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A REVIEW OF THE ENVIRONMENTAL BENEFITS OF NATURAL FIBER COMPOSITES (NFCs): A STEP TOWARD SUSTAINABLE MANUFACTURING

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Abstract

Natural fiber composites have garnered significant attention as a sustainable alternative to traditional synthetic materials due to their environmental benefits. This study reviews the environmental impacts of natural fiber composites, focusing on their lifecycle, resource efficiency, and potential for reducing ecological footprints. Natural fiber composites offer a lightweight design, reducing fuel consumption in transportation and lowering greenhouse gas emissions. Their durability extends product lifespans, reducing resource consumption and waste generation. Additionally, many natural fiber composites are biodegradable or recyclable, promoting sustainable waste management practices. However, challenges remain in optimizing the manufacturing processes to minimize energy consumption and the use of harmful chemicals. Resource depletion and toxicity are also concerns, particularly when non-renewable resources are used, or toxic substances are released during the lifecycle of these composites. To mitigate these impacts, several strategies are recommended, including advancing recycling technologies, exploring alternative materials with lower environmental footprints, improving manufacturing efficiency, and conducting comprehensive lifecycle assessments. The study's results indicate that while natural fiber composites present a promising path towards sustainable manufacturing, careful consideration of their entire lifecycle is essential to maximize their environmental benefits. The development of efficient recycling methods and the adoption of bio-based materials can further enhance the sustainability of these composites.

Keywords: Alternative Materials, Environmental İmpact, Natural Fiber Composites, Recyclability, Sustainable Manufacturing.

INTRODUCTION

In contemporary industrial realms, the imperative to embrace sustainable manufacturing practices has become paramount, spurred by growing concerns over environmental degradation and resource depletion. This paradigm shift has catalyzed a concerted exploration of eco-friendly materials, driving innovation across various sectors. Among these materials, natural fiber composites, derived from replenishable sources such as jute, hemp, flax, and kenaf, have garnered significant attention for their potential to mitigate the environmental impact associated with traditional synthetic composites (Andrew & Dhakal, 2022; Maiti et al., 2022).

The environmental advantages of natural fiber composites have been extensively documented. For instance, reductions in carbon footprint and energy consumption have been demonstrated in various studies (Nathaniel & Adeleye, 2021; Sharma et al., 2021; Usman & Radulescu, 2022). The biodegradability of natural fibers has also been highlighted as a key benefit, offering a more sustainable end-of-life solution compared to synthetic fibers (Arya et al., 2024; Elfaleh et al., 2023). The socio-economic benefits, including the potential for job creation in rural areas, have further underscored the importance of these materials in promoting sustainable development (Falk et al., 2021; Hilson & Maconachie, 2020).

Significant research has been directed towards understanding the life cycle impacts of natural fiber composites. Comparative analyses have revealed that natural fiber composites generally exhibit lower environmental impacts than their synthetic counterparts across various stages of their life cycle, from raw material extraction to end-of-life disposal (Al-Maharma et al., 2022; Malviya et al., 2020; Ramesh et al., 2020). The use of renewable resources and the potential for recycling and biodegradation have been identified as critical factors contributing to the superior environmental performance of natural fiber composites (Rajeshkumar et al., 2021; Suárez et al., 2021; Zhao et al., 2022).

By elucidating the multifaceted environmental benefits of natural fiber composites, this paper aims to contribute to the ongoing discourse on sustainable manufacturing. It is hoped that the insights provided will encourage the increased adoption and integration of these materials into mainstream industrial practices, thereby facilitating a transition towards more sustainable manufacturing processes.

Environmental Impact of Synthetic Composites

Conventional synthetic composites, such as carbon fiber and fiberglass, are predominantly derived from non-renewable petroleum sources. The extraction, processing, and disposal of these materials entail substantial environmental ramifications, encompassing greenhouse gas emissions, energy consumption, and waste generation. Additionally, the persistence of synthetic composites exacerbates long-term environmental degradation and resource depletion. Synthetic composites, engineered by combining two or more materials to create a new substance with improved properties, present a complex environmental picture with both positive and negative aspects.

Table 1: Positive Environmental Impact of Synthetic Composites

Impact	Description
Lightweight Design	Reduces fuel consumption in transportation, consequently lowering greenhouse gas emissions.
Durability	Leads to longer product lifespans, decreasing the frequency of replacements and reducing overall resource consumption.
Recyclability	Allows recycling or repurposing, diminishing the volume of waste sent to landfills and promoting sustainable waste management.
Material Efficiency	Achieves comparable strength or functionality with reduced material usage, translating to diminished resource extraction and a lesser environmental footprint.

Table 2: Negative Environmental Impact of Synthetic Composites

Impact	Description
Manufacturing Process	Entails energy-intensive procedures and the utilization of harmful chemicals, emitting greenhouse gases (e.g., manufacturing carbon fiber).
End-of-Life Disposal	Many composites are not easily biodegradable, and improper disposal can result in environmental pollution and long-term ecological consequences.
Resource Depletion	Relies on non-renewable resources such as petroleum-based polymers or rare metals, leading to resource depletion and environmental degradation.
Toxicity	Contains toxic substances like heavy metals or volatile organic compounds (VOCs), posing risks to human health and the environment if released during manufacturing, usage, or disposal.

Table 3: Mitigation Strategies for Synthetic Composites

Strategy	Description
Recycling and Reuse	Developing technologies for recycling composite materials can reduce the need for new raw materials and minimize waste.
Alternative Materials	Researching and adopting alternative materials with lower environmental impacts, such as bio-based composites or recycled materials, can help mitigate negative effects.
Efficient Manufacturing Processes	Improving manufacturing processes to reduce energy consumption and minimize the use of harmful chemicals can lower the environmental impact.
Lifecycle Assessment	Conducting comprehensive lifecycle assessments can identify opportunities for improvement and guide decision-making towards more sustainable materials and processes.

The environmental impacts of synthetic composites, both positive and negative, have been extensively documented in recent studies. The lightweight design of synthetic composites has been found to contribute significantly to reduced fuel consumption in transportation, which subsequently lowers greenhouse gas emissions (Agarwal et al., 2019; Elsabbagh, 2023; Mohammadi et al., 2022). The exceptional durability of these materials has been noted to extend product lifespans, thereby decreasing the frequency of replacements and reducing overall resource consumption (Mesa et al., 2022). Additionally, the recyclability of certain synthetic composites has been observed to diminish the volume of waste sent to landfills, promoting a more sustainable waste management system (Ferdous et al., 2021; Patti et al., 2020). The material efficiency of synthetic composites has also been highlighted, as less material is required to achieve comparable strength or functionality compared to conventional materials, which translates to diminished resource extraction and a lesser environmental footprint (Andrew & Dhakal, 2022).

Conversely, the negative environmental impacts associated with synthetic composites have raised significant concerns. The production of these materials has been found to entail energy-intensive procedures and the utilization of harmful chemicals, with carbon fiber manufacturing emitting substantial amounts of greenhouse gases (Carmona-Martínez et al., 2024). The challenge of end-of-life disposal has been exacerbated by the non-biodegradability of many synthetic composites, leading to environmental pollution and long-term ecological consequences (Al-Maharma et al., 2022; Andrew & Dhakal, 2022). Resource depletion has also been a critical issue, as the reliance on non-renewable resources such as petroleum-based polymers and rare metals has led to significant environmental degradation (Adekomaya & Majozi, 2022; Mori, 2023). The toxicity of certain composite materials, containing substances like heavy metals or volatile organic compounds (VOCs), has posed risks to human health and the environment if released during manufacturing, usage, or disposal (David & Niculescu, 2021; Pachaiappan et al., 2022).

Mitigation strategies have been proposed and implemented to address these environmental impacts. The development of recycling technologies has been suggested to mitigate the environmental impact by reducing the need for new raw materials and minimizing waste (Krauklis et al., 2021; Spooren et al., 2020). The research and adoption of alternative materials with lower environmental impacts, such as bio-based composites or recycled materials, have been identified as essential steps toward sustainability (Andrew & Dhakal, 2022; Azhar et al., 2022; Suárez et al., 2021). Improvements in manufacturing processes to reduce energy consumption and minimize the use of harmful chemicals have been emphasized as critical for lowering the environmental impact of synthetic composites (Andrew & Dhakal, 2022; Maiti et al., 2022). Furthermore, comprehensive lifecycle assessments of synthetic composites have been recommended to identify opportunities for improvement and guide decision-making towards more sustainable materials and processes (Ead et al., 2021; Rodriguez et al., 2020; Tapper et al., 2020).

The environmental impacts of synthetic composites are multifaceted, encompassing both significant benefits and considerable drawbacks. The positive aspects, such as reduced fuel consumption, extended product lifespans, and material efficiency, must be weighed against the negative impacts of energy-intensive manufacturing, non-biodegradability, resource depletion, and toxicity. Implementing effective mitigation strategies, the long-term sustainability of synthetic composites can be enhanced, contributing to a more sustainable and environmentally friendly future (Ead et al., 2021; Rodriguez et al., 2020; Tapper et al., 2020).

Biodegradability and End-of-Life Management

In contrast to synthetic counterparts, which endure in the environment, natural fiber composites are biodegradable, decomposing into organic matter over time. This characteristic significantly diminishes the environmental impact of waste disposal and facilitates recycling or composting of end-of-life components. Integrating natural fiber composites into product design underscores circular economy principles, curbing environmental pollution associated with landfilling or incineration.

Table 4: SWOT Analysis of Natural Fiber Composites vs. Synthetic Composites

Strengths	Weaknesses
Natural Fiber Composites (NFCs)	**Synthetic Composites**
Renewable and biodegradable	Non-renewable sources
Lower energy consumption	High energy consumption
Reduced carbon footprint	Higher carbon footprint
Biodegradability	Non-biodegradable
Sustainability benefits	Long-term environmental degradation
	Opportunities
Growth in green industries	Development of recycling technologies
Local agricultural economy support	Alternative materials research
Lower material costs	Enhanced efficiency in manufacturing
Versatile applications	Lifecycle assessment for improvement
Threats	Potential challenges for both types
Market competition with synthetics	Regulatory changes impacting materials usage
Performance limitations in some uses	High initial investment for green technologies

The data illustrates that natural fiber composites (NFCs) present significant environmental and socioeconomic advantages compared to synthetic composites. According to recent studies, the production of natural fibers results in significantly lower energy consumption and greenhouse gas emissions compared to the production of synthetic fibers. For example, the cultivation of jute and hemp fibers has been shown to sequester considerable amounts of carbon dioxide, effectively acting as a carbon sink. This characteristic, coupled with the biodegradability of NFCs, results in a substantially lower environmental footprint over their lifecycle.

Moreover, the adoption of NFCs has been associated with positive socioeconomic impacts. Local agricultural economies benefit from the cultivation of natural fibers, promoting rural development and providing diversified income streams for farmers. Data from renewable energy projects indicate that job creation in the green energy sector, encompassing installation, maintenance, and operation, significantly boosts local economies and enhances energy independence.

On the other hand, synthetic composites, despite their performance benefits, pose significant environmental challenges. The energy-intensive manufacturing processes and reliance on non-renewable petroleum sources contribute to higher greenhouse gas emissions and resource depletion. Additionally, the non-biodegradable nature of synthetic composites results in long-term environmental pollution, emphasizing the need for improved recycling technologies and the development of sustainable alternatives.

The SWOT analysis highlights the strengths, weaknesses, opportunities, and threats associated with both natural fiber and synthetic composites. While NFCs offer considerable sustainability benefits, there are challenges related to market competition and performance limitations in certain applications. Conversely, synthetic composites, despite their durability and recyclability, face threats from regulatory changes and the high initial investment required for green technologies.

The transition towards natural fiber composites is supported by both environmental data and socioeconomic considerations. Enhancing recycling technologies, researching alternative materials, and implementing efficient manufacturing processes, the long-term sustainability of composite materials can be significantly improved. The collective efforts of industries, governments, and communities are crucial in achieving a more sustainable and environmentally friendly future.

CONCLUSION

Synthetic composites offer substantial benefits such as lightweight design, durability, and material efficiency, which contribute to reduced fuel consumption and resource conservation. However, their environmental impact, including energy-intensive manufacturing, non-biodegradability, resource depletion, and toxicity, presents significant challenges. To mitigate these impacts, it is crucial to prioritize recycling and reuse technologies, adopt alternative materials with lower environmental footprints, improve manufacturing processes for efficiency and reduced chemical use, and conduct thorough lifecycle assessments. These steps are essential for promoting sustainable practices in composite manufacturing and advancing environmental stewardship across industries. Embracing these strategies will not only mitigate environmental harm but also pave the way for a more sustainable future.

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Author contributions

AZ conceived the idea and framework of the study; HW conducted literature review and data collection; WAW performed data analysis and interpretation; ADD drafted the manuscript and coordinated revisions.

References

1) Adekomaya, O., & Majozi, T. (2022). Promoting natural cycle and environmental resilience: A pathway toward sustainable development. South African Journal of Chemical Engineering, 42, 229–240. https://doi.org/10.1016/j.sajce.2022.09.002

2) Agarwal, J., Sahoo, S., Mohanty, S., & Nayak, S. K. (2019). Progress of novel techniques for lightweight automobile applications through innovative eco-friendly composite materials: A review. Journal of Thermoplastic Composite Materials, 33(7), 978–1013. https://doi.org/10.1177/0892705718815530

3) Al-Maharma, A. Y., Patil, S. P., & Markert, B. (2022). Environmental impact analysis of plant fibers and their composites relative to their synthetic counterparts based on life cycle assessment approach. In Elsevier eBooks (pp. 741–781). https://doi.org/10.1016/b978-0-12-824543-9.00022-0

4) Andrew, J. J., & Dhakal, H. (2022). Sustainable biobased composites for advanced applications: recent trends and future opportunities – A critical review. Composites. Part C, Open Access, 7, 100220. https://doi.org/10.1016/j.jcomc.2021.100220

5) Arya, M., Skrifvars, M., & Khalili, P. (2024). Performance and Life Cycle Assessment of Composites Reinforced with Natural Fibers and End-of-Life Textiles. Journal of Composites Science, 8(6), 196. https://doi.org/10.3390/jcs8060196

6) Azhar, N. N. H., Ang, D. T., Abdullah, R., Harikrishna, J. A., & Cheng, A. (2022). Bio-Based materials riding the wave of sustainability: common misconceptions, opportunities, challenges and the way forward. Sustainability, 14(9), 5032. https://doi.org/10.3390/su14095032

7) Carmona-Martínez, A. A., Rueda, A., & Jarauta-Córdoba, C. A. (2024). Deep decarbonization of the energy intensive manufacturing industry through the bioconversion of its carbon emissions to fuels. Fuel, 371, 131922. https://doi.org/10.1016/j.fuel.2024.131922

8) David, E., & Niculescu, V. (2021). Volatile Organic compounds (VOCs) as environmental pollutants: Occurrence and mitigation using nanomaterials. International Journal of Environmental Research and Public Health/International Journal of Environmental Research and Public Health, 18(24), 13147. https://doi.org/10.3390/ijerph182413147

9) Ead, A. S., Appel, R., Alex, N., Ayranci, C., & Carey, J. P. (2021). Life cycle analysis for green composites: A review of literature including considerations for local and global agricultural use. Journal of Engineered Fibers and Fabrics, 16, 155892502110269. https://doi.org/10.1177/15589250211026940

10) Elfaleh, I., Abbassi, F., Habibi, M., Ahmad, F., Guedri, M., Nasri, M., & Garnier, C. (2023). A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials. Results in Engineering, 19, 101271. https://doi.org/10.1016/j.rineng.2023.101271

11) Elsabbagh, A. (2023). Materials development in transportation industry: Fuel consumption, safety and recycling. Ain Shams Engineering Journal/Ain Shams Engineering Journal, 14(6), 102096. https://doi.org/10.1016/j.asej.2022.102096

12) Falk, J., Angelmahr, M., Schade, W., & Schenk-Mathes, H. (2021). Socio-economic impacts and challenges associated with the electrification of a remote area in rural Tanzania through a mini-grid system. Energy, Ecology and Environment, 6(6), 513–530. https://doi.org/10.1007/s40974-021-00216-3

13) Ferdous, W., Manalo, A., Siddique, R., Mendis, P., Zhuge, Y., Wong, H. S., Lokuge, W., Aravinthan, T., & Schubel, P. (2021). Recycling of landfill wastes (tyres, plastics and glass) in construction – A review on global waste generation, performance, application and future opportunities. Resources, Conservation and Recycling, 173, 105745. https://doi.org/10.1016/j.resconrec.2021.105745

14) Hilson, G., & Maconachie, R. (2020). Artisanal and small-scale mining and the Sustainable Development Goals: Opportunities and new directions for sub-Saharan Africa. Geoforum, 111, 125–141. https://doi.org/10.1016/j.geoforum.2019.09.006

15) Krauklis, A. E., Karl, C. W., Gagani, A. I., & Jørgensen, J. K. (2021). Composite Material Recycling Technology—State-of-the-Art and Sustainable Development for the 2020s. Journal of Composites Science, 5(1), 28. https://doi.org/10.3390/jcs5010028

16) Maiti, S., Islam, M. R., Uddin, M. A., Afroj, S., Eichhorn, S. J., & Karim, N. (2022). Sustainable Fiber-Reinforced Composites: a review. Advanced Sustainable Systems, 6(11). https://doi.org/10.1002/adsu.202200258

17) Malviya, R. K., Singh, R. K., Purohit, R., & Sinha, R. (2020). Natural fibre reinforced composite materials: Environmentally better life cycle assessment – A case study. Materials Today: Proceedings, 26, 3157–3160. https://doi.org/10.1016/j.matpr.2020.02.651

18) Mesa, J. A., Gonzalez-Quiroga, A., Aguiar, M. F., & Jugend, D. (2022). Linking product design and durability: A review and research agenda. Heliyon, 8(9), e10734. https://doi.org/10.1016/j.heliyon.2022.e10734

19) Mohammadi, H., Ahmad, Z., Mazlan, S. A., Johari, M. a. F., Siebert, G., Petrů, M., & Koloor, S. S. R. (2022). Lightweight Glass Fiber-Reinforced Polymer Composite for automotive bumper applications: A review. Polymers, 15(1), 193. https://doi.org/10.3390/polym15010193

20) Mori, R. (2023). Replacing all petroleum-based chemical products with natural biomass-based chemical products: a tutorial review. RSC Sustainability, 1(2), 179–212. https://doi.org/10.1039/d2su00014h

21) Nathaniel, S. P., & Adeleye, N. (2021). Environmental preservation amidst carbon emissions, energy consumption, and urbanization in selected african countries: Implication for sustainability. Journal of Cleaner Production, 285, 125409. https://doi.org/10.1016/j.jclepro.2020.125409

22) Pachaiappan, R., Cornejo-Ponce, L., Rajendran, R., Manavalan, K., Rajan, V. F., & Awad, F. (2022). A review on biofiltration techniques: recent advancements in the removal of volatile organic compounds and heavy metals in the treatment of polluted water. Bioengineered, 13(4), 8432–8477. https://doi.org/10.1080/21655979.2022.2050538

23) Patti, A., Cicala, G., & Acierno, D. (2020). Eco-Sustainability of the textile production: waste recovery and current recycling in the composites world. Polymers, 13(1), 134. https://doi.org/10.3390/polym13010134

24) Rajeshkumar, G., Seshadri, S. A., Devnani, G., Sanjay, Siengchin, S., Maran, J. P., Al-Dhabi, N. A., Karuppiah, P., Mariadhas, V. A., Sivarajasekar, N., & Anuf, A. R. (2021). Environment friendly, renewable and sustainable poly lactic acid (PLA) based natural fiber reinforced composites – A comprehensive review. Journal of Cleaner Production, 310, 127483. https://doi.org/10.1016/j.jclepro.2021.127483

25) Ramesh, M., Deepa, C., Kumar, L. R., Sanjay, & Siengchin, S. (2020). Life-cycle and environmental impact assessments on processing of plant fibres and its bio-composites: A critical review. Journal of Industrial Textiles, 51(4_suppl), 5518S-5542S. https://doi.org/10.1177/1528083720924730

26) Rodriguez, L. J., Peças, P., Carvalho, H., & Orrego, C. E. (2020). A literature review on life cycle tools fostering holistic sustainability assessment: An application in biocomposite materials. Journal of Environmental Management, 262, 110308. https://doi.org/10.1016/j.jenvman.2020.110308

27) Sharma, R., Sinha, A., & Kautish, P. (2021). Does renewable energy consumption reduce ecological footprint? Evidence from eight developing countries of Asia. Journal of Cleaner Production, 285, 124867. https://doi.org/10.1016/j.jclepro.2020.124867

28) Spooren, J., Binnemans, K., Björkmalm, J., Breemersch, K., Dams, Y., Folens, K., González-Moya, M., Horckmans, L., Komnitsas, K., Kurylak, W., Lopez, M., Mäkinen, J., Onisei, S., Oorts, K., Peys, A., Pietek, G., Pontikes, Y., Snellings, R., Tripiana, M., . . . Kinnunen, P. (2020). Near-zero-waste processing of low-grade, complex primary ores and secondary raw materials in Europe: technology development trends. Resources, Conservation and Recycling, 160, 104919. https://doi.org/10.1016/j.resconrec.2020.104919

29) Suárez, L., Castellano, J., Díaz, S., Tcharkhtchi, A., & Ortega, Z. (2021). Are Natural-Based composites sustainable? Polymers, 13(14), 2326. https://doi.org/10.3390/polym13142326

30) Tapper, R. J., Longana, M. L., Norton, A., Potter, K. D., & Hamerton, I. (2020). An evaluation of life cycle assessment and its application to the closed-loop recycling of carbon fibre reinforced polymers. Composites. Part B, Engineering, 184, 107665. https://doi.org/10.1016/j.compositesb.2019.107665

31) Usman, M., & Radulescu, M. (2022). Examining the role of nuclear and renewable energy in reducing carbon footprint: Does the role of technological innovation really create some difference? Science of the Total Environment, 841, 156662. https://doi.org/10.1016/j.scitotenv.2022.156662

32) Zhao, X., Copenhaver, K., Wang, L., Korey, M., Gardner, D. J., Li, K., Lamm, M. E., Kishore, V., Bhagia, S., Tajvidi, M., Tekinalp, H., Oyedeji, O., Wasti, S., Webb, E., Ragauskas, A. J., Zhu, H., Peter, W. H., & Ozcan, S. (2022). Recycling of natural fiber composites: Challenges and opportunities. Resources, Conservation and Recycling, 177, 105962. https://doi.org/10.1016/j.resconrec.2021.105962