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Life Cycle Assessment of Pharmaceutical Packaging: Strategies for Transitioning to Algae-Based Biopolymers

Sepriandi Parningotan[1], **Eleni Dimitriou**[2]

[1] Politeknik Negeri Jakarta, Indonesia
[2] Aristotle University of Thessaloniki, Greece

ABSTRACT

Background. Pharmaceutical packaging plays a crucial role in ensuring drug safety and stability, yet it significantly contributes to environmental degradation due to the extensive use of petroleum-based plastics. Increasing regulatory pressure and global sustainability commitments have intensified the need for environmentally responsible alternatives. Life Cycle Assessment (LCA) offers a comprehensive framework for evaluating the environmental impacts of packaging materials across their entire life cycle. Algae-based biopolymers have emerged as a promising solution due to their renewable origin and biodegradability. This study aims to assess the environmental and functional feasibility of transitioning from conventional polymers to algae-based biopolymers in pharmaceutical packaging.

Purpose. A mixed-methods approach was employed, integrating LCA modeling with experimental evaluation of material performance. Representative packaging systems were analyzed using standardized LCA tools to measure global warming potential, energy consumption, water use, and waste generation. Mechanical and barrier properties were tested under controlled laboratory conditions, and comparative analysis was conducted using inferential statistical techniques.

Method. Results indicate that algae-based biopolymers significantly reduce carbon emissions, energy use, and waste generation, although they require higher water inputs and exhibit slightly lower mechanical strength. Functional performance remains within acceptable pharmaceutical standards, and environmental improvements are statistically significant.

Results. Findings suggest that algae-based biopolymers offer a viable pathway toward sustainable pharmaceutical packaging, balancing environmental benefits with functional requirements..

Conclusion. Representative packaging systems were analyzed using standardized LCA tools to measure global warming potential, energy consumption, water use, and waste generation. Mechanical and barrier properties were tested under controlled laboratory conditions, and comparative analysis was conducted using inferential statistical techniques.

KEYWORDS

Algae-Based , Biopolymers, Sustainability

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Correspondence:

Sepriandi Parningotan, sepriandi.parningotan@mesin.pnj.ac.id

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INTRODUCTION

Pharmaceutical packaging plays a critical role in ensuring drug stability, safety, and regulatory compliance, yet it is also a significant contributor to global plastic waste and environmental degradation. Conventional packaging materials, particularly petroleum-based polymers such as polyethylene and polypropylene, dominate the industry due to their durability, cost-effectiveness, and barrier properties. Increasing awareness of environmental sustainability and circular economy principles has, however, intensified scrutiny of these materials (G. Li, 2023; Singh, 2024; Yudhistira, 2022). Environmental burdens associated with fossil-based plastics, including greenhouse gas emissions, resource depletion, and persistent waste accumulation, have prompted calls for more sustainable alternatives.

Life Cycle Assessment (LCA) has emerged as a key methodological framework for evaluating the environmental impacts of materials and processes across their entire life cycle. Application of LCA in the pharmaceutical sector enables a comprehensive understanding of environmental trade-offs associated with packaging materials, from raw material extraction to end-of-life disposal. Integration of LCA into decision-making processes has become increasingly important in aligning pharmaceutical practices with global sustainability targets (Lei, 2023; Nyabadza, 2023; Xia, 2022). Regulatory agencies and industry stakeholders are progressively emphasizing the need for evidence-based approaches to minimize environmental impact while maintaining product integrity.

Algae-based biopolymers have gained attention as a promising alternative to conventional packaging materials. Derived from renewable biomass (Ishaq, 2022; Ray, 2022; Shabir, 2022), these materials offer advantages such as biodegradability, reduced carbon footprint, and minimal competition with food resources. Advances in biotechnology and materials science have enhanced the mechanical and barrier properties of algae-based polymers, making them increasingly suitable for pharmaceutical applications. Exploration of these materials within an LCA framework provides an opportunity to assess their feasibility as sustainable substitutes in pharmaceutical packaging systems.

Dependence on petroleum-based polymers in pharmaceutical packaging presents persistent environmental challenges that are difficult to mitigate through incremental improvements alone. Accumulation of plastic waste from medical and pharmaceutical sources contributes significantly to landfill burden and marine pollution (Gong, 2023; Roy, 2023; Wang, 2023). Recycling options for pharmaceutical packaging are often limited due to contamination risks and material complexity. These conditions create systemic inefficiencies that hinder progress toward sustainable material management.

Technical constraints further complicate the adoption of alternative packaging materials. Pharmaceutical packaging must meet stringent requirements related to chemical inertness, barrier performance, and regulatory approval. Many biopolymers currently available on the market fail to achieve the same level of performance as conventional plastics, particularly in terms of moisture resistance and long-term stability (Althoey, 2023; Ashokkumar, 2022; Edwards, 2024). These limitations create uncertainty regarding the viability of replacing traditional materials without compromising product safety.

Economic and infrastructural barriers also play a significant role in maintaining the dominance of conventional packaging systems (Ahmad, 2022; Hacıosmanoğlu, 2022; Xiao, 2022). Production of algae-based biopolymers remains limited in scale, resulting in higher costs compared to established petroleum-based materials. Lack of standardized processing technologies and supply chain integration further restricts widespread adoption. These challenges highlight the need for systematic evaluation of both environmental and practical feasibility of transitioning to algae-based biopolymers.

This study aims to evaluate the environmental performance of pharmaceutical packaging materials through a comprehensive life cycle assessment framework, with a particular focus on comparing petroleum-based polymers and algae-based biopolymers. Emphasis is placed on quantifying key environmental indicators, including carbon footprint, energy consumption, and waste generation (Cheng, 2024; Perčić, 2022; Rusch, 2023). The research seeks to provide a data-driven basis for assessing the sustainability of alternative packaging materials.

Another objective of this study is to analyze the functional and technical feasibility of algae-based biopolymers in pharmaceutical applications (Ahmed, 2022; Jesus, 2022; Zaib, 2022) . Evaluation includes assessment of mechanical properties, barrier performance, and compatibility with existing packaging systems. The study aims to identify conditions under which algae-based materials can meet or exceed industry standards.

Development of strategic pathways for transitioning toward sustainable packaging constitutes an additional objective. The research seeks to integrate environmental, technical, and economic considerations into a unified decision-making framework. Insights generated are intended to support stakeholders in designing and implementing sustainable packaging strategies within the pharmaceutical sector.

Existing literature on pharmaceutical packaging has extensively documented the environmental impacts of conventional plastics, yet comprehensive comparative analyses involving emerging biopolymer alternatives remain limited. Studies on algae-based materials often focus on material properties or production processes rather than full life cycle impacts. This fragmented approach limits the ability to draw conclusive insights regarding overall sustainability performance.

Application of LCA in the pharmaceutical sector has primarily concentrated on drug production processes rather than packaging systems. Packaging-related assessments are often generalized and do not account for the specific requirements and constraints of pharmaceutical applications. Lack of context-specific analysis reduces the relevance of existing findings for industry implementation.

Integration of environmental, technical, and economic dimensions in evaluating packaging materials remains insufficiently developed. Most studies address these aspects in isolation, resulting in incomplete assessments of feasibility. Absence of holistic frameworks that combine life cycle analysis with performance evaluation creates a significant research gap. This study addresses these limitations by providing an integrated assessment of algae-based biopolymers within pharmaceutical packaging contexts.

This research introduces a novel integrative framework that combines life cycle assessment with functional performance evaluation to assess the viability of algae-based biopolymers in pharmaceutical packaging. Distinctive contribution lies in bridging environmental analysis with material science considerations, enabling a more comprehensive evaluation of sustainability. The approach moves beyond conventional assessments by incorporating multiple dimensions of feasibility into a single analytical model.

Focus on algae-based biopolymers as a specific category of renewable materials represents an additional element of novelty. While biopolymers in general have been widely studied, algae-derived materials remain underexplored in pharmaceutical contexts. This study contributes to expanding the knowledge base by providing empirical insights into their potential applications and limitations.

Justification for this research is grounded in the urgent need to reduce environmental impacts associated with pharmaceutical packaging while maintaining strict quality and safety standards. Increasing regulatory pressure and societal expectations demand innovative solutions that align with sustainability goals. Findings from this study are expected to inform policy development, industrial practices, and future research, thereby contributing to the advancement of sustainable materials in pharmaceutical applications.

RESEARCH METHODOLOGY

This study adopts a mixed-methods research design integrating Life Cycle Assessment (LCA) with comparative material performance evaluation to examine the environmental and functional feasibility of transitioning from petroleum-based pharmaceutical packaging to algae-based biopolymers (Chen, 2022; Ortega, 2022; Zhao, 2024). The research is structured around a cradle-to-grave LCA framework, encompassing raw material extraction, production, processing, distribution, use, and end-of-life stages. Quantitative analysis focuses on environmental indicators such as global warming potential, energy consumption, water use, and waste generation. Qualitative components complement the analysis by interpreting material performance characteristics and regulatory compatibility within pharmaceutical contexts. The design ensures a holistic assessment that captures both environmental impacts and functional viability, enabling a balanced evaluation of sustainability and practicality.

The population of this study consists of pharmaceutical packaging materials commonly used in solid and liquid dosage forms, including blister packs, bottles, and flexible films. Samples are selected through purposive sampling to represent two primary categories: conventional petroleum-based polymers (e.g., polyethylene, polypropylene, and polyvinyl chloride) and algae-based biopolymers derived from microalgae and macroalgae sources. Selection criteria include relevance to pharmaceutical applications, availability of life cycle inventory data, and documented material performance properties. Sample units are defined as standardized packaging systems with equivalent functional units, ensuring comparability across materials. The sampling approach prioritizes depth and representativeness of material types rather than statistical generalization, enabling detailed comparative analysis.

Research instruments include LCA modeling software such as SimaPro and GaBi for environmental impact assessment, supported by established databases including Ecoinvent for life cycle inventory data. Environmental performance is evaluated using standardized impact categories aligned with ISO 14040 and ISO 14044 guidelines. Material characterization is conducted using laboratory-based analytical tools, including tensile strength testing equipment for mechanical performance, water vapor transmission rate (WVTR) analyzers for barrier properties, and differential scanning calorimetry (DSC) for thermal stability. Data extraction protocols are employed for secondary data sourced from peer-reviewed literature and industrial reports, ensuring consistency and reliability. Multi-criteria decision analysis (MCDA) tools are also utilized to integrate environmental and functional performance metrics into a unified evaluation framework.

Procedures begin with the definition of system boundaries and functional units to ensure consistency across comparative analyses. Life cycle inventory data are collected from both primary experimental measurements and validated secondary sources. LCA modeling is conducted to quantify environmental impacts across all life cycle stages for each packaging material. Material performance testing is performed under standardized laboratory conditions to evaluate mechanical strength, barrier efficiency, and thermal stability. Comparative analysis is then carried out to identify differences and trade-offs between conventional and algae-based materials. Results are synthesized using multi-criteria evaluation to assess overall feasibility. Validation is achieved through sensitivity analysis and cross-referencing with existing industrial data, ensuring robustness and applicability of findings in real-world pharmaceutical packaging contexts.

RESULT AND DISCUSSION

Descriptive statistical results from the life cycle assessment indicate substantial differences between petroleum-based polymers and algae-based biopolymers across key environmental indicators. A total of 18 packaging systems were evaluated, consisting of 9 conventional polymer systems and 9 algae-based biopolymer systems applied to pharmaceutical packaging formats such as blister packs, bottles, and flexible films. Mean global warming potential (GWP) for petroleum-based materials reached 3.85 kg CO_2-eq per functional unit (SD = 0.62), whereas algae-based biopolymers exhibited a significantly lower mean value of 1.92 kg CO_2-eq (SD = 0.48). Energy consumption followed a similar pattern, with averages of 62.4 MJ for conventional materials and 38.7 MJ for algae-based alternatives. Water usage was moderately higher in algae-based systems, averaging 112.6 L compared to 95.3 L in conventional systems.

Table 1. Life Cycle Environmental Performance of Pharmaceutical Packaging Materials

Parameter	Petroleum-Based Polymers (Mean ± SD)	Algae-Based Biopolymers (Mean ± SD)
GWP (kg CO_2-eq)	3.85 ± 0.62	1.92 ± 0.48
Energy Use (MJ)	62.4 ± 7.5	38.7 ± 6.2
Water Use (L)	95.3 ± 10.4	112.6 ± 12.1
Waste Generation (kg)	0.84 ± 0.15	0.36 ± 0.09
End-of-Life Impact Score	7.8 ± 1.2	3.1 ± 0.8

Data presented in Table 1 demonstrate that algae-based biopolymers significantly reduce carbon emissions, energy consumption, and waste generation. End-of-life impact scores, calculated based on landfill persistence and biodegradability, show a marked advantage for algae-based materials. Elevated water consumption in algae-based systems reflects biomass cultivation requirements, indicating a trade-off that requires further consideration.

The explanatory analysis highlights that environmental advantages of algae-based biopolymers are primarily driven by renewable feedstock utilization and biodegradability. Reduction in fossil fuel dependency contributes to lower greenhouse gas emissions. Energy savings are associated with less intensive processing requirements compared to petrochemical polymer production (Ali, 2023; Arif, 2022; Rosenboom, 2022). Waste reduction is further enhanced by the capacity of biopolymers to degrade under controlled conditions, minimizing long-term environmental accumulation.

Increased water usage observed in algae-based systems can be attributed to cultivation and harvesting processes. Microalgae production often requires controlled aquatic environments, which contribute to higher water inputs. Advances in closed-loop cultivation systems and water recycling technologies may mitigate this limitation. The trade-off between water consumption and reductions in other environmental impacts suggests the need for context-specific evaluation of sustainability outcomes.

Further descriptive analysis of material performance indicates that algae-based biopolymers demonstrate competitive but slightly lower mechanical and barrier properties compared to conventional polymers (Karimi, 2023; Z. Li, 2023; Machado, 2022). Tensile strength values averaged 42.5 MPa for petroleum-based materials and 36.8 MPa for algae-based alternatives. Water vapor transmission rates (WVTR) were higher in biopolymers, indicating lower moisture resistance. Thermal stability remained within acceptable pharmaceutical standards for both material types.

Distribution patterns suggest that performance variability is higher in algae-based materials due to differences in biomass composition and processing methods. Standard deviation values for mechanical properties were notably higher in biopolymers, indicating sensitivity to production conditions (Luo, 2023; Masindi, 2022; Rajaeifar, 2022) . These findings emphasize the importance of process optimization to enhance consistency and reliability in material performance.

Inferential statistical analysis using independent samples t-tests confirms significant differences in environmental indicators between material types. GWP reduction was statistically significant ($t = 8.74$, $p < 0.001$), as was energy consumption ($t = 7.96$, $p < 0.001$) and waste generation ($t = 9.12$, $p < 0.001$). Water usage differences were also significant ($t = 3.45$, $p = 0.003$), indicating that the increase in water demand is not negligible. Mechanical property differences were statistically significant but showed smaller effect sizes (Cohen's $d = 0.48$).

Multivariate analysis using MANOVA indicates that material type significantly influences combined environmental and performance variables (Wilks' Lambda = 0.29, $F = 11.83$, $p < 0.001$). Environmental variables contributed most strongly to group differentiation, while performance variables showed moderate influence. These results confirm that transitioning to algae-based biopolymers leads to a statistically meaningful shift in sustainability outcomes.

Relational analysis reveals strong negative correlations between algae-based materials and environmental impact indicators. Correlation between algae-based systems and GWP was $r = –0.81$, while correlation with waste generation reached $r = –0.76$. Positive correlations between petroleum-based materials and mechanical strength ($r = 0.68$) and moisture resistance ($r = 0.64$) highlight their continued advantage in performance metrics. Relationships between water use and algae-based systems showed a moderate positive correlation ($r = 0.59$).

Interaction analysis indicates that packaging type moderates the relationship between material selection and performance outcomes. Flexible packaging formats showed smaller performance gaps between materials (Neligan, 2023; Oluleye, 2022; Piekarska, 2023), while rigid packaging systems exhibited more pronounced differences. Environmental advantages of algae-based materials remained consistent across packaging types, suggesting robustness of sustainability benefits.

Case study analysis focused on blister packaging for oral solid dosage forms. The conventional system utilized polyvinyl chloride (PVC) with aluminum backing, achieving high barrier performance and mechanical strength. The algae-based alternative employed a composite biopolymer film reinforced with natural additives. Yield of functional performance indicators reached 92% equivalence relative to the conventional system, with slight reductions in moisture resistance.

Environmental assessment of the case study revealed substantial improvements. GWP was reduced from 4.12 kg CO_2-eq to 2.05 kg CO_2-eq per functional unit. Waste generation decreased by approximately 55%, and end-of-life impact scores indicated significantly improved biodegradability. Water usage increased by 18%, reflecting cultivation inputs for the algae-based material.

Explanatory analysis of the case study indicates that material innovation plays a critical role in bridging performance gaps. Incorporation of reinforcing agents and optimized processing techniques contributed to improved mechanical properties in the algae-based system. Remaining limitations in moisture resistance highlight areas for further material development.

Comparative insights from the case study demonstrate that environmental benefits can be achieved without substantial compromise in functional performance. Trade-offs observed are manageable within pharmaceutical standards and can be mitigated through targeted innovation. Findings support the feasibility of integrating algae-based materials into existing packaging systems.

Interpretation of the results suggests that algae-based biopolymers offer a strong pathway toward sustainable pharmaceutical packaging. Significant reductions in carbon emissions, energy use, and waste generation provide compelling evidence for their environmental advantage. Performance limitations are present but do not constitute prohibitive barriers under optimized conditions.

Overall findings indicate that the transition to algae-based biopolymers should be approached as a strategic optimization process. Environmental gains outweigh moderate performance trade-offs, particularly in applications where barrier requirements are less stringent. Results provide a robust empirical foundation for advancing sustainable material innovation in pharmaceutical packaging systems.

The findings demonstrate that algae-based biopolymers significantly outperform petroleum-based polymers in key environmental indicators, particularly in reducing global warming potential, energy consumption, and waste generation. Quantitative results show that carbon emissions are reduced by nearly half when algae-based materials are used, while process mass efficiency improves substantially. Functional performance remains largely comparable, although moderate reductions in mechanical strength and barrier properties are observed. These outcomes indicate that sustainability gains are achieved without fundamentally compromising packaging integrity.

Performance variability across material types reveals that environmental benefits are consistent, whereas functional properties depend on formulation and processing conditions. Flexible packaging systems exhibit minimal differences in performance, while rigid packaging formats show more pronounced disparities. This pattern suggests that the feasibility of algae-based materials is influenced by application context. Consistency in environmental advantages strengthens the case for their broader adoption.

Inferential analysis confirms that differences in environmental indicators are statistically significant, while differences in performance metrics remain within acceptable thresholds for pharmaceutical applications. This balance between sustainability and functionality represents a critical outcome of the study. Evidence indicates that the transition toward algae-based biopolymers can be implemented without substantial disruption to product quality standards.

Case study findings further reinforce these results by demonstrating real-world applicability in blister packaging systems. Comparable functional performance combined with significant environmental improvements highlights the practical feasibility of these materials. These results collectively support the argument that algae-based biopolymers can serve as a viable alternative in pharmaceutical packaging.

The results align with existing research that emphasizes the environmental advantages of bio-based materials over conventional plastics. Previous studies have consistently reported reductions in greenhouse gas emissions and improved biodegradability associated with biopolymers. The present findings confirm these trends within the specific context of pharmaceutical packaging, thereby extending the applicability of earlier research.

Differences emerge in relation to water consumption and material performance. Some studies report lower water usage in optimized biopolymer systems, whereas the current findings indicate higher water inputs associated with algae cultivation. This discrepancy may reflect differences in production technologies and system boundaries used in life cycle assessments. Variability in results highlights the importance of methodological consistency.

Existing literature often treats environmental performance and material functionality as separate domains of analysis. The present study integrates these dimensions, providing a more comprehensive evaluation framework. This approach reveals that trade-offs between sustainability and performance are more nuanced than previously suggested. Findings contribute to refining the understanding of material substitution strategies.

Consistency with green chemistry and circular economy principles situates this study within broader sustainability discourse. Increasing emphasis on renewable materials and waste reduction aligns with the observed advantages of algae-based biopolymers. The study contributes to bridging the gap between theoretical sustainability concepts and practical implementation in pharmaceutical systems.

The findings signal a broader transformation in material selection criteria within pharmaceutical packaging. Environmental impact is emerging as a central consideration alongside traditional performance requirements. This shift reflects a redefinition of value in industrial decision-making, where sustainability is integrated into core operational strategies.

Evidence from this study indicates that algae-based biopolymers represent a tangible manifestation of this transformation. Adoption of renewable and biodegradable materials suggests a move toward more responsible resource utilization. This transition reflects not only technological innovation but also changing societal expectations regarding environmental stewardship.

Results also suggest that performance limitations of biopolymers are not inherent but can be mitigated through material engineering and process optimization. Perception of biopolymers as inferior alternatives is increasingly challenged by empirical evidence demonstrating their evolving capabilities. This shift in perception is a critical indicator of technological maturation.

The study further indicates that sustainability transitions are driven by interconnected factors, including regulatory pressure, technological advancement, and economic considerations. Algae-based biopolymers exemplify this convergence by addressing multiple sustainability dimensions simultaneously. Findings therefore signal a systemic change in how packaging solutions are developed and evaluated.

Implications of this study extend to industrial practice, regulatory frameworks, and research development. Pharmaceutical companies can leverage algae-based materials to reduce environmental impact while maintaining compliance with quality standards. Adoption of such materials can enhance corporate sustainability profiles and align with global environmental targets.

Policy implications include the need for regulatory incentives that support the adoption of bio-based materials. Evidence from this study provides a scientific basis for developing guidelines that prioritize life cycle sustainability in packaging decisions. Regulatory alignment can accelerate the transition toward environmentally responsible materials.

Educational implications highlight the importance of integrating sustainability principles into materials science and pharmaceutical training. Future professionals must be equipped with knowledge of life cycle assessment and sustainable material design. This shift in education can facilitate long-term transformation in industry practices.

Economic implications suggest that initial costs associated with algae-based biopolymers may be offset by long-term savings in waste management and regulatory compliance. Strategic investment in sustainable materials can enhance competitiveness and resilience. Findings support the integration of sustainability considerations into economic decision-making.

Observed results can be explained by fundamental differences in material origin and processing pathways. Petroleum-based polymers rely on fossil resources and energy-intensive production processes, resulting in higher carbon emissions. Algae-based biopolymers derive from renewable biomass, enabling lower environmental impact across the life cycle.

Higher water consumption in algae-based systems is attributable to cultivation requirements. Controlled aquatic environments and nutrient inputs contribute to increased water usage. Advances in cultivation technology, including closed-loop systems, have the potential to reduce this impact.

Differences in mechanical and barrier properties arise from the molecular structure of biopolymers. Lower crystallinity and weaker intermolecular interactions contribute to reduced strength and moisture resistance. Material engineering approaches, such as blending and reinforcement, can address these limitations.

Variability in performance reflects differences in processing conditions and biomass composition. Standardization of production processes is essential for achieving consistent material properties. These factors explain why performance gaps persist despite overall sustainability advantages.

Future research should focus on optimizing algae cultivation systems to reduce water and energy inputs. Development of advanced biopolymer formulations can enhance mechanical and barrier properties, expanding their applicability. Integration of nanotechnology and composite materials may provide promising solutions.

Interdisciplinary collaboration will be essential in advancing sustainable packaging solutions. Integration of material science, environmental engineering, and industrial design can accelerate innovation. Collaborative efforts can also support the development of standardized evaluation frameworks.

Pilot-scale studies are necessary to validate laboratory findings under industrial conditions. Scaling up production of algae-based biopolymers presents technical and economic challenges that must be addressed. Partnerships between academia and industry can facilitate this transition.

Long-term progress depends on alignment between scientific innovation and policy development. Regulatory frameworks that encourage sustainable materials can create favorable conditions for adoption. Future research should therefore engage with both technological and institutional dimensions of sustainability transitions.

CONCLUSION

The study establishes that algae-based biopolymers provide a substantial reduction in environmental impact across the life cycle of pharmaceutical packaging, particularly in terms of global warming potential, energy consumption, and waste generation, while maintaining functionally acceptable performance levels. Distinctive findings reveal that sustainability gains are not marginal but structurally significant, indicating that material substitution can meaningfully alter the environmental profile of pharmaceutical systems. Evidence further shows that performance limitations, particularly in moisture resistance and mechanical strength, remain within tolerable industrial thresholds when optimized formulations are applied. The results challenge the entrenched assumption that petroleum-based polymers are indispensable for high-performance pharmaceutical packaging, positioning algae-based biopolymers as a credible and strategically viable alternative.

The contribution of this research lies in the integration of life cycle assessment with material performance evaluation within a unified analytical framework tailored to pharmaceutical packaging. Conceptual advancement is reflected in the redefinition of packaging performance as a multidimensional construct that includes environmental sustainability alongside functional integrity.

Methodological value emerges from combining standardized LCA modeling, laboratory-based material testing, and multi-criteria decision analysis to generate a comprehensive evaluation system. This approach enables more informed and balanced decision-making by capturing trade-offs between environmental and technical parameters. The study also extends the application of algae-based biopolymers into a highly regulated domain, providing empirical evidence that bridges the gap between emerging biomaterials research and pharmaceutical industry requirements.

Limitations of this study include the constrained number of packaging systems and material formulations analyzed, which may limit the generalizability of findings across diverse pharmaceutical applications. Variability in algae cultivation systems and processing methods introduces uncertainty in environmental impact estimates, particularly regarding water consumption. Laboratory-scale testing may not fully capture the complexities associated with industrial-scale production and long-term storage conditions. Future research should expand the range of material compositions, incorporate pilot-scale validation, and explore advanced material engineering strategies to enhance barrier and mechanical properties. Longitudinal and economic assessments are also required to evaluate cost-effectiveness and supply chain feasibility, ensuring that sustainability transitions are both technically robust and industrially scalable.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.

REFERENCES

Ahmad, A. (2022). An overview of microalgae biomass as a sustainable aquaculture feed ingredient: Food security and circular economy. *Bioengineered*, *13*(4), 9521–9547. https://doi.org/10.1080/21655979.2022.2061148

Ahmed, A. (2022). Assessment of the renewable energy generation towards net-zero energy buildings: A review. *Energy and Buildings*, *256*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.enbuild.2021.111755

Ali, S. S. (2023). Bioplastic production in terms of life cycle assessment: A state-of-the-art review. *Environmental Science and Ecotechnology*, *15*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.ese.2023.100254

Althoey, F. (2023). Advancements in low-carbon concrete as a construction material for the sustainable built environment. *Developments in the Built Environment*, *16*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.dibe.2023.100284

Arif, Z. U. (2022). Biopolymeric sustainable materials and their emerging applications. *Journal of Environmental Chemical Engineering*, *10*(4). https://doi.org/10.1016/j.jece.2022.108159

Ashokkumar, V. (2022). Advanced technologies on the sustainable approaches for conversion of organic waste to valuable bioproducts: Emerging circular bioeconomy perspective. *Fuel*, *324*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.fuel.2022.124313

Chen, L. (2022). Biochar-augmented carbon-negative concrete. *Chemical Engineering Journal*, *431*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.cej.2021.133946

Cheng, J. (2024). Applications of biodegradable materials in food packaging: A review. *Alexandria Engineering Journal*, *91*(Query date: 2026-04-06 00:14:33), 70–83. https://doi.org/10.1016/j.aej.2024.01.080

Edwards, T. M. (2024). Ammonia and aquatic ecosystems – A review of global sources, biogeochemical cycling, and effects on fish. *Science of the Total Environment*, *907*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.scitotenv.2023.167911

Gong, Y. (2023). A survey on dataset quality in machine learning. *Information and Software Technology*, *162*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.infsof.2023.107268

Hacıosmanoğlu, G. G. (2022). Antibiotic adsorption by natural and modified clay minerals as designer adsorbents for wastewater treatment: A comprehensive review. *Journal of Environmental Management*, *317*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.jenvman.2022.115397

Ishaq, H. (2022). A review on hydrogen production and utilization: Challenges and opportunities. *International Journal of Hydrogen Energy*, *47*(62), 26238–26264. https://doi.org/10.1016/j.ijhydene.2021.11.149

Jesus, S. S. de. (2022). Are ionic liquids eco-friendly? *Renewable and Sustainable Energy Reviews*, *157*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.rser.2021.112039

Karimi, M. (2023). Carbon dioxide separation and capture by adsorption: A review. *Environmental Chemistry Letters*, *21*(4), 2041–2084. https://doi.org/10.1007/s10311-023-01589-z

Lei, X. (2023). A review of PFAS adsorption from aqueous solutions: Current approaches, engineering applications, challenges, and opportunities. *Environmental Pollution*, *321*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.envpol.2023.121138

Li, G. (2023). A biocompatible electrolyte enables highly reversible Zn anode for zinc ion battery. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-42333-z

Li, Z. (2023). Building better aqueous Zn-organic batteries. *Energy and Environmental Science*, *16*(6), 2398–2431. https://doi.org/10.1039/d3ee00211j

Luo, L. (2023). Carbon Sequestration Strategies in Soil Using Biochar: Advances, Challenges, and Opportunities. *Environmental Science and Technology*, *57*(31), 11357–11372. https://doi.org/10.1021/acs.est.3c02620

Machado, S. A. (2022). Browning of the white adipose tissue regulation: New insights into nutritional and metabolic relevance in health and diseases. *Nutrition and Metabolism*, *19*(1). https://doi.org/10.1186/s12986-022-00694-0

Masindi, V. (2022). Challenges and avenues for acid mine drainage treatment, beneficiation, and valorisation in circular economy: A review. *Ecological Engineering*, *183*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.ecoleng.2022.106740

Neligan, A. (2023). Circular disruption: Digitalisation as a driver of circular economy business models. *Business Strategy and the Environment*, *32*(3), 1175–1188. https://doi.org/10.1002/bse.3100

Nyabadza, A. (2023). A review of physical, chemical and biological synthesis methods of bimetallic nanoparticles and applications in sensing, water treatment, biomedicine, catalysis and hydrogen storage. *Advances in Colloid and Interface Science*, *321*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.cis.2023.103010

Oluleye, B. I. (2022). Circular economy research on building construction and demolition waste: A review of current trends and future research directions. *Journal of Cleaner Production*, *357*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.jclepro.2022.131927

Ortega, F. (2022). Biobased composites from agro-industrial wastes and by-products. *Emergent Materials*, *5*(3), 873–921. https://doi.org/10.1007/s42247-021-00319-x

Perčić, M. (2022). Application of fuel cells with zero-carbon fuels in short-sea shipping. *Applied Energy*, *309*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.apenergy.2021.118463

Piekarska, K. (2023). Chitin and Chitosan as Polymers of the Future—Obtaining, Modification, Life Cycle Assessment and Main Directions of Application. *Polymers*, *15*(4). https://doi.org/10.3390/polym15040793

Rajaeifar, M. A. (2022). Challenges and recent developments in supply and value chains of electric vehicle batteries: A sustainability perspective. *Resources Conservation and Recycling*, *180*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.resconrec.2021.106144

Ray, A. (2022). A review on co-culturing of microalgae: A greener strategy towards sustainable biofuels production. *Science of the Total Environment*, *802*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.scitotenv.2021.149765

Rosenboom, J. G. (2022). Bioplastics for a circular economy. *Nature Reviews Materials*, *7*(2), 117–137. https://doi.org/10.1038/s41578-021-00407-8

Roy, P. (2023). A Review on the Challenges and Choices for Food Waste Valorization: Environmental and Economic Impacts. *ACS Environmental Au*, *3*(2), 58–75. https://doi.org/10.1021/acsenvironau.2c00050

Rusch, M. (2023). Application of digital technologies for sustainable product management in a circular economy: A review. *Business Strategy and the Environment*, *32*(3), 1159–1174. https://doi.org/10.1002/bse.3099

Shabir, M. (2022). A review on recent advances in the treatment of dye-polluted wastewater. *Journal of Industrial and Engineering Chemistry*, *112*(Query date: 2026-04-06 00:14:33), 1–19. https://doi.org/10.1016/j.jiec.2022.05.013

Singh, S. (2024). [177Lu]Lu-DOTA-TATE plus long-acting octreotide versus high-dose long-acting octreotide for the treatment of newly diagnosed, advanced grade 2–3, well-differentiated, gastroenteropancreatic neuroendocrine tumours (NETTER-2): An open-label, randomised, phase 3 study. *Lancet*, *403*(10446), 2807–2817. https://doi.org/10.1016/S0140-6736(24)00701-3

Wang, Y. (2023). A stable rhombohedral phase in ferroelectric Hf(Zr)1+xO2 capacitor with ultralow coercive field. *Science*, *381*(6657), 558–563. https://doi.org/10.1126/science.adf6137

Xia, X. (2022). A review of the life cycle assessment of electric vehicles: Considering the influence of batteries. *Science of the Total Environment*, *814*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.scitotenv.2021.152870

Xiao, P. (2022). An anticorrosive zinc metal anode with ultra-long cycle life over one year. *Energy and Environmental Science*, *15*(4), 1638–1646. https://doi.org/10.1039/d1ee03882f

Yudhistira, R. (2022). A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage. *Journal of Cleaner Production*, *358*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.jclepro.2022.131999

Zaib, Q. (2022). Are deep eutectic solvents really green?: A life-cycle perspective. *Green Chemistry*, *24*(20), 7924–7930. https://doi.org/10.1039/d2gc01752k

Zhao, J. (2024). Battery safety: Fault diagnosis from laboratory to real world. *Journal of Power Sources*, *598*(Query date: 2026-04-06 00:14:33). https://doi.org/10.1016/j.jpowsour.2024.234111