (PEF). This method plays a critical role in importing rubber products into Europe. Primary products consist of fresh latex, cup lump, and Hevea wood. Fresh latex and cup lump are natural rubber harvested, but the cup lump is collected in solid form in the tapping cup with the addition of sulfuric acid. In comparison, Hevea wood is harvested from rubber trees at the end of their economic lifetime, which is approximately 25-30 years. The normalized PEF values of primary rubber products are reported in Table 12.

Based on the results, human toxicity, cancer effects, and marine eutrophication are the major environmental impact categories. In fresh latex, pesticides, urea, potassium chloride, diammonium phosphate, and herbicides are used in rubber plantations. In addition, water consumption impacts water resource depletion, consisting of direct water use in cultivation and indirect water use from raw materials usage in rubber planting. Direct water consumption is affected by the characteristics of rubber and planting location. Rubber plants require high amounts of water for growth. In Thailand, the majority of rubber is grown in the south, where there is a high precipitation rate that provides enough rainwater to grow rubber trees. As a result, the rubber plants require little direct irrigation. The indirect consumptive water use is determined as a major contributor to the cultivation [46].

Table 11 The environmental impacts of Hevea natural rubber and synthetic rubber.

Environmental impacts	Unit	Hevea rubber	Synthetic rubber
Global warming potential	kg CO_2-eq	33.75	2.7
Acidification potential	kg SO_2-eq	0.077	0.01
Ozone depletion potential	kg CFC-11 eq	6.90E-08	8.63E-07

Table 12 Normalized PEF values of rubber primary products [46].

Rubber products	Normalized PEF values
Fresh latex	0.194
Cup lump	0.437
Hevea wood	0.229

Compared to Hevea wood, the main environmental damages are generated by the wood cultivation in human toxicity (cancer effects), particulate matter/ respiratory inorganics, and eutrophication (aquatic marine) categories which also contributed by chemicals and water use in cultivation dan diesel consumption in wood production. Cup lump is the product with the largest PEF values among primary rubber products. The cup lump production process requires sulfuric acid, a major contributor to human toxicity (cancer effects). To produce a cup lump, sulfuric acid needs to be added to fresh latex. Furthermore, the use of urea and polyethylene bags for rubber seedlings contribute significantly to particulate matter/respiratory inorganics and eutrophication (aquatic marine), respectively.

3.6 Bamboo

Bamboo is a fast-growing plant that can be found in most tropical countries. It grows rapidly and has a short rotation age, approximately 3-5 years. Another advantage of bamboo is that the entire root system is not disturbed when raw materials are extracted [49]. Bamboo production material consists of the process of cultivating bamboo plants followed by harvesting. The harvested bamboo is then transported to manufacture to be processed into the end products, including plywood, fiber, building materials, pipes, poles, composites, etc.

There has been a lot of research on bamboo LCA compared to other products. There are studies on bamboo logs and bamboo derivative products, such as polishes and panels [50], flattened bamboo [49-51]; mat and flooring [50, 52], composite and fiber [49, 53-54], building and bioenergy support materials [55-57], earth-based mortars with bamboo particles (EMB) [57], frames [58], and plybamboo and laminated veneer bamboo (LVB) [17, 49, 51, 59]. The life cycle stages, and process of selected studies are presented in Figure 9 and Table 13. The system boundary used of LCA studies on bamboo products varies and it is dominated by cradle to gate and cradle to grave, with functional units based on the mass of products or the number of final product entities produced.

3.6.1 Environmental impacts

In the case of various bamboo products from Vietnam [52], including handicrafts, kitchen countertop panels, strand woven flooring, and mat, the electricity requirement is indicated as one of the three major carbon emissions sources besides board and paper packaging, as well as transportation in handicrafts; also freight shipping and glue application in other products. In another study, the amount of energy used in the production process was a critical parameter [50]. The bamboo materials processing has a significantly higher environmental impact on the ecosystem than other steps due to natural gas consumption for drying processes. Chang et al. [17] discovered that power consumption for the mechanical equipment used during the bamboo processing step was important potential environmental influence in the LCA. In bleached glue-laminated bamboo board production, the power consumption during the three-layer lamination process also had the highest potential environmental impact, especially respiratory inorganics. In the case of bamboo for the building sector, the operation phase is the largest contributor to the steel-bamboo composite frame structure for residential houses, accounting for up to 36.4% of total emissions [53]. Cooling, heating, and lighting influenced the emissions of reinforced concrete and steel-bamboo frame structural schemes.

3.6.2 Challenges

The establishment of nationwide databases is critical to the inventory data stage; thus, more representative results for the specific product can be obtained to track material-based energy and carbon flows rather than case studies. Moreover, the methodology's robustness could be improved by analyzing the effect of other input parameters on the environmental impacts of the products [56-57]. Another challenge is reducing energy consumption throughout all stages of its life cycle. In the case of handicraft production, it is recommended to use hydro and solar electricity and explore innovative alternatives regarding dimensional design and packaging materials [52]. For the building sector, it is also challenging to lower the energy use from construction to demolition. According to the United Nations Environment Program, buildings consume approximately 40% of global energy and account for approximately 1/3 of global greenhouse gas (GHG) emissions [57].

Table 13 Life cycle processes from existing literatures for bamboo-based products.

Ref	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	C	D1	D2	D3	D4	D5
Chang et al. [17]		✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kavanagh [49]	-	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Escamilla and Habert [50]	✓	✓	-	-	-	-	-	-	-	✓	✓	✓	✓	-	-	✓	-	✓	-	-	-	-	-	-	-
van der Lugt and Vogtlander [51]	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Phuong and Xuan [52]	-	✓	-	-	-	-	-	-	-	-	-	✓	-	✓	✓	✓	-	-	-	-	-	-	-	-	-
Zhang et al.[53]	✓	✓	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	✓	✓	✓	-
Shi et al.[54]	-	✓	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	✓
Akoto et al. [55]	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
Paiva et al. [57]	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	✓
Yu et al. [56]	✓	✓	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-
Agyekum et al. [58]	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	-
Li et al. [59]	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-

Note: The unit processes of bamboo production are defined in Figure 9.

Bamboo production A	Product manufacturing B	Use phase C	End of life D
1. Cultivation 2. Harvesting	1. Plybamboo 2. Fiber 3. Resident building material 4. Pipe 5. Earth mortar bamboo 6. CLT 7. Composite frame 8. Pole 9. Flattened bamboo 10. Woven bamboo mat 11. Woven bamboo mat panel 12. Kitchen countertop panel 13. Strand woven flooring 14. Strand woven mat 15. Bicycle frame 16. Glued-laminated bamboo 17. Charcoal	-	1. Disposal 2. Demolish 3. Waste recycling 4. Incineration 5. Waste processing

Figure 9. Life cycle stages of bamboo-based products.

3.6.3 Consideration of biogenic carbon sequestration

Several studies considered biogenic carbon into their calculations [17, 49, 51-52, 57]. Biogenic carbon represents the CO_2 sequestered by biomass as a result of photosynthesis [57]. Bamboo produces up to 35% more oxygen than a comparable stand of trees while reducing CO_2 emissions. One hectare of bamboo absorbs 62 tonnes of CO_2/year [49]. Bamboo materials are beneficial for lowering CO_2 emissions, energy conservation, carbon storage, and fuel substitution alternative. However, carbon sequestration can be involved in life cycle assessments when bamboo is burned to generate electricity or heat [51]. The positive impact of temporary carbon storage in durable products cannot be assessed using a single product, though an attempt has been made in two important LCA systems, i.e., the ILCD Handbook and the Publicly Available Specification (PAS) 2050:2011, by including a credit for temporary carbon storage in bio-based products. Furthermore, this method overestimates the benefits of temporary biogenic CO_2 fixation and should be avoided [60].

3.6.4 Product comparison

In this section, the selected bamboo products from previous studies are compared to wood products with the same functional unit, i.e., woven mat panels and glulam bamboo [50] compared to plywood and glulam wood [15]. In addition, there are environmental impacts results of plybamboo and plywood [17]. All studies were conducted using endpoint indicators.

3.6.4.1 Glued laminated (glulam) and veneer-based products

Compared to the glulam bamboo and woven bamboo mat panels [50], there are wood products from the laminated and veneer structural wood, i.e., glue-laminated (glulam) timber, plywood, and solid wood panel (SWP) [15]. The functional unit of these studies was 1 m^3. This functional unit was chosen based on previous experience developing LCA data for wood products for the EcoInvent database. Glulam is a popular building material all over the world. It is made by gluing lamellas together in a length parallel to the direction of the fiber. Because of its high strength and ability to form an arch, it can be used as a beam or a roof structure. In this case, glulam timber and wood used urea-formaldehyde as the adhesive. Plywood is a wood-based composite material made up of an odd number of layers of veneer laid perpendicular to the grain direction. Plywood, like glulam, used UF as a bonding agent. The manufacturing process of these selected wood-based construction materials was similar, but some processes varied. The process is started with log debarking, then formed into veneers for plywood and laths for glulam.

Both glulam and bamboo are composed of slats and a bonding agent. Splitting, trimming, and then planning are the processes used to create slats, which vary in shape and size depending on the material's production and application. To form the laminate, the slats are glued, placed in a mold, and hot-pressed.

A woven bamboo mat panel, which is similar to glue-laminated bamboo, is currently used as an alternative to plywood. Woven bamboo mats are layered, glued together with a bonding agent, and then hot-pressed to form the composite material.

In addition, the solid wood panel consists of thick layers of lamellas. The production of solid wood panel is similar to glulam. The lamellas are dried, planed, joined, and glued into long slats to form a block, then cut into boards and surface treatment. Figure 10 compares the endpoints of environmental impacts for wood [15] and bamboo [50] products using IMPACT 2002+ with normalized endpoint indicators.

The results showed that glulam wood had lower environmental impacts than glulam bamboo. In bamboo products, the electricity used for cutting, pressing, and transportation contributed the major environmental impacts at around 40 to 50% and 15 to 25%, respectively. However, the production of bamboo-based materials could vary depending on the bamboo species used and the manufacturing processes efficiency. Moreover, a country's electricity mix can affect a product's environmental impacts. All bamboo products were calculated using China’s electricity mix, where the bamboo-based construction materials are produced. The transportation sector contributes a significant amount because bamboo products are frequently transported from the factory to retailers or distributors over distances varying from 0 to 600 km [50].

The greatest environmental impact of bamboo products is on human health, followed by resources, and climate change. On the other hand, for wood products the greatest environmental impacts are on human health, followed by ecosystem quality, and resources. This is because both types of products require formaldehyde adhesives which impact respiratory organics for human health, and electricity consumption which impacts resources. In addition, the climate change in bamboo products is caused by high electricity usage and transportation. In wood products, the significant impact on ecosystem quality is caused by large land use, while land use does not make a significant environmental impact on bamboo products [15, 50].

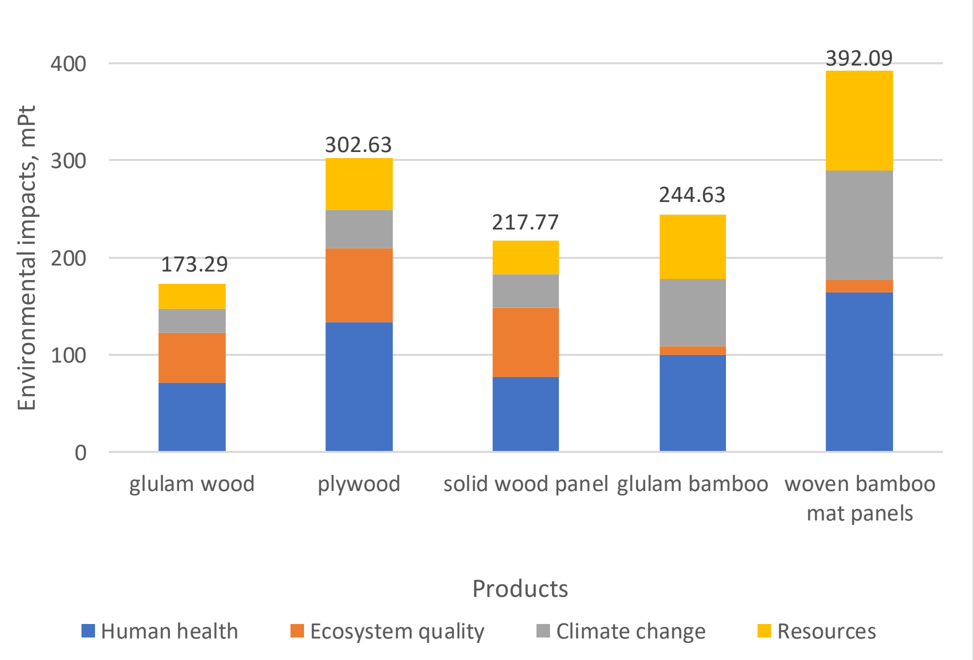


Figure 10. The environmental impacts comparison of selected wood and bamboo products [15, 50].

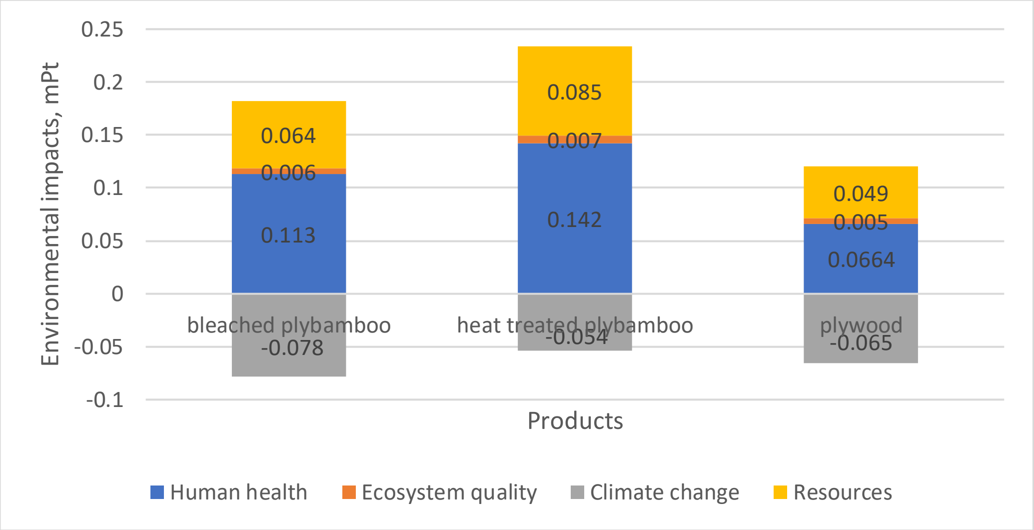


Figure 11. Environmental impacts of plywood and plybamboo [17].

The results found that the environmental burdens of plywood and plybamboo production are mainly due to power and high glue consumption. Furthermore, urea-formaldehyde adhesive may potentially release free formaldehyde during each processing phase that affects significantly to non-carcinogenic toxicity, ozone layer depletion, respiratory inorganics, terrestrial acidification, terrestrial nitrification, and mineral exploration which contribute to human health, ecosystem quality, and resource availability categories [17].

According to the findings, bleached plybamboo showed a lower environmental impact than heat-treated plybamboo in all four categories despite the lower power consumption. However, both products showed greater impacts than plywood. This is probably due to electricity consumption, which accounts for approximately 60% of the environmental impacts of glulam bamboo [50]. H_2O_2 also has a high potential environmental impact on plybamboo products, particularly carcinogenic toxicity. In the case of heat-treated plybamboo, the drying process has the highest potential environmental impact of any processing stage.

Bamboo products, like timber, involve biological materials containing approximately 50% carbon [17]; thus, the bamboo materials used are equivalent to carbon storage in an organic form. Both products have a negative carbon emission value, which shows that carbon storage compensates for carbon emissions during the processing phases.

4. Conclusion

LCA has been widely used to calculate the environmental profiles of selected NTFPs to investigate the environmental sustainability and hotspots of the production systems. This study presented a comparison of these products with their alternative products which could be substituted by them. Some NTFPs, namely tannin, honey, and cork are more likely to have ecological benefits than the substituted products for most environmental impact categories. The environmental impact of tannin, honey, and cork production on global warming is lower than their substitute products. In tannin, the acidification potential produced is also lower than its substitute products, namely formaldehyde-based adhesives, i.e., melamine and urea formaldehyde due to the presence of urea and phenol in the raw material and the release of free formaldehyde during each processing phase. Likewise, natural cork has lower acidification than its substitutes for closures production, namely aluminum and plastic materials. As for honey, substitute products such as xylitol and sorbitol have a higher potential for global warming due to the energy and chemical requirements for production.

However, other commodities have higher impacts on the environment than their alternatives. Other products, such as silk, rubber, and bamboo, have greater environmental impacts on global warming than their substitutes. Aside from contributing to global warming, silk also causes ecological damage such as eutrophication and ecotoxicity, which has a greater environmental impact than its substitute products such as sheep wool, cotton fiber, and nylon 66. Several factors have been identified as causing the high environmental effects, including agricultural infrastructure inefficiencies and cocoon production, which is contributed by electricity supply, irrigation, and fertilizer use.

In rubber products, apart from global warming, there is also an acidification potential which results in a higher environmental impact than its substitute product, namely synthetic rubber. Those environmental damages are caused by the use of LPG for drying during the rubber milling process. Compared to similar products made from wood, the bamboo products reviewed include plywood, glulam, and woven mat panel products. According to the findings, bamboo products have a greater environmental impact than wood products. Climate change in bamboo products is caused by high electricity consumption and transportation.

Attention needs to be directed to the unique characteristics and properties of NTFPs in comparing their impacts on a functionally equivalent basis. Thus, the functional unit of the system should consider the different properties and use phase for the appropriate comparison. The comparative LCAs in this study were carried out by only considering a single functional unit from available previous studies. The functional units used for environmental assessment of various NTFPs products vary depending on the type of product. Chemicals, silk, and honey are mostly evaluated based on the mass of products. On the other hand, the functional units of cork, rubber, and bamboo are more varied. As for rubber, the basis for the mass of the product or the raw rubber input or the area used to produce the final product are widely used. In addition, the functional units of cork and bamboo refer to the mass or volume of products or the number of product entities produced. Besides, an energy base or an area base is also used to evaluate the valorized product and the slab or panel board, respectively.

There were properties in each NTFPs that were not considered in these comparative LCAs, such as the nutrients contained in honey and the duration of the other products' use phase. In a comparative study, the functional unit should consider differences in the product's properties or use phase. Therefore, it is recommended to take into account the functions of each product for future comparison studies. A multifunctional unit must be defined if more than one function is analyzed. Moreover, the rigorous comparison of the LCA methodologies, the goals and boundaries of the systems, and the local factors affecting the process is crucial in comparing different LCA studies. Furthermore, it is critical to understand the alignments, divergences, and impacts on the results.

The selection of system boundaries is critical in environmental assessment because it determines the scope of the assessment and the extent to which different environmental impacts are taken into account. Furthermore, in the case of comparative analysis, there are challenges and trade-offs in selecting an appropriate and feasible system boundary for the assessment. Furthermore, when capturing the full life cycle of a product, it is important to achieve a balance between comprehensiveness and simplicity. However, comparative analysis can be conducted to benchmark the system boundary choices with other studies in the forestry sector and evaluate the consistency and compatibility of the chosen system boundary.

Nevertheless, comparing analyses and considering the differences are beneficial in developing a deeper understanding of the parameters that influence environmental impact for each product. This practice can create new knowledge about process differences that can impact the process's overall impact and challenges to reduce emissions. Moreover, the provided information about emission hotspots and some key points of each production process in this LCA study could help identify process improvement strategies to develop the NTFPs production system and support sustainable development.

The environmental impacts of NTFPs are closely linked to emissions from the manufacturing process, such as the raw material production and the electricity consumption to operate equipment in the production processes. Furthermore, additional operations, such as harvesting and transporting raw material from forests, cannot be dismissed and become potentially significant sources of environmental impacts from forestry activities. The upscaling process, use of renewable energy, and technical product developments are some of the main challenges in the production and LCA study of NTFPs.

The sustainability of NTFPs needs to be achieved due to their role in supporting rural livelihoods, culture, and businesses in order to maintain human well-being. Future studies that can support the sustainability of NTFPs should focus on several topics. Developing sustainable harvesting practices is important to ensure the long-term viability of NTFPs. This involves understanding the reproductive biology of the species, the impact of harvesting on population dynamics, and the development of harvesting methods that minimize damage to the forest.

In addition, empowering forest communities through communication with relevant stakeholders is critical in sustainable NTFPs management to understand the socioeconomic context of NTFPs management, the role of local institutions in managing NTFPs, and the development of policies that empower forest communities to manage NTFPs sustainably. Besides, developing value chains that link NTFP producers to markets is essential to ensure the economic viability of NTFPs. Studies should focus on the development of value-added products, the efficiency of transportation, and understanding the market demand for NTFPs. Developing technology of NTFPs production is also important to increase efficiency and renewable energy use, reduce costs, improve product quality, and streamline production processes. Moreover, technology development can also promote optimizing resource utilization, reducing waste, and enhancing product innovation and development.

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