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Original Research Article

Life Cycle Assessment of Bamboo Biochar Production: A Case Study of a Malaysian Manufacturer

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Abstract: Bamboo biochar is an organic product with a high carbon content which is produced by pyrolysis at high temperatures, and it has been widely used for air purification, soil fertility enhancement, and wastewater treatment. However, there is a lack of studies on the environmental impacts of bamboo biochar. In order to address this issue, this study aims to evaluate the life cycle assessment of locally produced bamboo biochar and provide recommendations for sustainable production practices. The functional unit of this study is 1 kg of bamboo biochar, and a cradle-to-gate approach was employed, excluding the usage and disposal phases. The environmental impacts were evaluated using OpenLCA software, the Industrial Design & Engineering Materials (IDEMAT) database, and the Environmental Footprint 3.0 (EF 3.0) method. The results revealed that raw material processing contributed the highest environmental impacts across multiple categories, primarily due to the long drying process and fuel consumption during transportation. In contrast, the carbonization and packaging stages exhibited relatively lower environmental impacts. To mitigate these impacts, this study suggests adopting natural or solar drying methods, utilizing renewable energy sources, and optimizing logistics to significantly reduce the overall environmental burden. Ultimately, this study provides valuable insights for bamboo biochar manufacturers to adopt more sustainable practices in their production processes.

Keywords: Bamboo, Biochar, Life Cycle Assessment

INTRODUCTION

Bamboo is a member of the Gramineae family and subfamily Bambusoideae, a fast-growing, multi-purpose plant tolerating wide climatic and edaphic conditions, including Malaysia [1] [2]. Commercial cultivation in Malaysia is, however, hampered by the problem of land acquisition [1]. Bamboo is noted for its strength in tension, longevity, and ecological benefits like soil stabilization and carbon sequestration [2] [3]. Its applications are diverse ranging from the textile and building material sectors to biochar [1] [3]. Bamboo biochar, produced through pyrolysis, is also noteworthy for its green applications like soil amendment, water remediation, and air purification [4] [5].

Biochar is an organic product with a high carbon content produced through pyrolytic thermal degradation of organic biomass under low oxygen conditions, typically through processes like pyrolysis [6] [7] [8]. Production involves the heating of biomass at high temperatures, and this creates a porous, stable, high surface area material [8] [9]. Biochar possesses numerous environmental benefits such as enhancing soil fertility, sequestering carbon, and reducing greenhouse gas emissions [6] [8] [10]. Its applications are diverse, from being a soil conditioner, water purifier, and use in renewable energy production [7] [8] [11]. Biochar can also be employed for the uptake of poisonous substances, and hence employed in environmental cleanup [10] [12].

Life Cycle Assessment (LCA) is a critical tool for evaluating the environmental performance of products and processes from cradle to grave [13] [14]. LCA has been employed in some studies in the production of biochar, citing its potential for carbon sequestration, improvement of soil quality, and climate change mitigation [15] [16]. For instance, LCA has been shown to have the potential to reduce greenhouse gas emissions and improve soil health [15] [16]. However, there is a wide-eyed gap in literature studies in LCA for the production of biochar in Malaysia. The majority of existing studies are region-focused on other regions, and a localized research gap still remains to ascertain specific environmental impacts and benefits in the Malaysian context.

In order to address this issue, this study is conducted to evaluate the Life Cycle Assessment (LCA) of Malaysian biochar production. This research aims to fill the gap offered by evaluating a systematic overview of the environmental impacts of indigenous biomass resource-based biochar production, thereby supplementing initiatives toward Malaysian sustainable waste management and greenhouse gas emissions mitigation.

MATERIAL AND METHODS

A. Goal, Functional Unit, and System Boundary

The goals of this study are to assess the life cycle of bamboo biochar produced by a local manufacturer and to provide recommendations for sustainable production practices. In this study, the functional unit is defined as 1 kg of bamboo biochar produced by the local manufacturer. Moreover, a cradle-to-gate approach is adopted, which consists of two main phases: production and transportation. This study excludes the assessment of environmental impacts during the usage and disposal phases, as the data for these stages are highly variable and difficult to obtain accurately. Fig. 1 presents the system boundary framework of this study.

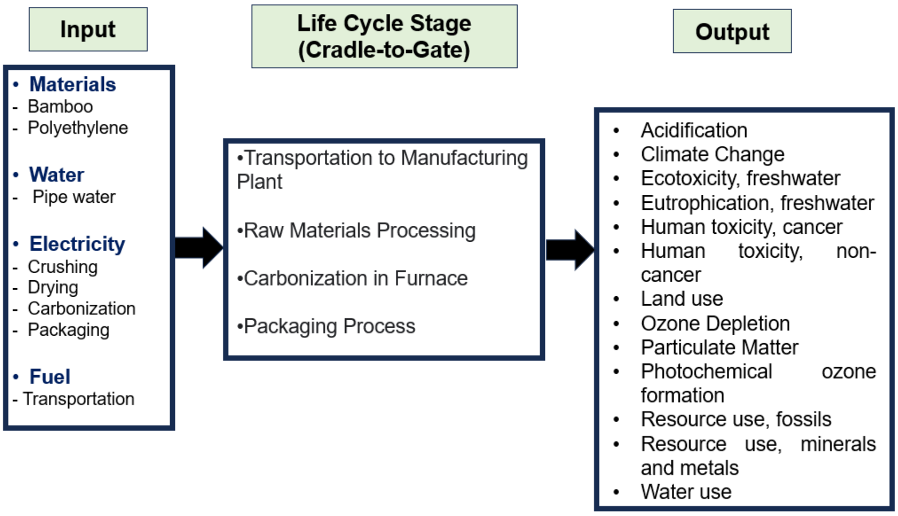

Fig. 1: System boundary framework of 1 kg bamboo biochar.

B. Life Cycle Inventory (LCI)

The LCI data, including materials, water, electricity, and fuel consumption, were collected through a qualitative approach. A semi-structured interview was conducted with the production manager of the manufacturing plant to obtain the necessary data. Furthermore, on-site observations during plant visits were also conducted to fully understand the manufacturing process and to gather additional information.

C. Life Cycle Impact Assessment and Interpretation

OpenLCA software version 2.2.0 was used to assess the life cycle of 1 kg of bamboo biochar. The Industrial Design & Engineering Materials (IDEMAT) and Environmental Footprint 3.0 (EF 3.0) databases were used as datasets for the assessment. Thirteen environmental impact categories were evaluated, including acidification, climate change, ecotoxicity (freshwater) eutrophication (freshwater), human toxicity (cancer), human toxicity (non-cancer), land use, ozone depletion, particulate matter, photochemical ozone formation, resource use, fossils, resource use (minerals and metals), water use. These impact categories were selected due to their significance in assessing the environmental impacts associated with bamboo biochar production.

RESULTS AND DISCUSSION

A. Production flow of bamboo biochar

The production of bamboo biochar in the selected company begins with the transportation of bamboo from the plantation, located more than 350 km from the manufacturing plant. The moisture content of the bamboo, as reported by the manufacturer's laboratory department, is approximately 18.5% on average. However, the specific bamboo species used was not disclosed due to business confidentiality. After transportation, raw material processing is carried out, which involves several steps such as removing impurities (e.g., soil and dust particles, crushing, and drying process. The drying process is typically performed using an indoor dryer to facilitate efficient drying and to prevent disruptions caused by unpredictable weather conditions. Once completely dried, the bamboo is transferred to the carbonization furnace and undergoes pyrolysis at high temperatures. However, the exact operating temperature was not revealed by the manufacturer for confidentiality reasons. After carbonization, the bamboo biochar is cooled down, which is then collected for packaging. According to the manufacturer, the yield rate of bamboo biochar from the process is approximately 25%. The packaging process involves the use of a sealed packaging machine and plastic bags, after which the final product is stored in a warehouse before being distributed to resellers. Fig. 2 shows the overall production flow of bamboo biochar.

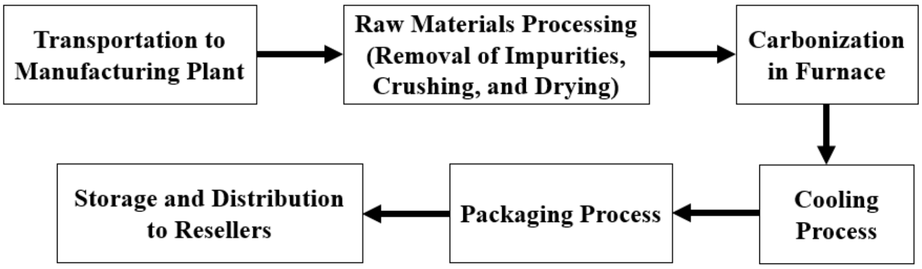

Fig. 2: System boundary framework of 1 kg bamboo biochar.

B. LCI data of bamboo biochar production

Table 1 shows the LCI data collected of 1 kg bamboo biochar through semi-structured interviews and observations. The LCI data were categorized into four main stages, namely Transportation to the Manufacturing Plant, Raw Materials Processing, Carbonization, and Packaging Process. Data such as fuel and electricity usage, as well as materials used, were collected for further analysis. The cooling process is neglected as it is naturally air-dried and does not involve any significant inputs or outputs. In addition, storage and distribution are excluded from this study, as the assessment focuses only on the cradle-to-gate stages.

C. LCA evaluation

Table 2 summarizes the life cycle impact assessment (LCIA) results for the 1 kg of bamboo biochar. The results are expressed according to their respective characterization units based on the ReCiPe midpoint indicators. The acidification potential is 0.0106 mol H^+ eq, while the climate change potential amounts to 5.066 kg CO_2 eq. The freshwater ecotoxicity is 0.494 CTUe, and the freshwater eutrophication potential is 1.91×10^{-6} kg P eq.

For human health-related impacts, the human toxicity (cancer) and human toxicity (non-cancer) potentials are 5.24×10^{-11} CTUh and 6.64×10^{-9} CTUh, respectively. The land use impact is 2.894 Pt, while the ozone depletion potential is 1.78×10^{-10} kg CFC-11 eq. The particulate matter formation and photochemical ozone formation potentials are 1.77×10^{-7} disease incidence and 0.00665 kg NMVOC eq, respectively.

Each indicator represents a distinct environmental mechanism; therefore, the values should not be compared directly across categories. Instead, they provide a profile of potential environmental burdens, allowing further interpretation once normalized or weighted according to regional or methodological criteria.

TABLE I
LCI DATA OF 1 KG BAMBOO BIOCHAR

Item	**Description and assumption**	**Unit**	**Functional Unit Value**
Transportation to Manufacturing Plant			
Fuel	350 km per trip with 10 metric tons of bamboo Assumption: Moisture content of bamboo is and yield rate of bamboo biochar production is 18.5% and 25%, respectively, meaning that 4.9 kg of raw bamboo is required to produce 1 kg of bamboo biochar. The presence of impurities is ignored, as their effect is considered minimal Hence, Distance per kg=10,000/350=0.035 km/kg F.U: 0.035 km/kg ×4.908 kg = 0.17 km	km	0.17
Raw Materials Processing			
Bamboo		kg	4.9
Water (Remove the impurities)	4.9 kg of bamboo	L kg m^3	9.8 L/kg; 0.0098 m^3
Electricity (Crushing)	4.9 kg of bamboo	KWh	0.2
Electricity (Drying)	Dryer capacity: 200 kg per batch Power: 4 kW Drying temperature: 70 °C Drying time: 24 hours Bamboo load (for this case): 4.9 kg	KWh	2.35
Carbonization			
Electricity (Furnace)	Furnace capacity: 150 kg per batch Power: 15 kW Heating rate: 5 °C/min Holding temperature: hidden Holding time: 1 hour	KWh	1.26 kWh
Packaging Process			
Sealable polyethylene pouches	Assume for 1 kg packaging	g	20
Electricity (Packaging Machine)	Machine power: 15 kW Operating time per package: 4 seconds Product: 1 kg bamboo biochar per package	kwh	0.016

TABLE 2
LCA RESULTS FOR THE 1 KG OF BAMBOO BIOCHAR

Environmental Impact	**Unit**	**Transportation to Manufacturing Plant**	**Raw Materials Processing**	**Carbonization**	**Packaging Process**	***Total***
Acidification	mol H+ eq	0.000471928	0.007001	0.002981124	0.0001666	*0.01062073*
Climate change	kg CO2 eq	0.184613998	3.4598953	1.356728421	0.0651611	*5.06639878*
Ecotoxicity, freshwater	CTUe	0.139063643	0.3398907	0.013249563	0.0022834	*0.49448721*
Eutrophication, freshwater	kg P eq	1.54133E-06	3.511E-07	1.26413E-08	2.191E-10	*1.9053E-06*
Human toxicity, cancer	CTUh	1.79727E-11	3.225E-11	1.33998E-12	8.6E-13	*5.2425E-11*
Human toxicity, non-cancer	CTUh	1.97215E-09	4.476E-09	1.79072E-10	9.938E-12	*6.637E-09*
Land use	Pt	0.846435681	1.9752807	0.070839526	0.0012148	*2.89377065*
Ozone depletion	kg CFC11 eq	5.5838E-11	1.008E-10	1.33572E-11	7.97E-12	*1.7799E-10*
Particulate matter	disease inc.	3.38822E-09	1.145E-07	5.30455E-08	5.959E-09	*1.769E-07*
Photochemical ozone formation	kg NMVOC eq	0.00037651	0.0043044	0.001881166	8.916E-05	*0.0066512*
Resource use, fossils	MJ	2.633720889	39.82925	14.92289379	1.2738101	*58.6596744*
Resource use, minerals and metals	kg Sb eq	2.17551E-08	1.275E-08	4.8514E-10	3.202E-10	*3.5311E-08*
Water use	m3 depriv.	0.000499002	1.013E-05	3.64808E-07	4.632E-09	*0.00050951*

Fig.3 shows the percentage contribution of each life cycle stage—namely transportation to manufacturing plant, raw materials processing, carbonization, and packaging process—to various environmental impact categories. The results are based on midpoint indicators following the ReCiPe methodology.

Overall, the raw materials processing stage was identified as the primary contributor across most impact categories, including acidification (65.92%), climate change (68.29%), ecotoxicity, freshwater (68.74%), human toxicity, cancer (61.52%), and non-cancer effects (67.44%). This is mainly attributed to the intensive energy and material consumption during the pretreatment and mechanical processing of bamboo.

The transportation to manufacturing plant stage also contributed noticeably, particularly to eutrophication, freshwater (80.90%), land use (29.50%), and ozone depletion (31.37%), reflecting the environmental burden associated with fuel combustion and logistics. In contrast, the Carbonization process showed a moderate contribution ranging between 2% and 28% across most categories, mainly due to thermal energy consumption and gaseous emissions during pyrolysis. The packaging process contributed the least (<5% in most categories), indicating minimal environmental load compared to other life cycle stages.

For resource-related categories, the raw materials processing again dominated, contributing 67.98% to resource use, fossils and 36.11% to resource use, minerals and metals. A similar pattern is observed for water use, where transportation accounted for 97.94%, primarily due to upstream water consumption linked to fuel production and supply chains. In summary, the analysis indicates that raw materials processing and transportation are the most environmentally demanding stages in the bamboo biochar production chain.

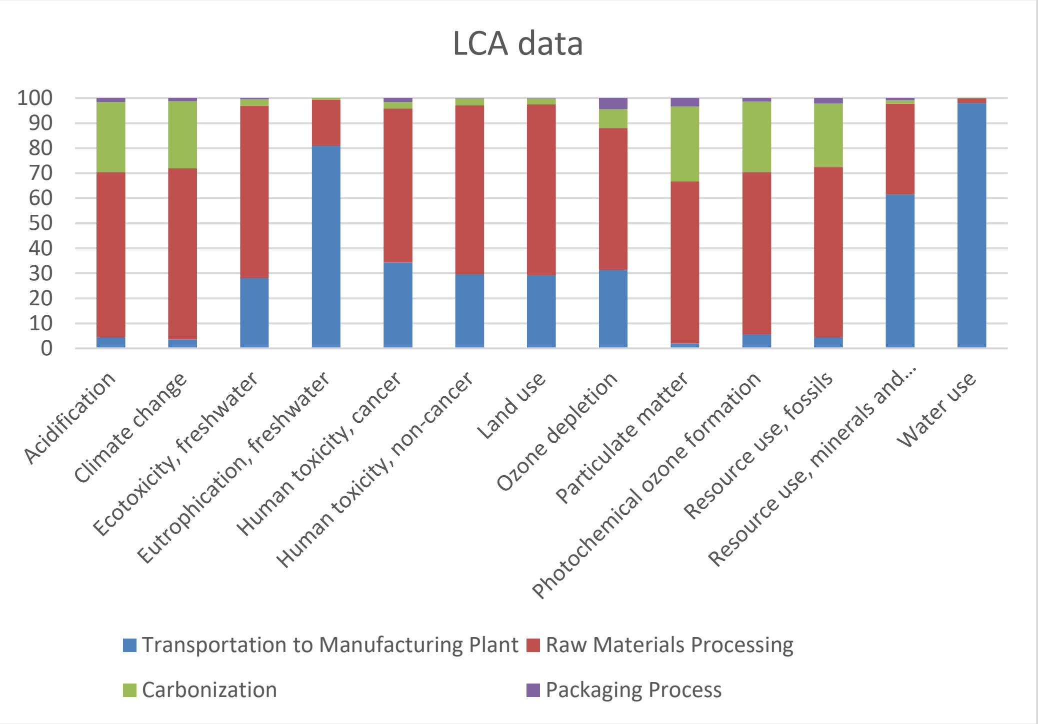

Fig. 3: System boundary framework of 1 kg bamboo biochar.

D. *Suggestion for Sustainable Practice*

Figures From the life cycle assessment results, raw material processing and transportation to the manufacturing plant were identified as the main contributors to the overall environmental impacts of bamboo biochar production. The significant impact during the raw material processing stage is primarily attributed to the energy-intensive drying process, which requires approximately 24 hours of continuous operation. This prolonged drying duration leads to substantial electricity and fuel consumption, particularly when conventional heat sources are used.

To address this issue, one sustainable solution is to adopt natural drying methods—such as air drying or sun drying—which utilize ambient conditions and renewable solar energy to remove moisture. These methods can significantly reduce energy demand and carbon emissions. However, natural drying also has limitations: it is highly weather-dependent, takes longer to complete, and may result in inconsistent moisture content due to fluctuations in atmospheric humidity. Therefore, it may not be ideal for large-scale or continuous production, where consistent quality and process control are essential.

To achieve a balance between production efficiency and sustainability, hybrid drying systems that combine solar pre-drying with low-energy mechanical drying can be employed. This approach shortens drying time while lowering energy consumption. Additionally, optimizing air flow, batching, and temperature can further enhance drying efficiency.

During the transportation phase, environmental impacts can be reduced by optimizing logistics routes, employing low-emission vehicles, and sourcing bamboo from nearby plantations to minimize fuel use. In the carbonization process, the regeneration of waste heat for pre-drying and the implementation of emission control systems can further mitigate environmental burdens. Although the packaging stage contributes relatively little to the total impact, it can be improved through the use of biodegradable or recyclable materials.

Overall, the adoption of renewable energy sources, hybrid drying technologies, and efficient logistics management are effective strategies to enhance the sustainability of bamboo biochar production. Further improvements can be achieved through circular resource utilization, such as recycling bamboo residues and valorizing carbonization by-products, thereby minimizing the overall life cycle environmental impacts.

CONCLUSION

This study assessed the environmental performance of the production of bamboo biochar according to a life cycle assessment. It was determined that the greatest environmental effect came from the raw materials processing phase owing mainly to the 24-hour energy-intensive drying process. The transportation phase also contributed significantly due to fuel usage and emissions. In contrast, the carbonization and packaging phases had relatively lower effects. To make it more sustainable, natural or solar drying can reduce energy consumption, though they are weather-dependent and slower in drying. A combined system for solar and mechanical drying is a more balanced solution. Additionally, the use of renewable energy, efficient transport logistics, and biodegradable packaging materials can also reduce the environmental footprint. Generally, improving the energy efficiency and adopting cleaner production measures are paramount to making the production of bamboo biochar more sustainable.

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