Journal of Biomaterials
2025, Vol. 9, No. 1, pp. 8-15
https://doi.org/10.11648/j.jb.20250901.12

Review Article

Bio-based and Sustainable Food Packaging Technology: Relevance, Challenges and Prospects

Alebachew Molla Nibret*

Department of Biotechnology, Wolaita Sodo University, Wolaita, Ethiopia

Abstract

Bio-based and sustainable food packaging technology has emerged as a crucial solution to address the environmental impact of conventional plastic packaging. Bio-based food packaging represents a vital advancement toward environmentally sustainable solutions in the food industry. These materials, derived from renewable biological sources such as polysaccharides, proteins, and biopolymers, offer significant benefits including reduced dependency on fossil fuels, biodegradability, and potential for compost ability, all contributing to lowered plastic pollution and carbon footprint. Their capacity to protect and preserve food while minimizing environmental impact aligns closely with global sustainability goals and growing consumer demand for eco-friendly products. Nevertheless, challenges remain in performance optimization, cost competitiveness, scalability, and regulatory acceptance that must be overcome for broader implementation. Addressing these obstacles requires continued research into enhancing mechanical and barrier properties, innovation in active and intelligent packaging technologies, and robust policy support to foster market adoption. Collaboration across industry, academia, and policymakers will be crucial to accelerating these developments. Looking ahead, the integration of emerging materials such as nanocomposites, advances in circular economy models, and stronger regulatory frameworks offer promising pathways to sustainable growth. Future research focusing on lifecycle impact reduction, multifunctional materials, and consumer education will ultimately drive the transition to a more sustainable packaging future. By embracing these innovations and commitments, bio-based food packaging stands to play a pivotal role in reducing environmental burdens while supporting food quality and safety. The review also discusses major challenges including material performance limitations, scalability, cost, and regulatory aspects. Finally, it highlights future prospects involving advanced bio-composites, active and intelligent packaging innovations, and circular economy integration, emphasizing the importance of multidisciplinary strategies for transitioning towards sustainable food packaging systems.

Keywords

Bio-based Polymers, Sustainable Packaging, Biodegradability, Active Packaging, Intelligent Packaging, Life Cycle Assessment, Circular Economy, Food Preservation

1. Introduction

Food packaging plays a critical role in protecting food products from contamination, extending shelf life, and ensuring safe transportation and storage [1, 2]. Traditionally, packaging materials have been derived from non-renewable petroleum-based plastics, which offer desirable mechanical and barrier properties but pose significant environmental

*Corresponding author: alexbm2127@gmail.com (Alebachew Molla Nibret)

Received: 8 September 2025; **Accepted:** 18 September 2025; **Published:** 10 October 2025

challenges due to their non-biodegradability and contribution to plastic waste accumulation [3, 4].

The widespread use of conventional packaging materials has led to serious environmental impacts, including pollution of land and water bodies, greenhouse gas emissions, and resource depletion [5]. These concerns have driven the search for more eco-friendly and sustainable alternatives that can reduce the environmental footprint of food packaging [6].

Bio-based and sustainable packaging materials, derived from renewable biological sources, present a promising solution to these issues by offering biodegradability, used as a compost, and reduced reliance on fossil resources [6]. Their development aligns with global sustainability goals and consumer demand for environmentally responsible products.

This review aims to comprehensively examine bio-based food packaging systems, focusing on their material properties, challenges in practical application, and future prospects for sustainable food packaging solutions. The objective is to provide insights into the current state of bio-based packaging, identify key hurdles, and explore innovative trends that can drive sustainable development in the food packaging industry.

2. Overview of Bio-based Packaging Materials

Bio-based packaging materials are derived wholly or partly from renewable biological sources such as plants, animals, and microorganisms, making them distinct from traditional fossil fuel-based plastics [7]. These materials can be naturally occurring polymers extracted directly from biomass or synthesized chemically from biomass-derived monomers [8]. It is important to differentiate bio-based materials, which refer to their origin, from biodegradable materials, which relate to their capacity to degrade under environmental conditions. The broad classification of bio-based materials includes polysaccharides, proteins, and biopolymers like polyhydroxy alkenoates (PHA) and polylactic acid (PLA) [7]. Polysaccharides such as starch, cellulose, and chitosan are abundant and commonly used due to their film-forming abilities and biodegradability [9]. Proteins sourced from plants (soy, pea) and animals (whey) offer good mechanical properties and can form edible films [10, 11]. Biopolymers like PLA and PHA are synthesized through microbial fermentation or polymerization of biomass-derived monomers and are prized for their biodegradability and suitability for various packaging formats [12, 13].

Among the most widely studied bio-based packaging materials are starch, used in films and composites; cellulose, employed in paper, cardboard, and nanocellulose films; and chitosan, valued for its antimicrobial properties [14, 15]. PLA and PHA represent prominent bioplastics with increasing commercial applications due to their good mechanical strength and the ability used as a compost [12]. Additionally, other bio-based plastics such as polyethylene furanoate (PEF) and bio-based polyethylene (Bio-PE) are emerging alternatives that offer improved barrier properties and sustainability potential [16]. Despite their many advantages, bio-based materials often require modifications or blending with other materials to enhance barrier and mechanical properties to meet the rigorous demands of food packaging applications [7]. Overall, bio-based packaging materials represent a diverse and growing class of sustainable alternatives that support the transition towards environmentally responsible food packaging systems.

3. Properties of Bio-based Packaging Materials

Bio-based packaging materials exhibit diverse properties that determine their suitability for food packaging applications. In terms of mechanical properties, these materials generally offer varying degrees of strength and flexibility, which are critical for maintaining package integrity during handling, storage, and transportation [17, 18]. For instance, polylactic acid (PLA), one of the most widely used bio-based polymers, demonstrates tensile strength comparable to conventional petroleum-based plastics but tends to be brittle with low plastic deformation unless plasticizers or blending agents are incorporated to enhance flexibility [19, 20]. Materials like Mater-Bi (a starch-based biopolymer) show more ductility but typically lower mechanical strength than synthetic films, though their properties can be improved using additives such as nano-clays or blending with other polymers [21, 22]. Protein-based films, including those derived from soy or whey, also exhibit tunable mechanical properties influenced by treatments like heat or the addition of plasticizers, which can increase tensile strength and elongation.

Barrier properties are another essential characteristic of bio-based packaging material, affecting their ability to protect food from moisture, oxygen, and other gases that can lead to spoilage [23]. Generally, bio-based polymers tend to have higher gas and moisture permeability compared to synthetic plastics, which can limit their use for certain high-barrier applications [4]. However, treatments such as coating with bio-nanocomposites or modifying the polymer structure have been employed to enhance barrier effectiveness [18]. For example, protein films incorporating nano-clays have shown reductions in water vapor permeability while improving tensile strength, making them more suitable for moisture-sensitive food products.

Biodegradability and ability used as a compost are key advantages of bio-based packaging materials, offering environmental benefits by reducing persistent plastic waste. Many bio-based polymers, including PLA, PHA, starch-based materials, and chitosan, can biodegrade under appropriate conditions, such as industrial composting environments [24, 25]. The presence of natural fibers and fillers in bio-composites further promotes microbial degradation by increasing the surface area accessible to microorganisms [26]. However, biodegradability varies widely depending on polymer composition, environmental conditions, and presence of additives.

Safety and food compatibility are critical for bio-based packaging materials, as they must not release harmful substances or alter food quality [27-29]. Many bio-based polymers like PLA have received regulatory approvals (e.g., FDA approval) for food contact applications, ensuring their safety. Additionally, bio-based films derived from proteins and polysaccharides are generally recognized as safe and edible in some cases, offering added functionality like antimicrobial properties [30]. Nonetheless, careful formulation and testing are required to ensure compliance with food safety standards and to prevent unwanted interactions between packaging and food.

4. Challenges in Bio-based Food Packaging

Bio-based food packaging faces several significant challenges that limit its widespread adoption and effectiveness compared to conventional plastics [31, 32]. One major challenge is the performance limitations of bio-based materials, which generally exhibit lower mechanical strength, reduced flexibility, and inferior barrier properties against moisture and gases compared to fossil-based plastics [7, 18]. These limitations can compromise the protection and shelf life of food products, particularly for those requiring stringent preservation conditions [33]. While modifications and blending with other materials can improve performance, these approaches often increase complexity and costs [34].

Scalability and cost-effectiveness also present considerable hurdles. The production of bio-based packaging materials is currently more expensive than conventional plastic manufacturing due to higher raw material costs, less mature processing technologies, and smaller-scale production facilities lacking economies of scale [6]. Additionally, the heterogeneous nature of biomass feedstocks can complicate production processes, further raising costs and affecting material consistency [7].

Shelf life and preservation issues arise from the relatively higher permeability of many bio-based materials to moisture and oxygen, which can accelerate food spoilage if not adequately addressed [35]. Achieving the delicate balance between biodegradability and functional barrier properties remains a technical challenge [36].

Finally, consumer acceptance and market adoption are influenced by perceptions around the performance, cost, and genuine environmental benefits of bio-based packaging [37]. Confusing or misleading labeling about biodegradability and sustainability can hinder consumer trust and willingness to transition from conventional packaging solutions. Awareness and education, along with clearer policy frameworks, are crucial to overcoming these social and market challenges. Together, these factors present complex but surmountable barriers to the broader use of bio-based food packaging, necessitating ongoing research, innovation, policy support, and public engagement to realize their full potential [6].

5. Sustainable Applications and Technologies

Sustainable applications and technologies in bio-based food packaging are rapidly evolving to address the dual goals of enhancing food preservation and reducing environmental impact [36]. Innovations in packaging design focus on developing bio-based materials with enhanced barrier and surface properties, such as antimicrobial and antifog functionalities, to extend food shelf life and safety [38]. Researchers are also advancing the use of composites from agricultural waste and byproducts, incorporating bioactive compounds into films and coatings to create environmentally friendly packaging with active food preservation capabilities [39, 40]. These bio-based materials are often designed within a circular economy framework to maximize waste minimization, recyclability, and biodegradability [6].

Active and intelligent packaging systems represent a major technological advancement in this field [41]. Active packaging incorporates substances that interact beneficially with the food or its environment, such as releasing antioxidants or antimicrobials and absorbing unwanted gases like oxygen. Intelligent packaging uses sensors or indicators to monitor food quality or freshness, providing real-time feedback to consumers and retailers to prevent food waste [41]. Recent developments include biobased sensors produced via 3D printing technology and nano-encapsulation of natural extracts for controlled release of functional agents, significantly improving the protective function of packaging while maintaining sustainability [41, 42].

Bio-based packaging is increasingly integrated with food preservation techniques like modified atmosphere packaging (MAP) and edible coatings, which together enhance food safety and prolong shelf life [36, 43]. Coatings developed with technologies such as sol-gel enable improved barrier properties to oxygen, moisture, and ultraviolet rays, while hydrophobic surfaces reduce bacterial adhesion [44]. These innovations work synergistically to maintain food quality while using fully biodegradable and compostable materials [6, 45, 46].

End-of-life management of bio-based packaging is critical for achieving sustainability goals [47]. Recycling methods include mechanical recycling as well as organic recycling such as industrial composting and anaerobic digestion, where biodegradable materials are converted to carbon dioxide, water, and biomass or biogas under controlled conditions [48]. Some bio-based plastics also allow energy recovery through incineration. Standards and regulations (e.g., European norms EN 13432) guide the certification of used as a compost and biodegradability to ensure environmental compatibility [49]. Furthermore, ongoing projects focus on creating value chains that convert food industry byproducts into high-performance bioplastics like polyhydroxy alkenoates (PHA), designed for both functional packaging applications and sustainable end-of-life management [50]. Overall, the combination of innovative bio-based materials, active and intelligent functionalities, integration with preservation techniques, and structured recycling and composting pathways holds great promise for the future of sustainable food packaging systems [51].

6. Environmental and Economic Impacts

The environmental impact of bio-based packaging materials is increasingly evaluated through comprehensive life cycle assessments (LCA) that analyze the entire product lifespan, from raw material extraction and production to use and end-of-life management [52, 53]. These assessments consistently demonstrate that bio-based packaging offers clear environmental benefits compared to conventional petroleum-based plastics, particularly in reducing greenhouse gas (GHG) emissions and abiotic resource depletion [54]. For example, bio-based polymers such as polylactic acid (PLA), bio-based polyethylene terephthalate (PET), and starch-based plastics can provide more than 65% savings in GHG emissions when their end-of-life scenarios involve appropriate composting or recycling, compared to only 14% savings with average EU waste management scenarios [55]. This substantial reduction in carbon footprint is a cornerstone of their environmental relevance. Moreover, other impact categories such as particulate matter formation, photochemical ozone creation, and terrestrial eutrophication are generally lower for bio-based materials when managed sustainably [56].

The reduction of plastic pollution is another critical environmental advantage of bio-based packaging [57]. Since many bio-based materials are biodegradable or compostable, they can significantly mitigate the accumulation of persistent plastic waste in ecosystems and waterways. However, the environmental benefit is maximized only when waste is properly segregated and managed in facilities designed to handle biodegradation or recycling [58]. Improper disposal can lead to pollution issues similar to conventional plastics, necessitating robust waste infrastructure and consumer education.

Economically, the feasibility of bio-based food packaging is improving as production technologies mature and market demand grows. While currently more expensive than traditional plastics due to higher feedstock costs and less developed supply chains, economies of scale and technological innovation are driving costs down. Market trends indicate increasing investment in bio-based packaging driven by consumer preference for sustainable products and tightened regulatory frameworks incentivizing plastic reduction and circular economy solutions. The integration of bio-based packaging in food sectors benefits from these trends, although broad adoption still requires overcoming challenges related to cost competitiveness, performance optimization, and consistent supply of raw materials [6].

7. Future Prospects and Research Directions

The future of bio-based food packaging is poised for significant growth, driven by emerging materials, nanotechnology applications, supportive policies, and the push towards circular economy models. Innovative biomaterials, including biodegradable polymers, composites, and edible films, continue to evolve with enhanced functional properties such as improved barrier performance and antimicrobial activity [59]. Nanotechnology plays a transformative role by enabling the incorporation of nanoparticles and nanofibers to boost mechanical strength, gas barrier properties, and active packaging functionalities like freshness indicators and controlled release of preservatives [60-62]. These advances extend the shelf life of food products while maintaining sustainability.

Industry and policy initiatives are accelerating the adoption of bio-based packaging. Several governments have introduced regulations banning or limiting conventional single-use plastics, creating strong incentives for companies to shift to sustainable alternatives. For example, the European Union's circular economy action plan aims for 100% recyclable or reusable plastic packaging by 2030. Industry collaborations focus on developing supply chains for scalable bio-based materials and investing in innovative recycling and composting infrastructure. Consumer demand for eco-friendly packaging further stimulates market growth and product innovation.

Circular economy adoption is increasingly recognized as essential for maximizing the sustainability of bio-based packaging [63]. This approach emphasizes designing packaging for reuse, recycling, or composting, integrating renewable feedstocks, and minimizing waste. Bio-based packaging materials sourced from agri-food waste exemplify circular resource use, supporting environmental and economic benefits. Closing the loop requires ongoing development of waste collection systems, advanced recycling technologies, and certification standards for used as a compost and biodegradability [52].

Despite promising advancements, areas needing further research include cost reduction through improved feedstock processing and manufacturing efficiency, enhanced performance without compromising biodegradability, comprehensive toxicological evaluations, and fully integrated life cycle assessments [64]. Innovations in multifunctional bio-based materials, smart packaging, and hybrid systems combining the best attributes of bio-based and conventional materials are also critical [36]. Continued interdisciplinary collaboration among academia, industry, and policymakers will be key to overcoming barriers and unlocking the full potential of sustainable bio-based food packaging.

8. Conclusion

Bio-based packaging materials hold significant relevance and offer numerous environmental and functional benefits in the food packaging sector. They provide a renewable alternative to conventional fossil-based plastics, contributing to reduced dependency on nonrenewable resources and lowering the environmental footprint associated with packaging. Their biodegradability, used as a compost and potential for recyclability help mitigate plastic pollution, a critical global environmental challenge. Additionally, bio-based materials can be engineered to enhance food preservation, ensuring product safety and extending shelf life, aligning with consumer and industry demands for sustainable and responsible packaging solutions.

Despite their promising attributes, wider implementation of bio-based food packaging faces challenges such as performance limitations, higher costs, scalability issues, regulatory hurdles, and the need for consumer education on sustainability claims. Addressing these challenges requires ongoing research and development to improve material properties, cost-effectiveness, and processing technologies. Collaboration between academia, industry, and policymakers is essential, along with supportive regulatory frameworks and market incentives that promote sustainable packaging adoption and infrastructure for proper waste management.

Looking forward, future innovations in bio-based packaging are expected to focus on emerging advanced materials, including nanotechnology-enhanced composites and multifunctional smart packaging systems. Policies supporting circular economy principles and increased industry investments will drive sustainable growth and integration of bio-based solutions. Continued efforts in research, technological innovation, and transparent communication will be vital to realize the environmental goals and consumer expectations associated with sustainable food packaging. By embracing these developments, the packaging industry can significantly contribute to a more sustainable, environmentally responsible future.

Abbreviations

GHG	Greenhouse Gas
LCA	Life Cycle Assessments
MAP	Modified Atmosphere Packaging
PEF	Polyethylene Furanoate
PET	Polyethylene Terephthalate
PHA	Polyhydroxy Alkenoates
PLA	Polylactic Acid

Author Contributions

Alebachew Molla Nibret is the sole author. The author read and approved the final manuscript.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or analyzed in this review.

Funding

This review received no external funding.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] M. A. Pascall, K. DeAngelo, J. Richards, and M. B. Arensberg. Role and Importance of Functional Food Packaging in Specialized Products for Vulnerable Populations: Implications for Innovation and Policy Development for Sustainability, *Foods*, vol. 11, no. 19, 2022. https://doi.org/10.3390/foods11193043

[2] C. Lacourt, K. Mukherjee, J. Garthoff, A. O'Sullivan, L. Meunier, and V. Fattori. Recent and emerging food packaging alternatives: Chemical safety risks, current regulations, and analytical challenges, *Compr. Rev. Food Sci. Food Saf.*, vol. 23, no. 6, pp. 1-29, 2024. https://doi.org/10.1111/1541-4337.70059

[3] I. Mutmainna, P. L. Gareso, S. Suryani, and D. Tahir. Microplastics from petroleum-based plastics and their effects: A systematic literature review and science mapping of global bioplastics production, *Integr. Environ. Assess. Manag.*, vol. 20, no. 6, pp. 1892-1911, 2024. https://doi.org/10.1002/ieam.4976

[4] S. Kumari, A. Rao, M. Kaur, and G. Dhania. Petroleum-Based Plastics Versus Bio-Based Plastics: A Review, *Nat. Environ. Pollut. Technol.*, vol. 22, no. 3, pp. 1111-1124, 2023. https://doi.org/10.46488/NEPT.2023.v22i03.003

[5] L. K. Ncube, A. U. Ude, E. N. Ogunmuyiwa, R. Zulkifli, and I. N. Beas. Environmental impact of food packaging materials: A review of contemporary development from conventional plastics to polylactic acid based materials, *Materials (Basel).*, vol. 13, no. 21, pp. 1-24, 2020. https://doi.org/10.3390/ma13214994

[6] M. T. Arshad *et al.* Emerging Trends in Sustainable Packaging of Food Products: An Updated Review, *J. Nat. Fiber*, vol. 22, no. 1, 2025. https://doi.org/10.1080/15440478.2025.2505608

[7] C. L. Reichert *et al.*, Bio-based packaging: Materials, modifications, industrial applications and sustainability, Polymers, vol. 12, no. 7. 2020. https://doi.org/10.3390/polym12071558

[8] C. B. Yuen, H. L. Chong, M. H. Kwok, and T. Ngai. Natural polymer-based food packaging: paving the way to a greener future - a review, *Sustain. Food Technol.*, vol. 3, no. 4, pp. 908-929, 2025. https://doi.org/10.1039/d5fb00021a

[9] M. Escamilla-García *et al.* Properties and Biodegradability of Films Based on Cellulose and Cellulose Nanocrystals from Corn Cob in Mixture with Chitosan, *Int. J. Mol. Sci.*, vol. 23, no. 18, 2022. https://doi.org/10.3390/ijms231810560

[10] V. Mihalca *et al.* Protein - based films and coatings for food industry applications," *Polymers (Basel).*, vol. 13, no. 5, pp. 1-24, 2021. https://doi.org/10.3390/polym13050769

[11] A. Linares-Castañeda *et al.* Cereal and legume protein edible films: a sustainable alternative to conventional food packaging, *Int. J. Food Prop.*, vol. 26, no. 2, pp. 3197-3213, 2023. https://doi.org/10.1080/10942912.2023.2267785

[12] A. Z. Naser, I. Deiab, and B. M. Darras. Poly (lactic acid) (PLA) and polyhydroxyalkanoates (PHAs), green alternatives to petroleum-based plastics: a review, *RSC Adv.*, vol. 11, no. 28, pp. 17151-17196, 2021. https://doi.org/10.1039/d1ra02390j

[13] A. Chouhan and A. Tiwari. Production of polyhydroxyalkanoate (PHA) biopolymer from crop residue using bacteria as an alternative to plastics: a review, *RSC Adv.*, vol. 15, no. 15, pp. 11845-11862, 2025. https://doi.org/10.1039/d4ra08505a

[14] K. Pal, P. Sarkar, A. Anis, K. Wiszumirska, and M. Jarzębski. Polysaccharide - based nanocomposites for food packaging applications, *Materials (Basel).*, vol. 14, no. 19, pp. 1-38, 2021. https://doi.org/10.3390/ma14195549

[15] H. Abral *et al.* Antimicrobial edible film prepared from bacterial cellulose nanofibers/starch/chitosan for a food packaging alternative, *Int. J. Polym. Sci.*, vol. 2021, 2021. https://doi.org/10.1155/2021/6641284

[16] J. H. Sanders *et al.* Biobased Polyethylene Furanoate: Production Processes, Sustainability, and Techno-Economics, *Adv. Sustain. Syst.*, vol. 8, no. 11, pp. 1-29, 2024. https://doi.org/10.1002/adsu.202400074

[17] Y. A. Shah *et al.* Mechanical Properties of Protein-Based Food Packaging Materials, *Polymers (Basel).*, vol. 15, no. 7, pp. 1-13, 2023. https://doi.org/10.3390/polym15071724

[18] M. Yanat and K. Schroën. Bio-nanocomposites as future food packaging materials: A multi-faceted comparison, *React. Funct. Polym.*, vol. 209, 2025. https://doi.org/10.1016/j.reactfunctpolym.2025.106184

[19] A. M. F. Elbaz, A. Al-Farga, and E. N. Mohamed. Enhancement of Polylactic Acid Packaging Sheet by Adding Three Biocomposites and Evaluating them as Bioplastic, *Egypt. J. Food Sci.*, vol. 52, no. 2, pp. 187-202, 2024. https://doi.org/10.21608/ejfs.2024.327353.1199

[20] D. S. Rajendran, S. Venkataraman, S. K. Jha, D. Chakrabarty, and V. V. Kumar. A review on bio-based polymer polylactic acid potential on sustainable food packaging, *Food Sci. Biotechnol.*, vol. 33, no. 8, pp. 1759-1788, 2024. https://doi.org/10.1007/s10068-024-01543-x

[21] C. Villegas, S. Mart, and A. Torres. Procesamiento, Caracterización y Propiedades de Desintegración de Biopolímeros Basados en Mater-Bi y Recubrimiento de Ácido Elágico Chitosan, *Polymers (Basel).*, vol. 15, no. 1548, pp. 3-16, 2023. https://www.scopus.com/record/display

[22] M. Morreale, M. Baiamonte, and F. P. La Mantia. Rheological and Mechanical Properties and Spinning Behavior of a Starch-Based Biodegradable Polymer, *Polymers (Basel).*, vol. 16, no. 23, 2024. https://doi.org/10.3390/polym16233306

[23] C. Tan, F. Han, S. Zhang, P. Li, and N. Shang. Novel bio-based materials and applications in antimicrobial food packaging: Recent advances and future trends, *Int. J. Mol. Sci.*, vol. 22, no. 18, 2021. https://doi.org/10.3390/ijms22189663

[24] N. Pooja, I. Chakraborty, M. H. Rahman, and N. Mazumder. An insight on sources and biodegradation of bioplastics: a review, *3 Biotech*, vol. 13, no. 7, pp. 1-22, 2023. https://doi.org/10.1007/s13205-023-03638-4

[25] E. Nwaka *et al.* Optimizing the production of biodegradable chitosan-glycerol bioplastics from potato starch, *Eur. J. Sustain. Dev. Res.*, vol. 9, no. 3, p. em0309, 2025. https://doi.org/10.29333/ejosdr/16354

[26] M. S. Haque and M. A. Islam. Microbial degradation of the waste jute fiber and sawdust fiber-based epoxy composites in drainage system, *Heliyon*, vol. 10, no. 20, p. e39397, 2024. https://doi.org/10.1016/j.heliyon.2024.e39397

[27] R. Afzal, L. Iqbal, I. Akram, S. R. F. Kazmi, M. A. Fatima, and H. Shahid. Biodegradable Food Packaging Innovations and Implications for Sustainable Food Systems, *J. Agric. Biol.*, vol. 3, no. 1, pp. 376-385, 2025. https://doi.org/10.55627/agribiol.003.01.1250

[28] B. Leya *et al.* Biopolymer-based edible packaging: a critical review on the biomaterials, formation, and applications on food products, *J. Appl. Biol. Biotechnol.*, vol. 12, no. 6, pp. 42-57, 2024. https://doi.org/10.7324/JABB.2024.145531

[29] S. Shaikh, M. Yaqoob, and P. Aggarwal. An overview of biodegradable packaging in food industry, *Curr. Res. Food Sci.*, vol. 4, pp. 503-520, 2021. https://doi.org/10.1016/j.crfs.2021.07.005

[30] Abdullah *et al.* Biopolymer-based functional films for packaging applications: A review, *Front. Nutr.*, vol. 9, pp. 1-20, 2022. https://doi.org/10.3389/fnut.2022.1000116

[31] S. Hu, L. Han, C. Yu, L. Pan, and K. Tu. A Review on Replacing Food Packaging Plastics with Nature-Inspired Bio-Based Materials, *Foods*, vol. 14, no. 10, 2025. https://doi.org/10.3390/foods14101661

[32] N. Vinitskaia *et al*. Environmental Sustainability, Food Quality and Convertibility of Bio-Based Barrier Coatings for Fibre-Based Food Packaging: A Semisystematic Review, *Packag. Technol. Sci.*, vol. 38, no. 3, pp. 255-280, 2025. https://doi.org/10.1002/pts.2868

[33] Versino, F. Ortega, F. Monroy, Y. Rivero, S. López, O. V. García, M. A. Sustainable and Bio-Based Food Packaging: A Review on Past and Current Design Innovations. Foods, 12, 1057, 2023. https://doi.org/10.3390/foods12051057

[34] R. Porta, M. Sabbah, and P. Di Pierro. Bio‐Based Materials for Packaging, *Int. J. Mol. Sci.*, vol. 23, no. 7, pp. 10-14, 2022. https://doi.org/10.3390/ijms23073611

[35] J. F. Macnamara, M. Rubino, M. Daum, A. Kathuria, and R. Auras. Biodegradable and Transparent Water and Oxygen Barrier Multilayer Film, *ACS Appl. Polym. Mater.*, vol. 6, no. 17, pp. 10865-10874, 2024. https://doi.org/10.1021/acsapm.4c01994

[36] M. Z. Al Mahmud, M. H. Mobarak, and N. Hossain. Emerging trends in biomaterials for sustainable food packaging: A comprehensive review, *Heliyon*, vol. 10, no. 1, p. e24122, 2024. https://doi.org/10.1016/j.heliyon.2024.e24122

[37] C. Herbes, C. Beuthner, and I. Ramme. Consumer attitudes towards biobased packaging - A cross-cultural comparative study, *J. Clean. Prod.*, vol. 194, pp. 203-218, 2018. https://doi.org/10.1016/j.jclepro.2018.05.106

[38] M. Vivero-Lopez *et al.* Phosphorylcholine-Based Contact Lenses for Sustained Release of Resveratrol: Design, Antioxidant and Antimicrobial Performances, and in Vivo Behavior, *ACS Appl. Mater. Interfaces*, vol. 14, no. 50, pp. 55431-55446, 2022. https://doi.org/10.1021/acsami.2c18217

[39] S. Paudel, S. Regmi, S. Bhattarai, A. Fennell, and S. Janaswamy. Valorization of grapevine agricultural waste into transparent and high-strength biodegradable films for sustainable packaging, *Sustain. Food Technol.*, vol. 3, no. 4, pp. 1218-1231, 2025. https://doi.org/10.1039/d5fb00211g

[40] A. I. Quilez-Molina, U. Chandra Paul, D. Merino, and A. Athanassiou. Composites of Thermoplastic Starch and Lignin-Rich Agricultural Waste for the Packaging of Fatty Foods, *ACS Sustain. Chem. Eng.*, vol. 10, no. 47, pp. 15402-15413, 2022. https://doi.org/10.1021/acssuschemeng.2c04326

[41] Y. Palanisamy, V. Kadirvel, and N. D. Ganesan. Recent technological advances in food packaging: sensors, automation, and application," *Sustain. Food Technol.*, vol. 3, no. 1, pp. 161-180, 2024. https://doi.org/10.1039/d4fb00296b

[42] Witek-Krowiak, A., Szopa, D., Anwajler, B. Advanced Packaging Techniques: A Mini-Review of 3D Printing Potential. Materials, 17, 2997, 2024. https://doi.org/10.3390/ma17122997

[43] P. M. De Farias *et al.* Biobased Food Packaging Systems Functionalized with Essential Oil via Pickering Emulsion: Advantages, Challenges, and Current Applications, *ACS Omega*, vol. 10, no. 5, pp. 4173-4186, 2025. https://doi.org/10.1021/acsomega.4c09320

[44] F. Trodtfeld, T. Tölke, and C. Wiegand. Developing a Prolamin-Based Gel for Food Packaging: In-Vitro Assessment of Cytocompatibility, *Gels*, vol. 9, no. 9, 2023. https://doi.org/10.3390/gels9090740

[45] E. Maurizzi, F. Bigi, A. Quartieri, R. De Leo, L. A. Volpelli, and A. Pulvirenti. The Green Era of Food Packaging: General Considerations and New Trends, *Polymers (Basel).*, vol. 14, no. 20, 2022. https://doi.org/10.3390/polym14204257

[46] J. R. Westlake, M. W. Tran, Y. Jiang, X. Zhang, A. D. Burrows, and M. Xie. Biodegradable Active Packaging with Controlled Release: Principles, Progress, and Prospects, *ACS Food Sci. Technol.*, vol. 2, no. 8, pp. 1166-1183, 2022. https://doi.org/10.1021/acsfoodscitech.2c00070

[47] C. Gioia *et al.* End of Life of Biodegradable Plastics: Composting versus Re/Upcycling," *ChemSusChem*, vol. 14, no. 19, pp. 4167-4175, 2021. https://doi.org/10.1002/cssc.202101226

[48] M. Zaborowska and K. Bernat. The development of recycling methods for bio-based materials - A challenge in the implementation of a circular economy: A review, *Waste Manag. Res.*, vol. 41, no. 1, pp. 68-80, 2023. https://doi.org/10.1177/0734242X221105432

[49] E. Van Roijen and S. A. Miller. Leveraging biogenic resources to achieve global plastic decarbonization by 2050, *Nat. Commun.*, vol. 16, no. 1, 2025. https://doi.org/10.1038/s41467-025-62877-6

[50] S. Hussain, R. Akhter, and S. S. Maktedar. Advancements in sustainable food packaging: from eco-friendly materials to innovative technologies, *Sustain. Food Technol.*, vol. 2, no. 5, pp. 1297-1364, 2024. https://doi.org/10.1039/d4fb00084f

[51] M. Thirupathi Vasuki, V. Kadirvel, and G. Pejavara Narayana. Smart packaging: An overview of concepts and applications in various food industries, *Food Bioeng.*, vol. 2, no. 1, pp. 25-41, 2023. https://doi.org/10.1002/fbe2.12038

[52] K. Yadav and G. C. Nikalje. Comprehensive analysis of bioplastics: life cycle assessment, waste management, biodiversity impact, and sustainable mitigation strategies, *PeerJ*, vol. 12, no. 9, pp. 1-29, 2024. https://doi.org/10.7717/peerj.18013

[53] G. Cappiello, C. Aversa, A. Genovesi, and M. Barletta. Life cycle assessment (LCA) of bio-based packaging solutions for extended shelf-life (ESL) milk, *Environ. Sci. Pollut. Res.*, vol. 29, no. 13, pp. 18617-18628, 2022. https://doi.org/10.1007/s11356-021-17094-1

[54] E. A. R. Zuiderveen *et al.* The potential of emerging bio-based products to reduce environmental impacts, *Nat. Commun.*, vol. 14, no. 1, 2023. https://doi.org/10.1038/s41467-023-43797-9

[55] E. Rezvani Ghomi *et al.* The life cycle assessment for polylactic acid (PLA) to make it a low-carbon material, *Polymers (Basel).*, vol. 13, no. 11, pp. 1-16, 2021. https://doi.org/10.3390/polym13111854

[56] R. J. K. Helmes, P. Goglio, S. Salomoni, D. S. van Es, I. Vural Gursel, and L. Aramyan. Environmental Impacts of End-of-Life Options of Biobased and Fossil-Based Polyethylene Terephthalate and High-Density Polyethylene Packaging, *Sustain.*, vol. 14, no. 18, 2022. https://doi.org/10.3390/su141811550

[57] A. Aburto Medina, S. Hassan, C. Dekiwadia, C. Chen, and A. S. Ball, "Bio-based plastics: a sustainable solution to plastic pollution, *Microbiol. Aust.*, vol. 46, no. 2, pp. 96-101, 2025. https://doi.org/10.1071/ma25027

[58] N. Mhaddolkar, T. F. Astrup, A. Tischberger-Aldrian, R. Pomberger, and D. Vollprecht. Challenges and opportunities in managing biodegradable plastic waste: A review, *Waste Manag. Res.*, vol. 43, no. 6, pp. 911-934, 2025. https://doi.org/10.1177/0734242X241279902

[59] L. Kumar, P. Tyagi, L. Lucia, and L. Pal. Innovations in Edible Packaging Films, Coatings, and Antimicrobial Agents for Applications in Food Industry, *Compr. Rev. Food Sci. Food Saf.*, vol. 24, no. 4, 2025. https://doi.org/10.1111/1541-4337.70217

[60] M. del R. Herrera-Rivera *et al.* Nanotechnology in food packaging materials: role and application of nanoparticles, *RSC Adv.*, vol. 14, no. 30, pp. 21832-21858, 2024. https://doi.org/10.1039/d4ra03711a

[61] J. Sadeghizadeh-Yazdi, G. A. Nayik, M. S. Hajimirzadeh, and N. Akramzade. Application of Nanomaterials in Food Packaging: A Review Study, *J. Food Qual. Hazards Control*, vol. 11, no. 3, pp. 149-156, 2024. https://doi.org/10.18502/jfqhc.11.3.16586

[62] S. Ghosh, R. K. Mandal, A. Mukherjee, and S. Roy. Nanotechnology in the manufacturing of sustainable food packaging: a review, *Discov. Nano*, vol. 20, no. 1, 2025. https://doi.org/10.1186/s11671-025-04213-x

[63] B. Li *et al.* Competing narratives inhibit a circular economy for bio-based plastic packaging: Insights from a social innovation lab study in Brazil, Canada, Poland and the UK, vol. 34, no. 1. 2025. https://doi.org/10.1002/bse.3997

[64] D. Maxie. Enhancing Biodegradable Packaging Materials: Innovations and Environmental Benefits, *Int J Waste Resour*, vol. 14, no. 1000575, pp. 1-2, 2024. https://doi.org/10.35248/2252-5211.24.14.575