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Emerging Trends in Food Packaging: Innovations, Sustainability, and Future Perspectives

Madeeha Khadim[1], Saba Noreen[4], Syeda Noor-ul-Ain Naqvi[1], Aman Arif[2], Aiman Yar[3], Anum Urooj[1], Muhammad Asif[1]

[1]National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan
[2]Department of Nutritional Sciences, Government College University, Faisalabad, Pakistan
[3]Department of Biochemistry, Bahauddin Zakariya University, Multan, Pakistan
[4]Food Science and Nutrition, Hallym University Chuncheon-si South Korea

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Correspondence to: Saba Noreen, Food Science and Nutrition, Hallym University Chuncheon-si South Korea.

Email: sabanooreen4@gmail.com

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ABSTRACT

The global food packaging industry is undergoing a transformative shift, driven by environmental concerns, evolving consumer preferences, and the need for enhanced food preservation. This review explores cutting-edge innovations in sustainable packaging, including biodegradable, edible, and recyclable materials; active and intelligent systems incorporating oxygen scavengers, antimicrobial agents, and freshness sensors; and advanced technologies such as nanotechnology, 3D printing, and AI-integrated smart packaging. The importance of packaging in lowering food waste, increasing shelf life, guaranteeing food safety, and facilitating real-time tracking and traceability is highlighted. Additionally, the study addresses challenges related to regulatory compliance, environmental impact, consumer acceptance, and scalability. By examining global trends, material science developments, and emerging technologies, this review provides a forward-looking analysis of how the food packaging industry can align with circular economy principles and support global sustainability goals.

INTRODUCTION

Importance of Food Packaging in Preservation, Safety, and Convenience

Packaging is a crucial and necessary for promoting food safety, extended shelf life and thereby promoting food security. Because of customers' increasing need for packaged and processed foods as a result of modernization, changing eating habits, and growing income levels, the packaging sector is expanding quickly. A surge in packaging innovations has been caused by the adoption of new technologies in the transportation, supply chain and logistics, post-harvest technology, evolution of e-commerce, growth of the new retail sector, need for single-use and single-dose consumer packs, and growing reliance on appliances like microwave ovens, refrigerators, and freezers (Khidkar & Khidkar, 2020).

Food packaging helps ensure the safety of food products and facilitates their handling and transportation by extending their shelf life and reducing chemical contamination, which benefits customers. Food packaging has made use of a variety of materials, including as papers and their composites, metals, glass, and plastics (Alamri et al., 2021). The art and science of preserving food for a predetermined amount of time or preserving its quality or integrity is known as food preservation. The use of packing enclosures is one of the food preservation procedures used to prevent food from external factors that could alter its original quality or nature. Food packaging protects food products from outside invasion and provides enclosure for food as a component of food preservation (Gerba, 2023). The preservation and safe distribution of food items until they are consumed are the main goals of food packaging. The food product's quality may decline both physically and chemically while it is being distributed. Food packaging keeps food products secure and high quality while extending their shelf life. Along with offering traceability, tamper indicators, and portion control, packaging also serves a crucial secondary purpose in marketing.

Food is one of the basic needs of the human being. It is necessary for proper growth and for the body's components to work normally. The convenience, value, appealing appearance, taste, and texture of ready to eat (RTE) snacks and ready to serve (RTS) food contribute to growing consumer interest in these products. Most foods come in plastic packaging. Long-term use of plastic-coated materials, however, is slowly poisoning people (tetteh, 2022). Using techniques and tools that not only efficiently preserve food but also reduce environmental impact and improve the nutritional value of food is the idea behind sustainable food preservation. This analysis highlights cutting edge preservation methods that are efficient and environmentally beneficial in an effort to investigate and progress the area. Innovative technologies that are attracting interest include pulsed light and cold plasma, which present potential alternatives for traditional techniques. Furthermore, there are numerous chances to reduce the dependency on artificial chemicals and enhance sustainability through the use of natural preservatives and cutting-edge packaging options like biodegradable materials and modified atmosphere packaging (MAP) (Lisboa et al., 2024).

Evolution of Food Packaging Over Time

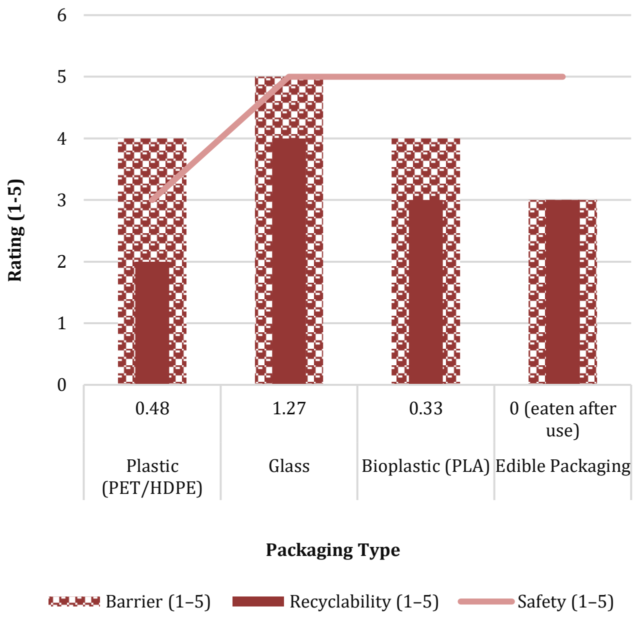
The market demand for food products and dietary supplements has increased significantly during the last few decades. The modern human lifestyle has been significantly impacted by nutritional supplements and packaged dietary items. Food product preservation and long-term use have been major problems for human beings from ancient times. Food products and dietary supplements are evaluated using a variety of criteria that are generally divided into two categories: quality assurance and control. Millions of tonnes of food are wasted every day on average throughout the world as a result of inadequate storage and transportation, which highlights disparities in packaging systems (Verma et al., 2021). New circular and sustainable systems should be designed with the development of sophisticated recycling and remanufacturing techniques in consideration. Recyclable and non-hazardous materials, effective transport and logistics systems, energy and resource efficient technologies, and product design that prioritizes reuse ability, manufacturability, and recycling are some important linked factors. Although recycling and reuse are part of the circular economy model, food packaging does not fully achieve this goal since it is hard to ensure the safety and quality of materials used in food contact using the waste management mechanisms that are already in place. Reuse is currently only practical for containers that can be cleaned and refilled, such as glass bottles and stainless steel containers. Long-term chemical safety of recycled food packaging could be attained by removing hazardous components from the design of the materials and preventing them from entering the recycling stream (Teixeira and Andrade, 2021).

Need for Innovation due to Environmental Concerns and Consumer Demands

Demand for sustainable food packaging solutions has increased in response to growing environmental concerns and consumer preferences for eco-friendly products (Hussain et al., 2024). The development of novel packaging materials with increased barrier qualities and durability is gaining growth, addressing environmental and health problems while also functioning package materials. In order to address sensitive concerns about the environment and consumer demand, it is necessary to focus on the limitations of conventional packaging materials used in the food industry as well as the various polymers derived from natural sources, their physiochemical properties, and their potential application as a sustainable material that reduces carbon emissions, improves food preservation, and ensures food safety. Conventional materials which rely largely on petroleum derived polymers are linked to a number of serious issues including environmental contamination, loss of resources, the production of single use trash and chemical leakage into food products, limited recycling, and others.

Figure 1

Graphical Representation of a Comparative Evaluation of Different Packaging Materials Based on Environmental Burden, Barrier Properties, Recyclability, and Safety Attributes



As the food industry aims to decrease its environmental impact, it promotes for groundbreaking advancements in a successful sustainable food packaging system. The main objective of industrial packaging was to create a biodegradable substance especially one sourced from renewable biomass materials, as an environmentally friendly alternative in the food industry. Khandeparkar et al. published their findings in 2024. Food loss and waste are caused by a range of factors such as agricultural processing and uneaten food at home. Advancements in packaging design and materials offer genuine prospects for reducing food waste throughout the supply chain. Furthermore, changes in people's lifestyles have led to a greater need for high quality, fresh, naturally processed, and ready to eat food products with extended shelf lives, which must comply with stringent and continually revised food safety regulations. To mitigate health risks and minimize food waste, it is essential to maintain accurate monitoring of food quality and spoilage. Food packaging plays a vital role in preserving food by shielding it from external factors and preventing contamination whether physical, chemical, microbiological, or through adulteration. It acts as a protective barrier, safeguarding food against moisture, oxidation, ultraviolet (UV) radiation, and microbial intrusion. Modern packaging technologies are being developed to extend shelf life by incorporating active components that inhibit oxidation and microbial activity. Furthermore, smart and intelligent packaging systems are capable of monitoring food quality and detecting spoilage, thereby enhancing consumer safety and reducing food losses due to poor storage, transport, or supply chain inefficiencies. Strategic investments in innovative packaging solutions can significantly lower the environmental impact throughout the food supply chain by curbing food waste (Versino et al., 2023). Consumer acceptance is critical for the effective application of smart packaging technology. While these systems provide major benefits for monitoring food quality and assuring safety, consumer trust and acceptance issues persist. The transition to bio-based materials and creative packaging marks an essential step in addressing both environmental concerns and the changing needs of the global food companies (D'Almeida & de Albuquerque, 2024). Packaging is crucial for ensuring food quality, but its harmful impact on the environment need to be eliminated worldwide in order to minimize pollution and prevent climate change. Innovative and sustainable packaging, in addition to novel reutilization strategies, are required to limit plastic waste accumulation, protect food quality and safety, and reduce food losses and waste. Edible food packaging resolves the issue of solid waste caused by conventional packaging, however customers' approval of this unique approach remains doubtful (Zhang et al., 2024).

Objectives of the review

1. Assess biodegradable, compostable, and explore edible packaging for waste reduction.
2. Study oxygen scavengers, antimicrobial systems, and moisture control methods to extend product shelf life
3. Examine smart tools for real time monitoring, safety, and traceability.
4. Research nanotechnology and 3D printing for enhanced functionality and customized designs.
5. Analyze consumer preferences, interactive packaging demand, cost implications, and willingness to pay.
6. Review global policies, identify scaling barriers, and propose AI/IoT integration for future packaging innovations.

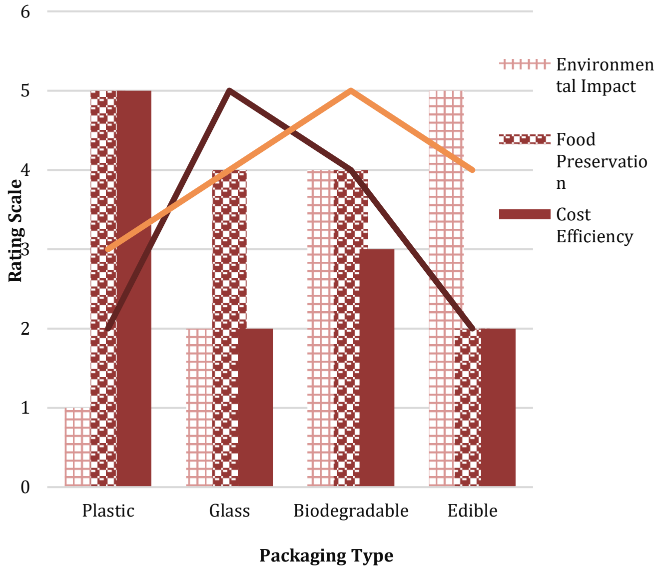
CURRENT CHALLENGES IN FOOD PACKAGING

Environmental Impact of Conventional Plastics

The increase of plastic waste has recently been identified as one of the most important environmental issues that impact the global economy, natural ecosystems, and all life forms. Finding more ecologically friendly alternatives to conventional disposal, such biodegradation, is crucial in light of this hazard. However, the effectiveness and mechanisms of plastic biodegradation are still poorly understood (Ali et al., 2021). Conventional disposal methods for plastic waste are generally divided into three types: landfill, incineration and recycling (Lim and Thian, 2022). The majority of plastic garbage is discarded or burnt worldwide, with only 9% recycled (Geyer et al., 2017). Although garbage dumps and burning are simple processes, they can produce severe environmental pollutants. For example, it has been suggested that garbage and burning are causing long-term changes in the characteristics of soil and soil microbiota, reducing soil fertility. (Kasmuri et al., 2022).

Figure 2

Comparative Efficiency of Packaging Types Based on Key Performance Indicators: Environmental Impact, Food Preservation, Cost Efficiency, Recyclability, and Consumer Safety



Dangerously, harmful gases such as methane, carbon monoxide, and polyaromantic hydrocarbons are produced during these processes, affecting the global carbon cycle both directly and indirectly, ultimately leading to the greenhouse effect and putting humans at risk of developing neoplasia through excessive inhalation (MacLeod et al., 2021). Considering all of these reasons, recycling (physical and chemical) is the best selection for managing the plastic waste problem; however, it suffers by several limitations (Lim and Thian, 2022). On the one hand, most of the positive characteristics of plastic disappear after recycling, and their commercial value is less than the human and material resources put in the process. However, there is still opportunity for improvement in the efficiency and viability of extracting monomers or valuable substances from plastic waste. As a result, it is urgently essential to find efficient and environmentally friendly methods to manage the problem resulting from plastic waste (Wu et al, 2023).

Food Waste and Shelf-Life Extension Challenges

Fresh food shelf life is an important variable in the food supply chain, containing the length during which food products maintain their safety, sensory qualities, and nutritional value under controlled storage and transportation conditions (M. Goransson et al., 2018). The incorrect handling of printed shelf life information, such as "use by" and "best before" dates, can result in needless food disposal and is one of the main causes of retail food waste. For instance, static expiration dates don't take into consideration the changeable circumstances in food supply chains, like temperature changes that occur during storage and transportation. As a result, when storage conditions are not ideal, customers could choose to buy deteriorated products or throw away edible food too soon (Han et al., 2021; Zou et al., 2022). In the food supply chain, retail settings are the most exposed and consumer-facing link. This stage turns into a major point of failure if temperature and quality criteria are not closely monitored. Unsuitable retail settings are thought to be the cause of more than 50% of unmarketable products (Wu et al., 2025). In recent years, advances in cooling technology and supply chain management have fueled efforts to improve retail temperature control. However, there are still challenges: Non-uniform product quality. Despite advancements, storage temperature fluctuations remain common. As a result, foods with the same manufacturing or harvest date can have significantly varying decline periods, reducing consumer trust and increasing waste. The direct impact of temperature variation on product quality necessitates a transition from static expiry date systems to more dynamic, adaptable solutions. According to Han et al. (2021), implementing dynamic shelf-life management systems could handle these anomalies, assuring food safety while also reducing waste.

Consumer Demand for Transparency and Safety

Packaging is critical for gaining consumer attention, communicating product identity, influencing product perception, and influencing approach based consumer behaviors. The physical characteristics of packaging have a major impact on customer attention during the initial encounter stage. At the beginning process, implicit emotions revealed more information about consumers' preferences. Nutritional information received the most visual attention (fixation counts = 0.40) during the evaluation stage, but the NZ-made logo (odds ratio = 15.62) influenced purchase intention. According to the study, product positioning on the shelf and what sort of packaging material used may have significant effects on consumer attention and evaluation. Transparent packaging provides advantages for using visual interest and influencing consumer behavior. Furthermore, the implicit emotional responses stimulated by packaging were related to respondents' visual attention and participation. During the evaluation stage, the consumer focused more on packaging texture and important features such as nutritional information. Their various elements inside the packaging design also greatly influenced customers' fixation and attention habits (Mehta et al., 2024). Both transparent and highly graphic window packaging draw more attention than standard window packaging, although a transparent window is not always more advantageous than an attractive image. Transparent or graphical frame packing is recommended for all three investigated products, with graphic window packaging being especially recommended for preserved fruits. Food makers should focus on sensory studies to improve packaging design for various food categories. Attractive packaging with evident characteristics increases the attraction of customers to purchase (Ma et al., 2020). A growing emphasis on food safety and quality is transforming global food purchasing choices. While some food attributes are visible to consumers, many of the attributes that they seek and are willing to pay a price premium for remain invisible. As a result, consumers depend on reliable indicators and information to enable them to verify the quality of food and the attributes of credibility they are looking for. Specifically, product assurance instils consumer trust through food packaging labels that communicate food attribute claims, certifications, country or region of origin, and information regarding food traceability (Wu et al., 2021).. Innovative food packaging represents a beneficial solution for the food industry in maintaining both food quality and safety. Recent developments have included extra features in barrier films to extend the shelf life of food, such as active packaging and intelligent packaging (Yan et al., 2022).

EMERGING TRENDS IN FOOD PACKAGING

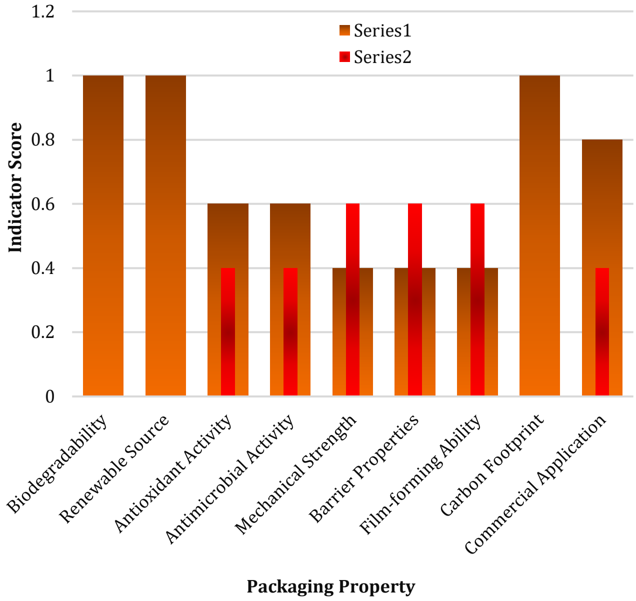
Sustainable and Eco-Friendly Packaging Materials

Edible packaging (protein & polysaccharide-based films)

Traditional packaging cannot track and record environmental variables or food quality conditions. This limitation is overcome by intelligent packaging, which brings intelligent elements into ordinary containers (Wang et al., 2023). Conventional packaging lacks the ability to monitor and document environmental factors or food quality standards. Intelligent packaging overcomes this limitation by incorporating intelligent elements into standard containers (Wang et al., 2023). This sustainable product and technology employs edible materials to package food items, integrating food and packaging through innovative design. Polysaccharides provide a reliable source of edible packaging materials that possess outstanding renewable, biodegradable, and biocompatible characteristics, along with antioxidant and antibacterial properties. Effectively utilizing polysaccharide-based materials significantly reduces reliance on petroleum resources, decreases the carbon footprint of the product packaging system, and offers a zero emission scheme. Up to now, they have been rapidly commercialized and developed in the food packaging industry for items such as fruits and vegetables, meat, nuts, confectioneries, and delicatessens. In comparison to petroleum based polymers and plastics, polysaccharides are currently limited in terms of film-forming, mechanical, barrier, and protective properties. Consequently, they require enhancement through reasonable alterations to their material composition (either chemical or physical in nature). This article provides a comprehensive review of the latest research developments, key topics, and current trends in polysaccharide-based materials used in edible packaging. Primary attention is focused on fundamental compositions and properties, functional alterations, food packaging uses, and safety risk evaluations of polysaccharides (including cellulose, hemicellulose, starch, chitosan, and polysaccharide gums) (Zhoa et al., 2021).

Figure 3

A Visual Representation Comparing the Strengths and Limitations of Polysaccharides-Based Edible Packaging



Plant-Based and Algae-Derived Packaging

The non-degradability of the majority of plastic packaging materials, the absence of recycling infrastructure, and the inadequate waste management of residues which are frequently thrown away without being utilized in other downstream processes make food processing plants hazardous to the environment. Natural, bio-, or biodegradable polymers are in high demand right now. Seaweed polysaccharide is a particularly promising substitute instance as are alginates. Brown algae are the primary source of these naturally occurring hydrophilic polysaccharide biopolymers. It has a low oxygen permeability, gloss, and good film forming qualities, yet it has no flavor or smell. Nevertheless, it has several drawbacks, including low tensile strength and water solubility (Tahreen et al., 2023).

Recyclable and Reusable Packaging Innovations

Recycling is thought to provide both environmental and economic benefits. Recycling has numerous benefits, including employment creation, energy savings, and the potential elimination of an environmental impact, the manufacturing of a product of nearly equal quality to its virgin equivalent, economic benefits, a reduction in greenhouse gas emissions, and more. In some nations with financial limitations, organizational collapse, and outdated treatment mechanisms, waste picking is either the predominant or primary method of collecting recyclable resources. Waste collectors play a crucial role in the circular economy in materialized economies by reusing waste packaging materials. The appeal aims to increase the involvement of waste pickers in household waste management, while also supporting the launch of a circular economy. Local authorities frequently fail to acknowledge waste pickers as service providers, often subjecting them to discriminatory treatment. According to Johnson et al.'s (2008) research, contemporary recycling applications decreased energy usage by 33% and lowered CO_2 emissions by 32%. For stainless-steel wire produced entirely from scrap materials, energy consumption would be reduced by 67% compared to production using virgin materials, while CO_2 emissions would decrease by 70% (Ibrahim et al., 2023)

Active and Intelligent Packaging

Consumer preferences for safe food have prompted advancements in packaging methods. Packaging technologies that are active and intelligent aim to provide safer and higher quality products. Active packaging involves adding substances to a package to preserve or prolong the product's quality and shelf life. Food that is packed is continuously monitored by intelligent systems, which report on its quality throughout transport and shelving. These innovations are intended to address the growing demand for safer foods that can last longer on the shelf (Biji KB et al., 2015).

Active Packaging

Oxygen Scavengers

Oxygen scavengers are a form of active packaging that prevents oxidative degradation of oxygen sensitive food products by absorbing dissolved oxygen or oxygen in the headspace. Examples of oxygen scavengers include iron, ascorbic acid and its derivatives, illumination activated scavengers, reducible organic compounds, and unsaturated hydrocarbon-based scavengers such as polyunsaturated fatty acids and polybutadiene. The mechanisms of action of each system are briefly outlined in this review. Furthermore, certain problems associated with the use of traditional transition metal catalysts to enhance the oxidation rate in oxygen scavenging systems are detailed, along with findings from a recent study that aimed to address these issues through the application of a TiO_2 photocatalyst (Kordjazi & Ajji 2022). The packaging industries and food manufacturers have been compelled to rethink the idea of food packaging due to the increase in consumer awareness of sustainability, the use of biomaterials in food packaging, and the desire for ready to eat or on the go food brought on by urbanization and globalization. The packaging industries were obliged to search for alternative packaging technologies, such as active packaging and intelligent packaging, due to the rise in consumer expectations regarding the availability, shelf life, and quality of fresh food. Active packaging began to develop in the late 1900s and has since advanced to the point where it is now a necessary component of human existence (Ramakanth et al., 2022).

Antimicrobial and Antioxidant Packaging

Food safety, quality, and shelf life extension are all greatly influenced by packaging. When it comes to food safety and quality, potential interactions between food and packaging are fundamental. The controlled/target release antibacterial and/or antioxidant packaging is one of the most significant forms of active packaging (Vasile & Baican, 2021). In the food business, antimicrobial and antioxidant packaging is crucial since it guarantees product quality and extends its shelf life (Dos Anjos et al., 2020). The food industry has numerous difficulties in meeting consumer's demands for excellent quality, convenient, flavorful, and long lasting food. We need new packaging solutions for food to reduce the amount of plastic that ends up in landless and the damage it causes to the environment. To reduce trash and save resources, food containers should be biodegradable, antimicrobial, and antioxidant. In terms of biopolymers used in food packaging, Polylactic acid (PLA) is by far the most common. Applications for PLA in biomedical materials and food packaging seem to be promising because of its biodegradability, FDA clinical approval, and renewability (Zende et al., 2025). Metals and metal oxides, organic acids, peptides and bacteriocins, plant-based antimicrobial agents, enzymes, lactoferrin, chitosan, allyl isothiocyanate, the reuterin system, and bacteriophages are the main categories of antimicrobial agents. These are added to or mixed with different kinds of packaging materials to prolong the shelf life of food (Duda-Chodak et al., 2023).

Intelligent/Smart Packaging

Time-Temperature Indicators (TTIs)

Time-temperature indicators (TTIs) can visually display the remaining shelf life of different products, particularly during cold chain transportation, while taking into account both time and temperature factors. Despite numerous TTIs being developed, only a small number have been commercially viable (Liu et al., 2023). The TTIs are categorized as critical temperature indicators (CTIs), critical temperature-time indicators, and full history indicators. These chemical TTIs may be grounded in polymerization, photochromic, redox, diffusion, or nanoparticle principles. These enzymatic TTIs are produced by lipase, amylase, polyphenol oxidase, glucoamylase, laccase, urease, depolymerase, peroxidase, and esterase. TTIs derived from lactic acid bacteria or Lactobacillus sakei are microbial. Additional innovative TTIs include blends of polymer and dye, photonic crystals, and electronic sensors. The TTIs have a wide range of applications in the food matrices of fruits, vegetables, milk products, meat products, and mushrooms (Gurunathan, 2024).

Freshness Sensors (pH, gas indicators)

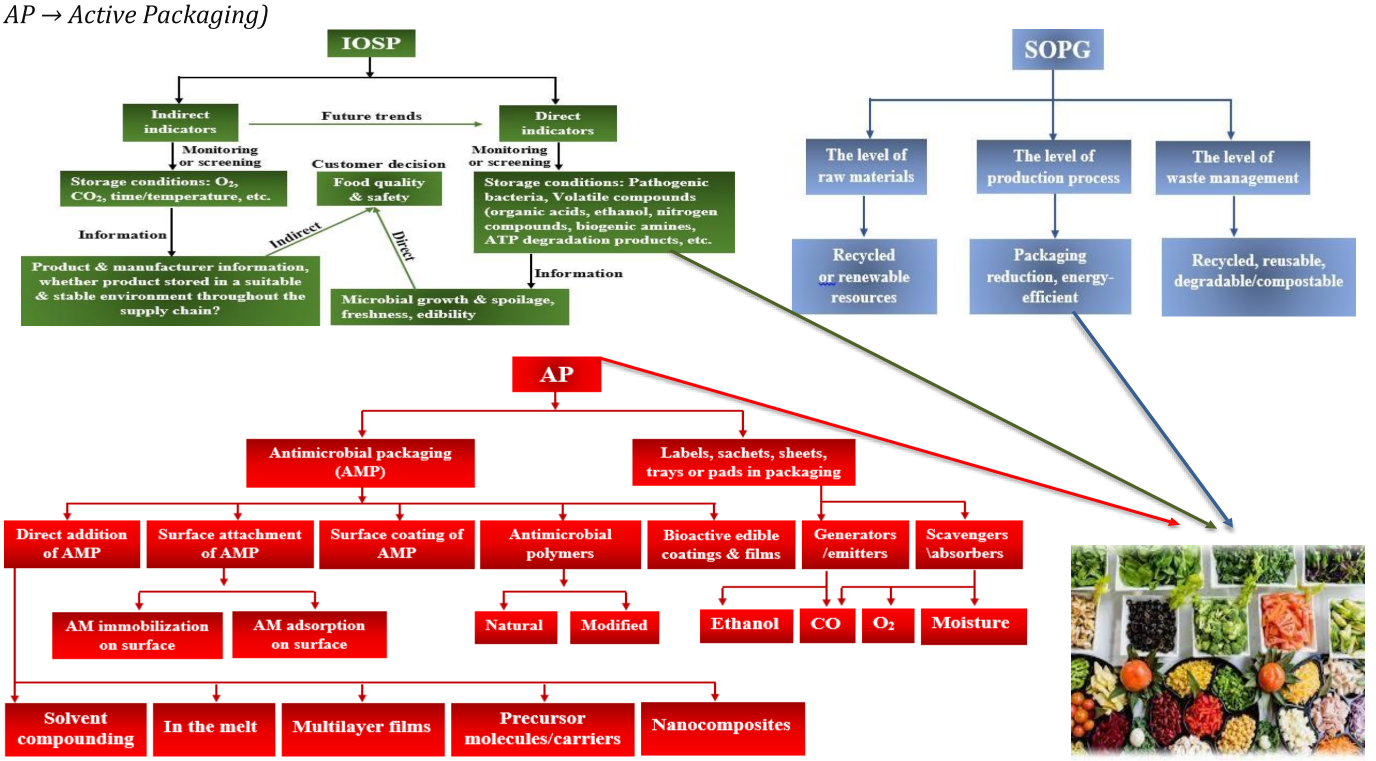
World hunger is deteriorating, with approximately one third of the world's produce going to waste and being left uneaten. Reducing food waste is crucial in promoting the sustainability of agri-food systems. Real time freshness monitoring through intelligent packaging, embedded with freshness indicators, can help reduce food waste caused by predetermined expiration dates and keep consumers informed about food safety concerns. Increasingly, biodegradable halo chromic films are being used as freshness indicators due to their minimal environmental impact (Yu et al., 2023). These indicators typically offer details, for instance, regarding the product's freshness level when packed, via a colour change that can be easily recognized by both the food distributor and the consumer. Most of the indicators in use today are non-renewable and made from non-biodegradable synthetic materials. Improving food packaging sustainability is essential, so sensor selection must also address this critical need. Bioactive extracts, such as anthocyanins, derived from a range of sources, like by-products of the food industry, have considerable potential to function as biosensors (Rodrigues et al., 2021). The incorporation of pH sensitive natural pigments into biopolymers has demonstrated promising prospects for smart packaging materials that are pH reactive. Natural pigments differ from synthetic ones in that they pose negligible toxicity risks to both humans and the environment while also exhibiting some nutritional and pharmacological benefits. Natural biopolymers have been found to be suitable options for developing smart packaging due to their biocompatibility, availability, biodegradability, stability, low toxicity, and ability to form good films. Packaged food quality is indicated by smart packaging in real time, through food deterioration indicators such as pH alteration (Ndwandwe et al., 2024). The development of indicators and sensors for smart packaging has been eagerly anticipated, particularly for gases associated with food spoilage and microbial development. However, the characteristics of indicators and sensors used in food packaging cannot be adjusted according to the specific food type, making it essential to select and apply suitable indicators and sensors for each type of food. Indicators and sensors for smart packaging are applied in forms such as films, labels, sachets, and devices. Detection methods employed by them encompass redox reactions, analytic binding, enzyme reactions, pH changes, electron transfer, conformational changes, and electrode reactions (Heo & Lim, 2024).

RFID and NFC for Traceability

There is increasing demand for low cost, portable, wireless, and passive detection systems for use in environment monitoring, food safety applications, and medical diagnosis. Implementation of Radio Frequency Identification (RFID) technology in the food industry as a smart label can enhance the tracking of food products, reduce spoilage, and guarantee food safety. The use of RFID technology in particular enables the development of battery free sensor systems, which also presents an attractive option for the use of sensing tags in smart food packaging. Wirelessly powered sensors using Near Field Communication (NFC) RFID enabled sensing can communicate wirelessly through inductive coupling. These tags or smart labels could decrease food waste by notifying the consumer or food supplier when a product is likely to spoil or has already spoiled, thereby assisting in addressing global hunger issues (El Matbouly, 2022).

Figure 4

Schematic Classification of Food Packaging (SOGP → Sustainable or Green Packaging, IOSP → Intelligent or Smart Packaging, AP → Active Packaging)



Nanotechnology in Food Packaging

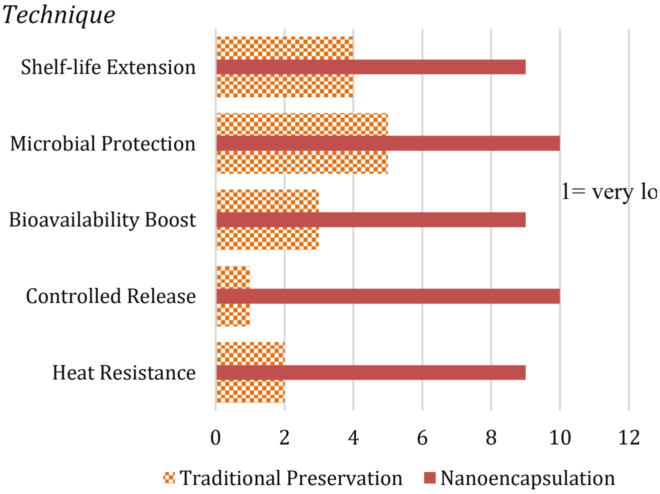
Nano-Composites for Improved Barrier Properties: Emerging promising solutions are nanomaterials, such as Nanoclays, metal oxide nanoparticles (e.g., ZnO, TiO_2), carbon based nanomaterials (e.g., graphene, carbon nanotubes), and biodegradable options like cellulose nanocrystals. These materials provide outstanding gas and moisture barrier properties, antimicrobial properties, and UV protection abilities. The review offers a comprehensive examination of different nanomaterials, showcasing their unique characteristics and the processes involved; including the tortuosity effects, which improve barrier performance by restricting permeability. The discussion also covers recent developments in incorporating nanomaterials into both flexible and rigid packaging systems, along with advancements in active and intelligent packaging that utilizes nanosensors for real time monitoring of freshness and spoilage (Mafe et al., 2024).

Nano-sensors for pathogen detection: The range of foodborne infections is constantly changing significantly over time, with well-established pathogens being brought under control or eradicated, and new ones arising. Foodborne diseases continue to pose a significant burden. The majority of these illnesses are not caused by pathogens that are already known, therefore more of them remain to be identified (Takhistov, 2009). Pregnancy test kits similar biosensors are being developed for the rapid, cost effective identification and quantification of pathogenic organisms. The tests are based on antibodies that can determine the presence of pathogens such as Campylobacter jejuni, Salmonella, Listeria, monocytogenes, and Escherichia coli. Bioanalytical microsystem, fabricated using nanotechnology, is observed to play a significant role in identifying pathogens in food (Patel et al., 2020). Biosensors that combine electrochemistry with nanomaterials have attracted significant attention for the detection and monitoring of pathogens. Electrochemical biosensors offer an exciting opportunity to conduct immediate and continuous pathogen detection for on-site risk assessment. Preparing food samples for pathogen detection and transporting them to the electrode surface can lead to the loss of the analytic. As a result, biosensors with advanced electrochemical properties based on nanomaterials should be designed to detect pathogens and their toxins in complex matrices without considerable interference. Detecting couplings with a microfluidic system for sample handling has significant potential (Bobrinetskiy et al., 2021). Nanoparticle-based sensors have greatly improved the rapid identification of contaminants such as Escherichia coli, Salmonella, and Listeria, providing higher sensitivity and specificity compared to conventional methods. Systems for smart packaging, which incorporate nanomaterials, offer real-time warnings for contamination and prolong shelf life by boosting their barrier and antimicrobial capabilities. Particles at the nanoscale, such as silver and zinc oxide, are being used more frequently in packaging to effectively restrict the growth of microbes. Methods of nano-encapsulation protect bioactive substances, such as antioxidants and antimicrobial agents, thereby ensuring their stability and controlled release, which in turn enhances food quality and safety heir stability and controlled release, which in turn enhances food quality and safety. The development of biodegradable nanocomposites and edible films provides environmentally friendly packaging options, which alleviate environmental concerns while preserving food integrity (Awlqadr et al., 2024). Currently, sensors with immobilized nanoparticles serve as spot indicators to enhance smart food packaging technology. Certain types of Nanobiosensors are deployed to monitor food product manufacture till packaging and to check the freshness of the product till spoilage identification. They are mainly using enzyme catalysts, which are highly sensitive to extreme environmental conditions. As a result, there is a greater evaluation requirement in nanosensor technology to adopt any temperature, pH, or other difficult parameters. Its stability, while in contact with food substrates, is another criterion that needs to be regularized (Guruprasath et al., 2024).

Nanoencapsulation for Controlled Release of Preservatives: One of the key uses of food nanotechnology is the nanoencapsulation of food additives. The technique of nanoencapsulation involves producing nanocapsules by enclosing core materials within a wall material. Food ingredients can be protected against degradation and interaction with other food components by using the nanoencapsulation technique. This method also aids in increasing the bioavailability of food ingredients by safeguarding them throughout the digestive processes, increasing uptake in the gastrointestinal tract, and facilitating transport to the target sites (Bratovcic & Suljagic, 2019). Several disadvantages arise when preserving food through conventional techniques. Nanoparticles containing active ingredients are said to boost both the effectiveness and shelf life of preservatives. The choice of materials for encapsulating active components should be non-toxic, biodegradable, efficient at binding active ingredients, cost effective, and resistant to changing environmental conditions such as high temperatures, humidity, and mechanical stress, while also possessing robust barrier properties. Nanoencapsulation is also effective at preventing the spread of contamination from microorganisms with a pathogenic nature in food (Das et al., 2020).

Figure 5

A Graphical Comparative Representation of Effectiveness of Nano Encapsulation vs. Traditional Food Preservation Technique



Smart and Interactive Packaging

- **QR Codes and Augmented Reality for Consumer Engagement:** Consumers today demand food packaging as equally significant as a product's brand. As a result, the rise in consumers' use of smartphones has prompted marketers to create new packaging designs. One of the most recent marketing trends is the emergence of smart packaging that incorporates QR Codes, which has the potential to significantly enhance the information available to consumers and shape their purchasing habits. Businesses can effectively impart timely and accurate information to consumers, thereby influencing their purchasing decisions positively, thanks to the adoption of QR Codes (Rotsios et al., 2022). The system can retrieve data embedded in a QR Code and display it in a 3D format, with the QR Code functioning as a conventional augmented reality marker. A significant benefit of QR Codes is their extensive information storage capacity, as well as their visual similarity to AR markers. Furthermore, the creation of more engaging and practical applications can be achieved by integrating the QR Code with the conventional AR system. A product's package features a QR code, which then displays a 3D virtual object upon it. This system enables customers to view the product through an even more direct and interactive interface (Kan et al., 2009). Augmented reality is considered to be one of the fastest growing and most promising trends in marketing (Kyguolienė & Braziulytė, 2022). Augmented Reality is a technology that enhances the physical world by adding virtual elements to it, making our physical world more interactive and engaging. AR has been applied to a variety of industries, including education, healthcare, and entertainment. The field of intelligent packaging, on the other hand, is expanding and uses a variety of technologies, like sensors and QR codes, to add value to packaging by improving their usability, convenience, and safety. By leveraging AR-enabled packaging, companies can create more engaging and interactive experiences for consumers, increase brand awareness, and differentiate their products in a crowded market. In addition, AR can provide valuable product information, gamification, sociability, interactive product demonstrations, and business cooperation opportunities (Yu & Zhang, 2023).
- **Self-Healing Packaging Materials:** Smart packaging can automatically repair the damaged area, restore the original properties, and prevent a decline in food quality and the loss of nutrients (Lai WF, 2023. Various materials based on different self-healing mechanisms have been developed and utilized on a laboratory scale in the form of coatings and films for food packaging. Additional efforts are required for the commercial application of these new self-healing packaging materials. Comprehending the self-healing mechanism of these packaging materials holds considerable importance for their commercial utilization (Wang et al., 2024). Food packaging materials are frequently and inconspicuously compromised during transportation, handling, and storage, and the breakdown of their integrity presents a challenge to food preservation. Packaging materials capable of self-healing can automatically restore damaged areas to their original condition, thereby preventing food quality from deteriorating and nutrients from being lost. Researchers have developed and tested self-healing materials that use dynamic covalent bonds or non-covalent interactions at the laboratory scale in the form of films and coatings for food packaging application (Huang & Wang 2023).

3D Printing and Customized Packaging

Currently, the food industry cannot afford intelligent packaging and point-of-use devices that monitor food quality and package integrity, as well as help authenticate food, due to the high costs associated with conventional fabrication methods, such as inkjet printing, gravure printing, and screen printing technologies. A significant obstacle is the accessibility and utilization of safe and food-compatible materials required to manufacture the intelligent components (namely, sensors, indicators, and tags) that track these parameters. Additive manufacturing, which includes stereolithographic and extrusion based 3D printing, has emerged as a cost-effective solution for fabricating these smart systems from materials considered safe and food friendly by internationally recognized food regulation agencies (Tracey et al., 2022).

Personalized Packaging Designs: Recent research has focused on the graphic design and packaging shape, separately examining their influence on a customer's decision-making process. The packaging's visual appearance is significantly influenced by its shape and graphic design, which draws the customer's attention. A product's packaging influences the customer's perception of it, indicating that packaging is a crucial element in promoting a product (Malešević & Stančić, 2021).

On-Demand Packaging Production: The majority of innovation in food packaging is driven by the creation of active and intelligent packaging technologies, which make it possible to provide safer and higher quality food products. Packaging that is active involves the inclusion of an active component within the package, with the goal of preserving or prolonging the product's quality and shelf life. The intelligent systems have the capability to keep track of the condition of packaged food, thereby furnishing information regarding the product's quality throughout transportation and storage processes. These packaging technologies can also work together synergistically to yield a multipurpose food packaging system (Drago et al., 2020). Presently, most food packaging systems are inanimate and fail to adjust to variations in the food environment as they occur. A smart packaging system that operates independently and without batteries has been developed, enabling wireless powering of closed loop sensing and the release of active compounds. This system combines a gas sensor for real time food monitoring, a Near Field Communication (NFC) antenna, and a controlled release of active compounds to prevent quality degradation in the complex food environment (Douaki et al., 2025). The basic responsibilities of packaging involve safeguarding the product, conveying product information, and assisting with transportation. As technology advances, dwindling resources, and a growing population necessitate additional responsibilities beyond the fundamental tasks of packaging, such as safeguarding the product's life and freshness, offering product details, expanding its usage capabilities, guaranteeing proper use, and maintaining environmentally friendly conditions. Sustainable, smart, and active packaging technologies are advancing in numbers every day. Functionalized packages are commonly used across the healthcare, food, and logistics sectors, as reported by (Verma et al., 2021).

- **Use of Food-Safe 3D Printing Materials:** Peanut hulls, also referred to as *Arachis hypogaea L.* particles (AHL), are a plentiful biomass source with a lengthy shelf life. Incorporating peanut hull powder into PLA polymer for 3D printing results in a material that is recyclable, biodegradable, and biocompatible, and also possesses antimicrobial properties due to the presence of AHL particles. Treat AHL particles specifically as a reinforcement for PLA polymer to create 3D printing filament that is compatible with the Fused Filament Fabrication (FFF) 3D printing method (Palaniyappan et al., 2025). Films made from a combination of plant- and animal derived proteins could integrate the best qualities of their respective domains, providing a vast potential for developing alternatives to plastics derived from petroleum (Alshehhi et al., 2024). This process involves layer by layer deposition of food materials to convert a three dimensional part model into a consumable product. This cutting edge food processing technology can improve food's acceptability, among other benefits, thereby advancing food security. Food printing has the potential to contribute to the SDG goal of Zero Hunger and Good Health and Well Being, due to the abundance of food materials that can be utilized as ingredients to fabricate 3D printed food. These ingredients also include food waste and climate resilient crops such as millet and legumes, which are now employed in 3D food printing to make valued added 3D printed edibles. In terms of printing technologies, extrusion printing is the most used technology in food printing because of its low cost, compatibility with traditional food materials, and simplicity in terms of equipment structure and operation. The other three technologies are only limited to powder form and low-viscosity materials as ingredients to fabricate intricate 3D food structures (Mudau & Adebo, 2024).

Table 1

Key Trends and Innovations in Smart, Interactive and 3D Printed Food Packaging

Packaging		Materials	Key Features	Outcomes	References
Sustainable and Eco-Friendly Packaging Materials	Edible Packaging	Protein and polysaccharide based films	Biodegradable, edible, food safe	Reduces plastic waste, safe for direct consumption	Alshehhi *et al.*, 2024
	Plant based and algae-derived packaging	Algae based and starch films	Renewable, biodegradable	Eco-friendly alternative to petroleum plastics	Mudau and Adebo, 2024
	Recyclable and Reusable Packaging	PLA composites, recycled bioplastics	Recyclable, compostable, durable	Promotes circular economy, reduces environmental Burden	Palaniyappan *et al.*, 2025

Active and Intelligent Packaging	Active Packaging	Oxygen scavengers (iron based, ascorbic acid)	Absorbs residual oxygen	Extends shelf life, delays spoilage	Verma *et al.*, 2021
		Antimicrobial agents (nano silver, essential oils)	Inhibits microbial growth	Improves food safety, preserves freshness	Lai, 2023; Huang and Wang, 2023
	Intelligent/Smart Packaging	Freshness sensors (pH/gas indicators)	Color changing films, real time signals	Enables spoilage detection and waste reduction	Drago *et al.*, 2020
		RFID and NFC tags	Wireless tracking	Improves supply chain traceability	Douaki *et al.*, 2025
Nanotechnology in Food Packaging	Nano Composites	Nano clay, nano cellulose, layered Hybrids	Improved mechanical and barrier properties	Enhances shelf life and reduces permeability	Wang *et al.*, 2024
	Nano Sensors	Quantum dots, nano gold	Detection of pathogens/spoilage indicators	Enhances food safety and quality control	Tracey et al., 2022
	Nano- Encapsulation	Chitosan based nanocarriers	Controlled release of antioxidants/preservatives	Maintains freshness without chemical overload	Alshehhi et al., 2024
Smart and Interactive Packaging	QR Codes and Augmented Reality (AR)	QR codes, AR platforms	Interactive product info, gamification	Improves user engagement and education	Rotsios et al., 2022; Yu andZhang, 2023
	Self- Healing Packaging Materials	Dynamic covalent/non-covalent polymer Systems	Autonomous repair of cracks upon stimuli	Maintains package integrity during storage/transport	Lai, 2023; Wang et al., 2024
3D Printing and Customized Packaging	Personalized Packaging Designs	3D printed structural components	Customizable shapes and branding	Enhances shelf appeal, consumer targeting	Malešević and Stančić, 2021
	On Demand Packaging Production	Additive manufacturing + NFC sensors	Real time monitoring, active compound release	Sustainability + smart packaging integration	Douaki et al., 2025
	Food Safe 3D Printing Materials	PLA with peanut hulls (AHL particles)	Biodegradable, antimicrobial, FFF compatible	Eco-friendly, functional filament for safe 3D printed packaging	Palaniyappan et al., 2025

ENVIRONMENTAL AND REGULATORY CONSIDERATIONS

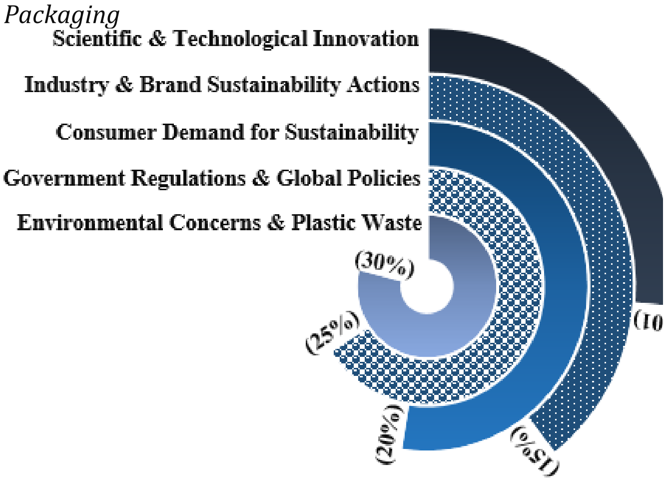
Life Cycle Assessment (LCA) of New Packaging Materials: The poor management of food packaging at the end of its life leads to a high volume of plastic waste, which has the potential to cause harm to wildlife and ecosystems. A key aspect of designing food packaging is reducing its environmental impact, which constitutes a substantial challenge for the industry (Bremenkamp & Gallagher, 2024). Life cycle assessment (LCA) can be used to assess the technical solutions used in the production process to determine the effects resulting not only from the production itself but also from the phases of use and end of life (EOL) issues that arise. The key components involved in the initial phase of LCA operation are shown. In the second phase of life cycle assessment, quantification of resource usage, material consumption, fuel usage, and energy consumption is required. Different packaging materials undergo unique life cycles that result in diverse environmental impacts throughout the supply chain and across various environmental metrics. The third stage of the LCA framework is the life cycle impact assessment, which focuses on assessing and understanding the environmental impacts identified through the LCI analysis (Salwa et al., 2021). Environmental friendliness is now a crucial requirement for packaging materials to remain competitive in the market. A Life Cycle Analysis (LCA) is an analytical tool that offers a framework for examining the environmental effects of products and services, essentially enabling the comparison of various products. LCA examines the use of resources and resultant emissions of pollutants on the environment throughout a product's entire life, from raw material exploitation to production, use, and treatment at the end of its life cycle recycling and final disposal (Šuput et al., 2022). Traditionally, life cycle assessments of food and beverage packaging have mainly concentrated on comparing the various packaging designs and arrangements, yet it is increasingly acknowledged that the LCA effect of the product itself, namely the food or drink, exceeds that of the packaging materials. Growing interest among multinational brand owner companies and retailers in implementing sustainable packaging strategies and systems is also driving a refinement in evaluation tools, metrics, and indicators (Brock & Williams, 2020).

- **Global Standards for Biodegradable and Compostable Packaging:** There is a growing need to create and manufacture environmentally friendly substitutes for food packaging. The significant environmental damage caused by the disposal of so called "single use plastics" is prompting the market to seek innovative solutions, and necessitates swift action from the scientific community, the industry, and government agencies to develop and implement new materials. Bioplastics comprise a class of materials that are partly or entirely manufactured from renewable resources. Certain bioplastics can biodegrade or be composted when certain conditions are met (Cruz et al., 2022). Research into biomaterials for sustainable food packaging offers a viable solution in addressing environmental concerns associated with conventional packaging materials. A range of alternatives for enhancing packaging sustainability are provided by metals and alloys, polymers, ceramics, and composite materials containing nanoparticles. These materials provide opportunities to decrease reliance on non-renewable resources, decrease pollution, and lower the ecological footprint of the packaging industry. Biodegradability, recyclability, and the use of renewable resources should be given priority in sustainable packaging solutions.

Moreover, incorporating cutting edge technologies such as intelligent packaging and sophisticated processing methods can enhance the effectiveness and performance of biomaterial based packaging (Al Mahmud et al., 2024). Eco-friendly packaging materials, including biodegradable plastics, compostable products, and recycled materials, are less detrimental to the environment than conventional packaging materials. They can help decrease the volume of waste in landfills and lower the carbon footprint of food packaging. A considerable number of consumers today are worried about the environmental effects of discarded packaging and tend to choose products packaged with eco-friendly materials. Food companies can foster brand loyalty and meet the demands of environmentally conscious consumers by adopting sustainable packaging methods. A multitude of countries and regions have implemented regulations mandating the use of sustainable packaging materials or have established targets for decreasing packaging waste. Single use and non-biodegradable plastics have a detrimental impact on the environment, leading to an increased emphasis on sustainable food packaging regulations worldwide. Several countries have introduced laws to reduce packaging waste and encourage environmentally friendly options. Frequently, the use of recyclable, compostable, or biodegradable materials is a common focus of these regulations, which may also require labeling and consumer education. Typically, the trend towards sustainable food packaging legislation is projected to persist, with an increasing number of countries and regions implementing policies to reduce waste and foster a circular economy. This is likely to prompt the development of new environmentally friendly packaging materials and encourage companies to employ greener methods (Thapliyal et al., 2024).

Figure 6

A Visual Representation of the Key Factors Influencing the Global Adoption of Biodegradable and Compostable Food Packaging



Future Perspectives and Challenges

- **Scaling up Sustainable Packaging Solutions:** Optimizing packaging systems through thorough consideration can help minimize food loss and waste. Five key issues were identified and categorized as follows: (1) collecting specific data on packaging functions that contribute to food waste; (2) evaluating the total environmental impact of products and packaging, taking into account the balance between product protection and environmental sustainability; (3) developing a better understanding of how packaging functions should be considered in environmental assessments; (4) refining packaging design processes to also focus on reducing food waste; and (5) examining the motivations of stakeholders to reduce food loss and waste. Packaging techniques that conserve food will be crucial to achieving the United Nations' Sustainable Development objective of reducing global food waste by half at the retail and consumer levels, as well as minimizing food losses throughout production and supply chains (Wikström et al., 2019). Pressure to develop more sustainable packaging solutions that meet both functional and circular design criteria has grown, compelling industries and academic researchers to respond due to the depleting fossil resources and increasing demand for plastic waste reduction. PLA, PHA, and whey proteins have been extensively researched as promising bio based polymers for packaging films and have been used in multilayer films or modified forms to enhance barrier properties (Eissenberger et al., 2023).
- **Cost-Effectiveness and Industrial Adoption:** Reducing packaging waste is essential to addressing the challenges of sustainable food consumption, particularly in minimizing the environmental footprint of pre-packaged foods worldwide. Sustainable packaging innovations aim to reduce food waste and losses by preserving food quality and addressing food safety concerns by preventing the spread of foodborne illnesses and chemical contamination. Additionally, these solutions must confront the persistent issue of plastic pollution, conserve natural resources such as oil and food, and support long-term environmental sustainability. To tackle global concerns regarding food and plastic waste, along with the disposal of durable materials, emerging strategies focus on developing resilient, waste based packaging systems. One promising approach involves the use of microbial biodegradable polymers derived from agro-food waste residues. These materials offer potential to reduce reliance on fossil fuels and support nutrient recycling back into the soil. Given the limited availability of effective tools for designing food packaging tailored to specific food needs, mathematical modeling based on mass transfer and reaction dynamics within food packaging systems presents a valuable opportunity. The next generation of such simulation tools is expected to assist the packaging industry in demonstrating the advantages of new materials and objectively selecting the most suitable packaging solutions. This will contribute significantly to reducing food waste and the accumulation of persistent plastic materials.
- **Integration of AI and IoT in Smart Packaging:** The incorporation of Artificial Intelligence (AI) into smart food packaging is revolutionizing the food industry. By utilizing

advanced AI algorithms, this cutting edge technology improves food safety, ensures quality control, and accurately predicts shelf life. Smart packaging systems, integrated with sensors and data analytics tools, allow real-time tracking of food status. This not only minimizes food waste but also enhances supply chain efficiency and increases consumer satisfaction. (MUSHEER et al., 2023). Biosensors and IoT enabled packaging dramatically improve traceability, reduce waste, and enhance supply chain efficiency though regulatory hurdles and consumer acceptance remain ongoing challenges (Rajan & Wani, 2025). In the food industry, innovative packaging solutions are increasingly important for reducing food waste and for contributing to global sustainability efforts. However, current food packaging is generally passive and unable to adapt to changes in the food environment in real-time (Douaki et al., 2025).

Potential Risks (Nanotoxicity, Biodegradation Limitations): The use of nanomaterials such as ZnO, TiO_2, silver, and silica nanoparticles enhances packaging properties but raises concern over nanoparticle migration and ecological accumulation. Chen et al. report emerging safety concerns with novel nanoparticles in food, urging toxicity evaluations (Ahmad et al., 2024). Toxicity uncertainties surrounding metal oxide nanomaterials, necessitating risk assessments and clearer regulation. Additionally, even biodegradable polymers like PLA may require industrial composting infrastructure to degrade properly; if not properly sorted, they can contaminate recycling streams or fail to degrade efficiently (Dubourg et al., 2024).

CONCLUSION

In response to increasing environmental concerns and consumer demand for safe, sustainable, and high performance food packaging, the industry is witnessing unprecedented innovation. From biodegradable materials and edible films to active, intelligent, and nanotechnology enhanced packaging systems, the focus is shifting toward solutions that extend shelf life, ensure safety, and reduce ecological impact. Technologies like RFID, TTIs, and AI-driven sensors are revolutionizing traceability and quality monitoring, while 3D printing and augmented reality are reshaping consumer engagement. However, widespread adoption is challenged by factors such as cost effectiveness, regulatory limitations, consumer trust, and infrastructure needs for biodegradation and recycling. To fully realize the potential of these advancements, a multidisciplinary approach involving policy reform, scientific research, industry collaboration, and public education is essential. Ultimately, the future of food packaging lies in harmonizing functionality with sustainability to support global food security and environmental stewardship.

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