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Assessing environmental impact and eco-efficiency of wood waste gallon holders using life cycle assessment

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ABSTRACT

The wooden furniture industry has become one of the most prominent sectors in recent years. Over the past five years, Indonesia's furniture export performance has increased by 77.9%. Despite this growth, the industry often overlooks the significant amount of wood waste it generates, which can contribute to environmental issues. Reusing wood waste offers an environmentally friendly solution, including repurposing it to produce gallon holders as part of recycling and waste reduction efforts. This study evaluates the environmental impact and eco-efficiency of gallon holder products made from wood waste using the life cycle assessment (LCA) method with SimaPro software. A comparative analysis was conducted between gallon holders made from wood waste and those made from virgin wood to identify the option with better eco-cost value. The findings revealed that products utilizing wood waste as raw material have a superior eco-cost value of IDR 171,586.523. Based on these results, two recommendations are proposed: adopting solar panels as an alternative energy source to replace conventional electricity and using biovarnish paint as a more sustainable alternative to conventional varnish.

Keywords: eco-efficiency, environmental impact, life cycle assessment, waste product, wood waste.

INTRODUCTION

The manufacturing industry now involves using amounts of raw materials, energy, and water consumption, one of which is the wooden furniture industry. As a result of this manufacturing process, large quantities of waste are often disposed of into the environment (Ahmad et al., 2019). The wooden furniture industry transforms processed wood into finished products with added value and more significant benefits. In Indonesia, the wooden furniture industry has developed rapidly, especially in major cities such as Jakarta, Semarang, Solo, Cirebon, Surabaya, Jepara, and Yogyakarta. This is due to the significant and sustainable profits this industry offers (Prabowo and Suhariyanto, 2021).

The production of wooden furniture in Indonesia is growing rapidly. The forestry sector has entered a new era since the enactment of the Job Creation Law (UUCK) No. 11 of 2020, Government Regulation No. 23 of 2021 concerning Forestry Management, and Ministry of Environment and Forestry Regulation No. 8 of 2021 regarding Forest Planning, Forest Management Plan Preparation, and Forest Utilization in Protected Forests and Production Forests. By incorporating the multi-business concept into a single business license, these regulations provide a strong policy framework that facilitates the utilization of forest production outputs for businesses. An increase in the production of raw wood and processed wood, as well as the export value of products from the forestry sector, supports this. In 2022, it was recorded that Indonesia had a production forest area covering 67.23 million hectares (Ministry of Environment and Forestry of the Republic of Indonesia, 2022). This opens up opportunities for the growth of the wood processing industry in Indonesia. One region that has seen an increase in the wood processing industry and micro-enterprises is Semarang.

Building this business requires a large number of raw materials and capital. The increase in business players in the wood processing sector in Semarang City proves that wood products, which were initially considered a secondary need, have now become a primary need (Cahyono and Ali, 2023). The rise in business players in the wood processing sector also demonstrates that the demand for wood products from forest resources increases yearly. This idea is further supported by the Coordinating Ministry for Economic Affairs of the Republic of Indonesia, which stated that the export performance of Indonesia's furniture industry has continued to increase over the last 5 years by up to 77.9%. In 2021, furniture export value reached USD 2.8 billion, an increase of 33% from 2020. Meanwhile, in 2022, wood and rattan furniture exports are projected to remain stable at around USD 2.9 billion (Coordinating Ministry for Economic Affairs of the Republic of Indonesia, 2023).

According to the data, the furniture industry experienced a growth of 8.16% in the gross domestic product (GDP) at constant prices (ADHK) amounting to IDR 29.39 trillion in 2021. The Minister of Industry, Agus Gumiwang Kartasasmita, stated that the growth of the furniture industry was driven by a major shift or reorganization in household spending. The demand for furniture also increased in line with the significant development and renovation of hotels (DataIndonesia.id, 2022).

The increasing demand for furniture year after year has resulted in growing industrial waste. This has led to restrictions on wood usage, which have eventually forced business owners to think creatively and seek alternatives, one of which is utilizing the available waste. By using waste, the economic value of the waste itself can be indirectly increased. Wood waste, which was previously considered trash, can become a source of income by being repurposed into valuable products with high economic value. Moreover, the utilization of waste can provide ecological benefits by reducing the amount of waste generated by the industry.

The object of focus in this research is a gallon holder made from processed wooden board waste. This product is an innovative development within a series of gallon holder products, engineered to function as storage for gallons with both manual and electric pumps, and made using recycled wood waste as the main material. This product has a high level of interest and can be made from wood waste due to its small dimensions (Sari et al., 2024). It is indeed made from recycled wood waste, and its use helps reduce waste production, thereby contributing to better waste management solutions. However, it is essential to measure the environmental impact of processing this waste to ensure that the steps taken truly support sustainability (Ingrao et al., 2021). Without measurable assessments, there remains a risk of undetected negative environmental impacts, such as carbon emissions or waste generated during the process (Terlouw et al., 2021). Moreover, measuring the environmental impact is necessary to determine whether using this waste produces lower emissions compared to using natural raw materials (Shahbazi et al., 2023). Therefore, a method is needed to evaluate the environmental impact based on the product's life cycle, namely LCA.

LCA has been widely recognized in environmental management as a comprehensive approach to assessing the potential environmental impacts that may occur throughout the life cycle of a product. LCA allows for a thorough evaluation of various stages of production, from raw material extraction to the disposal of the final product, which is essential for understanding the environmental impact holistically (Villagran et al., 2024). Previous research has shown that LCA is effective in identifying critical stages in the production process that contribute to environmental degradation (Nurbaiti et al., 2021). Additionally, LCA provides a comprehensive understanding of the environmental impacts of materials and products, which is crucial for making sustainable decisions (Kareen et al., 2009).

Not only focuses on environmental impacts, but it is also important to evaluate the economic dimension of the product life cycle. By incorporating eco-efficiency strategies into LCA, the utilization of raw materials, water, and energy can be optimized, leading to both environmental and economic advantages (Dias-Sardinha et al., 2002). This integration of eco-efficiency within the LCA framework enables companies to reduce environmental impacts while maintaining cost competitiveness, which is a key factor in the long-term success of sustainable business practices (Ijaz et al., 2024). Therefore, LCA is essential for assessing product sustainability, as it provides a comprehensive view of the product's life cycle impacts and supports decision-making aimed at reducing ecological footprints and resource consumption (Moutik et al., 2023).

The choice of LCA in this study is particularly appropriate for evaluating the production of gallon holders made from wood waste. LCA provides a clear picture of how using recycled wood waste can reduce environmental impacts compared to using raw wood, which requires more intensive logging and processing (Elginoz et al., 2024). The research indicates that LCA is a useful tool for pinpointing which stages of production contribute most to environmental harm. Additionally, it provides a comprehensive view of the environmental impacts throughout the entire life cycle of a product, from raw material extraction to end-of-life disposal (Nurbaiti et al., 2021). By comparing the use of wood waste to raw wood, this research aims to evaluate whether using wood waste is more environmentally friendly, both in terms of reducing carbon emissions, saving energy, and conserving natural resources (Pinho and Calmon, 2023). This study also helps to identify the sustainability potential of the wood recycling industry and demonstrates the ecological and economic benefits of using wood waste in the production of consumer products (Sari et al., 2024).

MATERIALS AND METHODS

This research aims to collect the necessary information as a basis for the next step, which is data processing, to achieve the research objectives. This study utilizes both primary and secondary data. Primary data collection is conducted through interviews with a wooden furniture SME in Semarang. The number of respondents used for the representative sampling was 3 individuals, all of whom are carpenters who meet the criteria of having worked in the wood furniture SME for at least 5 years.

Boundaries system

This study has several boundaries system. The boundaries system focuses on gallon holders made from wood waste. The LCA is conducted using the SimaPro software with the Eco-cost method, with the scope limited to gate-to-gate, covering only the stages from production to the product leaving the manufacturing facility. In this study, the proposed improvements are limited to calculating recommendations without direct implementation of those recommendations. The product used in this study is a gallon holders designed based on the results of design research in previous studies (Sari et al., 2024). The applied boundaries system help limit the scope of analysis and focus on specific stages of the product life cycle, making the research outcomes more targeted and specific (Li et al., 2014).

Data collection

The data collection process is carried out by identifying and gathering the necessary data for the research. Primary data is obtained through interviews with a small business in Semarang to gather information about the waste generated from their production processes. Meanwhile, secondary data includes information related to materials, energy, processes, as well as details on production costs, material costs, and the selling prices of the products produced. In the LCA method, the weight of raw material waste is used as the baseline to calculate the expected outcomes. The cost-benefit analysis (CBA) method, on the other hand, is used to evaluate the benefits of implementing wood waste recycling practices. The data required for this method includes material and energy costs, production costs, and the selling price of the products. The method used refers to the ISO 14040:2006 standard with a LCA approach, through several stages: goal and scope definition, inventory analysis, impact assessment, and recommendation interpretation. Primary data is analyzed using the Simapro 9.5.0.2 software, while secondary data is obtained from literature studies. Figure 1 shows the framework in the life cycle assessment (Negishi, 2019).

Based on ISO 14040:2006, LCA serves as an esential tool for applying the principles of sustainability and assesing the environmental impacts linked to a product (Sari et al., 2024). LCA is defined as a quantitative measure of sustainability, often represented through graphs or diagrams (Herrmann and Moltesen, 2015). The LCA method is graphically represented, making it easier to identify areas that contribute to adverse environmental impacts and to develop effective recommendations for minimizing these effects (Iswara et al., 2020).

Goal and scope is the initial phase in the LCA method. This stage aims to define the objectives and scope of the research, the background of the study, the boundaries of the research, the research methods, the types of impacts involved, and other relevant details (Moutik et al., 2023). The study establishes one unit of a gallon holder made from 66 kg of wood waste, converted into boards with a standard dimension of 0.060 m^3, as the functional unit. This functional unit serves as the basis for calculating environmental impacts and analyzing eco-efficiency. All stages of the product's life cycle, from raw material procurement and production processes to the product's departure from

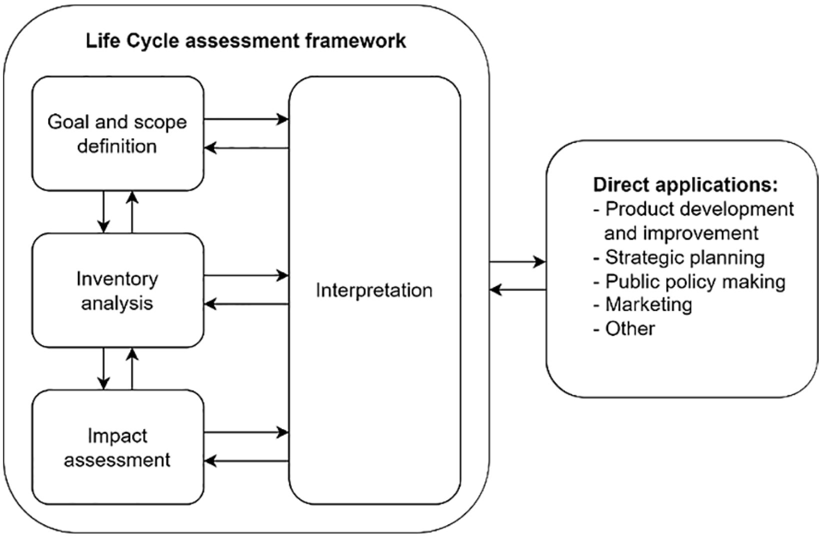

Figure 1. Framework LCA stage

the manufacturing facility, are evaluated based on this unit. This approach allows for a more focused analysis, enabling comparisons of environmental impact and eco-efficiency with similar products made from different raw materials.(Zieminska-Stolarska et al., 2022) This study aims to assess the environmental impact resulting from the use of wood waste as raw material. To support this research, the environmental impact is also compared with that of using raw wood as a material (Pitti et al., 2020).

Life cycle inventory is the second stage in the LCA method. LCI specifically identifies the inputs and outputs at each stage of the production process (Cucurachi et al., 2019). Inputs include raw materials and energy resources, while outputs encompass the main products, by-products, emissions, and waste. Once the identification of inputs, processes, and outputs is completed, it is followed by quantitative calculations (Dianawati et al., 2023). In this study, equipment depreciation costs are also included as a significant component in the product life cycle cost analysis. Depreciation is calculated based on the economic lifespan of the equipment used during the production process of gallon holders made from wood waste (Rieckhof and Guenther, 2018). This approach is essential to provide a more comprehensive overview of environmental impacts and eco-efficiency, as depreciation costs reflect the contribution of resource usage to the overall product life cycle. For example, the sanding machine used has a specific initial value and an estimated economic lifespan of 5 years, with a daily usage of approximately 8 hours. Assuming a straight-line depreciation method, the hourly depreciation cost is calculated for each production stage. This data is then input into the SimaPro software to analyze the contribution of depreciation costs to environmental impacts, particularly in the context of energy and resource utilization. Table 1 shows the types of inputs used in the study (Wu et al., 2023).

LCIA is the third stage in LCA. LCIA aims to evaluate environmental impacts by linking LCI information to specific environmental impact categories and indicators (Negishi, 2019). According to ISO 14040 standards, LCIA consists of five stages: classification, characterization, normalization, weighting, and single score (Hauschild and Huijbregts, 2015). The first phase is classification and characterization. Classification aims to categorize inputs and outputs into specific groups, such as resource consumption. Meanwhile, characterization is used to represent and assess the materials involved in each impact category. After classification and characterization, the process known as normalization is carried out. Normalization is the result of multiplying the normalized values by the characterization values, which allows for the comparison of the impact categories generated. The third phase is weighting. The weighting values are obtained by multiplying the impact category by its corresponding weighting factor, which is then summed to produce a total value. Weighting aims to assign relative importance to the various categories, reflecting their relative significance in the overall assessment. The final phase is single score. The purpose of

Table 1. Research variables

Unit process	Input	Unit	Output
LCA	Weight of wood material	kg	The environmental impact value generated and the environmental cost
	Amount of electrical energy	Kwh	
	Type and amount of waste	kg	
	Weight of supporting raw materials	kg	
Cost benefit analysis	Raw material cost	IDR	Net value
	Electricity cost	IDR	
	Labor cost	IDR	
	Equipment depreciation cost	IDR	
	Product selling price	IDR	
Eco-effciency index	Net value of product	IDR	Information on product affordability and sustainability
	Eco-cost	IDR	
Eco-cost/value ratio	Net value of product	IDR	EVR Value
	Eco-cost	IDR	
Eco-efficiency ratio rate	EVR Value	-	Product eco-efficiency level

single score is to classify the impact categories of activities so that it is possible to identify which activities contribute to environmental impacts.

Eco-efficiency measurement

Eco-efficiency was introduced by WBCSD in 1992 as a method to assess organizational performance by considering two main aspects: a) economic welfare and b) resource use efficiency. Several authors have conducted in-depth environmental evaluations in eco-efficiency analysis. The concept of eco-efficiency can be applied for this purpose as it allows the identification of a balance between the environmental impact of a product and its economic value. This information can be used in decision-making process to choose more sustainable options (Chancharoonpong et al., 2021). The process for calculating eco-efficiency is outlined in Figure 2.

The calculation of efficiency begins with the cost-benefit analysis (CBA), which is a method used to determine the net value of a product. This analysis helps assess the benefits derived from the product in comparison to the costs incurred during its production and implementation. Therefore, the net value is influenced by the production cost and the product's sales (O'Mahony, 2021). CBA is used to determine whether the product is feasible to be marketed or not. The net value calculation can be done using Equation 1 (Purwaningsih et al., 2020).

$$Net\ value = selling\ price - production\ cost \quad (1)$$

The Net Value is used in the calculation of EEI to assess whether the product meets the standards of ecological efficiency (sustainability) and economic efficiency (profitability) (Purwaningsih et

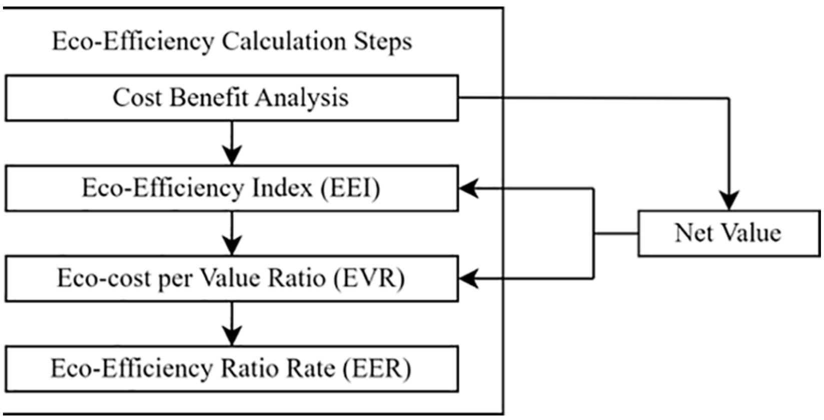

Figure 2. Eco-efficiency calculation steps

al., 2021). The Eco Efficiency Index value is obtained from Equation 2 (Purwaningsih et al., 2020).

$$EEI = \frac{Net\ value}{Eco\ cost} \quad (2)$$

If the EEI value of a product is > 1, the product can be considered affordable and sustainable. Conversely, the product is affordable but unsustainable if the EEI value is 0 to 1. If the EEI value of the product is < 0, the product is considered neither affordable nor sustainable (Vogtländer et al., 2001).

The eco-costs value ratio (EVR) is a parameter that compares the environmental costs in the production process of a product, which reflects its ecological value, with the net value of the product, which reflects its economic aspect (Purwaningsih et al., 2021). The EVR calculation is obtained by dividing the ecological cost value by the net value. The input consists of the eco-cost figure and the net value of the product. The output of this calculation is the EVR value of the product, which shows the ratio of eco-cost to the product's net value. The EVR is obtained from Equation 3 (Vogtländer et al., 2001).

$$EVR = \frac{Eco\ cost}{Net\ value} \quad (3)$$

The eco efficiency ratio (EER) is a measure of the percentage of environmental performance efficiency in the production process. The EER value is obtained by subtracting the Eco-cost value, derived from the production process, from the net value. In other words, the EER rate calculation is done by subtracting the EVR value obtained from the previous calculation from the number 1. The EER value is obtained from Equation 4 (Purwaningsih et al., 2021).

$$EER = (1 - EVR) \times 100\% \quad (4)$$

SimaPro software

SimaPro has been on the market for more than two decades. PRE consultants, who focus on LCA, have recognized and developed SimaPro to collect, assess, and monitor the environmental impact of the use of goods and services. The complex, organized, and clear LCA analysis, conducted in accordance with the ISO 14040 series, makes SimaPro easy to operate. In this data processing, users utilize SimaPro version 9.5.0.2. This version of SimaPro offers enhanced performance and reliability, making it an excellent choice for comprehensive LCA analysis. Users must also thoroughly examine the LCA cycle for each stage, including materials, procedures, transportation, recycling, disposal, reuse, the life cycle network and environmental impact. Users can insert processes or input materials into the database and use them in the application. When users add new parameters or elements, SimaPro 9.5.0.2 also supports the function of these equations. With this feature, the software becomes more flexible and efficient. Additionally, SimaPro 9.5.0.2 presents results more transparently and accurately (Herrmann and Moltesen, 2015).

RESULT AND DISCUSSION

Life cycle inventory (LCI)

The results of the LCI for gallon holders made from wood waste indicate that the use of raw materials from wood waste has a positive impact on the environment. Wood waste as the primary material helps reduce the logging of new trees and uses leftover wood from the wood industry that would otherwise be discarded (Alanya-Rosenbaum et al., 2022). The amount of wood waste generated by the wooden furniture SME in Semarang reached 66 kg. Wood waste produced in the furniture industry can originate from various stages of production, such as cutting, smoothing, or processing other materials. Efficient management of this waste is crucial, considering its environmental impact and potential for reuse, such as for fuel or other processed products. Therefore, monitoring and reducing the amount of wood waste can help enhance the sustainability of the furniture industry and reduce the environmental footprint it generates (de Souza Pinho et al., 2023). In terms of energy, the production process of this gallon holder requires less energy compared to similar products made from new raw materials, as there is no significant raw material extraction process involved (Pinho and Calmon, 2023). However, processing wood waste into ready-to-use products still requires energy, such as electricity and fuel for sawing and shaping (Alanya-Rosenbaum et al., 2022). Overall, this product has a lower carbon footprint compared to products made from conventional raw materials, providing a more environmentally friendly solution for gallon holder needs.

This is because the production of wood-based materials generates significantly lower carbon emissions compared to processes involving materials such as concrete and steel, which are known to have a high carbon footprint. In addition, the use of waste wood in the production of this product not only reduces waste but also utilizes renewable resources, thereby helping to improve atmospheric carbon balance. This approach supports the principles of sustainability, where processed wood materials can replace the use of more environmentally harmful materials, resulting in products with a smaller environmental impact (Alanya-Rosenbaum et al., 2022). Table 2 shows the life cycle inventory results of the gallon holder product made from wood waste.

Life cycle impact assessment (LCIA)

The characterization stage aims to identify and group factors that have the potential to impact the environment. The calculation of impact categories is conducted using SimaPro software. Table 3 shows a recap of the impact characterization values at each stage of the gallon holder production process using SimaPro software. A single score is a method aimed at classifying impact category values based on activities or processes. The single score calculation value is obtained from the weighting of each process (Purwaningsih et al., 2020). The initial single score value, which was in euros, will be converted into Indonesian rupiah based on the exchange rate of April 24, 2024, amounting to IDR 17,353.08 for 1 euro. The total single score from the production process is €9.888, which is equivalent to IDR 171,586.523. The recap of the single

Table 2. Life cycle inventory activities

Unit Process	Input/Output	Unit	Amount
Cutting	Input		
	Wood material weight	kg	66
	Amount of electrical energy	kWh	0.875
	Output		
	Wood pieces	kg	55.028
	Wood chips (NPO)	kg	8.557788
	Saw dust (NPO)	kg	2.139447
	Dust particle emission	kg	0.0004375
	Noise	dB	85
Sanding	Input		
	Wood pieces	kg	55.3028
	Amount of electrical energy	kWh	0.3375
	Output		
	Sanded wood pieces	kg	52.6693
	Saw dust (NPO)	kg	2.633465
	Dust particle emission	kg	00002765
	Noise	dB	25.31
Wood painting	Input		
	Sanded wood pieces	kg	52.6693
	Varnish paint	kg	3
	Output		
	Painted wood	kg	52.6693
Assembly	Input		
	Wood glue	kg	0.241
	Mini hinges	kg	0.005
	Key slot	kg	0.075
	Cator wheel	kg	0.8
	Nail	kg	0.0005
	Bolt & nut	kg	0.01
	Output		
	Finished product	kg	53.8008

Table 3. Recapitulation of gallon holder characterization output

Impact categories	Total	Cutting	Refinement	Painting	Assembly
Climate change	23.5304	1.1183	1.5543	10.3211	10.5367
Human toxicity	0.0223	0.0029	0.0040	0.0076	0.0078
Ecotocicity	0.0271	0.0038	0.0052	0.0089	0.0091
Resource scarcity	0.2347	0.0056	0.0078	0.1096	0.1117

score results processed using SimaPro software is shown in Table 4.

In the study that measures the environmental impacts and eco-efficiency of a gallon holder product made from wood waste using the LCA method, four main processes are analyzed: cutting, sanding, coloring, and assembly. Each process contributes to climate change, resource scarcity, ecotoxicity, and human toxicity. In the cutting process, the use of electric tools such as electric saws consume energy, which generates carbon emissions, especially if the energy source is derived from fossil fuels, contributing to the increase in greenhouse gas (GHG) emissions (Martínez-Alonso and Berdasco, 2015). This process also consumes wood materials, which can impact wood stock if raw materials are not sustainably managed. Furthermore, the wood dust produced during cutting can contaminate the environment and negatively affect human health if inhaled (Vallières et al., 2015). The refinement process requires a significant amount of electricity, which also contributes to GHG emissions. In addition, sanding generates wood dust residues that are often not reusable, thereby increasing waste, which impacts resource depletion. This wood dust can also cause air pollution, posing a health risk to workers, such as respiratory issues (Nylander and Dement, 1993). In the painting process, the use of chemicals in paints and solvents can generate volatile organic compound (VOC) emissions, which contribute to global warming (Ghobakhloo et al., 2023). Paints and solvents are typically petroleum-based, thus increasing dependence on non-renewable resources. Liquid waste from the coloring process can contaminate groundwater and the surrounding environment, while exposure to chemicals in the paint is harmful to worker health (Hassan et al., 2013). Finally, in the assembly process, the energy used is relatively lower compared to other processes but still generates emissions from the use of electric tools. This process also requires nails, glue, or other supplementary materials, all of which depend on natural resources. Some materials, such as adhesives or glues, may contain toxic compounds that pose environmental and health risks to workers (Littorin et al., 2000).

The calculation of raw material costs is done by multiplying the price per unit of raw materials by the amount of material used during the production process. The raw material costs were obtained by conducting a literature study of previous researchers and interviewing one of the SMEs in Semarang.

Labor costs refer to the amount of money paid by a company to employees for the work performed. Labor costs are measured by the number of workers or operators who are paid per production set. The labor cost incurred for making the gallon holder amounts to IDR 15,000, with 2 people involved in the production process.

In addition to raw material and labour costs, there are also overhead costs, including electricity costs and equipment depreciation costs. Electricity costs are calculated by multiplying the duration of machine use by the machine's power consumption (Pratista and Santoso, 2024). After that, the resulting power is multiplied by the flat electricity rate per kWh. The basic electricity tariff used in this study

Table 4. Recapitulation of gallon holder single score output

Impact categories	Unit	Total	Cutting	Refinement	Painting	Assembly
Climate change	Euro	5.058	0.254	0.353	2.204	2.247
Human toxicity	Euro	0.979	0.117	0.163	0.346	0.352
Ecotocicity	Euro	0.548	0.011	0.015	0.259	0.263
Resource scarcity	Euro	3.303	0.012	0.017	0.763	2.512

is IDR 1,447, resulting in a total electricity usage cost of IDR 1.754. The equipment depreciation cost used is IDR 684, with an economic lifespan of each piece of equipment being 5 years. The detailed cost breakdown can be seen in Table 5.

Eco-efficiency

Table 6 shows the eco-efficiency values that have been obtained. From the calculations in Table 6, an EEI value of 0.31 was obtained. This value falls between 0 and 1, indicating that the gallon holder product is affordable and not sustainable. The gallon holder product is categorized as affordable because wood waste is one of the materials that is easy to find (Amarasinghe et al., 2024). Wood waste is often available in abundance and at a low cost and can even be obtained for free (Maier, 2021). The gallon holder product is categorized as unsustainable because using wood waste as a raw material requires sustainable sourcing. Furthermore, the production process of gallon holders from wood waste can have negative environmental impacts if not conducted in an environmentally friendly manner (de Souza Pinho et al., 2023).

According to Table 6, the EVR value obtained for the gallon holder's production process is 1.852. This value indicates that the environmental costs incurred are still very high, which indicates that the gallon holder's production process is still inefficient from an environmental perspective. The high EVR value signifies that the economic benefits generated are not sufficient to offset the environmental damage that occurs (Li et al., 2024).

From the results in Table 7, an EER value of -0.82% was obtained. The unfavorable ratio indicates that the production process of the gallon holder still needs to be optimized in terms of both economics and the environment. This is due to the net value of the product being lower than the costs incurred to account for the environmental impact. The negative EER value can be triggered by several factors, such as high energy use or harmful

Table 6. Eco-efficiency index

Eco-efficiency	Value
EEI	0.31
EVR	1.825
EER	-0.82

Table 7. Comparison of eco-cost values

Raw material	Eco-cost value (Euro)	Eco-cost value (IDR)
Wood waste	9.888	171,586.523
Log wood	14.115	245,625.368

Table 5. Production cost

Type	Unit	Quantity	Price
A. Raw material cost			
Wood waste	m^3	0.066	IDR 3,874
Mini hinge	Pcs	5	IDR 45,000
Key slot	Pcs	1	IDR 12,500
Wood glue	Pcs	1	IDR 7,571
Caster wheel	Pcs	4	IDR 23,160
Varnish paint	Pcs	1	IDR 3,874
Nail	Gram	0.5	IDR 1,500
Screw & nut	Pcs	5	IDR 4,425
Total raw material cost			IDR 197,030
B. Labor cost			
Production	Person	2	IDR 30,000
Total labor cost			IDR 30,000
C. Overhead cost			
Electricity	kWh	1.2125	IDR 1,752
Depreciation of equipment			IDR 684
Total overhead cost			IDR 2,436
Total production cost			IDR 134,340

waste emissions (Wei et al., 2021). The low EER value indicates that the production process needs to be reviewed and improved to achieve better sustainability goals (De Simone et al., 2023).

Comparison of raw material usage

Using wood waste and primary wood (logs) to produce gallon holders demonstrates two different approaches to utilizing natural resources. The use of wood waste as raw material has the potential to reduce negative environmental impacts by recycling discarded waste and making use of existing resources (Kiesnere et al., 2024). Additionally, the utilization of wood waste also plays a role in reducing pressure on forests and their ecosystems (Amarasinghe et al., 2024). Table 7 shows a comparison of eco-cost values between the use of wood waste raw materials and logs.

Based on the eco-cost calculations for both materials, it was found that the eco-cost value generated by using log wood is greater than that of using wood waste. The value generated from using log wood is €14.115, equivalent to IDR 245,625.368. In contrast, the value generated from wood waste is €9.888, equal to IDR 171,586.523. This indicates that the environmental costs incurred by using wood waste as raw material for product manufacturing are more efficient.

Based on the calculation of eco-efficiency values using eco-cost values, it was found that the eco-efficiency value generated by using log wood tends to be less favorable than comparable wood waste. The EEI generated using log wood is 0.40, while the EEI generated from wood waste is 0.31. The EVR generated using log wood is 2.612, whereas the EVR generated from wood waste is 1.825. The EER produced using log wood is -1.61, while the EER generated from wood waste is -0.82.

Several factors may contribute to the lower eco-efficiency value of using log wood compared to using wood waste. The processing of log wood requires more energy, starting from logging, and transportation, to processing into finished products. Additionally, using log wood has negative environmental impacts due to tree logging, contributing to deforestation and loss of natural habitats (Amarasinghe et al., 2024b). On the other hand, using waste materials to make water jug holders utilize existing resources, reduces the volume of waste that needs to be disposed of, and lowers the demand for new materials (Reis et al., 2023). Thus, this process is more energy-efficient and environmentally friendly as it reduces carbon emissions and the consumption of new natural resources. Using waste as raw material also alleviates pressure on limited natural resources, making it a more environmentally sustainable choice (Bocken et al., 2016). Therefore, EEI, EVR, and EER values in producing water jug holders from log wood tend to be lower compared to using waste materials.

Based on the price comparison of water jug holders made from wood waste versus those made from solid wood, it was found that the price of water jug holders made from wood waste is cheaper than those made from solid wood (Kües, 2007). Water jug holders made from wood waste have a selling price of IDR 228,377, while the price for those made from solid wood is IDR 269,100. Additionally, the prices for solid wood water jug holders on the same e-commerce platform were IDR 964,500 and IDR 890,000. Thus, it can be concluded that water jug holders made from wood waste have a more economical selling price.

Improvement recommendations

The proposed improvement recommendation is using solar panels as an alternative to replace electrical energy. This recommendation aims to determine appropriate corrective actions in the production process. Utilizing solar panels as an alternative energy source can reduce both environmental impact and operational costs in production (Tan et al., 2023). Solar panels enable energy production without generating greenhouse gas emissions and do not pollute the surrounding air (Fthenakis and Kim, 2011). Although the initial investment for installing solar panels is higher, business operators can save on operational costs because solar panels can directly harness solar energy for free and can be used in the long term (Peng et al., 2013). The eco-cost value generated after using the improvement recommendation is €7.909 (Table 8), equivalent to IDR 137,245.51. Table 8 shows the comparative values of the impact of electricity and solar energy usage using SimaPro software.

Table 8. Comparison of energy source impact values

Impact category	Electric energy value (Euro)	Solar power value (Euro)
Climate change	5.058	3.776
Human toxicity	0.979	0.372
Ecotocicity	0.548	0.492
Resource scarcity	3.303	3.269

The second recommended improvement proposed is using bio-varnish paint as an alternative to varnish paint. Utilizing biovarnish paint as a substitute for varnish paint can be a better step toward enhancing environmental sustainability and producing more eco-friendly products (Savov et al., 2023). Bio-varnish paint is typically made from natural or environmentally friendly materials, reducing negative impacts compared to varnish paint, which may contain harmful chemical compounds (Teacă et al., 2019). Bio-varnish paint can provide the same level of protection as conventional varnish paint, making it a viable alternative (Kaygin and Akgun, 2008).

CONCLUSIONS

Based on the calculations in this study, the impact category with the highest Eco-cost value is the assembly of the gallon holder, amounting to IDR 93,246.949. The environmental impact category with the highest score is climate change, valued at IDR 87,870.38. The second-highest environmental impact category is resource scarcity, valued at IDR 57,322.68. The third-highest environmental impact category is human toxicity, valued at IDR16,980.46. Meanwhile, the environmental impact category with the lowest single score is ecotoxicity, valued at IDR 9,503. The net value obtained from the eco-efficiency calculations is IDR 94,038. This value is then used to calculate the EEI of the product. The EEI value generated from the production process is 0.31. Since this value falls between 0 and 1, the gallon holder product is categorized as affordable but not sustainable. The EER generated from this production is -0.82%. This value indicates that the production process of the gallon holder is still not optimal in terms of economic and environmental aspects. Recommended improvements that can be proposed to reduce potential environmental impacts from both economic and environmental perspectives include the application of solar panels as an alternative energy source and the use of bio-varnish paint as an alternative to varnish paint.

Based on the calculations in this study, the impact category with the highest Eco-cost value is the assembly of the gallon holder, amounting to IDR 93,246.949. The category with the highest single score for environmental impact is climate change, valued at IDR 87,870.38. The second-highest environmental impact category is resource scarcity, valued at IDR 57,322.68. The third-highest environmental impact category is human toxicity, valued at IDR 16,980.46. Meanwhile, the category with the lowest single score for environmental impact is ecotoxicity, valued at IDR 9,503. The net value obtained from the eco-efficiency calculations is IDR 94,038. This value is then used to calculate the product's EEI. The EEI value generated from the production process is 0.31. Since this value falls between 0 and 1, the gallon holder product is categorized as affordable but needs to be more sustainable. The EER generated from this production is -0.82%. This value indicates that the production process of the gallon holder still needs to be optimal in terms of economic and environmental aspects. The two most significant environmental impacts identified in this study are GHG emissions from energy consumption in the cutting and sanding processes, and the release of volatile organic compounds (VOCs) and chemical waste during the coloring process. The cutting and sanding processes contribute to GHG emissions due to the high energy usage of electric tools and equipment, as well as resource depletion from excessive wood dust waste. Meanwhile, the coloring process generates VOCs and hazardous chemical waste, leading to air pollution and potential contamination of water sources, while also increasing reliance on non-renewable petroleum-based materials. Both of these impacts pose substantial risks to both the environment and human health. Recommended improvements that can be proposed to reduce potential environmental impacts from both economic and environmental perspectives include applying solar panels as an alternative energy source and using bio-varnish paint as an alternative to varnish paint. For future research, it can be developed for marker acceptance analysis of the gallon holder design results and for developing wood waste for other products in small dimensions.

REFERENCES

1. Ahmad, S., Wong, K. Y., & Ahmad, R. (2019). Life cycle assessment for food production and manufacturing: Recent trends, global applications and future prospects. Procedia Manufacturing, 34, 49–57. https://doi.org/10.1016/j.promfg.2019.06.113
2. Alanya-Rosenbaum, S., Bergman, R., Gething, B., & Mousavi-Avval, S. H. (2022). Life cycle assessment of the wood pallet repair and remanufacturing sector

in the United States. Biofuels, Bioproducts and Biorefining, 16(5), 1342–1352. https://doi.org/10.1002/bbb.2379

3. Amarasinghe, I. T., Qian, Y., Gunawardena, T., Mendis, P., & Belleville, B. (2024a). Composite panels from wood waste: A detailed review of processes, standards, and applications. Journal of Composites Science 8,(10). https://doi.org/10.3390/jcs8100417
4. Amarasinghe, I. T., Qian, Y., Gunawardena, T., Mendis, P., & Belleville, B. (2024b). Composite Panels from Wood Waste: A Detailed Review of Processes, Standards, and Applications. Journal of Composites Science 8,(10). https://doi.org/10.3390/jcs8100417
5. Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124
6. Cahyono, A., & Nusron Ali, M. (2023). Overview of the Production Process Layout Through the Technology Group at PT. Kayu Mebel Indonesia Semarang Attribution-Share Alike 4.0 International (CC BY-SA 4.0). Asian Journal of Social and Humanities, 1(8), 407. https://ajosh.org/
7. Chancharoonpong, P., Mungkung, R., & Gheewala, S. H. (2021). Life cycle assessment and eco-efficiency of high value-added riceberry rice products to support Thailand 4.0 policy decisions. Journal of Cleaner Production, 292. https://doi.org/10.1016/j.jclepro.2021.126061
8. Coordinating Ministry for Economic Affairs of the Republic of Indonesia. (2023). Improving Product Quality and Competitiveness, Government Targets Wider Export Market for Furniture Industry. https://www.ekon.go.id/publikasi/detail/5008/tingkatkan-kualitas-dan-daya-saing-produk-pemerintah-bidik-pasar-ekspor-industri-furnitur-makin-luas
9. Cucurachi, S., Scherer, L., Guinée, J., & Tukker, A. (2019). Life cycle assessment of food systems. in one earth 1(3), 292–297. Cell Press. https://doi.org/10.1016/j.oneear.2019.10.014
10. DataIndonesia.id. (2022). The Furniture Industry Grew by 8.16% in 2021. https://dataindonesia.id/industri-perdagangan/detail/industri-furnitur-tumbuh-816-pada-2021
11. De Simone, V., Di Pasquale, V., Nenni, M. E., & Miranda, S. (2023). sustainable production planning and control in manufacturing contexts: A bibliometric review. Sustainability (Switzerland), 15(18). https://doi.org/10.3390/su151813701
12. de Souza Pinho, G. C., Calmon, J. L., Medeiros, D. L., Vieira, D., & Bravo, A. (2023). Wood waste management from the furniture industry: The environmental performances of recycling, energy recovery, and landfill treatments. Sustainability, 15(20), 14944. https://doi.org/10.3390/su152014944
13. Dianawati, Indrasti, N. S., Ismayana, A., Yuliasi, I., & Djatna, T. (2023). Carbon footprint analysis of cocoa product indonesia using life cycle assessment methods. Journal of Ecological Engineering, 24(7), 187–197. https://doi.org/10.12911/22998993/164750
14. Dias-Sardinha, I., Reijnders, L., & Antunes, P. (2002). From environmental performance evaluation to eco-efficiency and sustainability balanced scorecards. Environmental Quality Management, 12(2), 51–64. https://doi.org/10.1002/tqem.10063
15. Elginoz, N., van Blokland, J., Safarian, S., Movahedisaveji, Z., Yadeta Wedajo, D., & Adamopoulos, S. (2024). Wood waste recycling in Sweden—Industrial, Environmental, Social, and Economic Challenges and Benefits. Sustainability (Switzerland), 16(14). https://doi.org/10.3390/su16145933
16. Fthenakis, V. M., & Kim, H. C. (2011). Photovoltaics: Life-cycle analyses. Solar Energy, 85(8), 1609–1628. https://doi.org/10.1016/j.solener.2009.10.002
17. Ghobakhloo, S., Khoshakhlagh, A. H., Morais, S., & Mazaheri Tehrani, A. (2023). Exposure to volatile organic compounds in paint production plants: Levels and potential human health risks. Toxics, 11(2). https://doi.org/10.3390/toxics11020111
18. Hassan, A. A. E. H., Elnagar, S. A. E. M., Tayeb, I. M. El, & Bolbol, S. A. E. H. (2013). Health hazards of solvents exposure among workers in paint industry. Open Journal of Safety Science and Technology, 3(4), 87–95. https://doi.org/10.4236/ojsst.2013.34011
19. Hauschild, M. Z., & Huijbregts, M. A. J. (2015). Ecotoxicity. Chapter 8 "Life Cycle Impact Assessment" (Hauschild MZ and Huijbregts MAJ eds). LCA Compendium - The Complete World of Life Cycle Assessment, Life Cycle Impact Assessment, 139–162. https://doi.org/10.1007/978-94-017-9744-3
20. Herrmann, I. T., & Moltesen, A. (2015). Does it matter which life cycle assessment (LCA) tool you choose? - A comparative assessment of SimaPro and GaBi. Journal of Cleaner Production, 86, 163–169. https://doi.org/10.1016/j.jclepro.2014.08.004
21. Ijaz, T., Qazalbash, A. H. R., Razzaq, A. A., Rafique, M. Z., Khan, M. A., & Jamshaid, S. H. (2024). Development of green manufacturing implementation framework based on life-cycle assessment. Sustainable Environment Research, 34(1). https://doi.org/10.1186/s42834-024-00229-7
22. Ingrao, C., Arcidiacono, C., Siracusa, V., Niero, M., & Traverso, M. (2021). Life cycle sustainability analysis of resource recovery from waste management systems in a circular economy perspective key findings from this special issue. Resources, 10(4). https://doi.org/10.3390/resources10040032
23. Iswara, A. P., Farahdiba, A. U., Nadhifatin, E. N., Pirade, F., Andhikaputra, G., Muflihah, I., & Boedisantoso, R. (2020). A Comparative Study of Life Cycle Impact Assessment using Different

Software Programs. IOP Conference Series: Earth and Environmental Science, 506(1). https://doi.org/10.1088/1755-1315/506/1/012002

24. Kaygin, B., & Akgun, E. (2008). Comparison of conventional varnishes with nanolacke UV varnish with respect to hardness and adhesion durability. Int. J. Mol. Sci, 9, 476–485. http://www.mdpi.org/ijms
25. Khasreen, M. M., Banfill, P. F. G., & Menzies, G. F. (2009). Life-cycle assessment and the environmental impact of buildings: A review. Sustainability, 1(3), 674–701. https://doi.org/10.3390/su1030674
26. Kiesnere, G., Atstaja, D., Cudecka-Purina, N., & Susniene, R. (2024). The Potential of Wood Construction Waste Circularity. Environments, 11(11), 231. https://doi.org/10.3390/environments11110231
27. Kües, U. (2007). Wood Production, Wood Technology, and Biotechnological Impacts. https://www.researchgate.net/publication/262179636
28. Li, T., Tian, W., Zhang, S., & Wang, S. (2024). Environmental regulation, high-quality economic development and ecological capital utilization. Frontiers in Environmental Science, 12. https://doi.org/10.3389/fenvs.2024.1325289
29. Li, T., Zhang, H., Liu, Z., Ke, Q., & Alting, L. (2014). A system boundary identification method for life cycle assessment. International Journal of Life Cycle Assessment, 19(3), 646–660. https://doi.org/10.1007/s11367-013-0654-5
30. Littorin, M., Rylander, L., Skarping, G., Dalene, M., Welinder, H., Strömberg, U., & Skerfving, S. (2000). Exposure biomarkers and risk from gluing and heating of polyurethane: a cross sectional study of respiratory symptoms. Occup Environ Med, 57.
31. Maier, D. (2021). Building materials made of wood waste a solution to achieve the sustainable development goals. Materials, 14(24). https://doi.org/10.3390/ma14247638
32. Martínez-Alonso, C., & Berdasco, L. (2015). Carbon footprint of sawn timber products of Castanea sativa Mill. in the north of Spain. Journal of Cleaner Production, 102, 127–135. https://doi.org/10.1016/j.jclepro.2015.05.004
33. Ministry of Environment and Forestry of the Republic of Indonesia. (2022). Potential for Surge in Forestry Multi-Enterprise Contributions to National Welfare. https://ppid.menlhk.go.id/berita/siaran-pers/6457/potensi-lonjakan-kontribusi-multiusaha-kehutanan-bagi-kesejahteraan-bangsa
34. Moutik, B., Summerscales, J., Graham-Jones, J., & Pemberton, R. (2023). Life Cycle Assessment Research Trends and Implications: A Bibliometric Analysis. Sustainability (Switzerland) 15(18). https://doi.org/10.3390/su151813408
35. Negishi, K. (2019). Development of a methodology of Dynamic LCA applied to the buildings.
36. Nurbaiti, G. A., Rachmanto, T. A., & Farahdiba, A. U. (2021). Cleaner production strategy as a supporting analysis of environmental impact on drinking water treatment process using life cycle assessment approach. 2021, 174–177. https://doi.org/10.11594/nstp.2021.1427
37. Nylander, L. A., & Dement, J. M. (1993). Carcinogenic effects of wood dust: Review and discussion. In American Journal of Industrial Medicine 24.
38. O'Mahony, T. (2021). Cost-Benefit Analysis and the environment: The time horizon is of the essence. Environmental Impact Assessment Review, 89. https://doi.org/10.1016/j.eiar.2021.106587
39. Peng, J., Lu, L., & Yang, H. (2013). Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renewable and Sustainable Energy Reviews, 19, 255–274. https://doi.org/10.1016/j.rser.2012.11.035
40. Pinho, G. C. de S., & Calmon, J. L. (2023). LCA of Wood waste management systems: Guiding proposal for the standardization of studies based on a critical review. Sustainability (Switzerland), 15(3). https://doi.org/10.3390/su15031854
41. Pitti, A. R., Espinoza, O., & Smith, R. (2020). The case for urban and reclaimed wood in the circular economy. BioResources, 15(3), 5226-5245.
42. Prabowo, E. D., & Suhariyanto, T. T. (2021). Implementation of life cycle assessment (LCA) and life cycle cost life (LCC) on particle board wood furniture industry in Yogyakarta. Opsi, 14(2), 271. https://doi.org/10.31315/opsi.v14i2.6089
43. Pratista, A. T., & Santoso, R. (2024). MSMEs product selling pricing strategy to increase profits using the cost plus pricing approach. International Journal of Economics, Business, and Accounting Research, 8. https://jurnal.stie-aas.ac.id/index.php/IJEBAR
44. Purwaningsih, R., Simanjuntak, C. F., & Rosyada, Z. F. (2020). Eco-efficiency ratio of pencil production using life cycle assessment for increasing the manufacture sustainability. Journal Teknik Industri, 22(1). https://doi.org/10.9744/jti.22.1.47-54
45. Purwaningsih, R., Susanto, N., Adiaksa, D. A., & Putri, A. A. A. (2021). Analysis of the eco-efficiency level in the dining table production process using life cycle assessment method to increase industry sustainability. IOP Conference Series: Materials Science and Engineering, 1072(1), 012014. https://doi.org/10.1088/1757-899x/1072/1/012014
46. Reis, W. F., Barreto, C. G., & Capelari, M. G. M. (2023). Circular Economy and Solid Waste Management: Connections from a Bibliometric Analysis. Sustainability (Switzerland), 15(22). https://doi.org/10.3390/su152215715
47. Rieckhof, R., & Guenther, E. (2018). Integrating life cycle assessment and material flow cost accounting

to account for resource productivity and economic-environmental performance. International Journal of Life Cycle Assessment, 23(7), 1491–1506. https://doi.org/10.1007/s11367-018-1447-7

48. Sari, D. P., Hartini, S., Azzahra, F., Arsiwi, P., & Prayoga, R. G. (2024). Modular-based multifunctional product design made from furniture waste toward the circular economy: Case in Indonesia. Management Systems in Production Engineering, 32(3), 303–316. https://doi.org/10.2478/mspe-2024-0029
49. Sari, D.P., Nugraeni, A R., Hartini, S., Azzahra, F., Wicaksono, P. A. (2024). Analysis of environmental impact on the production process of packaged drinking water using the life cycle assessment methods. IOP Conference Series: Earth and Environmental Science, 1414(1), 012084. https://doi.org/10.1088/1755-1315/1414/1/012084
50. Savov, V., Antov, P., Zhou, Y., & Bekhta, P. (2023). Eco-friendly wood composites: design, characterization and applications. Polymers 15(4). https://doi.org/10.3390/polym15040892
51. Shahbazi, A., Moeinaddini, M., Abdoli, M. A., Hosseinzadeh, M., Jaafarzadeh, N., & Sinha, R. (2023). Environmental damage of different waste treatment scenarios by considering avoided emissions based on system dynamics modeling. Sustainability (Switzerland), 15(23). https://doi.org/10.3390/su152316158
52. Tan, D., Wu, Y., Zhang, Z., Jiao, Y., Zeng, L., & Meng, Y. (2023). Assessing the life cycle sustainability of solar energy production systems: A toolkit review in the context of ensuring environmental performance improvements. Sustainability (Switzerland), 15(15). https://doi.org/10.3390/su151511724
53. Teacă, C.-A., Roşu, D., Mustaţă, F., Rusu, T., Roşu, L., Roşca, I., & Varganici, C.-D. (2019). Natural bio-based products for wood coating and protection against degradation: A review. BioResources, 14(2), 1-29.
54. Terlouw, T., Bauer, C., Rosa, L., & Mazzotti, M. (2021). Life cycle assessment of carbon dioxide removal technologies: A critical review. Energy and Environmental Science, 14(4), 1701–1721. https://doi.org/10.1039/d0ee03757e
55. Vallières, E., Pintos, J., Parent, M. E., & Siemiatycki, J. (2015). Occupational exposure to wood dust and risk of lung cancer in two population-based case-control studies in Montreal, Canada. Environmental Health: A Global Access Science Source, 14(1). https://doi.org/10.1186/1476-069X-14-1
56. Villagrán, E., Romero-Perdomo, F., Numa-Vergel, S., Galindo-Pacheco, J. R., & Salinas-Velandia, D. A. (2024). Life cycle assessment in protected agriculture: where are we now, and where should we go next? Horticulturae 10(1). https://doi.org/10.3390/horticulturae10010015
57. Vogtländer, J. G., Brezet, H. C., & Hendriks, C. F. (2001). The virtual Eco-costs '99: A single LCA-based indicator for sustainability and the Eco-costs - Value ratio (EVR) model for economic allocation: A new LCA-based calculation model to determine the sustainability of products and services. International Journal of Life Cycle Assessment, 6(3), 157–166. https://doi.org/10.1007/BF02978734
58. Wei, T., Wu, J., & Chen, S. (2021). Keeping track of greenhouse gas emission reduction progress and targets in 167 cities worldwide. Frontiers in Sustainable Cities, 3. https://doi.org/10.3389/frsc.2021.696381
59. Wu, M., Sadhukhan, J., Murphy, R., Bharadwaj, U., & Cui, X. (2023). A novel life cycle assessment and life cycle costing framework for carbon fibre-reinforced composite materials in the aviation industry. International Journal of Life Cycle Assessment, 28(5), 566–589. https://doi.org/10.1007/s11367-023-02164-y
60. Zieminska-Stolarska, A., Pietrzak, M., & Zbicinnki, I. (2022). Comparative LCA analysis for replacement of materials to reduce environmental impact. Chemical Engineering Transactions, 96, 145–150. https://doi.org/10.3303/CET2296025