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Sustainable Food Packaging: Recent Advances in Biodegradable and Smart Packaging Technologies

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Abstract

The recent increase in global plastic waste crisis, alongside the growing consumer interest in environmentally conscious solutions, has spurred an unprecedented surge in sustainable food packaging development. This review paper thoroughly discusses the recent developments in two interrelated areas: biodegradable packaging materials, such as polylactic acid (PLA), polyhydroxyalkanoates (PHAs), starch-based composites, and cellulose derivatives; and smart packaging technologies, including active, intelligent, and AI-based systems. The addition of nanomaterials and bioactive substances has enabled current biodegradable polymers to enhance their mechanical strength, barrier properties, and shelf-life. The ability to monitor the quality of food along the supply chain in real time has been made possible, thanks to smart packaging, time-temperature indicators (TTIs), freshness sensors, RFID, and QR-enabled traceability instruments. Additionally, the combination of AI and smart packaging is a paradigm shift in predictive shelf-life control and quality control. The main issues such as scalability, cost competitiveness, regulatory harmonization and consumer acceptance are evaluated critically. The review ends by identifying future researches that involve the models of circular economy, multifunctional bio-nanocomposites, and integration of digital and physical packaging.

Keywords: Sustainable packaging, biodegradable polymers, smart packaging, active packaging, intelligent packaging, PLA, PHA, nanocomposites, food safety, shelf-life extension

INTRODUCTION

Food packaging is an essential contact point between the food product and the outside world, which functions as the basic protection, containment, communication, and convenience functions. Traditionally, the food industry was dominated by the use of conventional plastic packaging materials, mainly polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS) due to their superior barrier properties, mechanical strength, transparency, and low cost. Nonetheless, environmental impacts of these materials have taken frightening levels. Plastics that are made using non-renewable fossil fuels are highly non-biodegradable; they remain in the environment over hundreds and thousands of years, and cause a lot of land and sea pollution [1, 2]. In recent years, global plastic manufacturing increased to more than 400 million metric tonnes per year, with food packaging having the largest share. Only less than 15 percent of plastic packaging is recycled worldwide, with the rest being burnt in the fire, discarded, or discharged into the environment. This structural breakdown has caused a waterfall of environmental effects such as

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microplastic pollution of food chains, soil erosion and greenhouse gas emissions. The world has seen a rapid increase in regulatory responses, with the Single-Use Plastics Directive of the European Union, the Plastic Waste Management Rules of India, and similar legislative frameworks establishing both regulatory and market incentives to go green with alternatives to plastics use [2, 3]. It is against this background that there are two key technological directions, which are biodegradable packaging materials based on renewable biological materials, and intelligent packaging systems, which combine active and smart capabilities to enhance food safety, limit waste, and increase the visibility of supply chains. The two realms are converging towards each other, creating multifunctional food packaging platforms that are both environmentally friendly and digitally conscious. It also showcases research on sustainable materials, nanocomposites use, and AI-based packaging systems and critically analyzes the issues at hand, safety, regulation, and future possibilities of enhancing food quality, shelf life, sustainability and consumer safety.

BIODEGRADABLE PACKAGING MATERIALS

Polylactic Acid (PLA)

The most commercially developed biodegradable polymer in food packaging is arguably polylactic acid. PLA, which is derived using fermented plant sugars, which are usually corn starch or sugarcane, has good optical clarity, rigidity, and printability and can therefore serve as a viable alternative to PET in packaging, including cups, trays, and clamshell containers. The glass transition temperature (approximately 55–60C) and somewhat moderate water vapor barrier properties of PLA have historically constrained its use in hot-fills or high-humidity environments. But these limitations have been greatly overcome, in recent innovations.The combination of PLA with polybutylene succinate (PBS), polybutylene adipate terephthalate (PBAT), and thermoplastic starch has provided better flex, impact strength, and break elongation in composite films. Stereocomplex PLA (sc-PLA), which is a product of 1:1 mixture of enantiomers of PLLA and PDLA, has a melting point that is about 50C above the normal PLA (~220C vs. ~170C), which greatly increases its processing temperature range. Plasma treatment and silica coating of surfaces have been shown to decrease oxygen permeation rates by 50 percent, making surface-modified PLA a contender to traditional multilayer films used to package fresh produce [4–6]. The market size of biodegradable plastics in the world was approximately USD 5.43 Billion in 2023 and is set to reach approximately USD 11.80 Billion in 2032 [7].

Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates are a group of naturally occurring polyesters that are produced by fermentation of organic wastes by microorganisms, including agriculture wastes and lignocellulosic biomass. Poly(3-hydroxybutyrate) (PHB), poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) and medium-chain-length PHAs are the most commercially important members. PLA, on the other hand, PHAs are actually biodegradable over a broad spectrum of conditions such as soil, compost, freshwater, and marine environments and are thus especially appealing to single-use food packaging when the probability of environmental release is high [8].

Having a better flexibility and a reduced crystallinity than PHB, PHBV has been used in fresh meat and cheese packaging films, showing oxygen permeability values comparable to low-density polyethylene (LDPE). Recent developments in metabolic engineering and synthetic biology have led to a very low cost of production; pilot-scale fermentations have been reported recently using waste glycerol and carbon dioxide feedstock, which further enhances the sustainability profile of PHA production. Bio based plastic package industries (including PHAs and other bioplastics) are expected to reach USD 2.86 billion in 2025 and USD 9.04 billion in 2031 [9].

Starch-Based Materials

One of the most common, cheap and entirely biodegradable packaging materials are thermoplastic starch (TPS). Starch, which is derived by using corn, potato, cassava and wheat, can be used to create films, foams, and coating using the right plasticizers like glycerol and water. The main drawback of starch based packaging is its strong hydrophilicity that makes it have low moisture barrier property and deteriorate mechanically in moist environments [9].

Much progress has been realized in combination of TPS with PLA, PHA, or synthetic polymers and in chemical modification such as esterification, etherification and cross-linking [4, 6]. Introduction of nanoclay, cellulose nanocrystals (CNCs), and graphene oxide in starch domains has produced nanocomposite films that have improved tensile strength up to 30120% and reduced water vapor permeability up to 60% relative to unmodified TPS. The most researched biodegradable nanocomposite system as far as food packaging is concerned is starch-clay nanocomposites. Additionally, addition of natural antioxidants and antimicrobials which include thymol, carvacrol and zinc oxide nanoparticles have made starch films functional active packaging materials [10].

Cellulose-Based Materials

The most common natural biopolymer today, cellulose, provides a highly versatile sustainable packaging material in various forms: bacterial cellulose (BC), cellulose nanofibers (CNF), cellulose nanocrystals (CNC), and regenerated cellulose films (including cellophane, Lyocell). The materials are very strong in tensile strength, have great film-forming capability and naturally biodegradable [3]. Wood pulp and cotton or agricultural residues are used to obtain cellulose nanocrystals that have outstanding mechanical properties (tensile modulus up to 150 GPa) and are utilized as reinforcement in biopolymer matrices. PLA and starch composites that are reinforced with CNC are always found to possess better water vapor and oxygen barrier properties. The bacterial cellulose of Komagataeibacter xylinus is a dense, pure nanofibrillar network that is highly mechanically stable and has been considered in transparent food packaging and edible coatings. Cellulose has been functionalized on its surface with silyl and acetyl groups to minimize hydrophilicity, but retain biodegradability. TEMPO-oxidized cellulose nanofibers have been shown to act as independent packaging films in terms of their gas barrier properties equal to those of ethylene-vinyl alcohol (EVOH) copolymers in the dry state [5–7].

Protein- and Lipid-Based Films

Whey, soy, gluten, zein (corn prolamin) and casein have been processed into clear, elastic films with better oxygen barrier properties than most synthetic polymers. Glycerol-plasticized whey protein isolate (WPI) films have oxygen permeability values of 0.43–3.5 cm3 -1 mm (m2 day day -1 kpa) that can compete with EVOH in low-humidity conditions. Zeins have been utilized to provide commercial coatings to nuts, confectionery and fresh produce to inhibit moisture loss and oxidative rancidity [11]. Lipid based films that include beeswax, carnauba wax and fatty acid derivatives have a better moisture barrier, but tend to be brittle with low tensile strength. Protein matrix/lipid dispersions Composite films Films made by a balance between water vapor resistance and mechanical performance Composite films, where the protein matrix is combined with lipid dispersions, are known as emulsion-based films. The addition of plant extracts with high levels of polyphenols (e.g., green tea extract, rosemary extract) to protein films also confers antimicrobial and antioxidant active packaging properties to them [12].

ACTIVE PACKAGING TECHNOLOGIES

Active packaging systems are not passive containment but rather interacts with the food or headspace around it in an active way to extend shelf life, preserve quality or enhance safety. These systems form a very crucial transition between traditional and intelligent packaging.

Antimicrobial Packaging

Antimicrobial packaging contains substances that prevent or slow down the proliferation of spoilage and pathogenic microorganisms on food surfaces or in headspace of the packaging. The agents used are organic acids (lactic acid, acetic acid), bacteriocins (nisin, natamycin), essential oil (thymol, eugenol, carvacrol), metallic nanoparticles (silver, zinc oxide, copper oxide), and chitosan. Silver nanoparticles can be considered as one of the most effective antimicrobial agents; its effect is due to the disruption of cell membrane integrity, DNA damage, and the production of reactive oxygen species (ROS) [13].

Chitosan is a particularly flexible antimicrobial packing substance because of its own antibacterial and antifungal effects, ability to form a film, and biodegradation properties, which are obtained by the deacetylation of the chitin shells of crustaceans. Chitosan films and coatings have demonstrated an increase in the shelf life of fresh strawberries, poultry and fish by 3–7 days at refrigeration. The latest advances involve the introduction of essential oil nanoemulsions to be incorporated into chitosan matrices to realize controlled release of antimicrobial compounds, greatly enhancing their effectiveness when compared to free essential oils [14].

Oxygen-Scavenging Packaging and Antioxidant

Lipid oxidation is a major cause of quality loss of lipid-rich foods like oils, nuts, meat, and dairy products. Antioxidant active packaging entails the addition of natural or synthetic antioxidants, including tocopherols, butylated hydroxytoluene (BHT), ascorbic acid, and polyphenols, into packaging films or sachets which are released to the food surface. Complementary protection is offered by oxygen-scavenging systems, which chemically or enzymatically absorb any remaining oxygen in the package headspace. Oxygen scavengers based on iron are also commercially popular with newer enzymatic systems based on glucose oxidase being cleaner in label appeal [2, 9–11]. A mature, though constantly developing active packaging technology, modified atmosphere packaging (MAP), which substitutes atmospheric air with controlled gas mixtures (usually CO2, N 2 and O 2 in food-specific ratios), is used to preserve food product quality and extend shelf life. The addition of MAP to oxygen-scavenging films has been reported to increase the shelf life of minimally processed fruit and vegetables 50–100% longer than when packed in air [12, 15].

Moisture Management Systems

The moisture control in food packages is essential to the food that is both prone to desiccation (baked goods, dried fruits) and to the microorganisms development triggered by condensation (fresh produce, cheese). Drying sachets of silica gel, zeolites or modified starches are commonly used and moisture-sensitive films with hygroscopic materials provide combined solutions. Hydrogel films based on humidity-adjustable gelatin hydrogel have shown good performance in the fresh produce packaging sector, where they could absorb and desorb moisture in response to relative humidity in the ambient environment, and could preserve good moisture levels without condensation [2–5].

INTELLIGENT AND SMART PACKAGING SYSTEMS

Intelligent packaging systems watch the state of packaged food or the surrounding environment and relay this data to the consumers or supply chain operators to enable dynamic shelf-life control and real-time quality assurance [16–24].

Time-Temperature Indicators (TTIs)

Probably the most commercialised intelligent packaging devices are time-temperature indicators. TTIs give a cumulative history of thermal treatment of a product taking advantage of the fact that microbial growth and biochemical deterioration reactions are temperature-dependent. Enzyme-based TTIs (e.g., Vitsab®) are based on a change in color due to a reduction of pH as a result of the lipase-mediated hydrolysis of triglycerides. Photochromic dyes in diffusion based TTIs (e.g., OnVu 001) have a temperature dependent bleaching rate. Microbiological TTIs use the mechanism of indicator through bacterial growth and the resultant metabolite generation [16].

Recent developments have seen the creation of TTIs based on biodegradable and food-safe materials. TTIs made with anthocyanin printed on cellulose substrates have been shown to give reliable thermal indications of abuse to chilled seafood, and their color transitions have been observed to cover the entire visible spectrum and can be easily read by smartphone cameras. With TTIs combined with RFID tags and cloud databases, real-time temperature tracking with automatic alerts in the cold chain is possible, which is a significant step forward compared to the traditional fixed expiry date labelling [17].

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Freshness Signals and Gas Detectors

Freshness indicators identify and signal alterations in biochemical indicators of food spoilage, such as total volatile basic nitrogen (TVB-N), the product of protein breakdown, CO2, respiration of microorganisms, and biogenic amines such as histamine and putrescine, the results of amino acid decarboxylation. The use of colorimetric pH indicators with natural dyes (anthocyanins red cabbage, purple sweet potato, butterfly pea flower) is especially promising due to their food safety, biodegradability, and wide color response (red at pH 23, yellow-green at pH 89) [7–12].

CO 2 and oxygen detection in modified atmosphere packages Optical gas sensors in packaging films have been developed CO2 and oxygen sensors in packaging for use in modified atmosphere packages. These sensors use optical fluorescent dyes or colorimetric reagents within polymer matrices, whose optical characteristics vary inversely with the concentration of gases. The future of intelligent packaging research is electrochemical sensors and biosensors that can detect a particular pathogen (e.g. Listeria monocytogenes, Salmonella) or toxin at part-per-billion concentrations, but the use of these sensors is still limited in cost and stability issues [18].

Traceability (RFID and NFC-enabled).

Near-field communication (NFC) and radio-frequency identification (RFID) tags in food packaging can facilitate digital communications in both directions between the package and the readers along the supply chain and at the interface with the consumer. At ultra-high frequencies (860960 MHz) RIFD systems allow multiple packages to be scanned without the need to see the package, significantly enhancing receiving, inventory control, and the efficiency of recalls in the distribution center. NFC tags that can be read by consumer smartphones enable the end-user to obtain real-time provenance information, allergen information, recipe recommendations, and disposal information- improving safety and consumer interaction [14, 15].

Low-cost RFID antennas and sensor platforms can now be produced on packaging substrates directly using silver nanoparticle inks and conductive polymer printing, since the development of printed, flexible electronics has allowed it to become cost-effective to deploy mass deployments. RFID systems with blockchain have been tested by large food corporations, such as IBM Food Trust collaborating with Walmart and Nestle, which offer immutable end-to-end records of traceability that greatly speed up the investigation of foodborne illness outbreaks [19].

NANOCOMPOSITES IN PACKAGING.

One of the most potent approaches to improving the mechanical properties, barrier properties, thermal properties, antimicrobial properties, and intelligent properties of traditional and biodegradable packaging materials simultaneously has been the incorporation of nanomaterials into the packaging matrices to create nanocomposites [8–11].

Clay and Silicate Nanocomposites.

The most researched nanofiller in food packaging is montmorillonite (MMT) nanoclay. When completely exfoliated and uniformly distributed in a polymer network, platelets of clay form a labyrinthine diffusion way of gases and water vapour and permeability changes considerably. At load levels of 2-5 wt% polymer-MMT nanocomposites have been reported to decrease oxygen permeability 50 75 percent and water vapor permeability 30 60 percent relative to the neat polymer. One of the early commercial applications of nanocomposites in food packaging was nylon-6/MMT nanocomposites which provided the proof of concept of this method [20].

PLA/MMT and starch/MMT nanocomposites have been shown to be able to deliver performance levels comparable to conventional plastics in biodegradable systems without losing compostability. Halloysite nanotubes (HNTs), an aluminosilicate nanoclay of tubular morphology, is a naturally occurring material that has received much recent interest as a multifunctional nanofiller that can enhance mechanical properties and be used as a controlled-release carrier of antimicrobial essential oils [16–19].

Metal and Metal Oxide Nanoparticles.

Silver nanoparticles (AgNPs) at concentrations of 0.1–2.0% in polymer films have been reported to exhibit a broad-spectrum antimicrobial effect against bacteria, yeasts and molds, and have been reported to reduce microbial counts by more than 4 log CFU/cm 2. One of the most promising alternatives to AgNPs is zinc oxide nanoparticles (ZnO NPs), which have antimicrobial properties and UV-blocking properties, allowing them to be used in photo-sensitive foods, and benefit from the fact that these nanoparticles have been declared as generally recognized as safe (GRAS) in the United States. Food packaging films with titanium dioxide (TiO2) nanoparticles are photocatalytic antimicrobial agents under UV and near-UV radiation, and are used in display packaging and retail stores [21].

Cobalt (II) oxide (CoO) nanoparticles have been shown to be remarkably antimicrobial, especially in antibiotic-resistant microbes such as methicillin-resistant Staphylococcus aureus (MRSA) and Escherichia coli O157:H7. Nevertheless, the threat of metal ion migration out of the packaging to the food stuff is a major regulatory and safety concern, and requires attention by designing barrier layers, as well as, by conducting stringent migration tests [22].

Carbon-Based Nanomaterials

Graphene and graphene oxide (GO) nanoplatelets in polymer matrices provide impressive mechanical strength, enhancement of gas barriers and conductivity. Graphene-PLA nanocomposites have shown tensile strength gains up to 40 percent at graphene loadings less than 1 wt. and corresponding gains in oxygen barrier which has been explained by the high aspect ratio of the graphene flakes which creates impenetrable barriers to gas diffusion. Electrical conductivity of graphene loaded films has been used in electrochemical sensing applications in smart packaging systems to allow passive barrier effect and active freshness sensing in a single functional layer [23].

Carbon nanotubes (CNTs) can provide equally remarkable mechanical properties but with more serious doubts concerning their possible cytotoxicity and regulatory risk, which have constrained their use in food contact materials.

AI AND DIGITAL INCORPORATION

Predicting Shelf-Life with AI

Smart food packaging is changing its operational capabilities due to artificial intelligence and machine learning. Machine learning algorithms such as artificial neural networks (ANNs), support vector machines (SVMs) and gradient boosting algorithms that have been trained on large sets of temperature profiles, gas compositions, and microbiological measurements can predict remaining shelf life with much higher accuracy than simple expiry date models. Combining ML algorithms with in-package sensor data sent with IoT connectivity can support dynamic shelf-life labeling, also known as so-called smart label systems, which dynamically update remaining shelf-life estimates in real time based on real-world product storage conditions instead of worst-case assumptions [24].

Research has found that AI-based smart packaging that allows dynamic shelf-life management can reduce food waste by 20–30% in the cold chain of retail stores by avoiding early disposal of securely and suitably preserved products. Moreover, AI-based quality prediction models have been used in optimizing MAP gas compositions to be applied to particular food commodities, allowing the use of personalized packaging guidelines to maximize shelf life and minimize gas usage [22–24].

Blockchain and Traceability

The IoT-enabled smart packaging, together with blockchain technology, provides the digital records of the complete life cycle of the product, farm-to-consumer, which are tamper-free. All nodes of the supply chain, including farm, processor, distributor, retailer, document verified transactions to a distributed ledger to form an immutable provenance record that consumers can view through QR codes scanning. The technology has been specifically useful in high-value and high-risk commodities such as fresh seafood, fresh-cut produce, infant formula, and organic-certified products, where the verification of the origin and handling conditions is both commercially and regulatorily important [24, 25].

Large-scale implementations have shown that blockchain traceability can cut down on the time needed to trace a foodborne illness outbreak by several times: 7 days to less than 2 seconds, which significantly enhances the response capabilities of the population. The most advanced modern implementation of smart packaging technology is the integration of blockchain, RFID, AI analytics, and smart packaging sensors into an all-encompassing digital food safety solution [26].

SUSTAINABILITY EVALUATION AND GREEN FACTORS

Life Cycle Assessment

The main instrument of objectively assessing the environmental impact of packaging materials over their lifecycle- the extraction and processing of raw material used and disposal- is the life cycle assessment (LCA). Biodegradable packaging materials have been examined over the years through LCA, which has yielded subtle results provoking naive ideas concerning the effectiveness of bio-based options. Although PLA continually beats conventional plastics in the aspects of fossil resource depletion and climate change impact, in other aspects, including land use, eutrophication and acidification, it might do worse, depending on the source of feedstock and agricultural management methods [9].

Waste streams, such as food processing effluents, agricultural residues, and CO2 released by industrial flue gases, yield PHAs that exhibit significantly improved overall environmental profiles as compared to those generated using virgin crops. The end-of-life route is especially crucial: industrial composting, anaerobic digestion, and mechanical recycling have their own environmental trade-offs, and the lack of proper composting facilities in most regions compromises the achieved environmental good of compostable packaging [6–9].

Regulatory Landscape

The rules and regulations surrounding sustainable and smart food packaging are changing at a very fast rate and there is a high degree of diversification in jurisdictions, which pose a challenge to manufacturers who want to access the global market. The Packaging and Packaging Waste Regulation (PPWR) of 2024 in the European Union has seen the imposition of mandatory recycled content quotas, recyclability and limits on unnecessarily packaged items, with the Framework of the Food Contact Materials regulation regulating migration limits of all packaging components including nanomaterials. The FDA oversees food contact materials in the United States by using food additive petition and GRAS notification system. The use of nanomaterials in food contact is still under consideration of case-by-case safety evaluation by the FDA and EFSA, and in line with this, there are guidance documents on migration testing requirements of nanocomposite packaging [27].

ACCEPTANCE OF THE CONSUMERS AND THE MARKET

A key factor in the commercial feasibility of sustainable and smart packaging innovations is consumer acceptance. Studies have repeatedly shown that consumers have very high stated preferences towards eco-friendly packaged foods, with surveys in the EU, North America, and Asia indicating that 60–80 percent of consumers would pay a premium to have their food products packaged in environmentally-friendly packages. Nevertheless, reality does not always follow intentions, that is, the so-called attitude-behavior gap, occurs due to the sensitivity to prices, uncertainty about the environmental statements (greenwashing), and a lack of knowledge about new materials [28].

The problem of intelligent packaging is a different issue: although the consumers are willing to receive real-time data about the freshness of products, the issue of data privacy related to NFC/RFID-tagged labels and the potential mistrust towards sensor-based systems to measure freshness levels needs to be addressed with the help of open communication and strict third-party assurance. The design of packaging is a key factor in consumer interaction; an easy-to-understand visual representation of smart packaging data by color-change indicators or smartphone apps is much more likely to be adopted than a complex numerical indicator of the same [2, 11–14].

DIFFICULTIES AND PROSPECTS

Technical and Commercial Problems

Although the prospects of sustainable and smart food packaging technologies are truly impressive, there are a number of significant obstacles to the large-scale commercial implementation of these new technologies. The most important obstacle is the cost-performance gap: PLA is already 2–4 times more expensive than similar fossil-based plastics on a per-kg basis, and PHA prices can be 5–10 times higher, and thus not economically viable to justify in most markets unless in high-end markets. Another important issue is processing compatibility; biodegradable polymers may need considerable adjustments of existing packaging equipment designed to handle traditional plastics, and this represents a huge investment by converters [29].

With nanomaterial based packaging, migration safety is a lingering issue that would need extensive migration testing in different food simulants and real food contact conditions, such as differences in temperature, time and pH. The absence of industrial composting infrastructure to realise the environmental good of compostable packaging creates a situation in which a large portion of compostable packaging is improperly disposed of, either in current plastic recycling streams or in landfills where it cannot be biodegraded due to anaerobic conditions [9, 10].

Future Directions

Sustainable food packaging is at the crossroads of digital technology, systems thinking, and materials science. The main research priorities are:

- Next-generation bio-nanocomposites Multiple reinforcing and functional nanofillers in a single biodegradable matrix to reach the same performance as multilayer conventional films [18].
- Self-healing packaging materials with microencapsulated healing agents, which autonomously heal mechanical damage and extend the useful life of packaging and reduce waste [13].
- Protein, polysaccharide and lipid-based edible coating and film applied on the surface of food, which removes packaging waste altogether in some types of food [9].
- Food safe conductive inks printed electronics to produce low-cost, flexible sensors and RFID antennas onto scale on sustainable packaging substrates.
- The integration of the circular economy Designing of a system of packaging to include clear material flows either closed-loop mechanical recycling, industrial composting, or anaerobic digestion of the initial design phase.

AI-accelerated material design, predicting the behavior of new biopolymer blends and nanocomposites in vitro, through machine learning and cutting discovery and optimization of materials development by many orders of magnitude.

CONCLUSION

Sustainable food packaging has ceased to be a niche environmental issue into a mainstream innovation requirement due to regulatory requirements, consumer demand and technological opportunity. Biodegradable materials, especially PLA, PHAs, starch based composites and cellulose derivatives, have reached a high level of technical maturity and nanocomposite reinforcement plans have narrowed most of the performance gap between them and conventional plastics. Active packaging technologies that add antimicrobial agents, antioxidants and gas scavengers have shown robust effectiveness in increasing food shelf life by 3–14 days in a variety of foods. Smart packaging systems that combine TTIs, freshness detectors, and RFID-blockchain traceability systems are shifting out of the laboratory proof-of-concept stage to commercial systems, made possible by the development of printed electronics and IoT connectivity. Artificial intelligence and smart packaging are the most disruptive near term opportunity, and they allow dynamic shelf-life control, predictive quality control, and logistics optimization of supply chains that collectively have the potential to save the world billions of tonnes of food each year of global waste. To achieve this possibility, it is imperative that concerted effort is put in material science, food technology, harmonization of regulations and developing infrastructure. Bio-based materials as a digital intelligence convergent in the next-generation sustainable food packaging system presents an attractive solution to developing food security, environmental sustainability, and consumer welfare simultaneously.

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