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Eco-friendly Biodegradable Packaging in the Food Sector: A Brief Overview

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ABSTRACT

The abstract provides an overview of environmentally friendly biodegradable packaging in the food industry. The summary explores key aspects such as the types of biodegradable materials utilized, their production processes and their pivotal role in addressing environmental concerns. By examining the food industry's reaction to biodegradable packaging, the abstract highlights the potential for mitigating ecological harm and fostering a more sustainable future.

Key words: Biodegradable, Degradation, Food industry, Packaging, Polymers, Properties.

In contemporary existence, polymers have become indispensable in daily activities owing to their numerous favourable characteristics and production convenience. Global plastic (thermoplastics, thermosets, elastomers, coatings and sealants and PP fibers) production reached approximately 400.3 million metric tons in 2022, reflecting a 1.6 percent increase from the year before. Asia is the world's leading region for plastic production, with China alone contributing 32 per cent of the global output in 2022. In recent years, China's monthly plastic production has ranged between six and 12 million metric tons. North America follows as the second-largest producer, accounting for 17 per cent of global plastic production in 2022 (Statista, 2024a). If plastic production continues to grow at an annual rate of 4%, emissions from plastics will triple to 6.78 gigatonnes by 2050 (Jones, 2024). Since its beginnings in 1957 with the production of polystyrene, India's plastics industry has expanded significantly, establishing itself as a major player in global production. With over 20,000 processing units, it contributes billions to India's economy and provides jobs for around four million people. India is also a key exporter, with polymer exports reaching approximately 1.5 million metric tons in 2021 (Statista, 2024b).

The petrochemical industry, excluding fertilizers, produces 63 per cent of all plastics, with more than a third of this output dedicated to packaging. Under a business-as-usual scenario, demand for oil in the plastics and petrochemical sectors is expected to double by 2050, resulting in emissions that would exceed the targets needed to keep global warming within 1.5°C. This growth is projected across all regions, with the highest increase in demand anticipated in China and developing Asian countries through 2050 (Zero Carbon Analytics, 2024). The top three sectors for plastics production are packaging, which accounts for 30-36%, followed by construction at 16% and textiles at 16-17% (Zero Carbon Analytics, 2024; Emami *et al.,* 2024). In 2020, plastic waste totalled approximately 460±22 kilotonnes, with around half of that waste originating from packaging (Emami *et al.,* 2024).

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Only 13% of plastic waste is recycled, while 46% is mismanaged, with the remainder either incinerated or discarded in landfills or the environment (Emami *et al.,* 2024). Nevertheless, synthetic plastics were incapable of undergoing physical, chemical and biological degradation, ultimately contributing to a rise in waste accumulation (Vert *et al.,* 2002). The accumulation of waste posed numerous significant environmental and health related challenges, manifesting in the obstruction of streets and roads, leading to the blockage of drains and subsequent overflow (Foolmaun and Ramjeeawon, 2012). A substantial volume of plastic waste is disposed of in oceans and rivers, causing harm to aquatic life. The incineration of plastic causes harmful petrol emissions to occur, including carbon dioxide, furans, chlorine, 1,3-butadiene, furans, carbon monoxide, amines and dioxin, *etc*., which degrade the excellence of air, heighten the global warming risk and poses numerous health concerns (Smith, 2005). The escalating challenges associated with waste disposal and the adverse effects on public health and the environment, stemming from an ability of many synthetic polymers to degrade, prompted global apprehensions, leading to intensified efforts worldwide to explore alternative materials with environmentally friendly attributes (Luckachan and

Pillai, 2011). Biodegradable polymers have surfaced as a *via*ble alternative strategy for several industrial applications aimed at mitigating the risks connected with non-biodegradable plastics. In accordance with the definition provided by the American Society for Testing and Materials (ASTM), A plastic is that which undergoes degradation due to the activity of naturally occurring microorganisms, including bacteria, fungi and algae (ASTM, 2004). Biodegradable polymers, which come from renewable resources, have water vapour transmission rates and oxygen transmission rates comparable to those of traditional plastics as PET (polyethylene terephthalate), PP (polypropylene), PE (polyethylene) and others, elongation at break and tensile strength (Kirwan and Strawbridge, 2003). The primary by-products of the breakdown of biodegradable polymers are carbon dioxide, water, inorganic chemicals, or biomass. This process is advantageous for the environment as it precludes the accumulation of waste. The primary utilization of biodegradable plastics was observed in the realms of packaging of food and agricultural sector. In food sector, packaging serves various functions (Song *et al.,* 2009).

Adoption of biodegradable materials

From 2012 to 2017, the use of biodegradable materials increased at a compound annual growth rate (CAGR) in the markets of North America, Europe and Asia which was between 15 and 20% (Chbib *et al*., 2019). However, comprehensive Africa's market data remains inadequately constituted (Atarés and Chiralt, 2016). The utilisation of crucial oils in the Spanish producers of biodegradable food packaging sheets aims to provide bio-based packaging with possible health benefits, such as antibacterial and antioxidant qualities. The packaging films' mechanical, optical and structural characteristics were improved by the lipidic makeup of essential oils, which also reduced the water vapour permeability in hydrophilic materials. Subsequently, biodegradable packaging films, developed and evaluated in Finland for preservation purposes, demonstrated an extension in the tomato fruit's shelf life (Kantola and Helen, 2007). A study conducted in Malaysia demonstrated gum arabic used as an edible covering film to improve the postharvest quality and extend the shelf life of tomatoes. Furthermore, starch-based edible coatings were applied, derived from native potatoes in Colombia to wild South American blueberries, or Andean blueberries, which led to a significant 27% decrease in respiration rate. However, previous research indicated that further study should focus on improving biodegradable films' physical strength to a degree equivalent to that of petroleum-based polyfilms (Ali *et al.,* 2010).

Biodegradable and biopolymer substances

Cotton fibres in South Africa, *Washingtonian filifera* in Algeria, *Luffa Cylindrica* in Nigeria, Napier grass in Botswana and *Hibiscus sabdariffa* in Kenya, Ethiopia and Uganda are among the countries that produce vegetable cellulose extracts are examples of biomass materials suitable for the production of both biodegradable and biopolymeric substances in Africa. Biopolymers like chitosan, cellulose and pectin have attracted a lot of interest from the scientific community as well as the food packaging production industry (Sanaa and Medimagh, 2019). Additionally, in Ethiopia, the pectin and chitosan extract-based film that was tested on tomatoes showed a 15 to 17 days shelf life, which was longer than the control group's shelf life of ten days. Furthermore, there are published findings from Nigeria that show a significant amount of biodegradable plastic film is produced there by combining biodegradable polymer ingredients with cassava starch. According to reports, the fresh tomato postharvest losses on the market the eastern part of sub-Saharan Africa, Central and Southern African countries were 9.50%, 9.80% and 10.04%, respectively. Notably, postharvest losses were documented in Kenya, South Africa and Nigeria at 10.10%, 10.20% and 13.40%, respectively (Sibomana, 2016). However, when recyclable cardboard boxes of various sizes, bulk bins, plastic crates and wooden crates were utilised for packing and shipping across the South African supply chain, postharvest losses among commercial or emerging tomato producers were decreased (Cherono and Workneh, 2018).

Food packaging films can be made from raw plastic polymers, biopolymers and biodegradable materials by techniques like lamination, casting, coextrusion or coating (Mathlouthi, 2013). Several foods packaging film were made of biopolymers, such as gelatin, starch, cellulose and bio-derived monomers like polylactic acid. Furthermore, substances produced by bacteria, include cellulose, xanthan, curlan and pullulan were utilized in the film production process. Chitosan, a natural polymer obtained through the chitin, the second most prevalent biopolymer in nature after cellulose, undergoes deacetylation, was also employed. Chitosan is characterized by being natural, non-toxic, edible and biodegradable. It is advised that various additives be added to the biodegradable film in order to improve its quality (Abdul Khalil *et al.,* 2018). Proteins and polysaccharides, two material components having hydrophilic properties, were added to stabilise edible biodegradable films. Drying was the next step in the film-forming aqueous dispersions casting process, also known as the coating process. During the dispersion process, essential oils were added to the film as additives and the mixture was homogenised or emulsified. As a result, the dried polymer, which included lipid droplets, formed the film's structural matrix (Atares and Chiralt, 2016).

The manufacture of biodegradable food packaging materials involves three generational stages of biodegradable polymers. The initial generation comprises 5 to 15% starch filters and autoxidative additives are included in low-density polyethylene (LDPE) film. Low-density polyethylene (LDPE), hydrophilic copolymer additives and 40 to 70% pregelatinized starch make up second-generation films. Third-generation materials are manufactured from biomaterials and can be divided into three categories: (a) biomonomers and polymers made from natural or genetically modified organisms; (b) polymers synthesised from bio-derived monomers, such as polylactate and (c) polymers extracted from biomass, such as starch, chitin, chitosan, plant proteins and soybeans. Nanocomposite materials have been recognised for their exceptional qualities, including their high performance, lightweight nature and environmental friendliness, were recognized as surpassing plastic food packaging materials (Youssef and El-Sayed, 2018). The cost-effectiveness, renewable nature and widespread availability of biopolymers represent key favourable considerations for thermoplastic starch-based materials utilized in food packaging (Khan *et al.,* 2017; Mayuri *et al.,* 2023).

Mechanisms involved in the preservation of savoury coatings

Fruit Deterioration in quality is closely associated with biochemical processes occurring within the cell structure, including changes in the composition of the intracellular components and the cell wall. Two significant cell wall hydrolase enzymes are cellulase and polygalacturonase, were found to be important contributors to have relationships with the softening and ripening phenomena in fruit (Lombardelli *et al.,* 2020). Fruits covered with edible coverings have the capacity to impede ripening by reducing the permeability of oxygen, leading to an elevation in intracellular carbon dioxide levels. Elevated carbon dioxide concentrations can inhibit the activities of cell wall hydrolase enzymes, thereby preserving fruit firmness throughout storage. This influence of a low oxygen environment has been effectively utilized to optimize storage conditions, transportation and extend the duration of the shelf life of various fruit commodities. Lower respiration rates in tomatoes with coatings may be a factor in the delayed ripening process, which would lead to fewer changes in physiological parameters as colour, titratable acidity, weight loss and firmness retention (Cukrov, 2018). The antimicrobial characteristics of edible coatings serve as a protective barrier for fruits, safeguarding them against agents that contribute to firmness degradation, such as insects and mites. Ripe tomato fruits might become softer and spoiled due to the fungal and bacterial spores carried by these vectors. Moreover, the use of biodegradable packing materials guarantees decomposability of fruits, such as tomatoes, facilitating soil microbial decomposition (Gharezi *et al.,* 2012).

Process by which biodegradable films degrade

Microorganisms found in soil can break down biodegradable materials into elemental molecules like carbon dioxide, water and methane. They can also produce monomers like alcohol, carboxylate acid and amine. The biodegradability of these materials is contingent upon factors such as chemical composition, bonding nature and water availability. The presence of specific peaks in the infrared spectra, particularly those associated with carbonyl signals, serves as an indication of the starch is broken down by enzymes into the disaccharide maltose and the monosaccharide glucose (Tai *et al.,* 2019). The primary mechanism of microbial activity is enzymatic. The microorganisms develop saprophytically, using plant metabolites as their substrates. Within this process, microorganisms secrete a variety of enzymes, including amylases and cellulases, which play key roles in the enzymatic hydrolysis and oxidative cleavage of glycosidic bonds present in starch and cellulose. Furthermore, labile aliphatic ester connections in plasticizing films are hydrolysed by extracellular enzymes such lipase, cutinase and esterase. These enzymatic activities result in the production of metabolites that microorganisms absorb to meet their energy requirements. The influence of these processes is demonstrated by the carbonyl signals in the IR spectra gradually decreasing and then disappearing over time (Bhatnagar *et al.,* 2018). The slow decrease in metabolites indicates that the saprophytic phase is progressing. UV radiation at wavelengths less than 350 nm has the ability to stimulate enzyme activity and cause chain scission in polymer molecules. Over the course of seven weeks, the simultaneous application of the cellulase enzyme and UV radiation led to the breakdown of 60% of cellulose acetate, surpassing the 23% degradation obtained with UV therapy alone. Thermal gravimetric Three-stage degradation profiles are produced by the biodegradation process, which is extensively characterised by thermogravimetric analysis (TGA). The loss of water and volatiles is the first stage; the synthesis of lower molecular weight starch subunits is the second; and the breakdown of the starch's constituent parts is the third (Tampau *et al.,* 2020). Biodegradable film degradation is dependent on a number of elements, such as temperature, sample surface area, crystallinity, molecular weight and microbial activity in water and soil (Table 1). Plasticizers that are hydrophilic also play a role. Plasticizers increase the amount of polar groups in the water, which accelerates their contact with it and their permeability to water in the samples. Biosurfactant plasticizers are highly active at the surface and interface, biocompatible and promote the biodegradation of soil hydrocarbons by lowering the interfacial tension between soil and water. A regulated fermentation technique that produced ideal pH conditions of 10 showed higher outputs of metabolites, including volatile fatty acids. Higher pH values might prevent acidophilic bacteria, which would limit the formation of metabolites. After being exposed to pulsed electric fields, films composed of zein, chitosan and poly (vinyl alcohol) exhibited enhanced durability against enzyme and electrolyte degradation (Giteru *et al.,* 2020).

Characteristics of biodegradable films

a) Characteristics of structure

The analysis of the chemical content and architectures of Fourier transform infrared (FTIR) spectroscopy and atomic force microscopy (AFM) were used in the packaging materials research (Hu *et al.,* 2018). The starch's crystalline and amorphous structures were assessed and quantified using the X-ray diffraction technique. The amylopectin molecule and crystallinity are intimately associated; amylose is primarily found in the amorphous lamellae of the starch granule, whereas amylopectin makes up the crystalline lamellae (Chisenga *et al.,* 2019). Dispersion properties, like how starch swells when plasticizers are present, are influenced by the degree of crystallinity. The common characteristic of the infrared (IR) spectrum is the way in which IR radiation and chemical bonds interact. The broad band observed in the infrared spectra of starch films was explained as the result of hydroxyl (-OH) groups' intra- and inter-chain vibrational str*etc*hing. Meanwhile, narrow bands were associated with the str*etc*hing of C-H bonds and peaks were linked to carbonyl (C=O) groups that were attached to the glucose ring. (Brandelero *et al.,* 2011).

Utilising scanning electron microscopy (SEM) and transmission electron microscopy (TEM), the researchers looked inside the surface microstructural of the film formations. PVA and starch films both showed smooth, homogeneous surfaces. The films' cross-section showed erratic, heterogeneous formations that looked like bubbles, with variations based on the crystallinity level. PVA and starch film mixes in particular showed signs of microstructure phase separation, which were explained by differences in the extrusion process, uneven crystallinity and inadequate miscibility. To mitigate phase separation in blended films, compatibilizer compounds like formaldehyde and poly (ethylene glycol) were introduced into the film blends (Vaezi *et al.,* 2019). The amount of phosphate and starch groups in the amylopectin chain is one of the elements influencing phase separation. Because the potato starch film has a higher phosphate group concentration than other native starches, it is noteworthy that it did not exhibit phase separation. The determination of film thickness using scanning electron microscopy (SEM) revealed that film blends exhibited greater thickness compared to pure starch films. These variations in thickness were explained by variations in molecular weight, where thicker molecules have a larger molecular weight. It is recommended for biodegradable edible packaging materials, whether coatings or films, to have a thickness below 254 μm (Liu *et al.,* 2020).

b) Characteristics of permeability

The researchers used transmission electron microscopy (TEM) and scanning electron microscopy (SEM) to examine, the polymer matrix must efficiently allow gases to move through. Water transfer between food and the environment has a significant impact on the shelf life and freshness of fruits and vegetables, including tomatoes. As a result, packaging's main purpose is to reduce water transmission. The hydrophilic nature of polysaccharides is the reason for the edible films' poor moisture resistance. Hydrophobic lipids improve the water vapour barrier qualities of films made of polysaccharides and chitosan. The entanglement of hydrogen bonding between the NH_2 group of chitosan and the OH group of plasticizers (*e.g.*, CAP and PVA) resulted in increased hydrophobicity of blended films (CAP/chitosan and PVA/chitosan), which led to a considerable sixfold reduction in the water transfer rate. The moisture permeability of biodegradable films was reduced upon the addition of silica nanoparticles. PVC, chitosan and silica can all be used to alter the oxygen permeability properties; this will rely on the product's respiratory requirements as well as the polarity of the components used in the packaging. The addition of silica to PVA/chitosan biodegradable films

Table 1: Application of diverse biodegradable films used in food sector.

Biodegradable film	Applicability for use	Reference
Polylactic acid (PLA)	Composite formation and laminating process	Nilsuwan *et al.,* 2020
Starch/PLA canna	Heat resistance of antimicrobial efficacy	Mania *et al.,* 2020
Chitosan	Covering, compatibility with biological systems, actions against cholesterol, ion sequestration functions and antimicrobial properties	De Queiroz Antonino *et al.,* 2017
Chitosan/PVA/PCL	Lamination and coating processes	Yar *et al.,* 2015
Chitosan-fungal	Microbial-resistant and oxidative defense	Koc *et al.,* 2020
Protein-lipid film	Enhancing water attraction	Lei *et al.,* 2007
Cassava starch/evan film	Consumable thin layer, protective, antioxidative, Anti-Inflammatory, anticancer, anti-HIV and blood sugar level moderating agent	Mantovan *et al.,* 2018
Ozone-starch film	Elevates the quantity of carbonyl and carboxyl functionalities	La Fuente *et al.,* 2020
Protein film	Linked through the action of transglutaminase	Tinoco *et al.,* 2020

resulted in a significant decrease in oxygen permeability values of about 26% (Yu *et al.,* 2018).

c) Characteristics of mechanical performance

To package cherry tomatoes, biodegradable polylactic films composed of polylactic acid and pea starch were created. However, compared to their petroleum-derived equivalents, these biodegradable polylactic films were shown to have worse mechanical qualities. Brittle films have been related to biopolymers such as starch. Hydrophilic plasticizers, such polyols (glycerol, sorbitol and polyethylene glycol), were added to the film-forming dispersions to reduce intermolecular pressures, which improved the polymers' extensibility and flexibility (Zhou *et al.,* 2019). The mechanical properties, such as strain, tensile strength and compression test and film-forming ability, are related to the amylose content and polymer crystallinity. These qualities are also influenced by the distribution of molecular weights and the concentration of additives. Because they create both intra- and intermolecular hydrogen bonds, plasticizing agents such as cellulose acetate phthalate (CAP) and polyvinyl alcohol (PVA) can change the mechanical behaviour of a material. PVA and starch combined to create a biodegradable film with improved mechanical properties. In comparison to pure chitosan film, a greater tensile strength was reported in the film blend consisting of chitosan CAP and nano ZnO. Increased interaction between the film's constituent parts is indicated by the higher tensile strength in film blends. Furthermore, as the concentration of the diblock copolymer increased, the films' tensile strengths showed an increase (Gomez-Aldapa *et al.,* 2020).

Varieties of biodegradable packaging

Films

Films represent a prevalent form of bio packaging across diverse sectors. Initially conceived as a substitute for PE film, biodegradable films were engineered with superior properties compared to non-degradable plastics (Balaji *et al.,* 2022). Essential attributes of a high-quality packaging film encompass:

- Facilitating regulated respiration.
- Possessing effective barrier properties.
- Sustaining structural integrity.
- Preventing or mitigating microbial spoilage.

A study was carried out to analyse the permeability of carbon dioxide and oxygen of the biodegradable film that is used to package tomatoes. The outcomes demonstrated that the fruit was able to breathe in the proper manner thanks to films with the best permeability, which kept microbes out and the fruit's quality intact (Muratore *et al.,* 2005). Applications for blown films include the manufacture of bags and different types of packaging. The base material for blown film production was polylactic acid (PLA), which showed exceptional mechanical and transparent qualities. A change in these films' degree of crystallinity influences their sealability property. For the creation of blown films, one biodegradable polymer is insufficient because of its low melting strength and delayed crystallisation. The polyesters are laminated using the co-extrusion technique. For instance, polymers like PHA and PHB are coated on thermoplastic starch (TPS) and blown into film during the coextrusion process. Avebe created ParagonTM, which is used in cheese packaging (Van Tuil *et al.,* 2000; Weber *et al.,* 2002; Ojha *et al.,* 2015).

Containers

Fruits, salads and vegetables can all be packaged in thermoformed trays or containers because these foods require a regulated environment to maintain their quality. The process involves the melt extrusion's polymer to create sheetsand subsequently, sheets are heated above the glass transition temperature point (Tg) and melting point (Tm) to assume a particular form (Pawar and Purwar, 2013). Most trays made of biodegradable polymers are moisture and brittleness resistant. When the tray freezes, its structural characteristics don't alter. Tropical fruits including mangoes and melons were kept fresh using oriented polylactic acid (PLA) trays. Fruits packed in these trays had a shelf life that was comparable to fruits that are arranged in PET trays (Chonhenchob *et al.,* 2007).

Foamed product

Starch-based foams are employed for loose-fill applications. A number of methods are used to produce foamed items, including expandable bead moulding, foam extrusion, loose-fill moulding and extrusion transfer moulding (Van Tuil *et al.,* 2000). Various foam-filled goods, such as trays and clamshells, derived from starch, find application in food packaging. However, coatings suitable for direct food contact are essential. Preferably, coatings made from Paraffin and other polymers are preferred over PLA and starch. An important factor is the adherence between the coating and the foamed product. The American-developed foam Novamontis a substance made of starch that finds use in a variety of packaging applications (Crow, 2020). The Landaal Packaging System invented Green Cell foam TM, a sustainable alternative to PP foams. Within four weeks, it completely degraded in a humid soil environment (Ibrahim *et al.,* 2022).

Biodegradation

Biodegradation is characterized as the transformation of microorganisms that help break down polymers into carbon dioxide, water, methane and biomass. The process by which polymeric materials biodegrades encompasses various stages, including.

• Biodeterioration

The fragmentation of the biodegradable substance happens as a consequence of the coordinated action of several abiotic stimuli and soil microbes.

• Depolymerisation

Enzymes are the main catalytic agents released by microorganisms. These agents cleave molecules to produce dimers, monomers and oligomers.

• **Recognition**

Certain broken-up dimers, monomers and oligomers can cross the microbial cell's plasma membrane thanks to the recognition of microbial receptors. Unidentified pieces persist within the surroundings outside of cells.

• **Assimilation**

Once inside molecules combine with metabolism in the cytoplasm to produce a range of primary and secondary metabolites, biomass and energy.

• **Mineralization**

Aldehydes and organic acids are two examples of metabolites that are secreted into the extracellular space by microbial cells. CO_2, CH_4, H_2O and other salts are released into the environment during this process (Lucas *et al.,* 2008).

CONCLUSION

In conclusion, the examination of environmentally friendly biodegradable packaging in the food sector underscores the significance of sustainable practices in addressing packaging challenges. The overview has illuminated the various aspects of biodegradable materials, their production and their crucial role in mitigating environmental impact. As the food industry continues to embrace eco-friendly alternatives, the implementation of biodegradable packaging emerges as a promising solution to reduce ecological harm and foster a more sustainable future.

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Disclaimers

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