Journal of Natural Fibers

ISSN: 1544-0478 (Print) 1544-046X (Online) Journal homepage: www.tandfonline.com/journals/wjnf20

AI-Powered Innovations in Natural Fiber Packaging for Sustainability

Guravtar Singh Mann, Bhupinder Singh, Khalid A. Alzahrani, Anish Khan, Raman Kumar, Arun Y. Patil & Basem E. Keshta

To cite this article: Guravtar Singh Mann, Bhupinder Singh, Khalid A. Alzahrani, Anish Khan, Raman Kumar, Arun Y. Patil & Basem E. Keshta (2026) AI-Powered Innovations in Natural Fiber Packaging for Sustainability, Journal of Natural Fibers, 23:1, 2640280, DOI: 10.1080/15440478.2026.2640280

To link to this article: https://doi.org/10.1080/15440478.2026.2640280

Published online: 07 Apr 2026.

JOURNAL OF NATURAL FIBERS
2026, VOL. 23, NO. 1, 2640280
https://doi.org/10.1080/15440478.2026.2640280

AI-Powered Innovations in Natural Fiber Packaging for Sustainability

Guravtar Singh Mann[a], Bhupinder Singh[a,b], Khalid A. Alzahrani[c], Anish Khan[d], Raman Kumar[e,f], Arun Y. Patil[g,h], and Basem E. Keshta[i]

[a]School of Mechanical Engineering, Lovely Professional University, Jalandhar, Phagwara, India; [b]Department of Mechanical Engineering, CT University, Ludhiana, India; [c]Chemistry Department, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia; [d]Center of Excellence for Advanced Materials Research, King Abdulaziz University, Jeddah, Saudi Arabia; [e]School of Mechanical Engineering, Rayat Bahra University, Kharar, India; [f]Faculty of Engineering, Sohar University, Sohar, Oman; [g]Bio-Inspired Design and Optimization Centre (BIODOC), Manipal Institute of Technology Bengaluru, Manipal Academy of Higher Education, Manipal, India-; [h]Manipal Institute of Technology Bengaluru, Manipal Academy of Higher Education, Manipal, India; [i]Chemistry Department, Faculty of Science, Tanta University, Tanta, Egypt

ABSTRACT

The need for improved and environmentally friendly sustainable packaging materials with exceptional physical, mechanical, and barrier qualities is growing. The existing industrial packaging materials primarily use non-biodegradable plastics and other raw materials with limited recyclability and has serious consequences toward raised carbon footprints. Therefore, the integration of artificial intelligence (AI) in the sustainable packaging industry is fundamentally changing how things are packaged and distributed, with emerging materials and technologies that promote safety, quality, and sustainability. Many AI-based tools are being used or evaluated for packaging systems, including (but not limited to) machine learning (ML), deep learning (DL), sensors for monitoring, predictive analytics, and generative models for accurate predictions of shelf life, automated identification of defects or contamination, traceability or authentication of a product's origins, optimal material selection for barrier and environmental properties, and more sustainable packaging designs. This article investigates various applications of AI for sustainable packaging for various applications. Moreover, various challenges in practice data heterogeneity, model generalizability, and scalability showing the importance strong and well-designed AI framework are necessary to implement effectively are also discussed. Overall, the sustainable-packaging sector can expect that AI innovations will improve productivity, food safety and waste management.

HIGHLIGHTS

(1) Discussed about growing demand for sustainable packaging materials
(2) Highlights superior physical, mechanical, and barrier properties to replace non-biodegradable plastics.
(3) Compiles about industrial packaging waste significantly contributes to environmental pollution and elevated carbon footprints.
(4) AI integration, including ML, DL, sensors, predictive analytics, and generative models, is involved.
(5) Challenges like data heterogeneity, model generalizability, and scalability highlight

摘要

对具有卓越物理性能、机械性能和阻隔性能的改进型环保可持续包装材料的需求正在增长. 现有工业包装材料主要采用不可降解塑料及其他回收性能有限的原料，对碳足迹增加产生严重后果. 因此，人工智能 (AI)在可持续包装行业的融合正在从根本上改变包装与配送方式，新兴材料与技术推动着安全、品质与可持续性的提升. 许多基于人工智能的工具正在被用于或评估包装系统，包括 (但不限于)机器学习 (ML)、深度学习 (DL)、用于监测的传感器、预测分析和生成模型，用于准确预测保质期、自动识别缺陷或污染、产品来源的可追溯性或认证、屏障和环境特性的最佳材料选择，以及更可持续的包装设计. 本文研究了人工智能在可持续包装中的各种应用. 此外，还讨论了实践中的各种挑战——数据异构性、模型泛化性和可扩展性——表明了有效实施强大而设计良好的人工智能框架的重要性. 总体而言，可持续包装行业可以期待人工智能创新将提高生产力、食品安全和废物管理.

KEYWORDS
Intelligent packaging; artificial intelligence; biobased materials; food safety; machine learning

关键词
智能包装; 人工智能; 生物基材料; 食品安全; 机器学习

CONTACT Arun Y. Patil patil.arun@manipal.edu; patilarun7@gmail.com Bio-Inspired Design and Optimization Centre (BIODOC), Manipal Institute of Technology Bangalore, Manipal Academy of Higher Education, Manipal 576104, India

Supplemental data for this article can be accessed online at https://doi.org/10.1080/15440478.2026.2640280

Introduction

Green packaging based on biodegradable bio composite materials has garnered substantial interest in various fields due to its distinct characteristics compared to conventional plastics derived from petrochemicals. As these materials cause lot of environmental damage. The fundamental issue of the packaging industry's heavy reliance is on the usage of plastic products, which has resulted in a significant increase in the amount of plastic waste (Bhat et al. 2017). The growing need to reduce the environmental impact of petroleum-based packaging has driven extensive research toward the development of sustainable alternative packaging materials. Conventional plastics, although durable and adaptable, resist disposal and persist in ecosystems, thereby contributing significantly to environmental degradation (Dejene, Birilie et al. 2024). While recyclability is a virtue of synthetic polymers, numerous limitations restrict this advantage (Murthy and Ramakrishna 2022). Thermosetting polymers, for instance, are non-recyclable as once hardened they cannot be remelted or molded. Furthermore, plastic garbage including food or other materials seriously compromises the recycling process. Even in some cases of recycling, the repetitive processing of plastics often results in a degradation in material qualities, therefore restricting their performance and lowering their reuse in high-quality applications (Dejene and Abtew 2025). Moreover, recycling infrastructure remains weak or inadequate in many parts of the world. which results in a notable fraction of recyclable plastics never being really recycled (A. Khan et al. 2020). This emphasizes the need for development of sustainable substitutes like biopolymers, which not only solve waste management problems but also fit more general environmental objectives like less dependence on fossil fuels and support of a circular economy (Chetbani et al. 2024). As packaging serves an essential function in the contemporary food supply chain through the preservation of the quality and safety of food items, in addition to this, it is significant because it protects packaged goods from the environment, influences the quality and safety of food items, and makes it easier to store, transport, and discharge products. Furthermore, the release of carbon and other hazardous gases during the production of plastic bags has a significant influence on the ecological system (A. K. Gupta et al. 2025). Hence, smart packaging systems can play significant role in innovations of environmentally friendly packaging solutions (Anas, Faheem, and Mikucioniene 2025). The main feature of this system is its sustainability, which has been proven by the studies using natural composites produced from lignocellulose materials, reduce plastic waste and can significantly help to alleviate the waste disposal problem to some extent. Moreover, increased concerns about the limits and inefficiency of plastic recycling mean that bioplastics provide a clear benefit over more traditional recyclable plastics (Mudi and Shaw 2024). Although conventional plastics are theoretically recyclable, problems include contamination, thermoset non-recyclability, and material property deterioration during recycling lower their useful value (Atalie, Abtew, and Zhao 2025) By contrast, bioplastics provide a more sustainable end-of-life option and are biodegradable (Silska and Górecki 2023). Although bioplastics have many benefits, their expensive cost has prevented their broad commercial use. However, new innovations in packaging system have cut production costs. Furthermore, using nanomaterials especially cellulose nanofibers which enhance molecular level functioning by their nanoscale interactions is one of the most exciting directions derived from natural sources, cellulose nanofibers (CNFs) are among the most plentiful, renewable, and sustainable polymeric materials accessible for industrial-scale uses (Khalil et al. 2014; Rhim and Ng 2007). For more than 150 years, cellulose-based materials such as hemp, jute, sisal which have intrinsic benefits like biocompatibility, biodegradability, and chemical stability have been used in a variety of industries, including textiles, medicines, and paper manufacture. Because of their remarkable mechanical and barrier-enhancing characteristics, CNFs have recently attracted a lot of interest in sustainable packaging (Mann et al. 2022). Other promising plant fibers include kapok (Ceiba pentandra), abaca (Musa textilis), and pineapple leaf fiber (PALF). Kapok fibers exhibit hydrophobicity due to a natural wax layer, low density (0.29 g/cm^3), and high buoyancy, making them ideal for lightweight, insulating packaging fillers, oil-absorbent materials, and protective cushions. Abaca fibers offer good tensile strength (up to 980 MPa), Moreover are lightweight and biodegradable, suitable for reinforced bio-polyethylene composites in durable food trays and structural packaging (30 wt.% loading improves flexural strength). Furthermore, pineapple leaf fibers (PALF) provide excellent mechanical properties (tensile strength 413–1627 MPa, modulus 34.5–82.5 GPa, low microfibril angle 14°), enhancing stiffness in bio composites for abrasion-resistant, eco-friendly packaging like trays and boxes. These fibers enhance circular economy practices by transforming agricultural waste into useful materials (Baraniak and Kania-Dobrowolska 2023; Flores Ramirez et al. 2015; Motaleb, Shariful Islam, and Hoque 2018). Packaging materials benefit from increased tensile strength, stiffness, and flexural properties due to their nanoscale dimensions, which enable a high surface area and strong intermolecular interactions. In terms of other potential applications, full-bio composites could be utilized to replace the plastics in various industries those accountable for 40% of the overall plastic market (Abekoon et al. 2024). The food packaging industry is mainly navigated by the market's desire to meet societal and economic demands. Market data show natural fiber composites in packaging have a notable increasing tendency (Yakoubi 2025). Rising at a CAGR of 7.6% from 2024 to 2034, the predicted worldwide market size by 2034 is USD 749.24 million. Strict environmental rules and growing customer demand for eco-friendly goods are driving this development (Singh, Dondapati et al. 2021). As a result, the most crucial packaging innovations can lead to practical solutions to meet those socioeconomic demands by providing high-quality, safe product food goods to consumers in a cost-effective manner (Nagaveni and Poosarla 2024). Functional requirements play an important role in determining which fiber materials are used in packaging applications. Cellulose and nanocellulose provide excellent barrier characteristics, biodegradable properties and compatibility with active and sensing additives, respectively, so they are primarily used in food and biomedical applications. Therefore, lignocellulosic fibers with higher mechanical strength are commonly used in rigid and load-bearing packaging structures, whereas low-density plant fibers are preferred for lightweight and cushioning applications. Furthermore, the integration of functional materials and intelligent components enables these fiber-based systems to be tailored for active, smart, and intelligent packaging, depending on the intended application (Rasheed, Jawaid, and Parveez 2021; Srivastava 2024; Vijaya Ramnath et al. 2016). The integration of green composites with ML, DL, and AI offers a revolutionary approach for delivering environmentally friendly packaging. Green composites are made from renewable materials, including plant fibers and biodegradable polymers, thereby serving as eco-friendly alternatives to conventional plastics. In contrast, advanced computational processes should be devised and implemented to maximize the attributes which green composites confer with regard to packaging applications. Cutting-edge algorithms which harness AI and ML have the potential to analyze vast amounts of data, providing the potential to forecast thermal and mechanical properties of green composites (Singh, Sharma et al. 2021). This approach facilitates the fabrication of materials with tailored properties. For example, deep learning (DL) models have been used to predict the properties of natural fiber polymer composites, which enhance suitability and quality of predicted characteristics for various packaging applications. Predictive modeling expedites the process to formulate packaging materials with prescribed properties and minimizes the need for extensive experimentation. In addition, AI-driven techniques in creative design contribute to the development of novel packaging designs that reduce material consumption while maintaining material performance and mechanical strength. The design plays a significant role helping to avoid waste and improve sustainability among packaging solutions. Green composites coupled with AI, ML, and DL improve recyclability and biodegradability of packaging (Zatsu et al. 2024). AI technologies create sustainable, high-performance materials by improving the chemical and physical properties of sustainable materials, as indicated in Figure 1. Lastly, intelligent and sustainable packaging solutions can only progress with the collaboration of AI technology and environmentally friendly composites. To make an overview of natural fibers for packaging and how AI/ML/DL improves the design, applications, and sustainability.

Need for intelligent & sustainable packaging

In today's world of rapid consumption and environmental degradation, the need for sustainable packaging has become more critical than ever. Often composed of non-recyclable materials and single-use plastics, traditional packaging greatly adds to landfill trash, ocean pollution, and pollution of other systems. These materials endanger ecosystems and human health over long terms as they take hundreds of years to break down (Du et al. 2025). One ecologically sensible substitute is sustainable packaging. Made with recyclable, biodegradable, or renewable materials, it lessens product environmental impact all during their lifetime (Bidyalakshmi et al. 2025). The ever-evolving landscape of consumer expectations and technological advancements has rendered traditional product packaging insufficient in addressing increasingly complex consumer needs. In response to this issue, new solutions from the field of intelligent packaging are emerging as a rapidly evolving area of interest. Intelligent packaging design offers the possibility of elevating

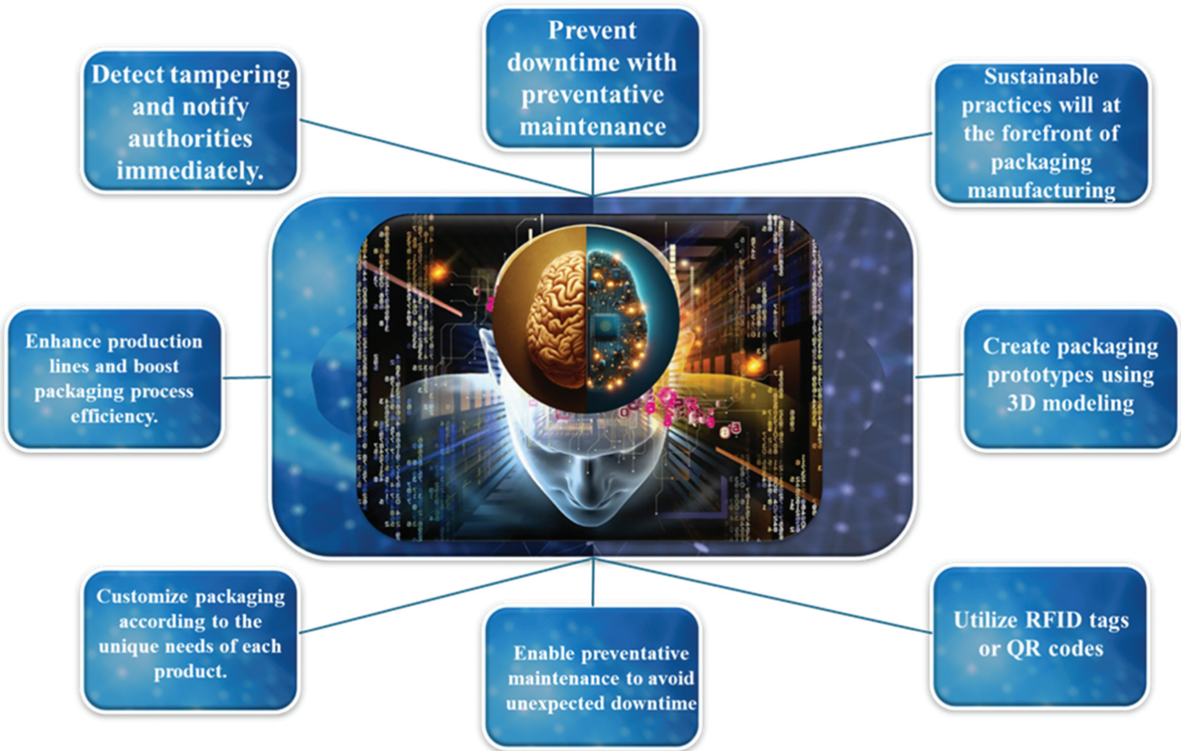

Figure 1. Benefits in sustainable packing using AI techniques.

traditional packaging designs through the addition of leading-edge science materials, data tracking, and an array of advanced technologies and functionalities, also engaging both digital and intelligent design features to produce greater overall value and consumer experience with product packaging. This collaborative approach has the potential to transform the packaging industry by offering creative solutions that respond to an ever-changing and active consumer market (Mkhari, Adeyemi, and Fawole 2025). A global rise in environmental consciousness has changed the use of packaging materials. AI has also impacted design, aided by ongoing development. Using AI for intelligent packaging and structures can enable better production speed and inform traditional design practices (Chiu and Yang 2024). The connection between customers and intelligent packaging is has also evolved as it is now emotionally connected and a "living product." Figure 2. Highlights various development considerations for intelligent packaging. With increasing consumer awareness of environmental issues, businesses are facing growing pressure to adopt sustainable and eco-friendly practices. Along with protection of natural resources, sustainable packaging improves brand reputation, fits with corporate social responsibility objectives, and attracts to consumers who care about the environment (Chougala et al. 2024). Moreover, governments throughout the world are enforcing tougher rules and restrictions on non-sustainable packaging materials, therefore hastening the change toward greener substitutes (Rom et al. 2024). Businesses which make investments in sustainable packaging today will be more suited to follow future laws and stay free from any fines (N. Gupta and Gupta 2024). Beyond its environmental benefits, sustainable packaging may ultimately be financially advantageous (Dejene, Gudayu et al. 2024). For example, by reducing waste, reusing resources, and improving container designs help to minimize shipping and manufacturing costs (S. Khan et al. 2024). The move to sustainable packaging is ultimately not only a trend but also a need for a sustainable future. Reducing environmental damage and encouraging responsible consumption help sustainable packaging significantly contribute to solve the global climate issue and provide a better, cleaner world for next generations (N. Kumar, Kaur, and Bhatia 2017). Globally, plastic waste includes a substantial share of plastic packaging. According to estimates, packaging uses over 40 percent of all plastic generated, so it is the most used use of plastic globally. This comes to around 141 million tons of plastic packaging generated yearly. Plastic packaging has a significant effect on the surroundings (D'Almeida and de Albuquerque 2024). Researchers and businesses

Figure 2. Various development factors of intelligent packaging.

throughout the food sector rely extensively on various forms of AI, including ML and DL. ML is building systems that is capable of automating many of the mundane and time-consuming tasks that humans currently do. Here in Table 1. the importance of AI is shown that integrating traditional practices with stainable development goals. ML allows for prediction and recommendations based on trends identified in data to aid human decisions. It may also facilitate the development of newer items by changing the current process. Introducing a machine that can learn from their mistakes and improve its operation will enhance productivity and creativity. Further, AI enables the development of novel packaging solutions that utilize data analytics and sensors to monitor and control factors like as shelf life, temperature, and freshness. This ensures that food products remain in optimal condition throughout the supply chain process.

A Dutch company has produced smart packaging that demonstrates self-regulating capabilities and respond to changes in the environment. Automated packaging that responds to different outside factors has been developed at Zhejiang University in Hangzhou, China. Even with the advances that have improved food freshness testing technology and reduced limitations, costs, and processing speeds, many areas still need to be researched. Moreover, to work for environmental sustainability as lot of plastic packaging trash

Table 1. Importance of Artificial Intelligence for sustainable development goals.

Traditional Knowledge	Aligned Sustainable Development Goals (SDGs)	Ref
Nutritional plants containing essential micronutrients	Contributing to the eradication of poverty by supporting livelihoods and ensuring basic nutritional needs (SDG 1)	Song, Xia, and Tang (2024)
Bioprospecting new plants for food and medicine	Supporting food security, nutritional improvement, and advancing sustainable agricultural practices (SDG 2)	Y. Chen et al. (2024); Reichert et al. (2020)
Medicinal plants having health beneficial compounds	Promoting better health outcomes and ensuring well-being for people across all age groups (SDG 3)	Lewis, Verghese, and Fitzpatrick (2010); Reichert et al. (2020).
Compounds showing actions against diseases	Enhancing global health by aiding in disease prevention and supporting healthy living for all (SDG 3)	Y. Chen et al. (2024); Song, Xia, and Tang (2024)
Sustainable traditional agricultural practices to climate change	Addressing climate change through eco-friendly farming practices adapted to local environments (SDG 13)	Y. Chen et al. (2024); Lewis, Verghese, and Fitzpatrick (2010); Reichert et al. (2020).
Collaborate with the people to understand their traditional systems and integrate new technologies	Encouraging responsible consumption and fostering sustainable production systems in collaboration with local communities (SDG 12)	Lewis, Verghese, and Fitzpatrick (2010); Reichert et al. (2020).
Sustainable and harmonious harvesting techniques	Promoting conservation of terrestrial ecosystems, supporting reforestation, combating desertification, and preserving biodiversity (SDG 15)	Y. Chen et al. (2024); Song, Xia, and Tang (2024)

finds its way into landfills or the natural surroundings because of its usually short lifetime and single-use character. Actually, wasted packaging makes up around 46% of all annual plastic trash generated (Singh, Sharma et al. 2021). Furthermore, fewer than 10% of all plastic garbage has been recycled. Every year, demand for packing is increasing, the total municipal solid waste (MSW) of plastic trash in the US accounted for 29.5% and 25% in Europe (Oun, Shankar, and Rhim 2020). Therefore, smart and sustainable packaging can play an integral role globally (Zhu et al. 2020). Furthermore, governments throughout the world are working hard to limit the use of plastic products.

Plant – based natural fibers for the packaging industry

The pursuit for sustainable alternatives in packaging is increasing everyday as environmental concerns about nonrenewable resources and plastic pollution are growing more intense (Lan et al. 2021). Therefore, the integration of AI with plant-based fibers allows the creation of intelligent packaging systems capable of monitoring and responding to environmental fluctuations. These technologies may identify spoilage, modify permeability, and deliver real-time feedback to customers, so improving food safety and minimizing waste. Moreover, AI technologies enhance production processes for biodegradable materials through data analysis from industrial facilities. This results in more sustainable and economical production techniques, enhancing the accessibility and affordability of biodegradable materials. Cellulose is a linear polysaccharide primarily derived from both wood and non-wood plant sources (Dejene etal. 2025). It consists of glucose monomers linked by (1→4)-β-D-glycosidic bonds. Within lignocellulosic biomass, cellulose accounts for approximately 45%, alongside other major constituents such as hemicellulose and lignin. Unlike hemicellulose and lignin, which possess amorphous structures, cellulose represents the only crystalline component in the plant cell wall (Saba, Sultan, and Jawaid 2020). The crystalline areas of cellulose have a strong hydrogen bond network between several hydroxyl groups. Cellulose is stable and unaffected by deterioration due to its tight and organized crystalline structure due to hydrogen bonding (Singh, Sharma et al. 2021). Fiber from cells shows a hierarchical, multi-scale arrangement. Cellulose chains create micro-fibrils at the nanoscale, which are then bundled into macro-fibrils, larger structures. Different nanostructured cellulose materials may be extracted thanks to this hierarchical construction. These comprise micro-fibrillated cellulose (MFC), microcrystalline cellulose (MCC), and forms of nanocellulose including nanocrystalline cellulose (NCC) and nano-fibrillated cellulose (NFC). As fillers in modern materials, particularly sustainable packaging, these many kinds of nano-cellulose have special qualities, including large surface area, mechanical strength, and biocompatibility. The extraction of fibers from agricultural waste is one of the most distinctive and lucrative processes among them (Dutra et al. 2021). Due to its distinctive features, biodegradability, and exceptional physical and mechanical capabilities, cellulose and nano- cellulose (NC), as well as their derivatives, are gaining popularity in the food packaging industry. Although there are numerous fibers from the planet, only a few have been studied yet (Shen, Qian, and Tu 2025). studied the broader trend of combining experimental rheology with RSM and MLP-ANN modeling for prediction and optimization of viscosity, G′, and G″ of sulfate nanocellulose hydrogels by varying processing settings. RSM method was used to locate optimal operating conditions and ANN for enhancing the prediction fidelity. The results revealed that hydrogel performance is best engineered through joint consideration of composition and the exact mechanical/flow conditions relevant to manufacturing process and end use. Some fibers are used as fillers in composites due to good mechanical properties, biocompatibility and durability (Hayase 2018, Kämpfer et al. 2017; Li et al. 2023; Pasqua et al. 2020). These fibers increase the strength, stiffness, and impact resistance of packaging when mixed with bio-based resins, therefore safeguarding a great variety of goods during handling and transit. Moreover, these fibers help to improve sound absorption and heat insulation, therefore giving the packing material additional useful value. This not only eliminates the requirement for burning agricultural waste or landfilling but also gives rural towns and farmers more revenue sources (Francucci, Rodríguez, and Vázquez 2012; Vogl et al. 2004). Furthermore, completely biodegradable, vegetable fiber filler-made packaging breaks down organically without generating harmful chemicals. This makes them a safer and more ecological choice than traditional plastic packaging, which ages in the environment for millennia. Furthermore, the need for environmentally friendly packaging is increasing as worldwide rules on single-use plastics and consumer awareness get stricter. Based on vegetable fibers, packaging solves consumer requirements as well as environmental ones, therefore encouraging a circular economy (Z. Ahmed and Akhter 2001; Frone et al. 2011; Hu et al. 2012; N. Reddy and Yang 2011). Because of their biocompatibility and environmental sustainability, these fibers are garnering a great deal of interest and are regarded as having major packaging industry uses. These low-cost materials have desirable mechanical qualities and are currently in high demand on the global market, mostly in food and textile industries. Figure 3 highlights some common plant-based fibers with their applications the food industry. In the next section various plant-based fibers and their applications will be discussed (Chaitanya and Singh 2017).

For example, hemp fibers are used because of their high cellulose and low lignin content, allowing for a speedier cellulose micro/Nano fiber isolation technique. The isolation of cellulose nano crystalline fractions, also known as nano whiskers, was achieved by acid hydrolysis of entire crystalline cellulose regions as a source of cellulose. It is a multipurpose crop that may provide a wide range of raw ingredients. The various advantages of the hemp crops led to the primary motivations for its future expansion. This plant is plentiful and widespread, and it is economically significant in various cultures. In one study (Barbash et al. 2022), extracted nanocellulose from organosolv hemp pulp and showed that adding 2% of this nanocellulose boosted paper breaking strength by 40%. In another investigation (Kaiser, Anuar, and Razak 2014), fabricated insulation boards from a blend of hemp fibers and shives; their findings demonstrated that the boards' porous, low-density structure effectively reduced heat transfer. Figure 4 illustrates the morphology of various natural fibers: (a) hemp, (b) flax, (c) coir, and (d) cotton, along with their corresponding structural images: (e) hemp, (f) flax, (g) coir, and (h) cotton. The FLHEA (Flax and hemp advanced fiber-based composites) project, which investigated the use of these two plants as sustainable source materials for superior packaging. Furthermore, Jute has recently emerged as a promising material for replacing conventional plastic bags, primarily due to its eco-friendly characteristics. In addition to being biodegradable and renewable, jute exhibits excellent insulating and antistatic properties, low thermal conductivity, and a moderate capacity for moisture absorption.

These attributes make jute bags a sustainable and practical alternative to non-biodegradable poly bags derived from fossil fuels (Kaiser, Anuar, and Razak 2014; Iqbal et al. 2025; Kurien et al. 2025). (Abdullah et al. 2006 prepared hybrid composites by hand lay-up, combining jute fiber (Hessian cloth) with Eglass mat, using suitable additives and an initiator (Abdullah-Al-Kafi et al. 2006). They found that replacing 25% of the glass with jute yielded the best mechanical improvements. In a separate investigation (K. S. Ahmed, Vijayarangan, and Rajput 2006), manufactured woven jute/glass hybrids and observed that the inclusion of jute significantly boosted both tensile and impact strengths. On the other hand, sisal stands out among leaf fibers and has been traditionally harvested in South and Central America for centuries to produce coarse yarns, twine, and cordage. Its robust leaves yield three distinct fiber types of mechanical, ribbon, and xylem that can thrive

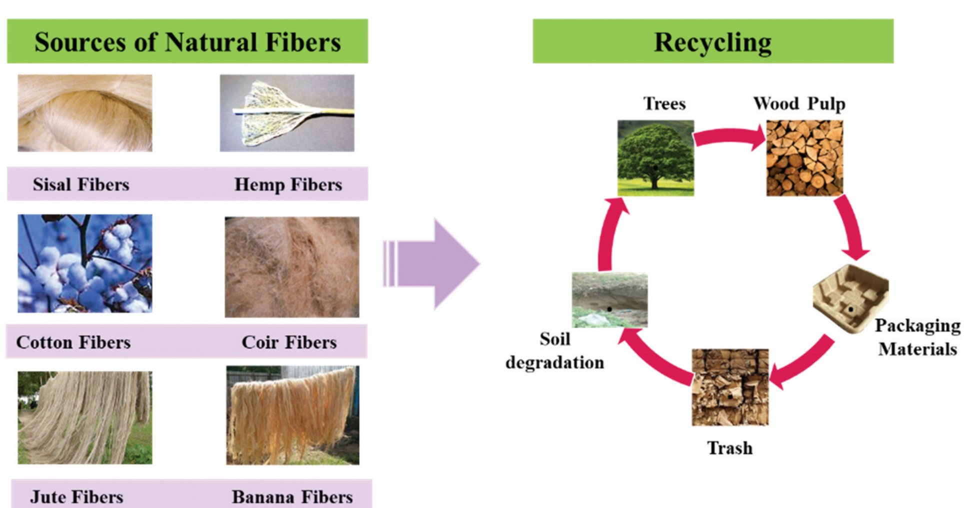

Figure 3. Some common plant bases fibers with their applications in food industry.

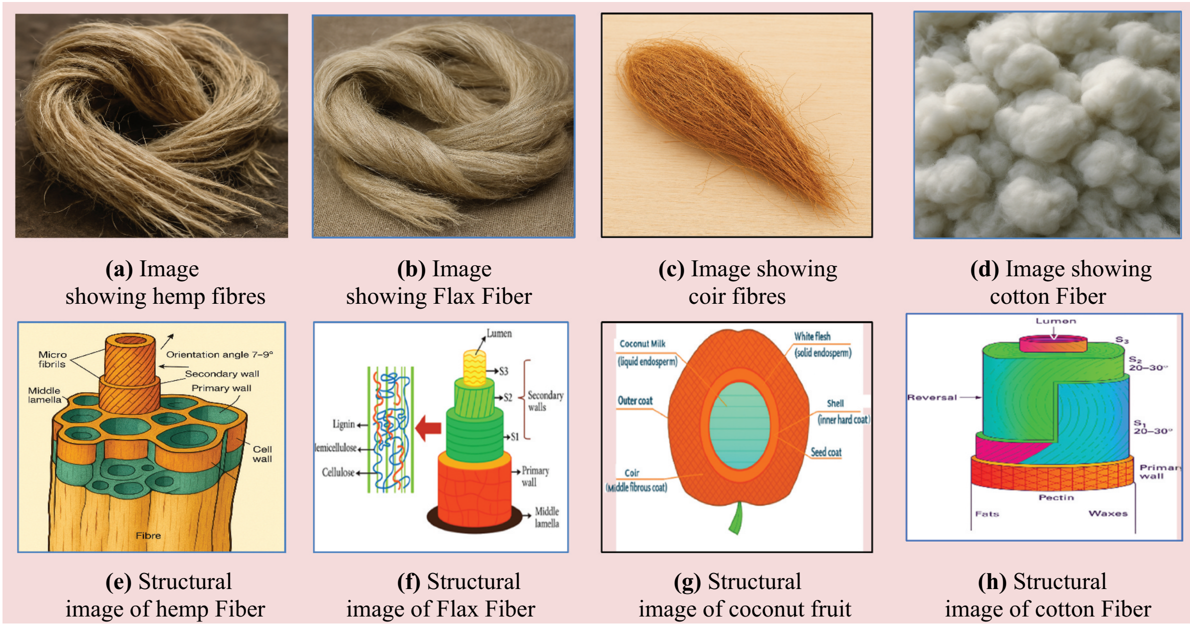

Figure 4. Illustrates the morphology of various natural fibers: (a) hemp, (b) flax, (c) coir, and (d) cotton, along with their corresponding structural images: (e) hemp, (f) flax, (g) coir, and (h) cotton.

under a wide range of climatic conditions (Chokshi et al. 2022; Dejene 2024; Gai et al. 2024; Kóczán and Pásztory 2024; Mihai and Ton-That 2019; Mohammadi, Ishak, and Sultan 2024). Another plant-based fiber, flax fibres have gained appeal as a reinforcement in composites these days, as the demand for sustainable materials grows year after year. The fibers extracted from the flax plant have good mechanical properties as compared to glass (Nayak et al. 2022). Additionally, incorporating wheat straw into poly(3-hydroxybutyrate-co-valerate) resulted in a 3.5-fold increase in water vapor permeability, a property particularly beneficial for packaging applications involving respiring food products such as strawberries (Hua et al. 2024; Ma, Yan, and Kasal 2025). Moreover, Coir, a lignocellulosic fiber derived from the outer husk that surrounds the coconut seed. Abundantly available along South Asian coastlines, the husk is a byproduct of copra (dried coconut kernel) production, after the oil – rich nut meat has been removed. Although India leads global consumption, only a small portion of the harvested husk is processed into fiber (Zamiri et al. 2024). Furthermore, Cotton is the most essential of all-natural fiber crops. Cotton fiber accounted for 61% of the market for garments and home textiles in the United States in 2010 (Cao 2024; Masud and Mubashar 2024). Throughout, the globe there is a comparable need for sustainable cotton fiber (Kumar, Dutt et al. 2025; Schiavon, Borges, and de Oliveira Andrade 2024). Each long cotton "lint" fiber is formed by a single epidermal cell on the ovule surface that undergoes remarkable polar expansion and cell wall thickening before transforming into the very elongated and strengthened dead fiber (Senthil Kumar et al. 2024; Tasgin et al. 2024; Wasti et al. 2024). Minimum-tillage techniques Intriguingly, the etymology of "cotton" remains unclear. While cotton naturally grows as a perennial, selective breeding has produced annual cultivars (Aslam et al. 2020; Bi et al. 2024; De Silva and Naveen 2024; Feng et al. 2024; Gui, Yang, and Xiang 2024; Hsieh 2024; Li et al. 2024; Yousef et al. 2020; Zeng et al. 2018). Table 2 presents a comprehensive comparison of the physical, chemical, and mechanical properties of five widely used natural fibers.

The table systematically organizes key characteristics such as scientific name, color, density, tensile strength, Young's modulus, elongation at break, moisture absorption, thermal conductivity, decomposition temperature, cellulose, hemicellulose, and lignin content, microfibril angle, fiber diameter, surface texture, and typical applications. This comparison highlights the diversity and suitability of each fiber for specific industrial and composite applications, providing a valuable reference for material selection and research in sustainable materials science.

Table 2. Comparison of the physical, chemical, and mechanical properties of used natural fibers.

Property	Flax	Hemp	Jute	Coir	Sisal	Kapok	Abaca	Pineapple
Scientific Name	*Linum usitatissimum*	*Cannabis sativa*	*Corchorus spp.*	*Cocos nucifera*	*Agave sisalana*	*Ceiba pentandra*	*Musa textilis*	*Ananas comosus*
Color	Light, beige	Light to brown	Golden to brown	Brown	Cream to yellow	White, silky	Creamy white	Cream-golden
Density (g/cm^3)	1.40	1.48	1.30	1.15–1.25	1.33–1.45	0.29	1.50	1.44
Tensile Strength (MPa)	500–1500	550–900	393–800	95–230	350–700	50–150	650–980	413–1627
Young's Modulus (GPa)	30–80	30–70	10–30	2–6	10–25	3–5	30–40	34.5–82.5
Elongation at Break (%)	1.2–3	1.6–3	1.5–2	15–40	2–5	10–20	3–10	1.6–14.0
Moisture Absorption (%)	8–13	8–13	12–13	10–15	10–12	8–10	7–9	10–12
Thermal Conductivity (W/m·K)	~0.038–0.045	~0.038–0.045	~0.038–0.045	~0.04–0.05	~0.04–0.05	~0.035–0.040	~0.040	~0.042
Decomposition Temp. (°C)	150–200	150–200	150–200	150–200	150–200	150–180	160–200	160–220
Cellulose Content (%)	60–70	60–75	55–65	32–46	65–75	64–70	56–74	70–82
Hemicellulose (%)	15–20	15–20	18–22	0.15–0.25	10–15	8–22	15–25	12–17
Lignin Content (%)	2–4	3–7	10–13	40–45	8–12	0–2	5–12	5–12
Microfibril Angle (°)	5–10	6–10	8–20	30–49	10–22	25–40	8–15	8–14
Fiber Diameter (μm)	12–16	16–50	15–25	100–450	50–300	120–190	12–30	20–80
Surface	Smooth, lustrous	Rough, durable	Rough, coarse	Rough, coarse	Rough, hard	Smooth, hollow	Smooth, lustrous	Rough, fibrous
Applications	Linen, composites, paper	Ropes, composites, textiles	Burlap, sacks, composites	Mats, geotextiles, insulation	Ropes, carpets, composites	Fillers, cushions	Trays, structural	Boxes, trays
Reference	Ghalme, Hayat, and Harne (2025); Santos et al. (2025); Stevens (2010)	Ghalme, Hayat, and Harne (2025); Santos et al. (2025); Stevens (2010)	Ghalme, Hayat, and Harne (2025); Santos et al. (2025); Stevens (2010)	Ghalme, Hayat, and Harne (2025); Santos et al. (2025); Stevens (2010)	Ghalme, Hayat, and Harne (2025); Santos et al. (2025); Stevens (2010)	Baraniak and Kania-Dobrowolska (2023)	Kurien et al. (2023)	Motaleb, Shariful Islam, and Hoque (2018)

Applications in the packaging sector

Plant-based fibers are increasingly being used in the packaging sector as a sustainable alternative to plastic and synthetic materials (Ul-Allah et al. 2021; Zafar et al. 2023). By providing sustainable, biodegradable, high-performance substitutes for traditional plastic materials, plant-based fiber composites are revolutionizing the packaging industry. These composites help in environmentally friendly solutions for packaging that satisfy functional needs by combining biodegradable or recyclable polymer matrices with natural fibers such as flax, hemp, jute, kenaf, bamboo, and sisal. The mechanical strength and durability of these composites stand out as significant advantages. Natural fibers exhibit significant tensile strength and stiffness, which, when incorporated into biopolymer matrices, improve the structural integrity of packaging materials. Nevertheless, for guaranteeing food safety, maintaining food quality, and minimizing food waste, packaging can offer passive protection to food products by utilizing the barrier properties of the packaging material. Active packaging technologies enhance packaging protection by utilizing the packaging material for antimicrobial agents, antioxidants, releasing agents, and absorbents to actively control its internal environment. The lack of real-time monitoring using AI technologies helps to identify the potential risk to consumer health regarding food freshness associated with active packaging. Therefore, new technologies and methods are being researched to enhance food freshness (Chen, Steuer et al. 2025).

Thus, they are well-suited for applications requiring robust, protective packaging solutions (Chen, He et al. 2025). Intelligent Packaging, a novel packaging approach, provides real-time product tracking, improves the transmission of Relevant information, enables fast detection of food freshness, and has significant applications. It enhances the safety and nutritional quality of food. Effective determination of food freshness might be achieved through state-of-the-art techniques such as pattern recognition and DL (Cui et al. 2024). developed a machine-learning framework for real-time remaining shelf-life prediction covering multiple marine fish for different storage temperatures, Therefore, addressing a common limitation of earlier studies that were typically constrained to a single species or condition. 14 input features were used for integrating species and temperature with freshness/spoilage indicators. Four algorithms were compared (BP, GA-BP, RBF, ELM). The results revealed that radial basis function (RBF) model achieved the best predictive performance, reporting a maximum absolute error of 0.48 and absolute errors < 0.5 across all test samples, indicating high accuracy for practical decision support. Using this best-performing method as a foundation, they created a live forecasting system, which was developed for operational use in cold-chain monitoring, food quality control and real-time management of food security for the seafood industry. In another study (Haque et al. 2025), developed multi-channel gas sensing system combined with edge-deployable using Machine Learning (ML) technology to provide a way to classify freshness in real time. Therefore, an IoT-based shelf-life estimation system for date fruits was integrated using multichannel gas sensing with edge-deployed machine learning for real-time freshness classification. The system monitored spoilage-related gas emissions alongside environmental parameters, therefore addressing the limitation of conventional cold storage that tracks temperature/humidity but cannot infer spoilage dynamics to reduce postharvest losses and strengthen food security. A chemical-free monitoring approach combining hyperspectral imaging (400–1000 nm) with AI was developed by (Siripatrawan and Makino 2025) for assessing dried shrimp quality and shelf life during storage at temperature of 30°C. Spectral fingerprints were pre- and explored via PCA, then a using feed-forward backprop ANN simultaneously predicted key quality indices such as astaxanthin, TBARS, TVB-N, and sensory scores with strong performance (R^2 ≈0.92–0.96) and low errors. This study also generated pseudo-color maps from ANN outputs to visualize spatial temporal quality changes, that demonstrated HSI+AI as an effective tool for shelf-life evaluation. Table 3 shows advanced overview of biodegradable packaging in different sectors. Therefore, AI-enabled natural fiber – reinforced polymer composites can serve as sustainable, environmentally friendly packaging materials (Goyal, Singha, and Singh 2024). As these technologies helps in several domains like material synthesis, information storage, wireless transmission, and information identification and processing. It is a novel knowledge system predicated on matter, with information as the nucleus and materials as carrier, and technology serves as instruments for examining the principles governing the interplay between matter and information, along with their applications. Therefore, integrating these technologies with plant-based fibers can play a vital role in various industrial applications (Gregor 2018). Hence, experts have pushed for ecologically friendly and biodegradable packaging made of plant-based fibers. The use of sustainable packing materials in various industries is covered in the following section (Gao et al. 2025). Moreover, methods for determining freshness are often employed to estimate food freshness based on the interaction between the food's metabolites (e.g., glucose, organic acids, ethanol, volatile nitrogen compounds, biogenic amines,

Table 3. Advanced overview of biodegradable packaging: sectors, applications.

Sector	Packaging Applications	Advantages	Examples/Case Studies	Ref
Food & Beverages	Trays, plates, cups, takeaway containers, molded pulp boxes, seaweed-based edible films	- Biodegradable & compostable – Grease/water resistance – Microwave & freezer safe – Extended shelf life	Notpla (seaweed films) [PMC] , Ecovative Design (mycelium foam)	Chen, Steuer et al. (2025)
Medical & Pharmaceutical	Syringe packs, surgical tool trays, paperboard cartons, bio-based blister packs, pill bottles	- Biodegradable & recyclable – Maintains sterility – Antimicrobial properties (bamboo, hemp) – Safe disposal	Bayer – PAPACKS fiber-based pharma packs, Astellas biomass blister packs	Marcoaldi et al. (2025); Pirsa (2024).
Industrial	Corrugated cartons, molded pulp inserts, pallets, crates, sacks & bags for bulk goods	- High strength & cushioning – Lightweight (reduced logistics cost) – Moisture resistance – Fully recyclable	Corrugated board (global logistics), hemp/flax composite pallets, jute/sisal sacks	Marcoaldi et al. (2025); Pirsa (2024).
Cross-Sector	Cushioning (coir, shredded pulp), smart packaging with nanofiber composites, intelligent labeling	- Reduced landfill waste – Adaptable for electronics, agriculture & construction – Potential AI-enabled monitoring	Plant-fiber nanocomposites with sensors for freshness tracking	Chen, He et al. (2025) Escobar-Sánchez et al. (2025)

carbon dioxide, ATP degradation products, and sulfuric compounds, together with the indications. To ensure contact with the compounds, the freshness indicators must be positioned within the container. Depending on the indication, this information can be discerned by several means' in the detection category. For, example certain foods are transported for storage, distribution, and consumption, where each phase presents a risk of food maturity that may affect their freshness. Therefore, monitoring the degree of maturity of food may not only assure the quality of food but also boost customer confidence.

Packaging of meals and beverages using intelligent systems

Pairing sustainable materials with conventional petroleum-based materials, plant-based fiber packaging is changing the food and beverage industry (Dejene, Gudayu et al. 2024). When coupled with AI, ML, and DL, the advantages become much more significant (Dong, Wang, and Abbas 2021). AI-assisted material discovery, for example, uses ML and deep neural networks to analyze large databases of plant fiber properties to predict combinations that provide the best strength, moisture resistivity, barrier properties, and compost ability to optimize wastes and be able to easily develop new materials, as exhibited in their recent collaboration with Nestlé and IBM researching generative AI tools for identifying and designing new high-barrier packaging materials. Additionally, DL can support quality control: computer vision models of plant-based packaging can scan for defects (e.g. uneven thickness, weak spots) during the production process and catch defects early to limit wasted materials (Yu et al. 2025). Predictive modeling using ML can also contribute to lifecycle assessment (LCA) to help estimate the environmental impacts of sourcing raw materials, manufacturing, product use, and disposal of the material waste. For food safety purposes, ML models can predict the leaching of chemicals across levels of variations and suggest safer material blends. Smart packaging systems with sensors + AI can monitor freshness, humidity or spoilage and help reduce food waste. As a whole, combining AI/ML/DL with plant fiber-based packaging expedites sustainable innovation, is functional, supports regulatory compliance, and reduces the environmental footprint throughout the life cycle of packaging. Plant-based fiber packaging is functionally water and grease-resistant, therefore fit for a range of food and drink uses (Zatsu et al. 2024). These materials guarantee the safety and quality of the packed contents by being microwave and freezer- safe, high- temperature resistant, and efficient insulating agents. As a result, there has been a steady increase in a keen interest in researching the migration of packaging components under a variety of conditions and the development of advanced analytical methodologies. At lesser concentrations, volatile chemicals can be detected (Huang et al. 2025). One of the most common uses is in food packaging, where plant-based fiber materials like molded pulp and paper-based packaging are used for trays, plates, cups, and takeaway containers. These materials are biodegradable, compostable, and suitable for direct food contact. Some are coated with biodegradable biopolymers to enhance water and grease resistance. Food packaging that can be reused, recycled, or incinerated is under increasing demand from society. Protecting food to maintain its freshness, quality, and safety is the core purpose of packaging. Cellophane, also known as regenerated cellulose in the film industry, is the furthermost extensively used cellulose-based food packaging. Packaging for meals and beverages is no longer just about wrapping today; intelligence is being woven into every layer, from design to safety to supply chain visibility. AI, ML, and DL are powering this transformation. In production lines, DL enabled computer vision systems inspect thermoformed meal trays, beverage bottles, or cans in real time, flagging defects such as poor seals, deformation, contamination, or foreign objects, ensuring that only products meeting strict quality thresholds reach consumers (B. S. H. Reddy, Venkatramana, and Jayasree 2025).

Label verification is also automated: models check that expiry dates and best-before labels are printed correctly and legibly, lowering health risks and compliance issues. Smart packaging systems extend functionality: embedded sensors detect changes in temperature, humidity, or gas composition, while ML algorithms interpret this data to predict spoilage or reduced freshness in packaged meals and beverages (Bradley, Castle, and Chaudhry 2011). These systems can use convolutional neural networks (CNNs) to recognize visual cues of degradation or sensors for volatile compounds, offering consumers and producers real-time feedback on food safety. Figure 5. Showing the application of AI in the packaging sector which enhances mechanical properties, improves physical properties and, finds the optimum formulation for customized packaging. Meanwhile, at the design stage, generative

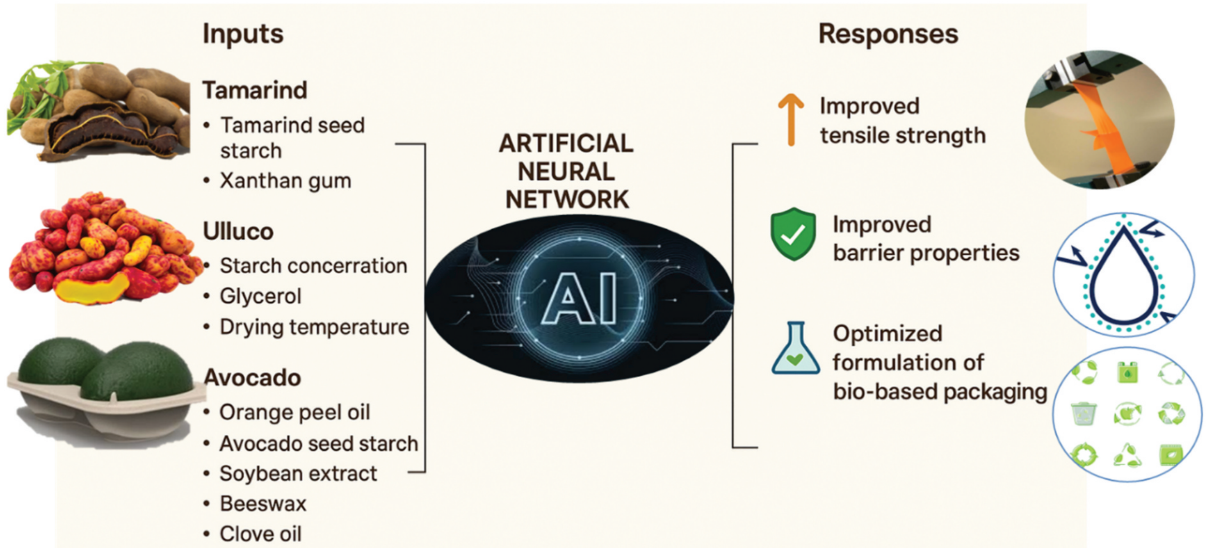

Figure 5. Applications of AI in food packaging.

AI tools analyze molecular structures (for barrier properties, moisture resistance, etc.), cost, and sustainability to propose new packaging materials for beverages that balance performance and environmental impact (Hasan, Vasker, and Khan 2024). Across the supply chain, ML helps optimize packaging shape and size for minimizing material use, forecasting demand to reduce over-production, and routing logistics to reduce carbon footprint. All together, these applications reduce waste, improve safety, speed up inspection, and help packaging evolve from passive containers to active, intelligent guardians of food and drink quality. Intelligent packaging systems have been extensively investigated for real-time monitoring of food quality through visual indicators such as color changes. Colorimetric sensors based on pH-sensitive dyes, natural pigments, or nanocomposite indicators have been successfully applied to detect spoilage in perishable foods, particularly meat and seafood, by responding to volatile amines and pH variations generated during microbial degradation. Several studies have demonstrated that such indicators provide a clear visual signal correlated with food freshness and shelf-life (Mehdizadeh et al. 2025). studied the development of a sensor array for classifying meat samples by sensor array – based approach for classifying meat freshness using Total Volatile Basic Nitrogen (TVB-N) as an indicator. The arrays used solutions of seven pH and redox indicators of dyes, and classification was achieved using LDA-PCA and genetic programming (GP). GP identified Chlorophenol red, while Cresol red, and Methyl violet as the most influential indicators. The developed models were implemented using smartphone application and demonstrated high classification performance, with LDA-PCA accuracies of 96% (buffalo), 81% (lamb), and 88% (beef). The results revealed that feasibility of dye-based sensor arrays combined with machine learning for real-time meat freshness assessment. When combined with data-driven analysis, AI-assisted interpretation of these visual signals further enhances the accuracy and reliability of spoilage detection, supporting informed decision-making throughout the food supply chain. Intelligent packaging integrates colorimetric sensors with AI/ML algorithms to monitor spoilage through pH changes and volatile organic compounds (VOCs), providing real-time feedback via color transitions% (Eisa Zadeh, Chatroudi, and Alizadeh 2025; Jazdi et al. 2021; Kumar, Rawat et al. 2025; Mehdizadeh et al. 2025). Cellulose-based pH sensors embedded with red cabbage anthocyanins detect beef spoilage progression as orange (fresh, pH 5.5) to green (use soon, pH 6.2) to dark green (spoiled, pH 6.8), extending shelf-life by 2 days with 95% accuracy. Polydiacetylene (PDA) hydrogel sensors respond to biogenic amines (cadaverine, putrescine) during meat degradation, exhibiting blue to red color shifts detectable by CNN-based image analysis (98% accuracy) (Chen et al. 2025; El-Mesery et al. 2025; Holliday and Zhang 2024; Pham and Chang 2023; Zhang et al. 2023). These systems link color intensity directly to spoilage biomarkers, outperforming traditional threshold sensors by 15–20%.

Medical and pharmaceutical industry

Medical and pharmaceutical industries require packaging solutions that offer product safety, sterility, and sustainability. Plant-based fibers sourced from renewable raw materials like bamboo, hemp, jute, flax, sugarcane bagasse and wood pulp are sustainable alternatives to traditional plastics. These natural fibers are biodegradable, recyclable, and compostable, minimizing environmental impact while still providing protection. As a result, packaging for more medical devices, instruments, and pharmaceutical products is increasingly being produced using molded pulp trays, cardboard boxes, and paperboard cartons, which not only provide cushioning and durability but are entirely biodegradable (Jadhav et al. 2025). The application of AI, ML and DL is changing this sector: ML/DL-driven computer vision technologies will enable the automatic detection of defects in fiber-based packaging products (tears, moisture exposure, weak seams), providing faster and more accurate quality control. Predictive ML models optimize fiber mix, moisture content, and operational parameters in real time to achieve a desired stiffness and performance (P. Kumar et al. 2010). In addition, AI supports supply chain optimization and life-cycle assessment, allowing manufacturers to predict demand, minimize waste, and ensure a level of high protective standards in sustainable packaging.

Packaging for syringes, bandages, gauze, and surgical tools frequently uses robust paper-based materials that comply with rigorous cleanliness and safety regulations (Wang and Li 2024). Moreover, Conventional blister packs for tablets and capsules are generally composed of plastic and aluminum materials. Now due to advancements in plant-based fiber technology have resulted in the creation of biodegradable blister packaging utilizing paper-based composites, cellulose derivatives, and bio-polymers has been created. These alternatives preserve product integrity and decrease plastic waste. Pill bottles and medication containers constructed from plant fiber composites or molded pulp present sustainable alternatives for pharmaceutical companies aiming to decrease their carbon footprint (Chang et al. 2025; Malik, Muhammad, and Waheed 2024; Mu et al. 2024; Yaiprasert and Hidayanto 2024; Zhao et al. 2025). Bamboo and hemp have inherent antibacterial characteristics that assist medical packaging in staying sterile. Antimicrobial packaging for wound care goods, surgical masks, and PPE may be made from these fibers. Plant-based coatings improve moisture resistance and pollutant prevention. Offering a mix of sustainability, safety, and utility, carton packaging is essential in the pharmaceutical industry. Its main purpose is to guard drugs from physical damage, contamination, and environmental elements including moisture and light, therefore guaranteeing the efficacy and safety of the goods through their shelf life. In addition, there is plenty of room on cartons for descriptive and accurate labeling, which is vital for informing patients and doctors about important details like how much to take, when it will expire, and any possible adverse effects (Akbar and Anal 2014). Both the brand's credibility and patients' compliance are bolstered by this level of openness.

Beyond information sharing and preservation, carton packaging is a very effective marketing technique. In a cutthroat market, its adaptability lets pharmaceutical businesses use distinctive colors, logos, and designs, thereby improving brand awareness and distinction. Furthermore, light-weight and reasonably priced, boxes help to lower environmental impact and transportation expenses. Their biodegradability and recyclability fit the rising customer need for environmentally friendly solutions, therefore establishing businesses as social conscious organizations (Bumbudsanpharoke et al. 2025). In an effort to achieve their goal of fully recyclable or reused packaging by the year 2030, notable firms such as Bayer have collaborated with PAPACKS to create fiber-based packaging for consumer health goods that is biodegradable. Similarly, Astellas Pharma took a giant leap toward carbon neutrality in pharmaceutical packaging when it released biomass-based plastic blister packets in Japan. These containers use polyethylene generated from sugarcane. Pharmaceutical companies are moving toward using plant-based fiber packaging more and more as a means to reduce their environmental impact. These materials provide an eco-friendly substitute for conventional plastics by being made from sustainable sources such as bamboo, sugarcane, and maize. The possibility of developing long-lasting and biodegradable packaging solutions is being investigated using innovations like bioplastics, cellulose-based materials, and composites made of mushroom mycelium. AI, ML, and DL are revolutionizing pharmaceutical and medical packaging by making design smarter, increasing efficiency, and minimizing waste. First, ML/DL-based computer vision systems can automate quality control. For example, these systems can identify defects, seals that are not intact, or errors in labeling on blister packs, vials, cartons, etc., much more quickly and accurately than a human in a packaging room can. This means fewer waste and less rejected batches. Predictive maintenance using AI to monitor packaging machinery faults before a component fails and shuts the machine down. By helping to eliminate unplanned shutdowns, companies decrease material scraps and energy waste. Thirdly, AI & ML tools will optimize design and material usage of packaging (Lin et al. 2024; Moustafa et al. 2025). For example, right-sizing cartons, optimizing the use of sustainable materials, optimizing packaging structures, maximizing cushioning vs material used, and simulating lifecycle impacts. These optimizations can reduce over-packaging, reduce carbon footprint, and enable continued use of biodegradable/recyclable fiber materials. Also, AI will add improved tracking systems and compliance: supply chain data tracking, temperature and sterility controls, and smart labeling, which together will help ensure packaging performs sustainability without sacrificing safety or regulatory standards of packaging.

Industrial packaging

AI, ML, and DL are being used in industrial packages to improve sustainability through smarter designs, efficient operations, and waste reduction. Generative AI tools are capable of simulating packaging designs in 3D, optimizing the material thickness, structural geometry, and barrier properties necessary to retain the needed level of protection while using less material. ML-driven predictive analytics can inform forecasting demand and managing inventory to ensure minimal overproduction and excess packaging (Sah and Kaity 2024). DL-based computer vision systems are used for real-time quality control to detect defects or misalignment at the point-of-production early, thus reducing scrap and reworks. AI is also useful for adaptive manufacturing: ML models can monitor process data (temperature, pressure, speed) to adjust parameters to achieve better energy efficiency and reduced off-spec production. Furthermore, (life-cycle analysis) sustainability assessments can also be enhanced with AI tools to compare the environmental impacts of materials so as to allow substitution with biodegradable, recyclable, or compostable alternatives (Jiang, Feng, and Wang 2013). Even supply chain optimizations (route planning, load optimization) can have an impact on lowering carbon footprints, as can AI-enabled smart recycling/sorting systems that allow materials to be recovered and closed in circular loops. One of the most common uses of plant-based fibers is the manufacture of corrugated cardboard and paper-based packaging. These materials, made of recycled paper, wood pulp, or agricultural leftovers, are used to make shipping cartons, industrial boxes, and packaging sleeves. Corrugated cardboard is strong, durable, and cushioned, making it ideal for carrying products over long distances (Marchese et al. 2015). Because it is totally recyclable and biodegradable, it generates substantially less trash than plastic-based alternatives. For example, molded pulp packing is an effective alternative to plastic like expanded polystyrene and polyurethane. It is fabricated of plant fibers including sugarcane bagasse, wheat straw, and recycled paper, which are molded into protective inserts, trays, and cushioning materials. These are widely utilized in the packaging of electronics, automobile parts, medical devices, and sensitive industrial components. Molded pulp is both sustainable and biodegradable, making it an ideal solution for companies looking to decrease plastic waste. Moreover, Pallets and crates are crucial for industrial logistics, storage, and transportation. Traditional wooden and plastic pallets contribute to deforestation and plastic pollution, but bio-based composite pallets manufactured from natural fibers like hemp, bamboo, or flax blended with biodegradable resins provide an environmentally beneficial alternative. These pallets are lightweight, sturdy, and moisture-resistant, making them excellent for transferring big loads while lowering the carbon impact of logistical operations.

Other potential uses of plant-based products

The packaging sector is investing heavily in technology innovations to provide ecologically friendly packaging materials that function well to preserve food. Furthermore, to have a good effect on user health, the packaging is developed by combining active substances in the wrapping structure with the wrapped food items (Youssef et al. 2015). High barrier material, active packaging, design and technological, nanotechnology, with digital printing innovations supporting developments across material engineering, electronics, and production methods. Packaging research is developing and promoting sustainable materials that can economically replace petroleum-based plastics and alleviate waste disposal issues. From manufacturing and usage to disposal or recycling, new applications of cellulose nanofibers in packaging can provide materials that perform well through their lifetime. This life-cycle approach assures product quality and advances environmental sustainability (Wakai and Almenar 2015). Furthermore, by means of greater product lifetime and more environmentally friendly manufacturing practices, adding CNFs into packaging systems will serve to improve user experience. Cellulose nanofibers offer a vast and general marketplace in the area of next-generation, sustainable packaging solutions (Zadbuke et al. 2013). The primary focus of contemporary packaging investigations is on the development and utilization of renewable, biodegradable "bioplastics," which provide sustainable alternatives to conventional petroleum-based plastics. The use of AI, ML, and DL is making industrial packaging smarter and greener. These technologies are allowing companies to innovate new materials faster; for instance, generative AI models are able to present new high-barrier bioplastics or nanocomposite materials that exhibit maximum protection (barrier properties) while remaining biodegradable. This is reducing the reliance on petroleum-based plastics. ML and DL-based prediction tools can optimize formulations of cellulose nanofibers (CNFs), active agents, and fillers (Dejene, Birilie et al. 2024), or predict how varying composition, moisture or fiber alignment will affect mechanical strength, barrier properties, and biodegradation. At production lines, systems that use DL -powered computer vision can detect defects, inconsistencies, or deviations related packaging films or coatings, which will minimize scrap and allow for more consistent quality. In addition, AI and machine learning models can aid in lifecycle analysis and the optimization of supply chains for their packaging lines: accurately forecasting customer demand and reducing over-production of packaging, while choosing more sustainable raw materials (Kodumuru et al. 2025). Therefore, using AI, machine learning, and DL will allow for the transformation of packaging design, manufacturing, and disposal, helping the industry better balance performance with environmental responsibility.

This helps to lower the environmental load related with to the disposal of plastic trash by substituting bio-based polymers with those sourced from fossil fuels. Among important sustainability issues, such as pollution, landfill overflow, and nonrenewable resource depletion, these environmentally friendly substitutes have the promise to solve them (Shukla 2025). Adding a suitable nanoparticle like cellulose nanocrystals (CNCs) or cellulose nanofibers (CNFs) to food wrapping can result in containers with stronger mechanical, barrier, and thermal qualities. Aside from bettering the qualities of food packaging, Bacteria and germs will not be able to infiltrate packaged food goods thanks to nano materials. Despite challenges such as cost and moisture sensitivity, continuous advancements in material science are improving the durability and functionality of plant-based fiber packaging. As consumer demand and regulations push for greener alternatives, plant-based fiber packaging is expected to play a vital role in reducing environmental impact.

Recent trends in packaging by aided by nanotechnology and AI

Progress has been made in the production of biodegradable materials from biological sources and some of the latest advances have emphasized the performance and function of biodegradable materials in specific applications, most notably applications related to packaging. This has involved a combination of natural polymers with nanomaterials and novel polymer processing techniques, resulting in plant-based materials that exhibit not only biodegradability but also improved strength, improved flexibility, and even antimicrobial characteristics (Kumar, Dutt et al. 2025). Currently AI, ML, and DL are an integral part in accelerating that pace of change in biodegradable packaging. Table 4 highlights the bio-nanocomposites for food packaging applications

Researchers studying starch chitosan bioactive films reinforced with beeswax and ZnO and activated with citrus extracts have recently demonstrated how ML workflows coupled with neural networks and response-surface methodology reduced experimental trials by about 65%, yet produced high tensile strength, low water-vapor permeability, and effective antimicrobial properties. DL models are being used for the prediction of polymers or copolymers properties (e.g., strength, barrier or biodegradability) based on chemical structure and process parameters to allow for the inverse-design of new plant-derived materials. Similarly, ML models that have been developed using meta-analyses can predict how structural ML could analyze previously published literature to create a predictive model that, for instance, predicts the rate and zone of inhibition of bacteria for an features such as molecular weight, side-chains, and the presence of ester

Table 4. Bio-nanocomposites for food packaging applications.

Sr.No.	Type of BNC film	Product	Observed properties/Results	Ref
1	Poly(glycidylmethacrylate-covinylferrocene) /grapheneoxide/ironoxidenanoparticle, and poly (glycidyl methacrylate-covinylferrocene) /MWCNT	Fish	Demonstrated rapid xanthine detection down to 0.12 µM within 4 s, enabling real-time monitoring of fish freshness	Kumar, Shyamala et al. (2025)
2	Soyproteinisolate – MMT (protein)	Fresh fruits and vegetables	Displayed higher tensile strength and thermal stability, along with reduced water-vapor transmission upon MMT incorporation	Kumar, Dutt et al. (2025); Heydari et al. (2024)
3	Tilapiaskingelatin hydrophilic – hydrophobic nano clays (protein)	_	Exhibited increased barrier resistance and improved mechanical integrity	Ashique et al. (2025); Sayyad and Attarde (2025).
4	Wheat gluten – lignin NPs (protein)	_	Showed lower water uptake, enhanced thermal endurance, and greater tensile strength	Sayyad and Attarde (2025)
5	Starch/halloysite/nisin	Soft cheese	Reinforced matrix strength and provided effective antimicrobial action against L. monocytogenes, C. perfringens, and S. aureus	Gorde et al. (2024); Moustafa et al. (2025)
6	Pectin/nanohybrid-layered double-hydroxide salicylate	Freshapricot	Offered greater film flexibility and moisture resistance, contributing to extended shelf life	Gorde et al. (2024); Sayyad and Attarde (2025)
7	Cornstarch/talc nanoparticles	Tomato	The material exhibited a 54% decrease in moisture permeability and a 26% reduction in oxygen permeability, accompanied by significant increases in both Young's modulus and yield stress.	Gorde et al. (2024); Sayyad and Attarde (2025)
8	Gelatine/ethanolic extract from coconut husk/ Cloisite Na+ nano clay	Meat powder	It effectively reduced lipid oxidation while enhancing moisture-barrier properties and prolonged product freshness	Kumar, Rawat et al. (2025); Heydari et al. (2024)
9	Nano zinc oxide – neem oil – chitosan	Carrot	Exerted strong antibacterial effects, particularly against E. coli	Gorde et al. (2024); Sayyad and Attarde (2025)
10	Alginate/nano-Ag	Shiitake mushroom	Prevented spoilage, preserved sensory quality, and minimized weight loss	(Gorde et al. 2024; Moustafa et al. 2025)
11	Edible coating of polyvinylpyrrolidone (PVP)containing silver nanoparticle	Asparagus	Inhibited psychotropic microbes during cold storage, reduced weight loss, and maintained color and texture for up to 25 days at 2°C (20 days at 10 °C)	Ashique et al. (2025); Sayyad and Attarde (2025).
12	Sodium alginate solution containing silver nanoparticles	Carrot and pear	Provided antibacterial protection versus E. coli and S. aureus, lowering moisture and protein loss to extend shelf life	Ashique et al. (2025); Sayyad and Attarde (2025).
13	Calcium alginate film loaded with zinc oxide nano particles	Ready-to-eat poultry meat	Reduced Salmonella typhimurium and E. coli counts by 7 log within 10 days at 8 ± 1°C	Gorde et al. (2024); Moustafa et al. (2025)
14	Silver nanoparticle-based cellulose absorbent pad	Beef meat	Released ~60 ppm Ag^+ to significantly lower aerobic, Pseudomonas, and Enterobacteriaceae counts without altering meat quality	Kodumuru et al. (2025).
15	Silver nanoparticle-based cellulose absorbent pads	Fresh-cut melons	Achieved ~3 log reduction in microbial load, delayed senescence, and preserved juiciness over 10 days	Youssef et al. (2015)
16	Nano- emulsion coating of chitosan and mandarin essential oil	Green beans	Lowered L. monocytogenes by < 1 log alone and by 4 log when paired with high-pressure processing	Wakai and Almenar 2015).
17	Chitosan/poly(vinyl alcohol)/ titanium nanoparticles	Soft white cheese	Delivered broad-spectrum Demonstrated antimicrobial efficacy against *S. aureus*, *P. aeruginosa*, *E. coli*, and *C. albicans*. and extended shelf life	Wakai and Almenar (2015)
18	Whey protein isolate (WPI)/MMT	Food models (water,3% acetic acid, 15% ethanol, olive oil)	Enhanced film tensile strength and reduced swelling by 35% across different model media	Gorde et al. (2024); Moustafa et al. (2025)

or ether linkages can impact biodegradation performance in aquatic or soil environments (Ashique et al. 2025; Gorde et al. 2024; Moustafa et al. 2025; Sayyad and Attarde 2025).

These nanoparticles are embedded in films of plant- or polymer-based matrices (with improved oxygen or UV permeability, moisture retention, and antimicrobial properties) to generate boundary films or composites. To create reliable polymers and biofilms, one would use stabilization techniques to avoid nanoparticle agglomeration, and surface functionalization to dictate the active ions or agents' release rate. Additionally, AI or ML can speed up the innovation process and allow for the prediction of antimicrobial activity, long-term stability, and safety, based on how the synthesis variables (e.g. nanomaterial size, capping chemical, shape, and concentration) or encapsulation matrix may impact the final product. ML could analyze previously published literature to create a predictive model that, for instance, predicts the rate and zone of inhibition of bacteria for an embedded starch biofilm activity, using prior experiments with ZnO-nanoparticle-embedded starch biofilms. AI-assisted optimization may also aid in avoiding trial-and-error for synthesis while selecting the best stabilizer or looking for acceptable synthesis parameters using the synthesis envelope concept. The combination of nanotechnology with AI and ML leads to smarter, secure, and more sustainable packaging. The addition of AI and ML models is disrupting this space by optimizing the extraction of nanocellulose, predicting the properties of the materials, and designing coatings with tailored functionalities. The methods of ML could predict fiber-polymer interactions, identify mechanical and barrier performance, and speed up the production of environmentally friendly composites. Cost-effective scaling, recycling strategies, and performance-based modifications can also be based on AI-driven predictive analytics for various uses of packaging. At the intersection of nanotechnology and intelligent AI-ML systems are high-performance sustainable and smart paper-based packaging solutions. Table 5 illustrates the comparison for fiber composites according to model and target properties of related fibers.

Various ML models have demonstrated high accuracy in predicting mechanical properties of natural fiber composites. For example, Random Forest (RF) regression predicted tensile ($R^2 = 0.98$) and flexural strengths ($R^2 = 0.95$) of hybrid flax/hemp composites, outperforming the Support Vector Machines (SVM) by 12% in cross-validation. Similarly, Gradient Boosting models achieved 95% accuracy in barrier property prediction for cellulose-based packaging, aligning with CNN-based defect detection studies (92% accuracy). Furthermore, Deep learning approaches show superior performance for complex formulations. A CNN-LSTM hybrid predicted optimal PLA/natural fiber ratios for food packaging (RMSE = 2.1 MPa), 18% better than traditional ANN models. These DL models require large datasets ($n > 5000$) as compared to the RF ($n > 500$), highlighting a scalability trade-off versus traditional DOE methods. Moreover, recent advancements demonstrate that artificial intelligence is increasingly employed to optimize packaging structures with the objective of minimizing material usage while maintaining mechanical integrity. ML models are trained using structural parameters such as geometry, fiber orientation, and load conditions for predicting stress distribution and material efficiency, enabling lightweight packaging design for natural fiber composites (El-Mesery et al. 2025). Furthermore, in manufacturing systems, deep learning-based computer vision systems are applied for automated quality control, where convolutional neural networks are used to analyze real-time images for detecting of defects, surface inconsistencies, and dimensional deviations with high accuracy (99.2%). Moreover, AI-driven optimization frameworks utilize process data including temperature, pressure, and processing time as inputs to predict optimal production parameters that enhance product consistency and reduce waste by 22–28% (Zhang et al. 2023). Therefore the novelty of AI-driven packaging innovation lies in its ability to replace traditional trial-and-error methodologies with data-driven, adaptive, and predictive models, thereby accelerating design cycles, improving manufacturing reliability, and enabling intelligent decision-making across the packaging materials life cycle assessment (R. Ahmed et al. 2025).

Table 5. AI model comparison for natural fiber composites.

Model	*Target Property*	*Accuracy/R^2*	*Dataset Size*	*Application*
Random Forest	*Tensile Strength*	0.98	850	Flax/hemp composites
Gradient Boost	*Barrier Properties*	95%	1200	Cellulose packaging
CNN-LSTM	*Fiber ratio opt.*	RMSE = 2.1 MPa	5200	PLA/natural fiber
SVM	*Flexural Strength*	0.86	850	Hybrid composites

Futuristic approaches

Emerging digital technologies are reshaping the sustainable packaging landscape, offering intelligent, data-driven solutions that go far beyond conventional methods.

AI, ML, and DL are enabling predictive modeling, real-time monitoring, and adaptive design strategies that significantly improve material efficiency, recyclability, and product shelf life. As illustrated in Figure 6, futuristic approaches such as ML, DL, and AI-driven circular economy strategies are reshaping sustainable packaging by enabling predictive design, smart monitoring, and intelligent recycling (Ashique et al. 2025; Heydari et al. 2024). These futuristic approaches not only optimize the performance of bio-based fibers and nanocellulose but also support circular economy models through intelligent recycling, smart packaging sensors, and predictive shelf-life modeling. Collectively, they represent a paradigm shift from traditional trial-and-error experimentation toward adaptive, sustainable, and smart packaging ecosystems.

Machine learning: predict fiber performance, optimize material blends

ML is transforming the optimization of material blends for more sustainable packaging by accurately predicting fiber performance. While conventional tests measuring fiber properties such as tensile strength, stiffness, barrier efficiency, and flexibility take time to conduct, ML models process large data sets of ever-changing fiber morphology, crystallinity, and blend ratios to provide outcome predictions nearly instantaneously (Sengottaiyan et al. 2024). For example, in nanocellulose-based packaging, Researchers have studied the effects of fibril diameter, aspect ratio, and surface chemistry on gas permeability, moisture resistance, and mechanical reinforcement when blended with biopolymers or paper substrates. By applying both regression and neural network algorithms, ML can simulate how nanocellulose fibers interact with polymers at the molecular level, thus enabling a researcher to identify optimal formulations without excessive experimentation and demonstrating its ability to develop packaging materials with improved flexible tensile strength, low oxygen transmission rates, and recyclability. Moreover, ML models continue to improve by incorporating data from the manufacturing process in real-time, allowing adaptive optimization in manufacturing on a larger scale. This ability to predict enables cost savings and material waste reduction while facilitating the design of sustainable packaging with high product performance compatible with industry

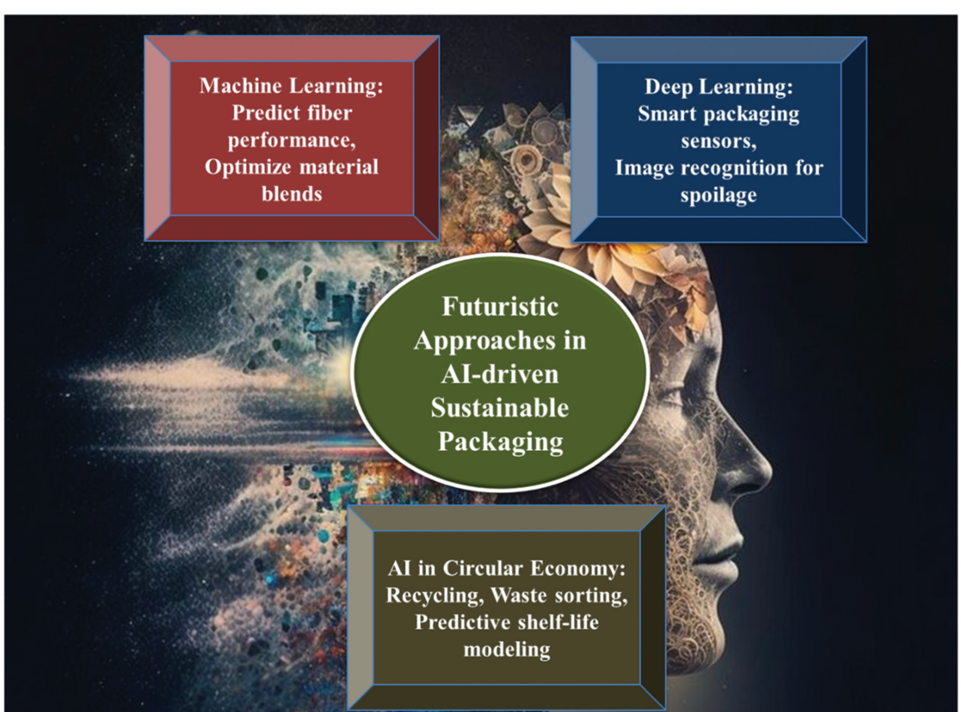

Figure 6. Futuristic approaches integrating ML, DL, and AI in sustainable packaging systems.

requirements. In sum, nanocellulose advancement fused with ML prediction systems enables smarter design, with longer shelf-life products, and a more sustainable move away from petroleum-based packaging (Sathiyamurthy, Saravanakumar, and Vinoth 2024).

Deep learning: smart packaging sensors, image recognition for spoilage

DL technologies are becoming widely utilized within sustainable packaging systems, assisting with advanced methods for monitoring food quality and safety. Smart packaging that integrates DL-enabled sensors has the capacity to continually monitor parameters such as temperature, humidity, or gas emissions, while presenting real-time updates on food quality or freshness. Moreover, image recognition algorithms can supplement this platform by identifying visual signs of food spoilage or damage, such as discoloration, the presence of fungal growth, or changes in texture, which are more difficult to determine through traditional means (Berladir et al. 2025). With this type of intelligent monitoring, DL can allow for early detection of contamination or spoilage, which then increases food waste reduction, extends product shelf-life, and improves consumer safety. Additionally, these technologies can help contribute to food traceability within supply chains, incorporating sensor data into digital platforms so consumers and retailers can communicate the quality of the product more transparently (Alagulakshmi et al. 2025). Therefore, DL-informed smart packaging will contribute to sustainability and food security in contemporary packaging ecosystems.

AI in circular economy: intelligent recycling & waste sorting

Environment-friendly packing is more essential than ever these days. People are becoming more aware of environmental issues, and rules are getting stricter. This is forcing the packing business to make big changes. A big part of this change is AI, which helps companies make better, greener, and more efficient packing that cuts down on waste and helps them reach their sustainability goals. Sustainable packaging enables the circular economy reduce waste, reuse resources, and create goods with long lifespans (Raut et al. 2025). By using biodegradable and recyclable plastics, companies may lessen their environmental impact. To reduce waste of resources, AI optimizes material selection, predicts recyclability, and monitors supply networks. AI-driven models allow closed-loop packaging systems that effectively collect, classify, and reuse old materials. AI combined with ideas from the circular economy speeds the design of sustainable, high-performance packaging (Çevik and Sarıışık 2025). AI is increasingly being utilized in packaging for waste reduction, the design of more efficient boxes, and the optimization of transportation. It aims to enhance the design, manufacturing, and management of packaging. Maxing out limited resources is the key. Reducing plastic, energy, and waste while improving outcomes (Mustafa et al. 2026). Using AI technologies, processes are becoming smarter and more environmentally conscious, whether it's selecting the correct material, cutting down on unnecessary packaging, or boosting recycling systems. AI is significantly influencing package design (Kamel et al. 2008). Conventional design methodologies predominantly depended on expertise and approximation. However, AI alters the narrative. Brands may now provide product specs for algorithms to identify the most efficient, recyclable, and cost-effective packaging solutions. Automated warehouses employ AI to optimize box dimensions, resulting in reduced air within packages and a decrease in the number of vehicles on the road. It is a simple idea with significant environmental benefits. Simultaneously, AI vision systems are detecting defects during production in real-time, reducing waste and enhancing quality. Algorithms for prediction in supply chains support organizations in planning more intelligently, minimizing overproduction and managing inventories, hence decreasing wasteful resource use. Modern sustainable packaging incorporates QR codes, RFID tags, and freshness sensors. These capabilities include real-time product sustainability, shelf life, and provenance data. Imagine fish wrapped in a biodegradable packaging that alerts you when it's ready to perish and releases natural preservatives. AI is the brain behind it, and it's occurring now. Edible packaging and predictive shelf-life modeling are transforming sustainable packaging with AI. AI and ML algorithms improve seaweed, starch, and protein biopolymer compositions for edible packaging. AI-driven simulations determine the best ingredient mix for tensile strength, solubility, and moisture resistance. Seaweed-based edible film startups utilize AI to improve durability and safety, while dairy-protein films use ML models to anticipate how compositional changes affect oxygen and water vapor barriers. In contrast, predictive shelf-life modeling predicts product freshness and deterioration using AI (Shehzad 2025; Tarlak 2023). ML systems can forecast packaged items' shelf life more accurately by incorporating sensor data, microbial growth patterns, and environmental factors. Smart packaging with AI sensors on fresh produce gives consumers and merchants real-time quality indications, decreasing food wastage. Predictive shelf-life models prioritize data-driven quality assurance and supply chain efficiency, whereas edible packaging supports material innovation and customer convenience. These AI-enabled methods provide additional approaches to eco-friendly, intelligent, and waste-reducing packaging.

Challenges and concerns regarding the utilization of AI for food packaging

The Smart packaging systems are intricate, encompassing several operations that go beyond merely manufacturing environmentally acceptable materials. It includes activities such as maintaining and updating hardware and packaging equipment, overseeing the secure organization and storage of food items or raw materials in households and companies, and ensuring general efficiency across the supply chain. The integration of digital technology and AI-driven solutions into this industry introduces additional ethical problems (Ablegue et al. 2025; A. Kumar et al. 2024; Siqueira, Bras, and Dufresne 2010). In addition to conventional issues like waste reduction and environmental effect minimization, questions of transparency, traceability, explainability, interpretability, accessibility, accountability, and responsibility emerge as crucial. These ethical considerations are especially vital in the realm of computational and AI systems, where data flows are markedly more varied and intricate than traditional personal data safeguarded by the European Union's General Data Protection Regulation (GDPR). Smart packaging solutions create data related to product tracking, consumer shopping habits, and environmental monitoring, necessitating enhanced protections and responsible governance to assure sustainability and ethical compliance. Figure 7 highlights the functions of intelligent, active, and smart packaging. Smart packaging facilitates tracking and monitoring, active packaging engages to prolong shelf life, and intelligent packaging offers real-time quality indications, therefore improving food safety and minimizing waste.

There are several obstacles and restrictions to overcome before AI can be fully incorporated into the food processing industry, notwithstanding its revolutionary potential. Having access to large-scale, diverse, and rich information is crucial for AI systems to learn effectively. Due to the extensive methods, stringent regulations, and nuanced variables in the food business, obtaining such datasets can be particularly challenging (Shehzad 2025. Consequently, developing reliable AI models that are highly accurate in their predictions becomes a major challenge. Universal AI solutions that can adapt smoothly across diverse sectors and geographical situations are limited by the absence of defined approaches. Making sense of complicated regulatory frameworks is another major roadblock to implementing AI-driven improvements in food packaging. However, it is necessary to comply with strict quality and safety requirements, doing so

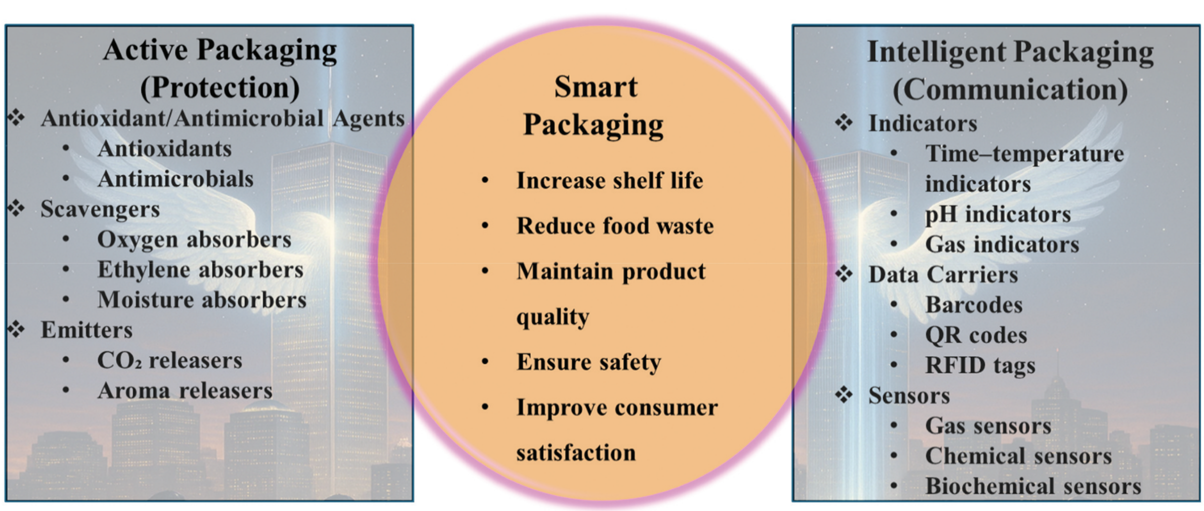

Figure 7. Various applications of smart packaging solutions using intelligent systems.

may impede or delay the industry's quick adoption of AI technology. Information on consumers, suppliers, and business operations can be delicate, yet AI systems need it to function (Bidyalakshmi et al. 2025) because breaches can result in huge financial losses, legal obligations, reputational harm, and a decrease in customer trust, protecting such data is crucial. Strong data security is especially important in the food business due to the growing popularity of AI-enabled applications like smart packaging, supply chain optimization, and analytics on customer behavior.

Advanced cybersecurity measures, such as encryption techniques, safe data storage systems, vulnerability testing on a regular basis, and threat monitoring in real-time, are necessary for effective protection. Unfair results may be produced by AI systems due to their vulnerability to biases included in training datasets. Particularly in areas like workforce recruiting, product suggestions, and customized nutrition assistance, addressing these problems is crucial for guaranteeing the ethical deployment of AI in decision-making processes (Oyegbade et al. 2025). Figure 8. illustrates the key barriers in the adoption of AI for food packaging, including ethical concerns, high implementation cost, data security risks, regulatory limitations, and integration challenges (Rezaei, Nasirpour, and Fathi 2015; Zatsu et al. 2024). Concerns about algorithmic fairness in the food sector are only the tip of the iceberg when it comes to ethical issues. It could be costly to install an expensive AI system. There may be expensive initial investments for things like infrastructure, technology, and expertise. Also, to make sure the AI systems are functioning as is necessary, as is continuous training, improvements, and upkeep. These expenses could be extremely significant for new businesses or ones with a limited budget (Dakhia, Russo, and Merenda 2025). It is not easy to incorporate AI into preexisting systems and procedures inside a company (Akinsemolu, Idowu, and Onyeaka 2024; Jamwal and Mittal 2024). When trying to integrate AI technology with their current systems, processes, and procedures, many companies run into problems. Particularly problematic for smooth adoption are older technologies that aren't always compatible with new AI applications. Thorough preparation, gradual rollout, and heavy investment in technology improvements are necessary to overcome these obstacles. Inadequate planning for integration increases the risk of delays, incomplete deployment, or inefficiency, which in turn reduces the likelihood of full AI adoption in the food business and limits its potential advantages (Krupitzer 2024). Although artificial intelligence has shown significant potential in advancing sustainable packaging research, its application must be evaluated critically rather than descriptively. Different AI methodologies vary considerably in terms of data requirements, scalability, interpretability, and real-world feasibility. Some conventional machine learning models remain the most practical for property prediction and process optimization due to their lower data dependency and ease of

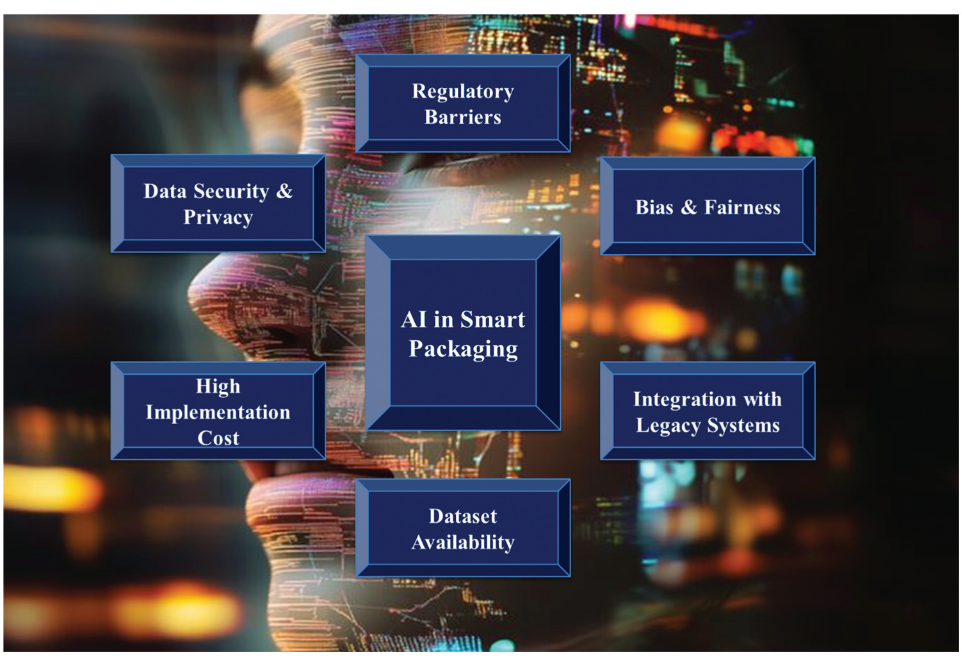

Figure 8. Challenges and barriers in the integration of AI in food packaging.

interpretation (Alghadeer et al. 2024). On the other hand, deep learning approaches offer superior performance for complex image- and sensor-based tasks, such as defect detection and spoilage monitoring, but often require large datasets and high computational resources (Liu et al. 2025; Malashin et al. 2025). Emerging generative AI techniques demonstrate promise for rapid packaging structure and material design; however, their application remains largely exploratory and requires further experimental validation (Hägele et al. 2025). Therefore, the selection of AI techniques in packaging research should be guided by application-specific.

The comparative analysis presented in Table 6 highlights that no single AI approach is universally optimal for all packaging applications. Instead, innovation arises from the targeted deployment of AI techniques aligned with specific material, structural, and manufacturing challenges (Abenghal et al. 2025; Gao et al. 2026). AI-driven research in the area of packaging is new as it has moved from the traditional trial-and-error process of experimentation to the use of data to create predictive and adaptive design frameworks which allow for better use of materials, better control of quality and reduce time for development cycles.

Challenges and limitations of AI applications in packaging

Generally, training machine learning models which predict the properties of packaging (such as barrier and mechanical performance of packaging) uses very large datasets, with the typical requirement being well over 1000 data points for each model; yet, there have been many studies published that have used datasets with fewer than 1000 samples, so those models do not generalize well outside the conditions they were trained under. Model validation commonly employs cross-validation and external test sets, yet the absence of standardized validation protocols often hinders reproducibility, particularly for natural fiber – based composites relevant to sustainable packaging. As summarized in Table 7, AI-driven models applied to property prediction, defect detection, and process optimization face persistent challenges related to data availability, validation, uncertainty, and failure modes.

Due to uncertainty resulting from changing environmental and operational conditions, AI models may be challenged during the process of optimizing a process. As a result, large and diverse multi-condition datasets are needed to produce better results when extrapolating from these conditions. Similarly, deep-learning-based defect-detection models require hundreds of thousands of labeled training images to help avoid overfitting to the training data and potential bias from the models. Use of attention mechanisms in the most recent models has also increased their sensitivity to detecting small and minor defects (Adeyi et al.

Table 6. Comparative overview of AI approaches in packaging research (Abenghal et al. 2025; Gao et al. 2026).

AI Method	Maturity Level	Scalability	Strengths	Limitations	Representative Applications
ML (RF, SVM, ANN)	High	Good (small to medium datasets)	Interpretable, fast training	Limited for highly complex systems	Prediction of fiber mechanical and barrier properties
DL (CNN, LSTM)	Moderate	Limited (large datasets required)	Effective for image and sensor data analysis	High computational cost, black-box nature	Automated defect detection and spoilage monitoring
Generative AI	Emerging	Experimental	Rapid design exploration	Limited validation and physical constraints	Lightweight packaging and structural design optimization

Table 7. Key challenges and data requirements for AI applications in sustainable packaging materials.

Aspect	AI Application in Packaging	Typical Data Requirement	Key Limitation	References
Data availability	Property prediction (ML)	300–1000 experimental datasets	Limited dataset size restricts generalization and leads to high-dimensionality issues	Madhu (2025)
Model validation	Barrier & mechanical prediction	Cross-validation, external test sets	Lack of standardized protocols and overfitting in heterogeneous data	El-Mesery et al. (2025)
Uncertainty	Process optimization	Multi-condition datasets (>1000 samples)	Prediction uncertainty rises with varying conditions; poor extrapolation	Alper, Sezen, and Balcıoğlu (2025)
Failure modes	Defect detection (DL)	1000+ labeled images	Overfitting, bias, limited transferability in complex backgrounds	Alper, Sezen, and Balcıoğlu (2025)

Table 8. Performance ranges and AI-enabled improvements reported in sustainable packaging studies.

Packaging Function	AI Task	Typical Performance Range (Literature)	AI-Enabled Insight	Key Takeaway	Reference
Mechanical strength	ML-based prediction	Tensile/flexural: 8–90 MPa (starch-CNF to hemp-NC)	30–40% strength gains; reduces trials by 50–65%	Efficient screening over trial-and-error	Adeyi et al. (2025).
Barrier properties	ML regression/ ensemble	WVTR: 3–13 g/m^2/day; OTR application-dependent	40–60% WVTR reductions via optimized nano-fillers	Data-driven formulation tuning	Othman et al. (2025)
Defect detection	DL (CNN)	Accuracy: 96.5%+ on packaging defects	>10% accuracy boost; <10 ms/image real-time	Scales quality control	Shirzad and Joodaky (2024)
Process optimization	ML/DL optimization	Multi-parameter windows (e.g., fiber content 1–10 wt.%)	Narrows optima, 20–35% waste cut	Lower waste & variability	Shen, Qian, and Tu (2025)

2025; Othman et al. 2021). Overall, these limitations highlight that AI should be regarded as a complementary decision-support tool rather than a universal solution for packaging innovation.

The data summarized in Table 8 indicate that There is evidence that AI-driven techniques can produce significant results in enhancing mechanical performance and barrier performance, as well as providing increased accuracy of defect detection and process optimization throughout a range of packaging types (Shirzad and Joodaky 2024). However, the magnitude of performance increases experienced will significantly depend on factors such as the materials used, how large the dataset is, how the models are built, how they will be validated, and whether the previous studies have met rigorous research standards. It should be noted that studies with much higher performance increases tend to use very clean datasets and conduct controlled laboratory conditions. This highlights the need for strong data availability and validation. From these findings, it can be concluded that any AI tool developed for specific applications should not be viewed as providing a general solution, but rather with careful consideration of each case in which they were utilized.

Conclusion and future perspective

Integrating AI with sustainable food packaging is a crucial step toward a smarter food supply chain. AI allows the production of eco-friendly materials and smart packaging solutions that monitor and enhance product quality during delivery. While analyzing massive information, AI-driven models may anticipate material performance, optimize packaging mixes, and build product-specific adaptive solutions. Promoting recyclable, biodegradable materials and fulfilling customer demand for safer, transparent, and ecologically responsible packaging solves major environmental issues (N. Gupta and Gupta 2024; Harikrishnan et al. 2025). AI and sustainable packaging form a closed-loop system that reduces waste, promotes circular economy goals, and makes the global food supply chain smarter and greener.

Additionally, testing is accelerated using AI-driven simulations, which reduces experimental time and expenses. In order to find creative solutions that address both environmental concerns and economic objectives, packaging industries, and AI specialists need to collaborate. Greener supply chains, less reliance on plastic, and the circular economy are all outcomes of these types of collaborations. Future smart, more sustainable packaging solutions have been prepared by interdisciplinary initiatives that combine conventional natural resources with modern digital technology. Intelligent sustainable packaging that can be scaled up to industrial levels combines cutting-edge digital technology with environmentally friendly materials. If we want biodegradable composites and natural fibers to supplant traditional plastics, we need to make sure they are strong, long-lasting, and inexpensive. Data analytics and AI can improve production efficiency on a grand scale by standardizing designs and making performance predictions. The use of smart sensors and automation allows for real-time quality control, which guarantees production consistency. In order to set standards, lower prices, and encourage adoption, industry, researchers, and lawmakers must work together. To address worldwide expectations for ecologically responsible packaging while limiting ecological impact, enterprises may develop scalable solutions by combining intelligence with sustainability. More and more, sustainable packaging is being pushed to incorporate AI, ML, and DL by policymakers, regulators, and international market trends. More and more, governments are cracking down on single-use plastics and pushing for more sustainable, recyclable alternatives. By improving material selection, decreasing waste, and providing traceability throughout supply chains, AI-driven systems assist compliance. Circular economy practices are pushed by international policies, which aim at fostering smart technology adoption by industries for sustainability and efficiency. Smart, AI-enabled solutions are seeing increased investment as a result of growing customer demand for environmentally friendly packaging in global markets. Intelligent sustainable packaging may gain a competitive edge on a global scale with the help of standardized standards and laws that promote its implementation.

Acknowledgment

Therefore, the authors acknowledged the financial and technical support of the DSR, King Abdulaziz University, Jeddah, Saudi Arabia

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This project was supported by the Deanship of Scientific Research (DSR) at King Abdulaziz University, Jeddah, Saudi Arabia, under grant no. (IPP:443-961-2025). The authors, therefore, acknowledge with thanks DSR for technical and financial support.

References

Abdullah-Al-Kafi, M. Z. Abedin, M. D. H. Beg, K. L. Pickering, and M. A. Khan. 2006. "Study on the Mechanical Properties of Jute/Glass Fiber-Reinforced Unsaturated Polyester Hybrid Composites: Effect of Surface Modification by Ultraviolet Radiation." *Journal of Reinforced Plastics & Composites* 25 (6): 575–588. https://doi.org/10.1177/0731684405056437.

Abekoon, T., B. L. S. K. Buthpitiya, H. Sajindra, E. R. J. Samarakoon, J. A. D. C. A. Jayakody, K. Kantamaneni, and U. Rathnayake. 2024. "A Comprehensive Review to Evaluate the Synergy of Intelligent Food Packaging with Modern Food Technology and Artificial Intelligence Field." *Discover Sustainability* 5 (1): 160. https://doi.org/10.1007/s43621-024-00371-7.

Abenghal, L., J. Bley, B. Tolnai, G. Njamen, and B. Chabot. 2025. "Development of a New Sustainable Packaging Paper Based on Cellulose Filaments and Refined Kraft Pulp." *Future Foods* 11:100540. https://doi.org/10.1016/j.fufo.2025.100540.

Ablegue, A. G. M. D., M. Zhang, Q. Guo, and L. Rui. 2025. "Monitoring and Shelf-Life Extension of Food Products Based on Machine Learning and Deep Learning: Progress and Potential Applications." *Food Reviews International*: 1–26.

Adeyi, T. A., C. O. Jaiyeola, O. I. Oresegun, and A. Dolapo. 2025. "AI and Nanotechnology Integration in the Development of Biodegradable Food Packaging Materials." *International Journal of Science and Research Archive* 14 (1): 726–736. https://doi.org/10.30574/ijsra.2025.14.1.0119.

Ahmed, K. S., S. Vijayarangan, and C. Rajput. 2006. "Mechanical Behavior of Isothalic Polyester-Based Untreated Woven Jute and Glass Fabric Hybrid Composites." *Journal of Reinforced Plastics & Composites* 25 (15): 1549–1569. https://doi.org/10.1177/0731684406066747.

Ahmed, R., K. H. Manik, A. Nath, J. R. Shohag, J. J. Mim, and N. Hossain. 2025. "Recent Advances in Sustainable Natural Fiber Composites: Environmental Benefits, Applications, and Future Prospects." *Materials Today Sustainability* 32:101220. https://doi.org/10.1016/j.mtsust.2025.101220.

Ahmed, Z., and F. Akhter. 2001. "Jute Retting: An Overview." *Journal of Biological Sciences* 1 (7): 685–688. https://doi.org/10.3923/jbs.2001.685.688.

Akbar, A., and A. K. Anal. 2014. "Zinc Oxide Nanoparticles Loaded Active Packaging, a Challenge Study Against Salmonella Typhimurium and Staphylococcus Aureus in Ready-to-Eat Poultry Meat." *Food Control* 38:88–95. https://doi.org/10.1016/j.foodcont.2013.09.065.

Akinsemolu, A. A., A. M. Idowu, and H. N. Onyeaka. 2024. "Recycling Technologies for Biopolymers: Current Challenges and Future Directions." *Polymers* 16 (19): 2770. https://doi.org/10.3390/polym16192770.

Alagulakshmi, R., R. Ramalakshmi, A. Veerasimman, G. Palani, M. Selvaraj, and S. Basumatary. 2025. "Advancements of Machine Learning Techniques in Fiber-Filled Polymer Composites: A Review." *Polymer Bulletin* 82 (7): 2059–2089. https://doi.org/10.1007/s00289-025-05638-1.

Alghadeer, M., N. D. Aisyah, M. Hezam, S. M. Alqahtani, A. A. Baloch, and F. H. Alharbi. 2024. “Machine Learning Prediction of Materials Properties from Chemical Composition: Status and Prospects.” *Chemical Physics Reviews* 5 (4). https://doi.org/10.1063/5.0235541.

Alper, M. M., B. Sezen, and Y. S. Balcıoğlu. 2025. “Machine Learning Applications in Packaging Industry Optimization: A Systematic Literature Review and Future Research Directions.” In *International NewYork Congress Conference*, Baku, Azerbaijan: BZT TURAN Publishing House.

Anas, M. S., M. Faheem, and D. Mikucioniene. 2025. “Challenges and Limitations in Recycling of Post-Consumer Cotton Denim Waste into New Textiles.” *Journal of Natural Fibers* 22 (1). https://doi.org/10.1080/15440478.2025.2570080.

Ashique, S., A. Raikar, S. Jamil, L. Lakshminarayana, S. A. Gajbhiye, S. De, and S. Kumar. 2025. “Artificial Intelligence Integration with Nanotechnology: A New Frontier for Sustainable and Precision Agriculture.” *Current Nanoscience* 21 (2): 242–273. https://doi.org/10.2174/0115734137275111231206072049.

Aslam, S., S. H. Khan, A. Ahmed, and A. M. Dandekar. 2020. “The Tale of Cotton Plant: From Wild Type to Domestication, Leading to Its Improvement by Genetic Transformation.” *American Journal of Molecular Biology* 10 (2): 91–127. https://doi.org/10.4236/ajmb.2020.102008.

Atalie, D., M. A. Abtew, and L. Zhao. 2025. “Recent Advances in Bio-Based Nonwoven Materials: Sustainable Production, Applications, and Circular Economy.” *Journal of Natural Fibers* 22 (1). https://doi.org/10.1080/15440478.2025.2565661.

Baraniak, J., and M. Kania-Dobrowolska. 2023. “Multi-Purpose Utilization of Kapok Fiber and Properties of Ceiba Pentandra Tree in Various Branches of Industry.” *Journal of Natural Fibers* 20 (1): 2192542. https://doi.org/10.1080/15440478.2023.2192542.

Barbash, V. A., O. V. Yashchenko, O. S. Yakymenko, R. M. Zakharko, and V. D. Myshak. 2022. “Preparation of Hemp Nanocellulose and Its Use to Improve the Properties of Paper for Food Packaging.” *Cellulose* 29 (15): 8305–8317. https://doi.org/10.1007/s10570-022-04773-6.

Berladir, K., K. Antosz, V. Ivanov, and Z. Mitaľová. 2025. “Machine Learning-Driven Prediction of Composite Materials Properties Based on Experimental Testing Data.” *Polymers* 17 (5): 694. https://doi.org/10.3390/polym17050694.

Bhat, A. H., Y. K. Dasan, I. Khan, and M. Jawaid. 2017. “Cellulosic Biocomposites: Potential Materials for Future.” In *Green Biocomposites: Design and Applications*, 69–100. Cham: Springer International Publishing.

Bi, Y., B. Zhou, P. Ren, X. Chen, D. Zhou, and S. Yao. 2024. “Effects of Bacillus Subtilis on Cotton Physiology and Growth Under Water and Salt Stress.” *Agricultural Water Management* 303:109038. https://doi.org/10.1016/j.agwat.2024.109038.

Bidyalakshmi, T., B. Jyoti, S. M. Mansuri, A. Srivastava, D. Mohapatra, and Y. B. Kalnar. 2025. “Application of Artificial Intelligence in Food Processing: Current Status and Future Prospects.” *Food Engineering Reviews* 17 (1): 27–54. https://doi.org/10.1007/s12393-024-09386-2.

Bradley, E. L., L. Castle, and Q. Chaudhry. 2011. “Applications of Nanomaterials in Food Packaging with a Consideration of Opportunities for Developing Countries.” *Trends in Food Science & Technology* 22 (11): 604–610. https://doi.org/10.1016/j.tifs.2011.01.002.

Bumbudsanpharoke, N., N. Harnkarnsujarit, J. F. Gilchrist, S. Ko, and T. Keawpetch. 2025. “The Rise of Nanotechnology in Pharmaceutical and Healthcare Packaging: Applications and Future Prospective.” *Packaging Technology and Science* 38 (1): 3–31. https://doi.org/10.1002/pts.2848.

Cao, D. 2024. “Investigation Into Surface-Coated Continuous Flax Fiber-Reinforced Natural Sandwich Composites via Vacuum-Assisted Material Extrusion.” *Progress in Additive Manufacturing* 9 (4): 1135–1149. https://doi.org/10.1007/s40964-023-00508-6.

Çevik, Z. A., and G. Sarıışık. 2025. “A Machine Learning-Driven Optimization of Machining Parameters for Nanoclay-Glass Fiber Polymer-Reinforced Composites for Performance Prediction and Process Enhancement.” *Journal of Tribology* 147 (9): 091117. https://doi.org/10.1115/1.4068354.

Chaitanya, S., and I. Singh. 2017. “Processing of PLA/Sisal Fiber Biocomposites Using Direct-and Extrusion-Injection Molding.” *Materials & Manufacturing Processes* 32 (5): 468–474. https://doi.org/10.1080/10426914.2016.1198034.

Chang, J., H. Wang, W. Su, X. He, and M. Tan. 2025. “Artificial Intelligence in Food Bioactive Peptides Screening: Recent Advances and Future Prospects.” *Trends in Food Science & Technology* 156:104845. https://doi.org/10.1016/j.tifs.2024.104845.

Chen, P., B. Steuer, G. Wu, L. Dong, X. Tong, M. de Jong, and M. Sauerwein. 2025. “A Life Cycle Assessment on Food Delivery Packaging in Guangzhou, China: Using Consumer Preferences to Infer Viable Circular Economy Policy Pathways.” *Journal of Environmental Management* 391:126478. https://doi.org/10.1016/j.jenvman.2025.126478.

Chen, X., S. He, K. W. Paik, Y. H. Wong, and S. Zhang. 2025. “Machine Learning-Driven Design and Optimization of Electronic Packaging: Applications and Future Developments.” *Journal of Materials Informatics* 5 (4). https://doi.org/10.20517/jmi.2025.26.

Chen, Y., Y. Wang, Y. Zhang, X. Wang, C. Zhang, and N. Cheng. 2024. “Intelligent Biosensors Promise Smarter Solutions in Food Safety 4.0.” *Foods* 13 (2): 235. https://doi.org/10.3390/foods13020235.

Chetbani, Y., M. Boumaaza, R. Zaitri, A. Belaadi, A. B. Mahammed, A. Laouissi, and D. Ghernaout. 2024. “Study of the Effect of Hemp Fibers and Brick Waste Powder on the Mechanical Characteristics of Mortar: Experimental and Statistical Analysis.” *Journal of Natural Fibers* 22 (1): 2438900.

Chiu, I., and T. Yang. 2024. “Biopolymer-Based Intelligent Packaging Integrated with Natural Colourimetric Sensors for Food Safety and Sustainability.” *Analytical Science Advances* 5 (5–6): e2300065. https://doi.org/10.1002/ansa.202300065.

Chokshi, S., V. Parmar, P. Gohil, and V. Chaudhary. 2022. “Chemical Composition and Mechanical Properties of Natural Fibers.” *Journal of Natural Fibers* 19 (10): 3942–3953. https://doi.org/10.1080/15440478.2020.1848738.

Chougala, V., A. C. Gowda, S. Nagaraja, and M. I. Ammarullah. 2024. “Effect of Chemical Treatments on Mechanical Properties of Sugarcane Bagasse (Gramineae Saccharum Officinarum L) Fiber Based Biocomposites: A Review.” *Journal of Natural Fibers* 22 (1). https://doi.org/10.1080/15440478.2024.2445571.

Cui, F., S. Zheng, D. Wang, L. Ren, Y. Meng, R. Ma, S. Wang, X. Li, T. Li, and J. Li. 2024. “Development of Machine Learning-Based Shelf-Life Prediction Models for Multiple Marine Fish Species and Construction of a Real-Time Prediction Platform.” *Food Chemistry* 450:139230. https://doi.org/10.1016/j.foodchem.2024.139230.

Dakhia, Z., M. Russo, and M. Merenda. 2025. “AI-Enabled IoT for Food Computing: Challenges, Opportunities, and Future Directions.” *Sensors* 25 (7): 2147. https://doi.org/10.3390/s25072147.

D’Almeida, A. P., and T. L. de Albuquerque. 2024. “Innovations in Food Packaging: From Bio-Based Materials to Smart Packaging Systems.” *Processes* 12 (10): 2085. https://doi.org/10.3390/pr12102085.

Dejene, B. K. 2024. “Advancing Natural Fiber-Reinforced Composites Through Incorporating ZnO Nanofillers in the Polymeric Matrix: A Review.” *Journal of Natural Fibers* 21 (1): 2356015. https://doi.org/10.1080/15440478.2024.2356015.

Dejene, B. K., and M. A. Abtew. 2025. “Chitosan/Zinc Oxide (ZnO) Nanocomposites: A Critical Review of Emerging Multifunctional Applications in Food Preservation and Biomedical Systems.” *International Journal of Biological Macromolecules* 316:144773. https://doi.org/10.1016/j.ijbiomac.2025.144773.

Dejene, B. K., A. A. Birilie, M. A. Yizengaw, and S. A. Getahun. 2024. “Thermoplastic Starch-ZnO Nanocomposites: A Comprehensive Review of Their Applications in Functional Food Packaging.” *International Journal of Biological Macromolecules* 282:137099. https://doi.org/10.1016/j.ijbiomac.2024.137099.

Dejene, B. K., and A. D. Gudayu. 2024. “Eco-Friendly Packaging Innovations: Integrating Natural Fibers and ZnO Nanofillers in Polylactic Acid (PLA) Based Green Composites-A Review.” *Polymer-Plastics Technology & Materials* 63 (12): 1645–1681. https://doi.org/10.1080/25740881.2024.2350686.

Dejene, B. K., and A. D. Gudayu. 2025. “Achieving Performance and Functionality in PLA-Based Packaging: Insights from Hybrid Composites with False Banana (Enset) Fiber and ZnO Nanoparticles.” *Journal of Thermoplastic Composite Materials* 38 (6): 2138–2168. https://doi.org/10.1177/08927057241288125.

Dejene, B. K., A. D. Gudayu, and M. A. Abtew. 2024. “Development and Optimization of Sustainable and Functional Food Packaging Using False Banana (Enset) Fiber and Zinc-Oxide (ZnO) Nanoparticle-Reinforced Polylactic Acid (PLA) Biocomposites: A Case of Injera Preservation.” *International Journal of Biological Macromolecules* 279:135092. https://doi.org/10.1016/j.ijbiomac.2024.135092.

De Silva, G. S., and P. Naveen. 2024. “Effect of Rice Husk Ash and Coconut Coir Fiber on Cement Mortar: Enhancing Sustainability and Efficiency in Buildings.” *Construction and Building Materials* 440:137326. https://doi.org/10.1016/j.conbuildmat.2024.137326.

Dong, S., P. Wang, and K. Abbas. 2021. “A Survey on Deep Learning and Its Applications.” *Computer Science Review* 40:100379. https://doi.org/10.1016/j.cosrev.2021.100379.

Donsì, F., E. Marchese, P. Maresca, G. Pataro, K. D. Vu, and S. Salmieri. 2015. “Green Beans Preservation by Combination of a Modified Chitosan Based-Coating Containing Nanoemulsion of Mandarin Essential Oil with High Pressure or Pulsed Light Processing.” *Postharvest Biology and Technology* 106:21–32.

Du, L., X. Huang, Z. Li, Z. Qin, N. Zhang, and X. Zhai. 2025. “Application of Smart Packaging in Fruit and Vegetable Preservation: A Review.” *Foods* 14 (3): 447. https://doi.org/10.3390/foods14030447.

Dutra, J. D. C. F., M. F. Passos, T. F. da Silva, and G. Mockaitis. 2021. “Pyrolysis and Anaerobic Digestion of the Egeria Densa Biomass in Different Pretreatment Conditions for Potential Use as a Substrate in the Generation of Bioproducts.” *Journal of Water Process Engineering* 40:101772. https://doi.org/10.1016/j.jwpe.2020.101772.

Eisa Zadeh, H., N. H. Chatroudi, and R. Alizadeh. 2025. “AI-Based Prediction and Numerical Analysis of Mechanical and Microstructural Parameters of Carbon Fiber Reinforced 3D Printed Composites.” *Materials Today Communications* 50:114566. https://doi.org/10.1016/j.mtcomm.2025.114566 .

El-Mesery, H. S., A. H. ElMesiry, M. Husein, Z. Hu, and A. Salem. 2025. “Artificial Intelligence and Machine Learning Models for Predicting and Evaluating the Influence of Shelf-Life Environments and Packaging Materials on Garlic (Allium Sativum L) Physicochemical and Phytochemical Compositions.” *Food Chemistry: X* 29:102731. https://doi.org/10.1016/j.fochx.2025.102731.

Escobar-Sánchez, G., E. Robbe, A. Baccar Chabaane, M. Gatel Rebours, and G. Schernewski. 2025. “Replacing Single-Use Plastics (SUPs) in Coastal Festivals: A Critical Evaluation of Bio-Based, Biodegradable and Compostable Tableware, Regulatory Policies and Public Awareness.” *International Journal of Environmental Research* 19 (5): 190. https://doi.org/10.1007/s41742-025-00842-3.

Feng, L., S. Wan, Y. Zhang, and H. Dong. 2024. "Xinjiang Cotton: Achieving Super-High Yield Through Efficient Utilization of Light, Heat, Water, and Fertilizer by Three Generations of Cultivation Technology Systems." *Field Crops Research* 312:109401. https://doi.org/10.1016/j.fcr.2024.109401.

Flores Ramirez, N., Y. Sanchez Hernandez, J. Cruz de Leon, S. R. Vasquez Garcia, L. Domratcheva Lvova, and L. Garcia Gonzalez. 2015. "Composites from Water Hyacinth (Eichhornea Crassipe) and Polyester Resin." *Fibers and Polymers* 16 (1): 196–200. https://doi.org/10.1007/s12221-015-0196-5.

Francucci, G., E. S. Rodríguez, and A. Vázquez. 2012. "Experimental Study of the Compaction Response of Jute Fabrics in Liquid Composite Molding Processes." *Journal of Composite Materials* 46 (2): 155–167. https://doi.org/10.1177/0021998311410484.

Frone, A. N., S. Berlioz, J. F. Chailan, D. M. Panaitescu, and D. J. P. C. Donescu. 2011. "Cellulose Fiber-Reinforced Polylactic Acid." *Polymer Composites* 32 (6): 976–985. https://doi.org/10.1002/pc.21116.

Gai, X., C. Liu, Z. Yu, Y. Li, Y. Wang, and C. Deng. 2024. "Functionalized Lignin Nanoparticles Prepared by High Shear Homogenization for All Green and Barrier-Enhanced Paper Packaging." *Resources Chemicals and Materials* 3 (3): 167–174. https://doi.org/10.1016/j.recm.2024.06.002.

Gao, Q., Z. Feng, J. Wang, F. Zhao, C. Li, and J. Ju. 2025. "Application of Nano-ZnO in the Food Preservation Industry: Antibacterial Mechanisms, Influencing Factors, Intelligent Packaging, Preservation Film and Safety." *Critical Reviews in Food Science and Nutrition* 65 (22): 4327–4353. https://doi.org/10.1080/10408398.2024.2387327.

Ghalme, S., M. Hayat, and M. Harne. 2025. "A Comprehensive Review of Natural Fibers: Bio-Based Constituents for Advancing Sustainable Materials Technology." *Journal of Renewable Materials* 13 (2): 273. https://doi.org/10.32604/jrm.2024.056275.

Gorde, P. M., D. R. Dash, S. K. Singh, and P. Singha. 2024. "Advancements in Sustainable Food Packaging: A Comprehensive Review on Utilization of Nanomaterials, Machine Learning and Deep Learning." *Sustainable Chemistry and Pharmacy* 39:101619. https://doi.org/10.1016/j.scp.2024.101619.

Gou, Z., W. Guo, T. Du, S. Liu, Y. Li, J. Wang, and J. Huang. 2026. "Nanotechnology Revolutionizing Food Processing Technology." *Foods* 15 (4): 643.

Goyal, R., P. Singha, and S. K. Singh. 2024. "Spectroscopic Food Adulteration Detection Using Machine Learning: Current Challenges and Future Prospects." *Trends in Food Science & Technology* 146:104377. https://doi.org/10.1016/j.tifs.2024.104377.

Gregor-Svetec, D. 2018. "Intelligent Packaging." In *Nanomaterials for Food Packaging*, 203–247. Elsevier.

Gui, Z., Z. Yang, and D. Xiang. 2024. "Tree-Inspired Coir Fiber-Based Array Evaporator with Rapid Water Transportation and Effective Solar Water Evaporation." *Chemical Engineering Journal* 494:153010. https://doi.org/10.1016/j.cej.2024.153010.

Gupta, A. K., A. Kumar, A. Kumar, and B. Kumar. 2025. "Advancing Sustainable Food Packaging: Integrating Machine Learning, Deep Learning, and Artificial Intelligence." *Trends in Food Science & Technology* 163:105148. https://doi.org/10.1016/j.tifs.2025.105148.

Gupta, N., and P. K. Gupta. 2024. "Robotics and Artificial Intelligence (AI) in Agriculture with Major Emphasis on Food Crops." *Digital Agriculture: A Solution for Sustainable Food and Nutritional Security*: 577–605. https://doi.org/10.1007/978-3-031-43548-5_19.

Hägele, J., C. Ludwig, M. Proffen, J. Hägele, J. Scholz, C. Vieweg, I. Rode, et al. 2025. "Machine Learning in Materials Science: A Review." *Frontiers in Immunology* 16. https://doi.org/10.3389/fimmu.2025.1580448.

Haque, A. U., M. A. Al Haque, A. Alabduladheem, A. Al Mulla, N. Almulhim, and R. Srinivasagan. 2025. "Machine Learning-Based Shelf-Life Estimator for Dates Using a Multichannel Gas Sensor: Enhancing Food Security." *Sensors* 25 (13): 4063. https://doi.org/10.3390/s25134063.

Harikrishnan, S., D. Kaushik, P. Rasane, A. Kumar, N. Kaur, C. K. Reddy, C. Proestos, F. Oz, and M. Kumar. 2025. "Artificial Intelligence in Sustainable Food Design: Technological, Ethical Consideration, and Future." *Trends in Food Science & Technology* 163:105152. https://doi.org/10.1016/j.tifs.2025.105152.

Hasan, M., N. Vasker, and M. S. H. Khan. 2024. "Real-Time Sorting of Broiler Chicken Meat With Robotic Arm: XAI-Enhanced Deep Learning and LIME Framework for Freshness Detection." *Journal of Agriculture and Food Research* 18:101372. https://doi.org/10.1016/j.jafr.2024.101372.

Hayase, S. 2018. "Manila Hemp in World, Regional, National, and Local History." *Journal of Asia-Pacific Studies* 31:171–188. https://doi.org/10.57278/wiapstokyu.31.0_171.

Heydari, S., N. Masoumi, E. Esmaeeli, S. M. Ayyoubzadeh, F. Ghorbani-Bidkorpeh, and M. Ahmadi. 2024. "Artificial Intelligence in Nanotechnology for Treatment of Diseases." *Journal of Drug Targeting* 32 (10): 1247–1266. https://doi.org/10.1080/1061186X.2024.2393417.

Holliday, E. G., and B. Zhang. 2024. "Machine Learning-Enabled Colorimetric Sensors for Foodborne Pathogen Detection." *Advances in Food and Nutrition Research* 111:179–213. https://doi.org/10.1016/bs.afnr.2024.06.004 .

Hsieh, Y. L. 2024. "Structural Development of Cotton Fibers and Linkages to Fiber Quality." In *Cotton Fibers*, edited by A. S. Basra, 137–165. CRC Press.

Hu, R. H., Z. G. Ma, S. Zheng, Y. N. Li, G. H. Yang, H. K. Kim, and J. K. Lim. 2012. "A Fabrication Process of High-Volume Fraction of Jute Fiber/Polylactide Composites for Truck Liner." *International Journal of Precision Engineering and Manufacturing* 13 (7): 1243–1246. https://doi.org/10.1007/s12541-012-0165-5.

Hua, K. Q., S. Z. Yi, Q. C. Sheng, W. Y. Fu, Z. Xuan, and S. Xia. 2024. “The Study Progress on Breeding of Flax and Industrial Hemp in China.” *Journal of Natural Fibers* 21 (1): 2389159. https://doi.org/10.1080/15440478.2024.2389159.
Huang, J., M. Zhang, A. S. Mujumdar, and C. Li. 2025. “AI-Based Processing of Future Prepared Foods: Progress and Prospects.” *Food Research International* 201:115675. https://doi.org/10.1016/j.foodres.2025.115675.
Iqbal, R. M., R. Ahammad, M. Arifuzzaman, M. S. Islam, and M. M. Islam. 2025. “Manufacturing and Properties of Jute Fiber-Reinforced Polymer Composites—A Comprehensive Review.” *Materials* 18 (5): 1016. https://doi.org/10.3390/ma18051016.
Jadhav, H. B., K. Alaskar, V. Desai, A. Sane, P. Choudhary, and U. Annapure. 2025. “Transformative Impact: Artificial Intelligence in the Evolving Landscape of Processed Food-A Concise Review Focusing on Some Food Processing Sectors.” *Food Control* 167:110803. https://doi.org/10.1016/j.foodcont.2024.110803.
Jamwal, V., and A. Mittal. 2024. “Recent Progresses in Nanocomposite Films for Food-Packaging Applications: Synthesis Strategies, Technological Advancements, Potential Risks and Challenges.” *Food Reviews International* 40 (10): 3634–3665. https://doi.org/10.1080/87559129.2024.2368065.
Jazdi, N., B. A. Talkhestani, B. Maschler, and M. Weyrich. 2021. “Realization of AI-Enhanced Industrial Automation Systems Using Intelligent Digital Twins.” *Procedia CIRP* 97:396–400. https://doi.org/10.1016/j.procir.2020.05.257.
Jiang, T., L. Feng, and Y. Wang. 2013. “Effect of Alginate/Nano-Ag Coating on Microbial and Physicochemical Characteristics of Shiitake Mushroom (Lentinus Edodes) During Cold Storage.” *Food Chemistry* 141 (2): 954–960. https://doi.org/10.1016/j.foodchem.2013.03.093.
Kaiser, M. R., H. Anuar, and S. B. A. Razak. 2014. “Improvement in Thermomechanical Properties of Injection Molded Nano-Modified Hybrid Biocomposite.” *Journal of Thermoplastic Composite Materials* 27 (7): 992–1009. https://doi.org/10.1177/0892705712461518.
Kamel, S., N. Ali, K. Jahangir, S. M. Shah, and A. A. El-Gendy. 2008. “Pharmaceutical Significance of Cellulose: A Review.” *Express Polymer Letters* 2 (11): 758–778. https://doi.org/10.3144/expresspolymlett.2008.90.
Kämpfer, C., T. B. Seiler, A. L. Beger, G. Jacobs, M. Löwer, and F. Moser. 2017. “Life Cycle Assessment and Sustainable Engineering in the Context of Near Net Shape Grown Components: Striving Towards a Sustainable Way of Future Production.” *Environmental Sciences Europe* 29 (1): 27. https://doi.org/10.1186/s12302-017-0125-x.
Khalil, H. A., Y. Davoudpour, M. N. Islam, A. Mustapha, K. Sudesh, R. Dungani, and M. Jawaid. 2014. “Production and Modification of Nanofibrillated Cellulose Using Various Mechanical Processes: A Review.” *Carbohydrate Polymers* 99:649–665. https://doi.org/10.1016/j.carbpol.2013.08.069.
Khan, A., S. M. Rangappa, S. Siengchin, and A. M. Asiri. 2020. *Biofibers and Biopolymers for Biocomposites*. Cham: Springer.
Khan, S., J. K. Monteiro, A. Prasad, C. D. Filipe, Y. Li, and T. F. Didar. 2024. “Material Breakthroughs in Smart Food Monitoring: Intelligent Packaging and On-Site Testing Technologies for Spoilage and Contamination Detection.” *Advanced Materials* 36 (1): 2300875. https://doi.org/10.1002/adma.202300875.
Kóczán, Z., and Z. Pásztory. 2024. “Overview of Natural Fiber-Based Packaging Materials.” *Journal of Natural Fibers* 21 (1): 2301364. https://doi.org/10.1080/15440478.2023.2301364.
Kodumuru, R., S. Sarkar, V. Parepally, and J. Chandarana. 2025. “Artificial Intelligence and Internet of Things Integration in Pharmaceutical Manufacturing: A Smart Synergy.” *Pharmaceutics* 17 (3): 290. https://doi.org/10.3390/pharmaceutics17030290.
Krupitzer, C. 2024. “Generative Artificial Intelligence in the Agri-Food Value Chain-Overview, Potential, and Research Challenges.” *Frontiers in Food Science and Technology* 4:1473357. https://doi.org/10.3389/frfst.2024.1473357.
Kumar, A., S. Kulshreshtha, A. Shrivastava, and A. Saini. 2024. “Biosensors for Food Spoilage Detection: A Comprehensive Review of Current Advances.” *Journal of Food Chemistry and Nanotechnology* 10:S73–S82. https://doi.org/10.17756/jfcn.2024-s1-010.
Kumar, L., R. Dutt, and K. K. Gaikwad. 2025. “Packaging 4.0: Artificial Intelligence and Machine Learning Applications in the Food Packaging Industry.” *Current Food Science and Technology Reports* 3 (1): 19. https://doi.org/10.1007/s43555-025-00064-w.
Kumar, N., P. Kaur, and S. Bhatia. 2017. “Advances in Bio-Nanocomposite Materials for Food Packaging: A Review.” *Nutrition & Food Science* 47 (4): 591–606. https://doi.org/10.1108/NFS-11-2016-0176.
Kumar, N., P. Rawat, and R. K. Kandasami. 2025. “Enhancing the Characteristics of Natural Coir Fiber Yarns Using Biopolymer for Textile Reinforced Cementitious Composites.” *Construction and Building Materials* 470:140427. https://doi.org/10.1016/j.conbuildmat.2025.140427.
Kumar, P., K. P. Sandeep, S. Alavi, V. D. Truong, and R. E. Gorga. 2010. “Effect of Type and Content of Modified Montmorillonite on the Structure and Properties of Bio-Nanocomposite Films Based on Soy Protein Isolate and Montmorillonite.” *Journal of Food Science* 75 (5): N46–N56. https://doi.org/10.1111/j.1750-3841.2010.01633.x.
Kumar, S. S., P. Shyamala, P. R. Pati, D. K. Mishra, V. Sharma, G. Tank, and M. Kanan. 2025. “Investigation and Machine Learning-Based Prediction of Mechanical Properties in Hybrid Natural Fiber Composites.” *Scientific Reports* 15 (1): 33700. https://doi.org/10.1038/s41598-025-18944-5.
Kurien, R. A., A. Arshad, A. Joseph, A. Sunil, B. T. Cherian, and S. M. Rangappa. 2025. “Agave-Jute Fiber–Reinforced Hybrid Composite for Lightweight Applications: Effect of Hybridization.” *Biomass Conversion and Biorefinery* 15 (8): 12241–12254. https://doi.org/10.1007/s13399-024-05984-6.

Kurien, R. A., D. P. Selvaraj, M. Sekar, C. P. Koshy, C. Paul, S. Palanisamy, and P. Kumar. 2023. "A Comprehensive Review on the Mechanical, Physical, and Thermal Properties of Abaca Fibre for Their Introduction into Structural Polymer Composites." *Cellulose* 30 (14): 8643–8664.

Lan, W., S. Wang, Z. Zhang, X. Liang, X. Liu, and J. Zhang. 2021. "Development of Red Apple Pomace Extract/ Chitosan-Based Films Reinforced by TiO2 Nanoparticles as a Multifunctional Packaging Material." *International Journal of Biological Macromolecules* 168:105–115. https://doi.org/10.1016/j.ijbiomac.2020.12.051.

Lewis, H., K. Verghese, and L. Fitzpatrick. 2010. "Evaluating the Sustainability Impacts of Packaging: The Plastic Carry Bag Dilemma." *Packaging Technology and Science: An International Journal* 23 (3): 145–160. https://doi.org/10.1002/pts.886.

Li, X., X. Jin, C. Yang, X. Liu, Y. Ni, and C. Dong. 2024. "A System with Efficient Flame Retardant and Antibacterial Properties for the Development of Exceptional Durable Functional Cotton Fabrics." *International Journal of Biological Macromolecules* 279:135245. https://doi.org/10.1016/j.ijbiomac.2024.135245.

Li, X., D. Liu, Y. Pu, and Y. Zhong. 2023. "Recent Advance of Intelligent Packaging Aided by Artificial Intelligence for Monitoring Food Freshness." *Foods* 12 (15): 2976. https://doi.org/10.3390/foods12152976.

Lin, A. C., J. Lee, M. K. Gabriel, R. N. Arbet, Y. Ghawaa, and A. M. Ferguson. 2024. "The Pharmacy 5.0 Framework: A New Paradigm to Accelerate Innovation for Large-Scale Personalized Pharmacy Care." *American Journal of Health-System Pharmacy* 81 (5): e141–e147. https://doi.org/10.1093/ajhp/zxad212.

Liu, G., S. Zhang, L. Wang, X. Li, and G. Li. 2025. "Research on Mechanical Automatic Food Packaging Defect Detection Model Based on Improved YOLOv5 Algorithm." *PLOS ONE* 20 (4): e0321971. https://doi.org/10.1371/journal.pone.0321971.

Ma, W., L. Yan, and B. Kasal. 2025. "Intensive Exploration: The Application Potential of Flax Fibre/Textiles as Reinforcement in Cementitious Composites." *Journal of Cleaner Production* 507:145457. https://doi.org/10.1016/j.jclepro.2025.145457.

Madhu, B. 2025. "AI-Driven Food Packaging Systems: A New Frontier in Intelligent Food Safety and Shelf-Life Management." *Journal of Food Science* 90 (12): e70716.

Malashin, I. P., D. Martysyuk, V. Nelyub, A. Borodulin, A. Gantimurov, and V. Tynchenko. 2025. "Deep Learning for Property Prediction of Natural Fiber Polymer Composites." *Scientific Reports* 15 (1): 27837. https://doi.org/10.1038/s41598-025-10841-1.

Malik, S., K. Muhammad, and Y. Waheed. 2024. "Artificial Intelligence and Industrial Applications-A Revolution in Modern Industries." *Ain Shams Engineering Journal* 15 (9): 102886. https://doi.org/10.1016/j.asej.2024.102886.

Mann, G. S., L. P. Singh, P. Kumar, A. Khan, A. A. P. Khan, and A. M. Asiri. 2022. "Effect of Process Parameters on the Fabrication of Hybrid Natural Fiber Composites Fabricated via Compression Moulding Process." *Journal of Natural Fibers* 19 (16): 14803–14812. https://doi.org/10.1080/15440478.2022.2069185.

Marcoaldi, C., V. Acampora, V. Venezia, C. Prieto, R. Grappa, B. Silvestri, and J. M. Lagaron. 2025. "Challenges in Lignin Integration Within Biopolymer Matrices: Toward Stable and Effective Lignin Nanoparticles as Additives for Sustainable Food Packaging." *Industrial Crops and Products* 224:120336. https://doi.org/10.1016/j.indcrop.2024.120336.

Masud, M., and A. Mubashar. 2024. "Effect of Hybridization on the Mechanical Performance and Cost Efficiency of Carbon/Flax Bio-Hybrid Composites." *Polymer Composites* 45 (11): 9766–9784. https://doi.org/10.1002/pc.28437.

Mehdizadeh, S. A., M. Noshad, M. Chaharlangi, and Y. Ampatzidis. 2025. "AI-Driven Non-Destructive Detection of Meat Freshness Using a Multi-Indicator Sensor Array and Smartphone Technology." *Smart Agricultural Technology* 10:100822. https://doi.org/10.1016/j.atech.2025.100822.

Mihai, M., and M. T. Ton-That. 2019. "Novel Bio-Nanocomposite Hybrids Made from Polylactide/Nanoclay Nanocomposites and Short Flax Fibers." *Journal of Thermoplastic Composite Materials* 32 (1): 3–28. https://doi.org/10.1177/0892705717743293.

Mkhari, T., J. O. Adeyemi, and O. A. Fawole. 2025. "Recent Advances in the Fabrication of Intelligent Packaging for Food Preservation: A Review." *Processes* 13 (2): 539. https://doi.org/10.3390/pr13020539.

Mohammadi, M., M. R. Ishak, and M. T. H. Sultan. 2024. "Exploring Chemical and Physical Advancements in Surface Modification Techniques of Natural Fiber Reinforced Composite: A Comprehensive Review." *Journal of Natural Fibers* 21 (1): 2408633. https://doi.org/10.1080/15440478.2024.2408633.

Motaleb, K. A., M. Shariful Islam, and M. B. Hoque. 2018. "Improvement of Physicomechanical Properties of Pineapple Leaf Fiber Reinforced Composite." *International Journal of Biomaterials* 2018 (1): 7384360.

Moustafa, H., M. H. Hemida, M. A. Nour, and A. I. Abou-Kandil. 2025. "Intelligent Packaging Films Based on Two-Dimensional Nanomaterials for Food Safety and Quality Monitoring: Future Insights and Roadblocks." *Journal of Thermoplastic Composite Materials* 38 (3): 1208–1230. https://doi.org/10.1177/08927057241264802.

Mu, W., G. A. Kleter, Y. Bouzembrak, E. Dupouy, L. J. Frewer, F. N. Radwan Al Natour, and H. J. P. Marvin. 2024. "Making Food Systems More Resilient to Food Safety Risks by Including Artificial Intelligence, Big Data, and Internet of Things into Food Safety Early Warning and Emerging Risk Identification Tools." *Comprehensive Reviews in Food Science and Food Safety* 23 (1): e13296. https://doi.org/10.1111/1541-4337.13296.

Mudi, C., and A. Shaw. 2024. "Investigations on the Mechanical Performance and Durability of Ramie Fibers Under Various Environmental Conditions." *Journal of Natural Fibers* 22 (1). https://doi.org/10.1080/15440478.2024.2433043.

Murthy, V., and S. Ramakrishna. 2022. "A Review on Global E-Waste Management: Urban Mining Towards a Sustainable Future and Circular Economy." *Sustainability* 14 (2): 647. https://doi.org/10.3390/su14020647.
Mustafa, M., B. Louhichi, Q. S. Khalid, and M. Rizwan. 2026. "An AI-Driven Framework for Smart Waste Classification and Recycling: Enabling Circular Economy Through CNN and IoT Integration." *International Journal of Environmental Science and Technology* 23 (3): 225. https://doi.org/10.1007/s13762-025-06823-5.
Nagaveni, S., and V. G. Poosarla. 2024. "Future Trends in Intelligent Packaging Solutions." In *Intelligent Packaging*, 383–411. Academic Press. https://doi.org/10.1016/B978-0-443-15388-4.00015-8.
Nayak, S. Y., M. T. H. Sultan, S. B. Shenoy, C. R. Kini, R. Samant, A. U. M. Shah, and P. Amuthakkannan. 2022. "Potential of Natural Fibers in Composites for Ballistic Applications–A Review." *Journal of Natural Fibers* 19 (5): 1648–1658.
Othman, S. H., B. M. Wane, N. Nordin, N. Z. A. Noor Hasnan, R. Talib, and J. N. W. Karyadi. 2021. "Physical, Mechanical, and Water Vapor Barrier Properties of Starch/Cellulose Nanofiber/Thymol Bionanocomposite Films." *Polymers* 13 (23): 4060. https://doi.org/10.3390/polym13234060.
Othman, S. H., N. S. Zaid, R. A. Shapi'i, N. Nordin, R. A. Talib, and I. S. M. A. Tawakkal. 2025. "Starch Biopolymer Films Containing Carbon Black Nanoparticles: Properties and Active Food Packaging Application." *Journal of Science: Advanced Materials & Devices* 10 (4): 100995.
Oun, A. A., S. Shankar, and J. W. Rhim. 2020. "Multifunctional Nanocellulose/Metal and Metal Oxide Nanoparticle Hybrid Nanomaterials." *Critical Reviews in Food Science and Nutrition* 60 (3): 435–460. https://doi.org/10.1080/10408398.2018.1536966.
Oyegbade, S. A., E. O. Mameh, J. G. Oni, M. A. Gbate, T. A. Oluwaseyi, and A. Wurie. 2025. *Innovations in Food Technology*. Intelligent Packaging and Advanced Traceability Solutions. https://doi.org/10.1039/9781837679119-00001.
Pasqua, T., C. Rocca, F. R. Lupi, N. Baldino, D. Amelio, and O. I. Parisi. 2020. "Cardiac and Metabolic Impact of Functional Foods with Antioxidant Properties Based on Whey Derived Proteins Enriched with Hemp Seed Oil." *Antioxidants* 9 (11): 1066. https://doi.org/10.3390/antiox9111066.
Pham, D. L., and T. W. Chang. 2023. "A YOLO-Based Real-Time Packaging Defect Detection System." *Procedia Computer Science* 217 (1): 886–894. https://doi.org/10.1016/j.procs.2022.12.285.
Pirsa, S. 2024. "Cellulose-Based Cartons: Production Methods, Modification, and Smart/Active Packaging." *Cellulose* 31 (6): 3421–3445. https://doi.org/10.1007/s10570-024-05826-8.
Rasheed, M., M. Jawaid, and B. Parveez. 2021. "Bamboo Fiber Based Cellulose Nanocrystals/Poly (Lactic Acid)/Poly (Butylene Succinate) Nanocomposites: Morphological, Mechanical and Thermal Properties." *Polymers* 13 (7): 1076. https://doi.org/10.3390/polym13071076.
Raut, S., N. U. I. Hossain, M. Kouhizadeh, and S. A. Fazio. 2025. "Application of Artificial Intelligence in Circular Economy: A Critical Analysis of the Current Research." *Sustainable Futures* 9:100784. https://doi.org/10.1016/j.sftr.2025.100784.
Reddy, B. S. H., R. Venkatramana, and L. Jayasree. 2025. "Enhancing Apple Fruit Quality Detection With Augmented YOLOv3 Deep Learning Algorithm." *International Journal of Human Computations & Intelligence* 4 (1): 386–396.
Reddy, N., and Y. Yang. 2011. "Biocomposites Developed Using Water-Plasticized Wheat Gluten as Matrix and Jute Fibers as Reinforcement." *Polymer International* 60 (4): 711–716. https://doi.org/10.1002/pi.3014.
Reichert, C. L., E. Bugnicourt, M. B. Coltelli, P. Cinelli, A. Lazzeri, and I. Canesi. 2020. "Bio-Based Packaging: Materials, Modifications, Industrial Applications and Sustainability." *Polymers* 12 (7): 1558. https://doi.org/10.3390/polym12071558.
Rezaei, A., A. Nasirpour, and M. Fathi. 2015. "Application of Cellulosic Nanofibers in Food Science Using Electrospinning and Its Potential Risk." *Comprehensive Reviews in Food Science and Food Safety* 14 (3): 269–284. https://doi.org/10.1111/1541-4337.12128.
Rhim, J. W., and P. K. Ng. 2007. "Natural Biopolymer-Based Nanocomposite Films for Packaging Applications." *Critical Reviews in Food Science and Nutrition* 47 (4): 411–433. https://doi.org/10.1080/10408390600846366.
Rom, M., J. Broda, T. Kukulski, A. Gawlowski, and K. Kobiela-Mendrek. 2024. "The Morphology of Wool Fibers Biodegraded in Natural Conditions in Soil." *Journal of Natural Fibers* 22 (1). https://doi.org/10.1080/15440478.2024.2446947.
Saba, N., M. T. H. Sultan, and M. Jawaid, Eds. 2020. *Biopolymers and Biocomposites from Agro-Waste for Packaging Applications*. Woodhead Publishing.
Sah, S. K., and S. Kaity. 2024. "Pharmaceutical Packaging: Recent Trends and Challenges." *Dosage Forms, Formulation Developments and Regulations*: 663–684. https://doi.org/10.1016/B978-0-323-91817-6.00009-7 .
Santos, C. M., T. F. Santos, J. H. O. Nascimento, S. M. Rangappa, F. Gapsari, and S. Siengchin. 2025. "Natural Fibers as a Conscious Choice for a Greener Future." *Discover Polymers* 2 (1): 22. https://doi.org/10.1007/s44347-025-00037-1.
Sathiyamurthy, S., S. Saravanakumar, and V. Vinoth. 2024. "Enhancing Tribological Performance of Hybrid Fiber-Reinforced Composites Through Machine Learning and Response Surface Methodology." *Journal of Reinforced Plastics & Composites* 44 (21–22): 2306–2324. https://doi.org/10.1177/07316844241256421.
Sayyad, J., and K. Attarde. 2025. "Synergizing Nanotechnology and Artificial Intelligence for Society 5.0 Advancement through Intelligent Systems." In *NanoMind: Exploring Synergies in Nanotechnology and Machine Learning*, 225–249. Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-77296-2_10.

Schiavon, J. Z., P. M. Borges, and J. J. de Oliveira Andrade. 2024. "Physical-Mechanical Properties and Microstructure Changes in Mortars with Chemically Treated Coir Fibers." *Journal of Materials Research and Technology* 30:4030–4043. https://doi.org/10.1016/j.jmrt.2024.04.109.

Sengottaiyan, S., S. Subbarayan, V. Viswanathan, and P. Pugazhendi. 2024. "Optimized Machine Learning With Hyperparameter Tuning and Response Surface Methodology for Predicting Tribological Performance in Bio-Composite Materials." *Polymer Composites* 45 (10): 9421–9439. https://doi.org/10.1002/pc.28418.

Senthil Kumar, M. S., L. Rajeshkumar, S. M. Rangappa, and S. Siengchin. 2024. "Mechanical Behaviour Analysis for Banana/Coir Natural Fiber Hybrid Epoxy Composites Through Experimental Modelling." *Journal of Polymer Research* 31 (6): 163. https://doi.org/10.1007/s10965-024-04018-z.

Shehzad, K. 2025. "Predictive AI Models for Food Spoilage and Shelf-Life Estimation." *Global Trends in Science and Technology* 1 (1): 75–94. https://doi.org/10.70445/gtst.1.1.2025.75-94.

Shen, B., B. Qian, and N. Tu. 2025. "Utilizing AI Algorithms to Model and Optimize the Composite of Nanocellulose and Hydrogels via a New Technique." *International Journal of Biological Macromolecules* 290:138903. https://doi.org/10.1016/j.ijbiomac.2024.138903.

Shirzad, K., and A. Joodaky. 2024. "Enhancing Sustainable Food Packaging Design: A Machine Learning Approach to Predict Ventilated Corrugated Paperboard Strength." *Biosystems Engineering* 247:26–41. https://doi.org/10.1016/j.biosystemseng.2024.08.012.

Shukla, A. K., Ed. 2025. *AI Applications in Food Processing and Packaging*. Royal Society of Chemistry. https://doi.org/10.1039/9781837679119-FP001.

Silska, G., and T. Górecki. 2023. "Fiber Content of the Flax Germplasm (Linum Usitatissimum L.) Originating from Different Parts of the World." *Journal of Natural Fibers* 20 (1): 2164108. https://doi.org/10.1080/15440478.2022.2164108.

Singh, B., R. Kumar, S. Sharma, A. Pattanaik, P. Kumar, A. Kedia, A. I. Mahapatro, V. K. B. Raja, D. Gupta, and A. I. Ismail. 2025. "Enhancing Cellulose-Rich Polylactic Acid (PLA)-Rice Residue-Reinforced Sustainable Biocomposites: Influence of Chemical Pretreatments on Strengthening the Thermomechanical Properties of Biocomposite Materials." *International Journal of Biological Macromolecules* 327:146631. https://doi.org/10.1016/j.ijbiomac.2025.146631.

Singh, B., R. Kumar, S. Sharma, T. Ramachandran, V. B. Raja, A. Mahapatro, D. Gupta, A. Kedia, A. I. Ismail, and A. Kumar. 2025. "Review on the Synergistic Mechanisms in Harnessing Rice Residue-Derived Cellulose Nanocrystals for Sustainable Water Purification and Wastewater Treatment." *International Journal of Biological Macromolecules* 311:143225. https://doi.org/10.1016/j.ijbiomac.2025.143225.

Singh, G., R. S. Dondapati, and L. P. Singh. 2021. "Biomaterials Printing for Sustainability." In *Sustainability for 3D Printing*, 15–28. Cham: Springer International Publishing.

Singh, G., S. Sharma, K. Sandhu, A. M. Asiri, and A. Khan. 2021. "Sustainable Product Packaging Using Vegetables Fibres and Its Composite." In *Vegetable Fiber Composites and Their Technological Applications*, 275–302. Singapore: Springer Singapore. https://doi.org/10.1007/978-981-16-1854-3.

Singh, R., C. Nickhil, R. Nisha, K. Upendar, B. Jithender, and S. C. Deka. 2025. "A Comprehensive Review of Advanced Deep Learning Approaches for Food Freshness Detection." *Food Engineering Reviews* 17 (1): 127–160. https://doi.org/10.1007/s12393-024-09385-3.

Siqueira, G., J. Bras, and A. Dufresne. 2010. "Cellulosic Bionanocomposites: A Review of Preparation, Properties and Applications." *Polymers* 2 (4): 728–765. https://doi.org/10.3390/polym2040728.

Siripatrawan, U., and Y. Makino. 2025. "Rapid and Chemical-Free Technique Based on Hyperspectral Imaging Combined with Artificial Intelligence for Monitoring Quality and Shelf Life of Dried Shrimp." *Food Research International* 213:116422. https://doi.org/10.1016/j.foodres.2025.116422.

Song, F., T. Xia, and Y. Tang. 2024. "Integration of Artificial Intelligence Technology and Visual Communication Design in Metaverse e-Commerce and Its Potential Opportunities." *Electronic Commerce Research*: 1–21. https://doi.org/10.1007/s10660-024-09855-0.

Srivastava, S. 2024. "Advancements in Nanocellulose Derived from Plant Waste: Strategies for Sustainable Innovations and Applications." *The Journal of Solid Waste Technology and Management* 50 (3): 543–563. https://doi.org/10.5276/jswtm/iswmaw/503/2024.543.

Stevens, C. V. 2010. *Industrial Applications of Natural Fibres: Structure, Properties and Technical Applications*. John Wiley & Sons.

Tarlak, F. 2023. "The Use of Predictive Microbiology for the Prediction of the Shelf Life of Food Products." *Foods* 12 (24): 4461. https://doi.org/10.3390/foods12244461.

Tasgin, Y., G. Demircan, S. Kandemir, and A. Acikgoz. 2024. "Mechanical, Wear and Thermal Properties of Natural Fiber-Reinforced Epoxy Composite: Cotton, Sisal, Coir and Wool Fibers." *Journal of Materials Science* 59 (24): 10844–10857. https://doi.org/10.1007/s10853-024-09810-2.

Ul-Allah, S., A. Rehman, M. Hussain, and M. Farooq. 2021. "Fiber Yield and Quality in Cotton Under Drought: Effects and Management." *Agricultural Water Management* 255:106994. https://doi.org/10.1016/j.agwat.2021.106994.

Vijaya Ramnath, B., S. Rajesh, C. Elanchezhian, A. Santosh Shankar, S. Pithchai Pandian, S. Vickneshwaran, and R. Sundar Rajan. 2016. "Investigation on Mechanical Behaviour of Twisted Natural Fiber Hybrid Composite

Fabricated by Vacuum Assisted Compression Molding Technique." *Fibers and Polymers* 17 (1): 80–87. https://doi.org/10.1007/s12221-016-5276-7.
Vogl, C. R., H. Mölleken, G. Lissek-Wolf, A. Surböck, and J. Kobert. 2004. "Hemp (Cannabis Sativa L.) as a Resource for Green Cosmetics: Yield of Seed and Fatty Acid Compositions of 20 Varieties Under the Growing Conditions of Organic Farming in Austria." *Journal of Industrial Hemp* 9 (1): 51–68. https://doi.org/10.1300/J237v09n01_06.
Wakai, M., and E. Almenar. 2015. "Effect of the Presence of Montmorillonite on the Solubility of Whey Protein Isolate Films in Food Model Systems with Different Compositions and pH." *Food Hydrocolloids* 43:612–621. https://doi.org/10.1016/j.foodhyd.2014.07.022.
Wang, M., and X. Li. 2024. "Application of Artificial Intelligence Techniques in Meat Processing: A Review." *Journal of Food Process Engineering* 47 (3): e14590. https://doi.org/10.1111/jfpe.14590.
Wasti, S., A. M. Hubbard, C. M. Clarkson, E. Johnston, H. Tekinalp, S. Ozcan, and U. Vaidya. 2024. "Long Coir and Glass Fiber Reinforced Polypropylene Hybrid Composites Prepared via Wet-Laid Technique." *Composites Part C Open Access* 14:100445. https://doi.org/10.1016/j.jcomc.2024.100445.
Yaiprasert, C., and A. N. Hidayanto. 2024. "AI-Powered in the Digital Age: Ensemble Innovation Personalizes the Food Recommendations." *Journal of Open Innovation, Technology, Market, & Complexity* 10 (2): 100261. https://doi.org/10.1016/j.joitmc.2024.100261.
Yakoubi, S. 2025. "Sustainable Revolution: AI-Driven Enhancements for Composite Polymer Processing and Optimization in Intelligent Food Packaging." *Food and Bioprocess Technology* 18 (1): 82–107. https://doi.org/10.1007/s11947-024-03449-2.
Yousef, S., M. Tatariants, M. Tichonovas, L. Kliucininkas, S. I. Lukošiūtė, and L. Yan. 2020. "Sustainable Green Technology for Recovery of Cotton Fibers and Polyester from Textile Waste." *Journal of Cleaner Production* 254:120078. https://doi.org/10.1016/j.jclepro.2020.120078.
Youssef, A. M., S. M. El-Sayed, H. H. Salama, H. S. El-Sayed, and A. Dufresne. 2015. "Evaluation of Bionanocomposites as Packaging Material on Properties of Soft White Cheese During Storage Period." *Carbohydrate Polymers* 132:274–285. https://doi.org/10.1016/j.carbpol.2015.06.075.
Yu, W., Z. Ouyang, Y. Zhang, Y. Lu, C. Wei, Y. Tu, and B. He. 2025. "Research Progress on the Artificial Intelligence Applications in Food Safety and Quality Management." *Trends in Food Science & Technology* 156:104855. https://doi.org/10.1016/j.tifs.2024.104855.
Zadbuke, N., S. Shahi, B. Gulecha, A. Padalkar, and M. Thube. 2013. "Recent Trends and Future of Pharmaceutical Packaging Technology." *Journal of Pharmacy & Bioallied Sciences* 5 (2): 98–110. https://doi.org/10.4103/0975-7406.111820.
Zafar, S., H. Afzal, A. Ijaz, A. Mahmood, A. Ayub, and A. Nayab. 2023. "Cotton and Drought Stress: An Updated Overview for Improving Stress Tolerance." *South African Journal of Botany* 161:258–268. https://doi.org/10.1016/j.sajb.2023.08.029.
Zamiri, M. A., M. N. Dafchahi, M. Ebadian, and B. Acharya. 2024. "Optimizing Production Conditions of Innovative Bio-Pellets Developed from Flax Straw." *Industrial Crops and Products* 218:118950. https://doi.org/10.1016/j.indcrop.2024.118950.
Zatsu, V., A. E. Shine, J. M. Tharakan, D. Peter, T. V. Ranganathan, and S. S. Alotaibi. 2024. "Revolutionizing the Food Industry: The Transformative Power of Artificial Intelligence-A Review." *Food Chemistry: X* 24:101867. https://doi.org/10.1016/j.fochx.2024.101867.
Zeng, L., S. R. Stetina, J. E. Erpelding, E. Bechere, R. B. Turley, and J. Scheffler. 2018. "History and Current Research in the USDA-ARS Cotton Breeding Program at Stoneville, MS." *Journal of Cotton Science* 22 (1): 24–35. https://doi.org/10.56454/UAMO1792.
Zhang, Y., G. X. Qi, Y. L. Yu, M. X. Liu, and S. Chen. 2023. "A Machine Learning-Based Colorimetric Sensor Array for High-Precision Pathogen Identification in Household Refrigerators." *Chemical Communications* 59 (49): 7603–7606. https://doi.org/10.1039/D3CC01320K.
Zhao, S., S. Y. S. S. Adade, Z. Wang, T. Jiao, Q. Ouyang, H. Li, and Q. Chen. 2025. "Deep Learning and Feature Reconstruction Assisted Vis-NIR Calibration Method for On-Line Monitoring of Key Growth Indicators During Kombucha Production." *Food Chemistry* 463:141411. https://doi.org/10.1016/j.foodchem.2024.141411.
Zhu, Q., Q. Yao, J. Sun, H. Chen, W. Xu, J. Liu, and Q. Wang. 2020. "Stimuli Induced Cellulose Nanomaterials Alignment and Its Emerging Applications: A Review." *Carbohydrate Polymers* 230:115609. https://doi.org/10.1016/j.carbpol.2019.115609.