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Comparative Environmental Impact Analysis for Natural and Synthetic Fiber Reinforced Composites from a Life Cycle Assessment Context

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ABSTRACT

Nowadays composites have become an interest for research due to their exceptional characteristics in various engineering fields. There are so many options available to be used as reinforcement in the composites. This results into combination of various desired properties for the suitable purposes. Despite these advantages, their production processes pose significant environmental concerns, warranting a thorough environmental impact assessment. Life Cycle Assessment (LCA) is an effective tool for evaluating the environmental implications of composite materials across their entire lifecycle, from "cradle to grave." this study, three distinct epoxy-based composite systems were analyzed: (1) glass fiber-reinforced, (2) jute fiber-reinforced, and (3) a hybrid composite combining natural and synthetic fibers. The assessment considered key environmental impact categories, including global warming potential, ozone depletion potential and non-carcinogenic human toxicity potential. To find out which composite is environmentally friendly the composites product system was compared using Openlca. Contribution analysis done for the composite containing both glass and jute fiber. Results reveal that jute fiber-reinforced composites, composed entirely of natural fibers, exhibited the lowest environmental impact due to their renewable and biodegradable nature. JFRPMC shows a GWP value of 1.933 kg CO2-eq, ODP value of 1.12x10-6 kg CFC-11-eq & HTP value of 2.2069 kg 1,4-DCB-eq. In contrast, the hybrid composite, incorporating both synthetic and natural fibers, demonstrated the highest impact in every evaluated category, attributed to the energy-intensive production of synthetic fibers and challenges in recycling mixed materials. Comparative analysis highlights the advantages of using natural fiber reinforcements for sustainable composite development, aligning with global efforts to minimize environmental footprints. This research underscores the importance of material selection and lifecycle optimization in reducing the ecological impact of composite production. The findings contribute valuable insights for industries aiming to balance performance and sustainability in composite manufacturing.

Keywords: Life Cycle Assessment, Environmental impact, Natural Fibers, Polymer Matrix Composite.

1. Introduction

Eco-efficient manufacturing has received remarkable consideration by meeting necessities not only from a financial but also from environmental perpective [1]. In recent years, the manufacturers and research institutions are driven by focusing on recyclability and ecological standards to create polymer composites that are more environmentally friendly [2]. Reinforced composite materials possess high chemical resistivity, exceptional strength, high corrosion resistance, impact resistance, high mechanical strength while maintaining low cost [3], [4]. Traditional fiber-reinforced composites consisting of carbon or glass fibers combined with unstructured polyester or epoxy resin, exhibit excellent mechanical and thermal properties. However, their disposal through incineration can pose environmental challenges. So, there is a growing interest in developing environmentally friendly composites that utilize natural fibres as reinforcement [5]. Composites comprising polymers reinforced by natural fibers (for example, flax, jute, plant fiber, wood-fibers) have gained considerable attention during the last decade due to their environmental friendliness and for having several benefits over synthetic fibers such as glass fibers, including inexpensiveness, sustainability, favorable specific strength, high resistance to chemicals, and major production benefits. Renewability of natural fibers makes these composites eco-friendly [6].

Jute, a plant-based material, seems to be a promising natural fiber which is both natural and recyclable along with affordable [7]. Jute fiber seems to have moderate mechanical characteristics. However, the fiber's mechanical properties can be improved by treating it with an alkaline media [8]. Single fiber pull out testing of discontinuous fiber composites revealed good fiber/matrix adhesion because its surface produce natural waxiness [9]. Braga et al. [10] conducted mechanical and thermal analyses on a jute/glass fiber reinforced epoxy-based matrix composite. The use of jute fiber enhances density, impact strength, tensile strength, and flexural strength, based on this study. However, a higher percentage of glass fiber results in greater strength.

Composites are manufactured for using in various applications in which various synthetic or natural fibres are used for manufacturing the fiber-reinforced composite. So, we should also be concerned about the environmental impacts as a result of the manufacturing process or by the total life cycle of the prepared composite. That's where the LCA comes into play. Making an assessment of the environmental properties of a material requires a better understanding of the fundamental loops and processes across the whole life cycle of the material, such as the phases of extraction, use, and

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disposal. A tool called life cycle assessment (LCA) was created expressly for determining how much of an impact a product has on the ecosystem overall. The outcomes can be used to improve a single product's environmental performance (eco-design) or to improve a company's environmental performance [6].

LCA, a technical tool, serves to quantify & identify the environmental consequences of a product or service throughout its entire life cycle. It assesses the environmental impact at each phase, starting from the extraction as well as raw materials processing, through manufacturing, distribution, customer use, maintenance, and eventually the end-of-life approaches. LCA is a complete study of a product or service's environmental footprint. from “cradle to grave” [11][12][13]. Life cycle assessment (LCA) which is a method for the purpose of evaluating the environmental impact of products or materials. LCA can be used to assess the environmental impact of NFCs. As LCA can provide a comprehensive overview of the environmental impact of a product, from the extraction of raw materials to the end of its life, this tool can be used to make informed decisions about the use of NFCs in different applications [14]. Researchers are increasingly interested in using LCA to assess the environmental impact of NFCs. The goal of LCA studies on NFCs is to quantitatively analyze the environmental performance of NFCs throughout their entire life cycle. This information can then be used to compare the environmental impact of NFCs to other materials [15]. In this work, the environmental impact of three polymer matrix composites reinforced with different natural fibers is compared along with the contribution of different process during the manufacturing of the composites. The only natural fiber which is used in this study is none other than jute fiber. The aim of this study is to show which composite acts better than the other one in consideration of environmental impacts and also mechanical behavior.

2. Methodology

2.1 Materials

Three composite samples were prepared using the hand layup process. Glass fiber, Jute fiber, Epoxy resin, Hardener are the components used in the composite. At first the raw materials were collected. Then the natural fibers were treated with NaOH solution. Then after weighting the materials according to requirement the composite were formed. The different weight percentage of the three composite samples are illustrated as Table 1:

Table 1 Different weight percentage of the three composite samples.

Sample	Glass fiber (wt %)	Jute fiber (wt %)	Epoxy and hardener
GFJFRPMC	37.5	12.5	50
GFRPMC	41.5	-	58.5
JFRPMC	-	25	75

2.2 Life Cycle Assessment

LCA can be introduced as a technique which is used to assess the environmental risks posed by any product or process. The Life Cycle Assessment, also known as (LCA) is a method for evaluating the adverse environmental effects of a product or process over the course of its entire life cycle. This was established by SETAC (Society of Environmental Toxicology and Chemistry) [16] and specified by ISO 14040-14044 [17][18].

2.3 Goal and scope

In this portion, the main goals are identified. The main goal of the current paper is to compare the environmental impacts of three different nature fiber reinforced polymer matrix composites. Besides comparison, contribution analysis of different processes during the manufacturing of the composite samples.

2.4 Functional unit

The functional unit was taken as the weight of the composite samples. Three composites weight different from each other. It can be clearly seen from Table 2.

Table 2 Different weight percentage of the three composite samples.

Samples	Functional unit
GFJFRPMC	512
GFRPMC	470
JFRPMC	270

2.5 System Boundaries

The LCA has been carried out from the 'Cradle to gate' perspective. The system boundary for this study has been extended from the raw materials collection, transportation and incorporation in the final composite samples. The system boundary can be illustrated in the Fig.1 [19]:

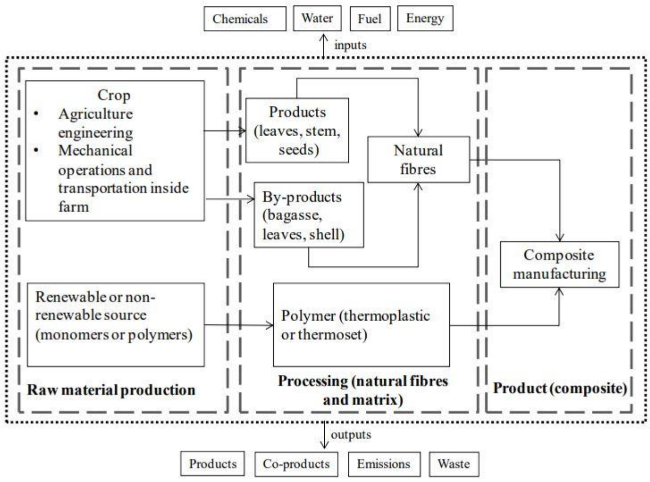

Fig.1 System boundary for natural fiber reinforced composite sample

2.6 Life cycle inventory

A summary of the tangled and varied techniques involved in the making of composite is found in this section. The composite Life Cycle Inventory was developed after an in-depth examination of every step of the manufacturing process of both natural fiber reinforced polymer matrix composite, as illustrated in Fig.2. The mass balance has been defined using the flow chart, taking into account emission levels, outputs, transportation and water usage.

2.7 Software

Various software can be used to obtain a LCA analysis. In this reseach, we utilized OpenLCA 1.11 which is a LCA software. The Ecoinvent 3.9 database was integrated for performing the analysis. Both reliable results the latest version of both the software and the database was taken into consideration.

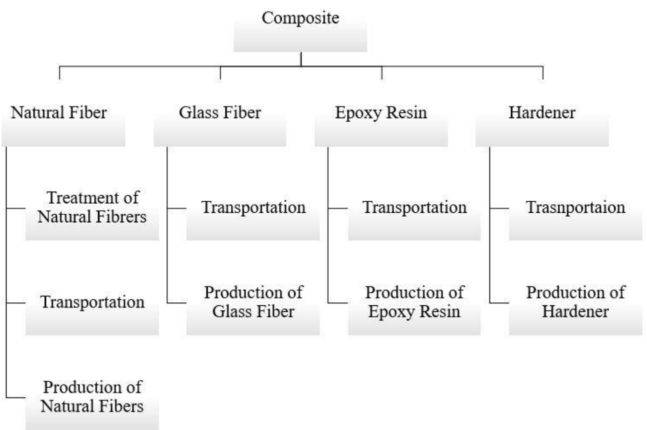

Fig.2 Contribution of different production steps in the various impact categories for GFCFRPMC composite

2.8 Impact assessment

According to ISO 14040, normalization and weighting sets were not selected as both of these steps are not a compulsory step of life cycle assessment [17]. For carrying out the impact assessment Recipe midpoint method was used. The 18 categories along with their units are listed as Table 3

2.9 Interpretation

This step is all about decision making. The best possible steps with least environmental impact will be found out here. The step with best environmental profile and least impact will be followed.

Table 3 Impact category along with their units for assessing life cycle assessment

Category of impact	Unit	Acronyms
Terrestrial-acidification potential	Kg-SO_2-Eq	TAP
Global-warming potential	Kg-CO_2-Eq	GWP
Freshwater-ecotoxicity potential	Kg-1,4-DCB-Eq	FETP
Marine-ecotoxicity potential	Kg-1,4-DCB-Eq	METP
Terrestrial-ecotoxicity potential	Kg-1,4-DCB-Eq	TETP
Fossil-fuel potential	Kg-oil-Eq	FFP
Freshwater-eutrophication potential	Kg-P-Eq	FEP
Marine-eutrophication potential	Kg-N-Eq	MEP
Carcinogenic-human toxicity potential	Kg-1,4-DCB-Eq	HTPc
Non-carcinogenic- human toxicity potential	Kg-1,4-DCB-Eq	HTPnc
Ionizing-radiation – ionizing-radiation potential	kBq-Co-60-Eq	IRP
Land-occupation potential	m^2*a-crop-Eq	LOP
Surplus-ore potential	Kg-Cu-Eq	SOP
Ozone-depletion potential	Kg-CFC-11-Eq	ODP
Particulate-matter formation potential	Kg-PM2.5-Eq	PMFP
Human health - photochemical oxidant formation potential: humans	Kg-NO_x-Eq	HOFP
Ecosystems-photochemical oxidant formation potential: ecosystems	Kg-NO_x-Eq	EOFP
Water consumption potential	m^3	WCP

3. Results & Discussion

3.1 Contribution analysis for GFJFRPMC composite

According to this contribution analysis in Fig.3, jute fiber has a higher contribution compared to glass fiber in almost all the impact categories. Jute fiber shows the highest contribution in case of LOP. So, jute production may be occupying a lot of land [20]. Besides, jute fiber has the lowest contribution in WCP category. Glass fiber has the lowest contribution in case of MEP impact category as well as highest contribution in TETP category. So, glass fiber contributes to production of less hazardous substances. So, less mineral is produced due geological process. Epoxy shows the highest contribution to the water consumption potential category while hardener contributes highest to the MEP. In case of hardener, it has the lowest contribution compared to all other processes [20].

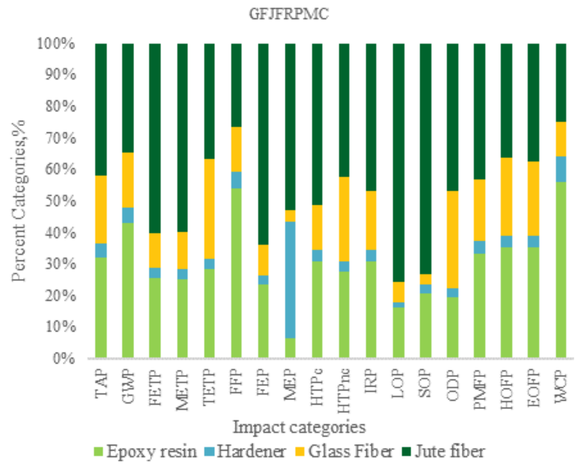

Fig.3 Contribution of different production steps in the various impact categories for GFJFRPMC composite

3.2 Comparison of environmental impact of three composites

From Fig.4, it is very crystal clear that GFJFRPMC has way higher impacts in each category compared to JFRPMC. From the previous contribution analysis, it was clear jute fiber in the GFJFRPMC was contributing higher in each impact categories. This may be due to some of the sub processes involved in the manufacturing of the composite samples. GFJFRPMC has an almost close impact about 80% in case of MEP. In case of GWP, TETP, FFP, ODP, HTPc, HTPnc JFRPMC has the lowest impact compared to the other impact categories. From this comparison it is very certain to say that JFRPMC is more ecofriendly than GFJFRPMC or GFRPMC

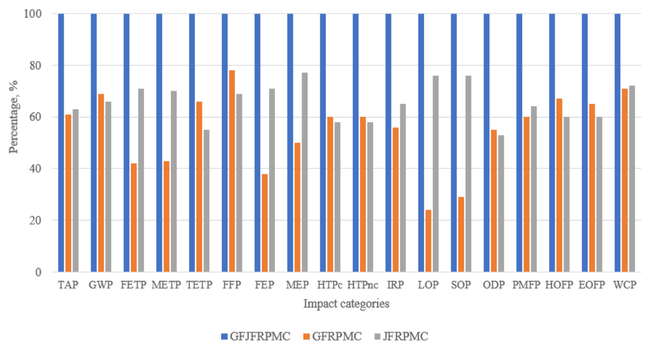

Fig.4 Comparison of environmental impacts among GFJFRPMC, GFRPMC, JFRPMC

3.3 Comparison of Global warming potential among the composites

GFJFRPMC shows very high GWP compared to JFRPMC according to Fig.5. Thus, adding both natural and synthetic fiber in a polymer matrix composite is leading to increase in global warming. Fertilizers and insecticides were needed for the commercial jute planting. Increased energy use is a result of transportation, fertilizers, and insecticides. There is a high correlation between energy use & CO_2 petrol emissions. An estimated 520–1120 kg of CO_2 gas is going to be generated in total for the manufacturing of one ton of jute fibers. To produce one tons of jute fibre, nevertheless, almost 2.4 tons of CO_2 gas must be extracted from the environment. For jute fibres of every ton, a positive balance of 1.3 to 1.9 tons of CO_2 is found. The energy consumption needed to manufacture woven jute of 1 kg will be deducted with the least positive energy balance of 8.7 MJ/kg, or 21.3 MJ/kg [21], because the use of jute fibres results in a positive energy balance. Therefore, less GWP results from the strengthening of jute fibre.

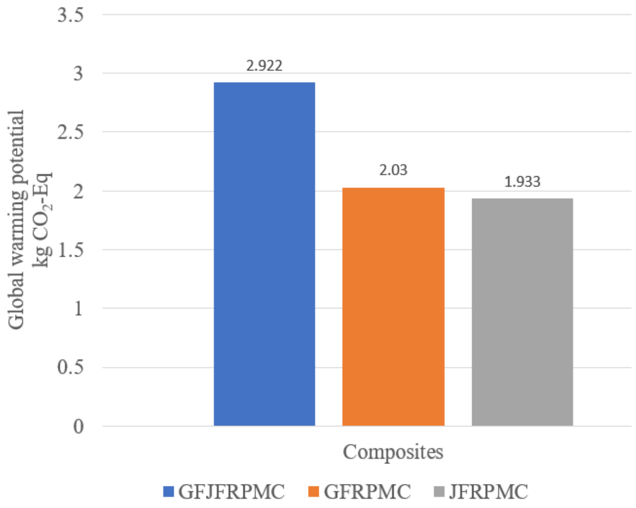

Fig.5 Comparison of Global warming potential for both composites

3.4 Comparison of Ozone depletion potential among the composites

Fig.6 shows the ODP of three composites. Here, GFJFRPMC again showed higher value. JFRPMC shows almost half of the value of GFCFRPMC. So, addition of both jute and glass fiber leads in higher ODP value. According to Victoria et. al. [22] synthetic fiber shows 6.87x10-5 kg CFC-11-eq. compared to jute which shows 4.93x10-7 kg CFC-11-eq. So, from previous literature it can be confirmed that Jute shows lower ODP value compared to glass. Because organic certification for jute is restricted, this analysis assumes that fertilizers and pesticides are employed in agricultural production tasks, which contribute to emissions in this effect category.

3.5 Comparison of Non-Carcinogenic Human Toxicity potential among the composites

From Fig. 7 it is very clear that Jute fiber reinforcement leads to less human toxicity. It shows a value of 2.2069 kg 1,4-DCB-eq. This is the lower than both the GFJFRPMC (3.776 kg 1,4-DCB-eq) and GFRPMC (2.282 kg 1,4-DCB-eq). Glass fiber production includes generation of human toxic substances. Jute fiber production processes are not related to them [23]. Thus, JFRPMC shows the lowest value. Due to the usage of some fertilizer and chemicals in jute fiber such value is shown as a result of reinforcement of jute fiber in the composite.

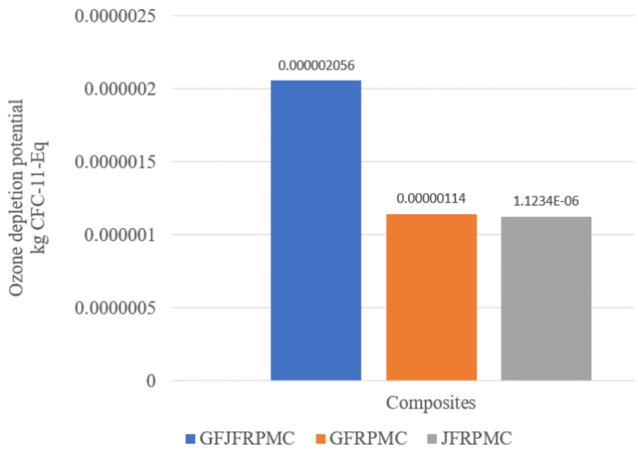

Fig.6 Comparison of Ozone depletion potential for both composites

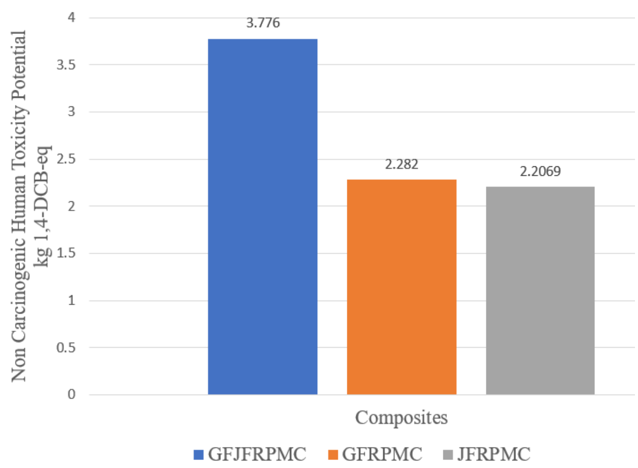

Fig.7 Comparison of Non-Carcinogenic Human Toxicity potential for both composites.

4. Conclusion

Both jute fiber and glass fiber reinforcement have impact on the environment. From the LCA results it is clear that JFRPMC is showing the lowest impact in almost all the impact categories. JFRPMC shows a GWP value of 1.933 kg CO2-eq, ODP value of 1.12x10-6 kg CFC-11-eq & HTP value of 2.2069 kg 1,4-DCB-eq. These values are the lowest if we compare it with other two composites. Glass fiber production processes provide toxic chemical vapors to the environment. Thus, leading to higher value of GFRPMC in terms of GWP (2.03 kg CO2-eq), ODP (0.00000114 kg CFC-11-eq) & HTP (2.282 kg 1,4-DCB-eq). GFJFRPMC shows the highest value in almost all categories. This is because of the contribution of both jute fiber and glass fiber. The contribution analysis shows the contribution of all the materials utilized in producing the GFJFRPMC. Here jute fiber is showing higher value because of the use of pesticides, chemical and other components harmful to the environment. So in conclusion it can be said that JFRPMC is the most environmentally friendly composite among the three.

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References

[1] Z. W. Zhong, "Processes for environmentally friendly and/or cost-effective manufacturing," *Mater. Manuf. Process.*, vol. 36, no. 9, pp. 987–1009, 2021.

[2] R. Balart, N. Montanes, F. Dominici, T. Boronat, and S. Torres-Giner, "Environmentally Friendly Polymers and Polymer Composites," *Materials (Basel).*, vol. 13, no. 21, p. 4892, Oct. 2020.

[3] Y. Pan, Y. Chen, and Q. Shen, "Flexural Mechanical Properties of Functional Gradient Hydroxyapatite Reinforced Polyetheretherketone Biocomposites," *J. Mater. Sci. Technol.*, vol. 32, no. 1, pp. 34–40, 2016.

[4] H. Zhu, B. Wu, D. Li, D. Zhang, and Y. Chen, "Influence of Voids on the Tensile Performance of Carbon/epoxy Fabric Laminates," *J. Mater. Sci. Technol.*, vol. 27, no. 1, pp. 69–73, 2011.

[5] T. Nishino, K. Hirao, M. Kotera, K. Nakamae, and H. Inagaki, *Kenaf reinforced biodegradable composite*, vol. 63, no. 9. 2003.

[6] X. Xu, K. Jayaraman, C. Morin, and N. Pecqueux, "Life cycle assessment of wood-fibre-reinforced polypropylene composites," *J. Mater. Process. Technol.*, vol. 198, no. 1–3, pp. 168–177, 2008.

[7] R. Gujjala, S. Ojha, S. K. Acharya, and S. K. Pal, "Mechanical properties of woven jute-glass hybrid-reinforced epoxy composite," *J. Compos. Mater.*, vol. 48, no. 28, pp. 3445–3455, 2014.

[8] A. Gopinath, M. Senthil Kumar, and A. Elayaperumal, "Experimental investigations on mechanical properties of jute fiber reinforced composites with polyester and epoxy resin matrices," *Procedia Eng.*, vol. 97, pp. 2052–2063, 2014.

[9] M. Brahmakumar, C. Pavithran, and R. M. Pillai, "Coconut fibre reinforced polyethylene composites: Effect of natural waxy surface layer of the fibre on fibre/matrix interfacial bonding and strength of composites," *Compos. Sci. Technol.*, vol. 65, no. 3–4, pp. 563–569, 2005.

[10] R. A. Braga and P. A. A. Magalhaes, "Analysis of the mechanical and thermal properties of jute and glass fiber as reinforcement epoxy hybrid composites," *Mater. Sci. Eng. C*, vol. 56, pp. 269–273, 2015.

[11] K. S. Sangwan, K. Choudhary, and C. Batra, "Environmental impact assessment of a ceramic tile supply chain–a case study," *Int. J. Sustain. Eng.*, vol. 11, no. 3, pp. 211–216, 2018.

[12] M. A. Curran, "Life Cycle Assessment: a review of the methodology and its application to sustainability," *Curr. Opin. Chem. Eng.*, vol. 2, no. 3, pp. 273–277, Aug. 2013.

[13] G. Ingarao, S. Licata, M. Sciortino, D. Planeta, R. Di Lorenzo, and L. Fratini, "Life cycle energy and CO2 emissions analysis of food packaging: an insight into the methodology from an Italian perspective," *Int. J. Sustain. Eng.*, vol. 10, no. 1, pp. 31–43, 2017.

[14] R. K. Malviya, R. K. Singh, R. Purohit, and R. Sinha, "Natural fibre reinforced composite materials: Environmentally better life cycle assessment - A case study," *Mater. Today Proc.*, vol. 26, no. xxxx, pp. 3157–3160, 2019.

[15] M. R. Mansor, M. S. Salit, E. S. Zainudin, N. A. Aziz, and H. Ariff, "Life Cycle Assessment of Natural Fiber Polymer Composites," in *Agricultural Biomass Based Potential Materials*, Cham: Springer International Publishing, 2015, pp. 121–141.

[16] J. Fava *et al.*, "A technical framework for life cycle assessment," *Soc. Environ. Toxicol. Chem.*, no. January, p. 134, 1991.

[17] ISO 14040, "Environmental management — Life cycle assessment — Principles and framework," 2006.

[18] ISO 14044, "Environmental management-Life cycle assessment-Requirements and guidelines Management environnemental-Analyse du cycle de vie-Exigences et lignes directrices," 2006.

[19] G. Campus, "LCA modelling for natural fibre composites Sandra Maria da Luz * and Vitor Magalini Zago de Sousa," vol. 10, no. March 2015, pp. 27–28, 2018.

[20] C. F. Toscano, C. Martin-del-Campo, G. Moeller-Chavez, G. L. de los Santos, J. L. François, and D. R. Fernandez, "Life cycle assessment of a combined-cycle gas turbine with a focus on the chemicals used in water conditioning," *Sustain.*, vol. 11, no. 10, 2019.

[21] N. A. A. and H. A. Muhd Ridzuan Mansor, Mohd Sapuan Salit, Edi Syam Zainudin, "Life Cycle Assessment of Natural Fiber Polymer Composites," *Agric. Biomass Based Potential Mater.*, no. April, pp. 1–505, 2015.

[22] V. Gonzalez, X. Lou, and T. Chi, "Evaluating Environmental Impact of Natural and Synthetic Fibers: A Life Cycle Assessment Approach," *Sustain.*, vol. 15, no. 9, 2023.

[23] M. Ramesh, C. Deepa, L. R. Kumar, M. R. Sanjay, and S. Siengchin, "Life-cycle and environmental impact assessments on processing of plant fibres and its bio-composites: A critical review," *J. Ind. Text.*, vol. 51, no. 4, pp. 5518S-5542S, 2022.

NOMENCLATURE

GWP : Global-warming potential, Kg-CO_2-Eq

ODP : Ozone-depletion potential, Kg-CFC-11-Eq

HTPnc: Non-carcinogenic- human toxicity potential, Kg-1,4-DCB-Eq