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Application of Life Cycle Assessment (LCA) to the Bioflapon Manufacturing Process Using the CML-Baseline Method at Pilot Plant Scale

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ABSTRACT

Bioflapon is a construction material developed as an alternative to gypsum, widely used as ceiling panels. As the demand for gypsum continues to increase, other alternatives such as bioflapon need to be evaluated. This study assesses the environmental impacts of pilot-scale bioflapon production using a Life Cycle Assessment approach. The Life Cycle Impact Assessment is conducted using the CML method, focusing on four key impact categories: Global Warming Potential (GWP), acidification, eutrophication, and human toxicity. The bioflapon production consists of two main stages: transportation and processing. The processing includes pulverisation, mixing, and curing. It shows that transportation and curing are the major contributors to environmental impacts. Transportation has the highest contribution to GWP (0.94 kg CO_2 eq), acidification (5.5×10^{-3} kg SO_2 eq), and human toxicity (0.41 kg 1,4-dichlorobenzene eq), mainly due to fuel use and emissions. In contrast, eutrophication is dominated by the curing stage, with a value of 2.5×10^{-3} kg PO_4^{3-} eq, associated with high energy consumption. These findings indicate that efforts to reduce the environmental impacts of bioflapon production should focus on optimising transportation and improving energy efficiency during the curing process.

KEYWORDS

Bioflapon; life cycle assessment; LCIA; environmental impacts

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1. INTRODUCTION

Gypsum is a non-metallic mineral with the chemical formula, commonly found in the form of a white powder. This mineral plays a strategic role across various industrial sectors, particularly as Indonesia's development activities increase. The rapid growth of infrastructure and property development has directly driven a rise in national gypsum demand [1]. In practice, gypsum is widely used as both a primary material and an additive in the construction industry. Its extensive use is supported by its advantageous characteristics, including relatively low weight, fire resistance, good flexibility, and ease of installation and design adaptation. Consequently, gypsum has become an essential material for modern building construction in Indonesia.

One of the main applications of gypsum is in the cement industry, where it is used as an additive, accounting for approximately 4% of total cement production capacity [2]. Along with the high level of domestic cement consumption, the demand for gypsum has also increased significantly. In 2020, national cement consumption reached 66.21 million tons, resulting in an estimated gypsum requirement of approximately 2,648,400 tons. These data indicate that the cement industry is one of the most significant contributors to gypsum demand in Indonesia.

In addition to the cement industry, gypsum boards also contribute significantly to the overall national demand for gypsum. Gypsum boards are widely used in infrastructure development and the property sector, particularly as wall and ceiling materials. In 2020, domestic demand for gypsum boards reached approximately 98 million m² per year. Meanwhile, the installed capacity of the gypsum board industry was recorded at 238 million m² per year, with an actual production realisation of around 120 million m² per year [3]. This condition indicates substantial potential for the domestic gypsum industry to develop further to meet national market demand. In line with the overall increase in gypsum demand in Indonesia's construction sector, gypsum board demand has continued to grow through 2024. Gypsum boards have

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become increasingly important in modern interior and structural construction due to their lightweight nature, ease of installation, and ability to support efficient architectural designs [4].

On the other hand, Indonesia generates large quantities of industrial and agricultural waste with considerable potential as additives for gypsum-based materials. Glycerin pitch, a by-product of the oleochemical and biodiesel industries, is estimated to reach approximately 44,000 tons per year [5]. Palm oil fly ash is produced from the combustion of biomass, such as palm kernel shells and fibres, in boilers at palm oil mills, where it is used as a process energy source. With more than 1,000 palm oil mills nationwide and very high crude palm oil production, palm oil fly ash is estimated to reach millions of tons per year. This ash waste is generally underutilised and often stockpiled within mill areas, thereby posing potential environmental problems. In addition, the palm oil industry generates large amounts of biomass waste in the form of empty fruit bunches (EFB), amounting to approximately 46 million tons per year [6]. The substantial quantities of these three types of garbage highlight their significant potential for utilisation as alternative additive materials in gypsum products.

Therefore, this study aims to evaluate the environmental impacts of gypsum production in the form of bioflapon, utilising waste materials derived from glycerin pitch, fly ash, and empty fruit bunches. The utilisation of these waste materials is expected to reduce environmental burdens associated with waste accumulation while supporting the development of sustainable building materials to meet the continuously increasing national demand for gypsum.

2. RESEARCH METHOD

2.1. Goal and Scope Definition

This study aims to evaluate the environmental impacts associated with bioflapon production at the pilot plant scale using the Life Cycle Assessment (LCA) approach. The assessment focuses on four impact categories: Global Warming Potential (GWP), acidification, eutrophication, and human Toxicity.

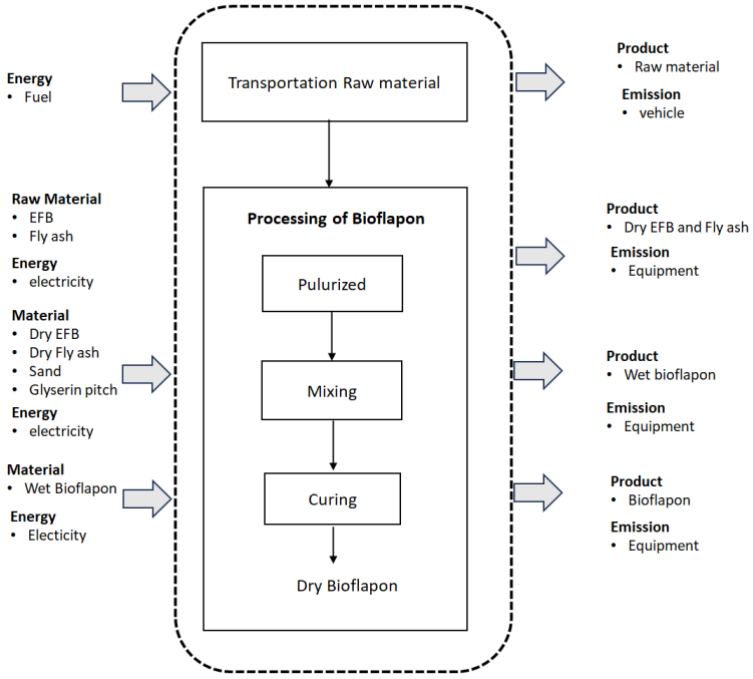


Figure 1. System Boundary of the processing bioflapon

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LCA is applied as a systematic tool to model the life cycle of bioflapon as a product system composed of interconnected unit processes linked by material and energy flows, as well as emissions released to the environment, in accordance with ISO 14040-14044 [7], [8]. The system boundary is defined as cradle-to-gate, from the transportation of raw materials and industrial by-products to the bioflapon production facility, to the final bioflapon product. The study focuses on raw material transportation and the production stages, including pulverising, mixing, and curing. The ecoinvent database, integrated into the openLCA software, is used to support secondary data requirements.

2.2. Functional Unit

The functional unit of this study is defined as 1 kg of bioflapon. All material inputs, energy consumption, and environmental emissions are calculated and normalised based on this functional unit to ensure consistency and comparability of the results.

2.3. Life Cycle Inventory (LCI)

The Life Cycle Inventory is developed primarily from primary data collected directly during pilot plant operations. The inventory includes data on raw material consumption, electricity use, and transportation activities. Data collection aims to quantify all relevant input and output flows associated with each unit process involved in bioflapon production.

Transportation inventory data include fuel consumption and truck capacity, while production inventory data consist of glycerin pitch, empty fruit bunches, fly ash, sand, and electricity usage. The compiled input–output data form the basis for calculating environmental emissions and impacts.

2.4. Life Cycle Impact Assessment (LCIA)

An environmental impact assessment was performed using the openLCA software with the CML-IA Baseline method. This method was selected due to its widespread application and robustness in evaluating midpoint ecological impact categories. The assessed impact categories include:

- Global Warming Potential (GWP), expressed in kg CO_2 equivalent, represents greenhouse gas emissions generated during bioflapon production.
- Acidification, expressed in kg SO_2 equivalent, accounts for emissions of acidifying substances such as sulfur dioxide and nitrogen oxides.
- Eutrophication, expressed in kg PO_4^{3-} equivalent, reflects nutrient enrichment caused by nitrogen- and phosphorus-based emissions.
- Human Toxicity, expressed in kg 1,4-dichlorobenzene equivalent, indicates potential adverse effects of emitted substances on human health.

2.5. Data Interpretation

Inventory data were converted into environmental impacts using characterisation factors provided by the CML-IA Baseline method. The contribution of each process stage was analysed to identify ecological hotspots and to support recommendations for impact reduction, particularly in transportation and energy-intensive curing processes.

3. RESULT AND DISCUSSION

Based on the midpoint impact assessment of the two process flows, transportation and production, it is evident that the transportation stage has the greatest environmental impact. This dominance is particularly reflected in the Global Warming Potential (GWP) value of 0.9357 kg CO_2 eq, which is significantly higher than that of the production process. The

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elevated GWP associated with transportation indicates that fossil fuel consumption and vehicle exhaust emissions from raw material and product transportation are the primary sources of greenhouse gas emissions.

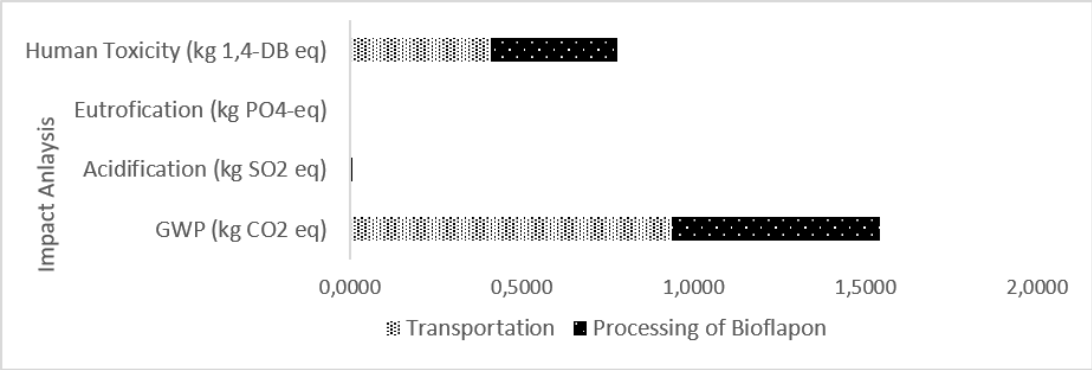


Figure 2. Impact Analysis

In addition, the human toxicity impact from the transportation stage is relatively high, reaching 0.4106 kg of 1,4-dichlorobenzene equivalent, suggesting a considerable potential risk to human health from airborne pollutant emissions, including particulate matter and other toxic compounds. In contrast, the eutrophication and acidification impact categories exhibit comparatively lower values, indicating that their contributions at this stage are relatively minor.

For the bioflapon production process, the resulting GWP is 0.606 kg CO_2 eq, while the human toxicity impact amounts to 0.3689 kg 1,4-dichlorobenzene equivalent. These two impact categories represent the major contributors within the production stage, reflecting energy consumption and the use of auxiliary materials during processing. Although the environmental impacts from the production stage are lower than those from transportation, the results clearly indicate that ecological improvement strategies should prioritise optimising the transportation system and enhancing energy efficiency in production processes to reduce the overall environmental footprint of bioflapon production effectively.

Figure 2 illustrates that the total Global Warming Potential (GWP) impact is dominated by the transportation process, which accounts for 60% of the total impact. In comparison, the bioflapon production process accounts for the remaining 40%. These results confirm that transportation activities represent the primary source of greenhouse gas emissions within the analysed system. This finding is consistent with previous LCA studies on construction materials, which report that transportation stages often represent a significant source of greenhouse gas emissions due to fossil fuel combustion and long-distance material logistics [9], [10].

Similarly, for the human toxicity impact category, the total contribution is relatively balanced between the two process flows. However, transportation still accounts for a slightly higher contribution, at 53%, compared to 47% from the bioflapon production process. This indicates that both process stages contribute significantly to potential human toxicity, although transportation remains the most dominant stage. Emissions from vehicle exhaust, including particulate matter and toxic compounds, are commonly identified as key contributors to human Toxicity in transportation-intensive systems [11], [12], [13]. Similar patterns have been reported in LCA studies using the CML-IA Baseline method, in which transportation and energy-intensive processes are consistently identified as dominant contributors to midpoint impact categories [14].

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3.1. Global Warming Potential (GWP)

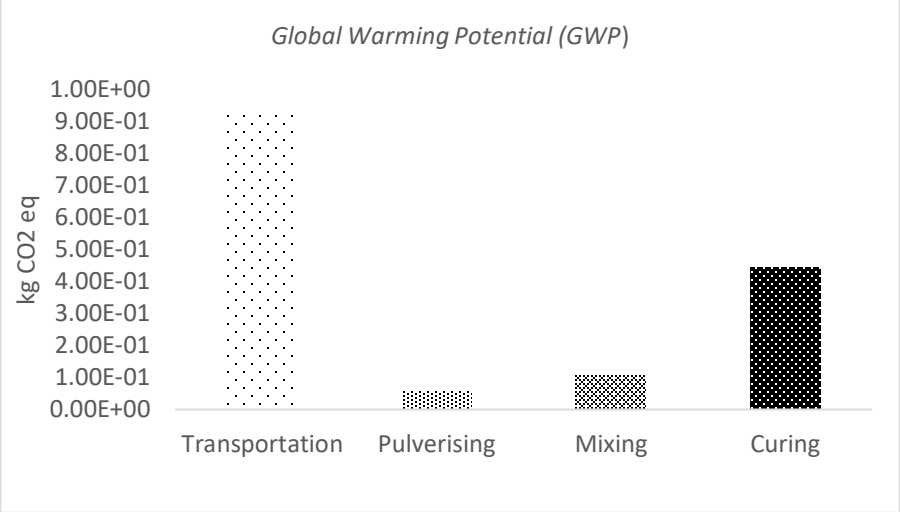


Figure 3. Global Warming Potential Impact

The CML method classifies and characterises environmental impacts into several midpoint categories, including Global Warming Potential (GWP), human Toxicity, acidification, and eutrophication, which are expressed in specific equivalent units. Based on calculations using the CML method, the transportation stage has the highest GWP contribution of 0.9357 kg CO_2 eq, indicating the dominance of greenhouse gas emissions from fossil fuel consumption and direct transportation emissions. This finding is consistent with the CML approach, which emphasises CO_2, CH_4, and N_2O emissions as the main contributors to the climate change impact category. According to Guinée J, transportation activities within material-based production systems significantly influence the climate change impact category through direct emissions of CO_2, NO_x, and other greenhouse gases [15], [16].

Furthermore, within the bioflapon processing flow, the curing stage contributes a relatively significant GWP of 0.44 kg CO_2 eq, reflecting the high energy demand during the material maturation process, including temperature control and curing time. Meanwhile, the mixing and pulverisation stages exhibit comparatively lower GWP values of 0.10 kg CO_2 eq and 0.05 kg CO_2 eq, respectively, indicating more limited energy consumption and emissions at these stages. Overall, this contribution pattern is consistent with the characteristics of the CML method, in which the climate change impact category is susceptible to fossil-based energy use and transportation intensity. Therefore, the results of this study confirm that the CML method is effective for identifying the most environmentally dominant process stages, providing a basis for formulating emission mitigation strategies through reduced transportation distances and improved energy efficiency in the curing process.

3.2. Acidification

Based on Figure 4, the transportation stage has the greatest impact on acidification, with a value of approximately 5.5×10^{-3} kg SO_2 eq, compared to the other process stages. This result is consistent with findings from various Life Cycle Assessment (LCA) studies, which indicate that transportation activities are among the main contributors to acidification impacts from SO_2 and NO_x emissions from fossil fuel combustion in motor vehicles [15], [16]. Within the CML method, emissions of these gases have high characterisation factors for the acidification impact category; therefore, process stages with high transportation intensity tend to exhibit dominant impact values.

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At the curing stage, the acidification impact is recorded at 1.8×10^{-3} kg SO_2 eq, indicating a significant contribution, although lower than that of transportation. This finding is consistent with previous studies on building materials and mineral-based products, which have reported that curing or thermal treatment processes contribute to acidification impacts due to energy consumption and indirect emissions from fossil-based electricity generation [17], [18].

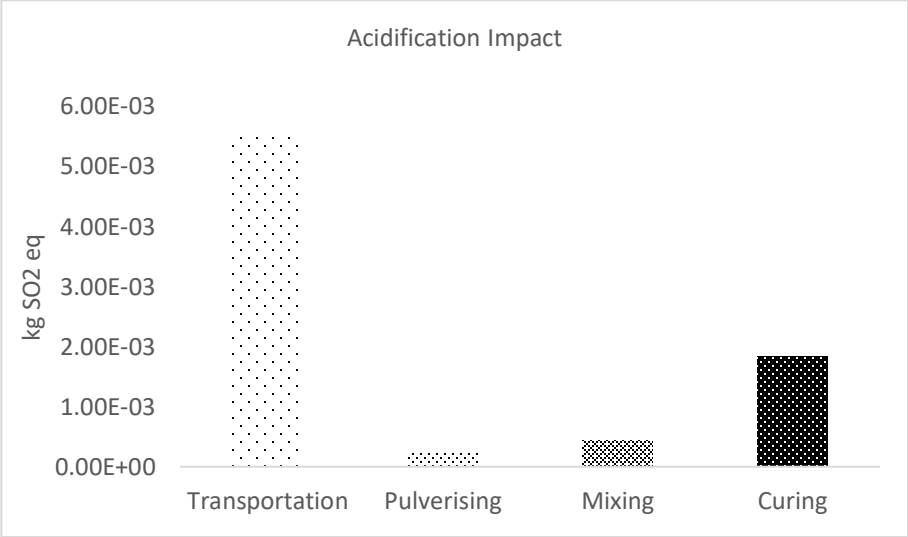


Figure 4. Acidification Impact

Meanwhile, the mixing and pulverisation stages show relatively low acidification impact values of 4.0×10^{-4} kg SO_2 eq and 2.0×10^{-4} kg SO_2 eq, respectively. These lower values indicate that acid gas emissions at these stages remain limited, in line with LCA literature, which states that processes with low energy requirements generally contribute only minor impacts to the acidification category [19]. Overall, the acidification impact contribution pattern observed in this study is consistent with previous findings reported in scientific journals and confirms that environmental impact mitigation strategies should focus on optimising transportation systems and improving energy efficiency at the curing stage.

3.3. Eutrophication

The eutrophication impact category in the bioflapon production system is dominated by the curing stage, with a value of approximately 2.5×10^{-3} kg PO_4^{3-} eq, indicating that this stage represents an environmental hotspot. The dominance of impacts at the curing process is closely related to high energy consumption and indirect emissions from electricity generation systems, particularly nitrogen compounds such as NO_x, which are converted into phosphate equivalents as indicators of eutrophication potential within the CML approach. This finding is consistent with LCA studies on construction materials published around 2020, which report that processes powered by thermal and electrical energy are major contributors to eutrophication and water quality degradation [18], [20].

In addition, the transportation stage provides the second-largest contribution, with a value of approximately 1.6×10^{-3} kg PO_4^{3-} eq, mainly driven by vehicle exhaust emissions during the distribution of raw materials and products. A study by Das P confirms that NO_x and NH_3 emissions from the transportation sector play an essential role in increasing eutrophication potential in LCA studies based on the CML method [21]. In contrast, the mixing and pulverisation stages show relatively small contributions, with values of approximately 5.0×10^{-4} kg PO_4^{3-} eq and 3.0×10^{-4} kg PO_4^{3-} eq, respectively, reflecting low energy intensity and minimal nutrient emissions in mechanical processes.

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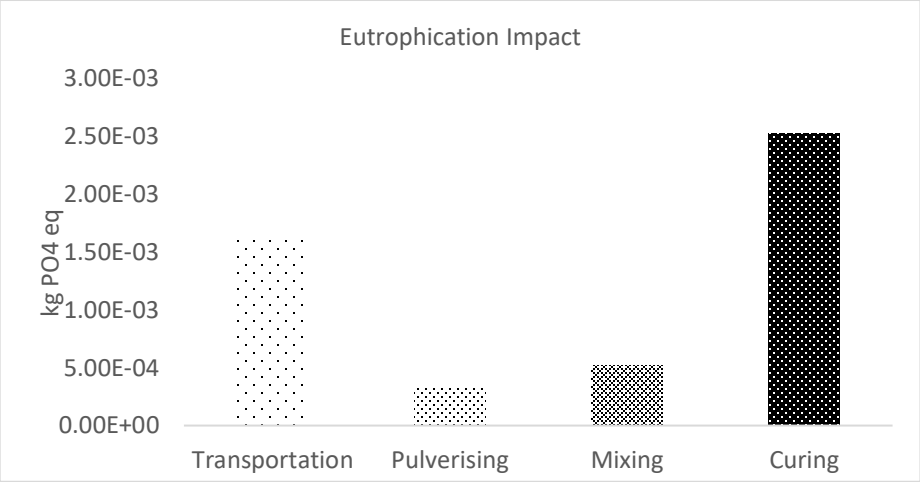


Figure 5. Eutrophication Impact

3.4. Human Toxicity

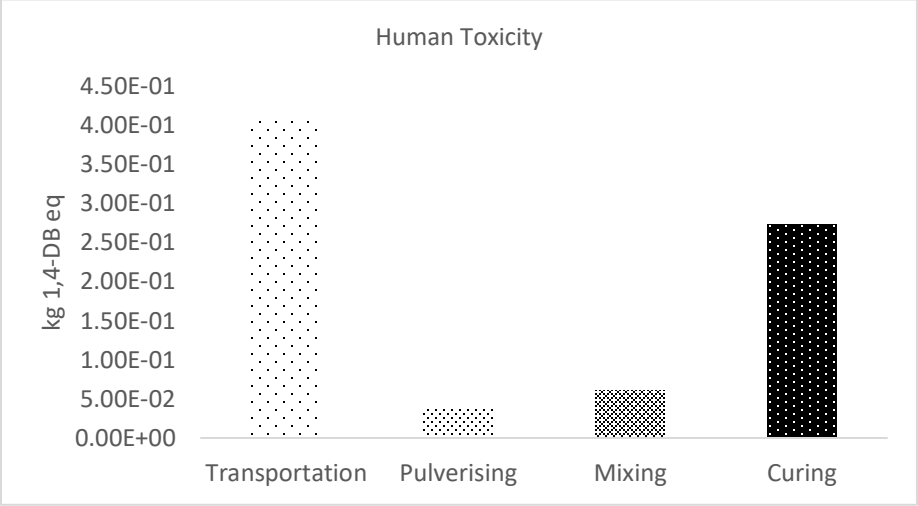


Figure 6. Human Toxicity Impact

The human toxicity impact category indicates that the transportation stage is the most significant contributor to the total impact, with a value of approximately 0.41 kg 1,4-DB eq. The high contribution at this stage suggests that transportation activities represent the primary hotspot within the human toxicity category. This impact is primarily influenced by emissions from motor vehicle exhaust, such as heavy metals, delicate particulate matter, and other hazardous compounds, which are characterised in the CML method using the 1,4-dichlorobenzene (1,4-DB) equivalent unit.

The curing stage ranks second, with a value of approximately 0.27 kg 1,4-DB eq, indicating a significant contribution to human Toxicity. This impact is associated with high energy consumption and indirect emissions from electricity generation, including the release of harmful inorganic compounds into the air that may pose risks to human health. This finding is consistent with LCA literature on building materials, which reports that energy-intensive processes contribute

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substantially to the human toxicity category. This approach is also aligned with recommendations from recent LCA studies on construction materials, which emphasise the importance of emission control during logistics and energy use phases to achieve more sustainable production systems [22].

Meanwhile, the mixing and pulverisation stages contribute relatively minor impacts, with values of approximately 0.06 kg 1,4-DB eq and 0.03 kg 1,4-DB eq, respectively. The low effects at these stages indicate that mechanical processes with lower energy intensity and minimal use of hazardous chemicals have a limited influence on human toxicity potential. This finding is consistent with the results reported by Qiu-Liang Cai and Armylisas, who state that transportation activities in building material production systems are the main contributors to human toxicity impacts within the CML-based LCIA approach [23], [24].

4. CONCLUSION

The results of the Life Cycle Impact Assessment (LCIA) using the CML method indicate that the environmental impacts of the bioflapon production system are predominantly influenced by the transportation flow and the curing stage. The transportation stage is the primary contributor to the Global Warming Potential (GWP) and human toxicity categories, with values of approximately 0.94 kg CO_2 eq and 0.41 kg 1,4-DB eq, respectively. These high contributions are mainly caused by fossil fuel consumption and vehicle exhaust emissions during the distribution of raw materials.

In addition, the transportation stage contributes most to the acidification category, with a value of approximately 5.5×10^{-3} kg SO_2 eq, associated with SO_2 and NO_x emissions from fossil fuel combustion. In contrast, the eutrophication impact category is dominated by the curing stage, with a value of approximately 2.5×10^{-3} kg PO_4^{3-} eq, reflecting the significant influence of energy consumption and indirect nutrient-related emissions during this process.

The internal material processing stages, namely pulverisation and mixing, show relatively minor contributions across all impact categories and therefore do not constitute major hotspots in the bioflapon production system. Overall, this study's findings confirm that transportation activities and the curing process are critical stages that determine the magnitude of environmental impacts. Therefore, efforts to reduce the ecological effects of bioflapon production should focus on optimising transportation systems and improving efficiency, while using low-emission energy sources during the curing process to support a more sustainable bioflapon output.

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6. REFERENCES

[1] M. R. Rambe, R. F. Pohan, F. Patriotika, S. Harahap, and A. S. Nasution, “Potential of Gypsum Waste as a Substitution and Filler Material in Concrete Manufacturing,” *Fluida*, vol. 16, no. 2, pp. 120–131, Nov. 2023, doi: 10.35313/fluida.v16i2.4471.

[2] C. G. Tebabal, “Effect of Gypsum Amount in Cement on Fresh and Hard- ened Properties of Self-Compacting Concrete,” *Global Scientific Journals*, vol. 8, no. 5, pp. 1–10, 2020, Accessed: Aug. 08, 2026. [Online]. Available: https://www.researchgate.net/publication/342199425_Effect_of_Gypsum_Amount_in_Cement_on_Fresh_and_Hard-_ened_Properties_of_Self-Compacting_Concrete

[3] M. E. Seyidgulu, R. Akhundov, and E. G. Hashimov, “Environmental Impact of Transportation Systems: Challenges and Sustainable Solutions,” in *Conference: Scientific review of the actual events, achievements and problems*, Berlin: Proceedings of the V International Scientific and Theoretical Conference, 2025. Accessed: Aug. 08, 2026.

https://doi.org/10.25077/greentech.v3i1.85
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[Online]. Available: https://www.researchgate.net/publication/396161235_ENVIRONMENTAL_IMPACT_OF_TRANSPORTATION_SYSTEMS_CHALLENGES_AND_SUSTAINABLE_SOLUTIONS
[4] J. Anderson and A. Moncaster, "Embodied Carbon, Embodied Energy and Renewable Energy: A Review of Environmental Product Declarations," in *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, Dec. 2023, pp. 986–997. doi: 10.1680/jstbu.21.00160.
[5] K. Symons, "Book Review: Embodied Carbon: The Inventory of Carbon and Energy (ICE). A BSRIA Guide," *Proceedings of the Institution of Civil Engineers - Energy*, vol. 164, no. 4, pp. 206–206, Nov. 2011, doi: 10.1680/ener.2011.164.4.206.
[6] R. Nabila *et al.*, "Oil Palm Biomass in Indonesia: Thermochemical Upgrading and its Utilization," *Renewable and Sustainable Energy Reviews*, vol. 176, p. 113193, Apr. 2023, doi: 10.1016/j.rser.2023.113193.
[7] "Environmental Management Life Cycle Assessment Requirements and Guidelines," Geneva, 2006.
[8] "Environmental Management Life Cycle Assessment Principles and Framework," Geneva, 2006.
[9] G. Hammond, "The evolution of English Bible Narrative: A Study of Tyndale's Translation Methods in The Book of Genesis," *English Studies*, vol. 61, no. 2, pp. 104–118, Apr. 1980, doi: 10.1080/00138388008598035.
[10] C. K. Chau, T. M. Leung, and W. Y. Ng, "A Review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on Buildings," *Appl. Energy*, vol. 143, pp. 395–413, Apr. 2015, doi: 10.1016/j.apenergy.2015.01.023.
[11] M. A. J. Huijbregts *et al.*, "ReCiPe2016: a Harmonised Life Cycle Impact Assessment Method at Midpoint and Endpoint Level," *Int. J. Life Cycle Assess.*, vol. 22, no. 2, pp. 138–147, Feb. 2017, doi: 10.1007/s11367-016-1246-y.
[12] G. P. Hammond and C. I. Jones, "Embodied Energy and Carbon in Construction Materials," *Proceedings of the Institution of Civil Engineers - Energy*, vol. 161, no. 2, pp. 87–98, May 2008, doi: 10.1680/ener.2008.161.2.87.
[13] L. Vandepaer, E. Panos, C. Bauer, and B. Amor, "Energy System Pathways with Low Environmental Impacts and Limited Costs: Minimizing Climate Change Impacts Produces Environmental Cobenefits and Challenges in Toxicity and Metal Depletion Categories," *Environ. Sci. Technol.*, vol. 54, no. 8, pp. 5081–5092, Apr. 2020, doi: 10.1021/acs.est.9b06484.
[14] G. P. Hammond, C. I. Jones, and R. Spevack, "A Technology Assessment of The Proposed Cardiff–Weston Tidal Barrage, UK," in *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, Dec. 2018, pp. 383–401. doi: 10.1680/jensu.16.00015.
[15] M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, *Life Cycle Assessment: Theory and Practice*. Springer International Publishing, 2017. doi: 10.1007/978-3-319-56475-3.
[16] J. B. Guinée *et al.*, "Life Cycle Assessment: Past, Present, and Future," *Environ. Sci. Technol.*, vol. 45, no. 1, pp. 90–96, Jan. 2011, doi: 10.1021/es101316v.
[17] H. R. Wati, M. A. Budihardjo, and P. Andarani, "Waste Transportation Environmental Impact Using Life Cycle Assessment: Bibliometric Analysis and Systematic Review," *Pol. J. Environ. Stud.*, vol. 34, no. 1, pp. 563–571, Jan. 2025, doi: 10.15244/pjoes/186580.
[18] L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, and A. Castell, "Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA) of Buildings and The Building Sector: A Review," *Renewable and Sustainable Energy Reviews*, vol. 29, pp. 394–416, Jan. 2014, doi: 10.1016/j.rser.2013.08.037.
[19] G. Finnveden *et al.*, "Recent Developments in Life Cycle Assessment," *J. Environ. Manage.*, vol. 91, no. 1, pp. 1–21, Oct. 2009, doi: 10.1016/j.jenvman.2009.06.018.
[20] P. Loubet, A. Benoist, J. Mariette, and A. Estevez-Torres, "Hybrid LCA of French Research Activities Reveals Limited Trade-Offs for Decarbonization Strategies Across Multiple Impacts," *J. Ind. Ecol.*, vol. 30, no. 4, pp. 1919–1933, Aug. 2026, doi: 10.1007/s44498-026-00131-y.

https://doi.org/10.25077/greentech.v3i1.85
Vol. 3, No. 1, 2026, Hal. 24-33

[21] P. K. Das, M. Y. Bhat, and S. Sajith, "Life Cycle Assessment of Electric Vehicles: A Systematic Review of Literature," *Environmental Science and Pollution Research*, vol. 31, no. 1, pp. 73–89, Dec. 2023, doi: 10.1007/s11356-023-30999-3.

[22] H. Zhao, F. Liu, H.-Q. Liu, L. Wang, R. Zhang, and Y. Hao, "Comparative Life Cycle Assessment of Two Ceramsite Production Technologies for Reusing Municipal Solid Waste Incinerator Fly Ash in China," *Waste Management*, vol. 113, pp. 447–455, Jul. 2020, doi: 10.1016/j.wasman.2020.06.016.

[23] Q.-L. Cai *et al.*, "The Characteristics and Mixing States of PM2.5 During a Winter Dust Storm in Ningbo of the Yangtze River Delta, China," *Science of The Total Environment*, vol. 709, p. 136146, Mar. 2020, doi: 10.1016/j.scitotenv.2019.136146.

[24] A. H. N. Armylisas, S. S. Hoong, and N. M. Ismail, "Characterization of Crude Glycerol and Glycerol Pitch from Palm-Based Residual Biomass," *Biomass Convers. Biorefin.*, vol. 14, no. 22, pp. 28341–28353, Nov. 2024, doi: 10.1007/s13399-023-04003-4.