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Reshaping food packaging through biodegradable materials, biopolymer films and sustainable innovations

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Abstract
As countries continue to develop and grow, concerns associated with conventional plastic packaging have accelerated the search for sustainable packaging alternatives. Awareness is rising about the harmful effects of microplastics, which can pose serious health risks to humans, animals, aquatic life, and the broader environment. To support a greener future, researcher and industries from various fields including food industry has embraced biodegradable packaging derived from renewable sources such as plants, animals, and microorganisms, offering an eco-friendly solution. These materials help preserve quality, safety and extend the shelf life of food products. Technological advancements, including nanotechnology, biopolymer engineering, and the incorporation of active agents, have enhanced the mechanical strength, barrier performance, and functionality of biodegradable packaging. Biodegradable packaging can be break down easily when disposed off in soil or water, reducing environmental impact by minimizing pollution, microplastic formation, and landfill accumulation. This article will provide an introduction to microplastics, describe common manufacturing processes for biodegradable packaging, Innovations such as nanocellulose, algae-based plastics, microbial bioplastics, edible films, and mushroom-based materials highlight the versatility and discuss the decomposition rates of biodegradable plastics. Such innovations contribute to achieving zero waste, with some materials offering the potential for recycling and utilization of agro waste.

Keywords: Packaging, microplastic, biopolymer, biodegradable packaging, nanocellulose, microbial bioplastics

Introduction
Packaging plays a critical role in preserving the quality, safety, and shelf life of food. Proper packaging safeguards products from physical, chemical, and microbial damage while also meeting consumer expectations for freshness and convenience (Alamri *et al.*, 2021) [2]. The core function of packaging is to shield food from external threats that could compromise its quality and safety. While designing food packaging systems, factors such as cost-effectiveness, material compatibility with the product, and preservation efficiency must be taken into account. An essential focus in packaging development is ensuring extended shelf life without compromising food safety. Common packaging materials in the food industry include paper, glass, metal, and plastics, while these materials have practical benefits; they also contribute significantly to environmental degradation. Addressing this requires sustainable strategies such as reducing raw material use, reusing packaging wherever possible, and increasing recycling efforts. Eventually, reduction minimizes energy and waste generation, while reuse prolongs the product life cycle. Recycling, although widely promoted, is often limited by the material type and degradation through repeated use (Marangoni *et al.* 2022) [26].
Modern packaging materials plastic, in particular, has become deeply embedded in modern life due to its low cost, light weight, durability, and flexibility. The International Union of Pure and Applied Chemistry (IUPAC) define plastic as a polymeric material often modified with additives for enhanced performance, plastic's global journey began in the late 19th century. Its usage has grown exponentially by 180 times between 1950 and 2018, with global production reaching 400.3 million tons by 2022 (Nayanathara *et al.*, 2024) [41]. The packaging

industry alone is responsible for about 141 million tons of plastic waste annually, much of which comes from non-degradable films and containers (Guo *et al.*, 2022) [17]. This accumulation of plastic waste contributes to widespread environmental issues, commonly referred to as "white pollution." Unfortunately, the qualities that make plastic so valuable also make it environmentally damaging.

Plastics, can pose health hazards due to the migration of chemicals. This migration occurs when small molecules from packaging components like adhesives, inks, or plastics transfer into the food. These compounds, under specific conditions, can introduce contaminants that degrade food quality and endanger consumer health (Seref, 2025) [34]. Migration can occur at various stages manufacturing, storage, transport, or during the food's use. Substances like dyes or odors may affect sensory qualities, while harmful chemicals can pose toxicological risks. Hence, regulatory oversight and improved material design are essential to prevent chemical migration and protect public health (Yenidoğan *et al.*, 2023) [39]. One of the most alarming consequences of plastic waste is its breakdown into microplastics and nanoplastics. These tiny particles spread easily through air, water, and soil, affecting wildlife and humans alike. Animals suffer from ingestion, injuries, reduced reproduction, and oxidative stress. Human exposure to microplastic is linked to cardiovascular issues, kidney disease, reproductive problems, and even cancer. This growing concern has prompted a push for sustainable end-of-life solutions like recycling, reprocessing, incineration with energy recovery, and land filling, with a strong emphasis on biodegradable alternatives (Nayanathara *et al.*, 2024) [41].

In response to the crisis, researchers have turned to Biodegradable packaging offering a compelling solution. These materials can mimic the desirable properties of traditional plastics while significantly reducing environmental impact especially in terms of carbon emissions. According to (Golden Eco, 2011) [15] through processes like industrial composting, biodegradable plastics can break down into water and carbon dioxide within 20 to 45 days, given the right conditions, humidity, oxygen, and microbial presence. As demand grows for sustainable, cost-effective alternatives, biodegradable packaging is being explored not just for its environmental benefits but also for its potential to reduce the burden on waste management systems and minimize pollution. The future of food packaging lies in materials that ensure safety, extend shelf life, and align with global sustainability goals.

Comparison of biodegradable plastic over conventional plastic

Table 1: Comparison of Biodegradable plastic and conventional plastic

Aspect	Conventional Plastic	Biodegradable Plastic
Source	Made from petroleum-based chemicals.	Made from renewable sources like Starch, sugarcane, or food / Agro waste.
Decomposition Time	Takes hundreds of years to decompose. Breaks into microplastics, harmful to health and environment	Breaks down in weeks to months under proper conditions. Degrades fully into Natural elements.
Environmental Impact	Causes long-term pollution, especially in oceans and soil. Incineration releases toxins	Has a lower environmental footprint. Composted under industrial or Controlled conditions.
Recyclability	Often recyclable but recycling Rates are low.	Not recyclable
Production Cost	Cheaper to produce at large scale.	Expensive due to raw materials, and low commercialization.
Durability	Highly durable and resistant to Degradation.	Less durable. However, Improve by blending with different biopolymers.
Health Impact	Leaching toxic chemicals causes carcinogenicity, endocrine disruption.	Natural Biopolymers contain bioactive compound, acts as neutraceuticals.
Customizability	--	Edible Packaging, Antimicrobial Packaging, Bioplastic etc…

What is biodegradable plastic?

According to the American Society for Testing and Materials (ASTM), biodegradable plastic is ''a plastic that degrades because of the action of naturally occurring microorganisms such as bacteria, fungi, and algae". They are produced from renewable sources and have similar properties (tensile strength, thermal properties, elongation at break, water vapor transmission rate and oxygen transmission rate) to conventional plastics like PET (polyethylene terephthalate), PP (poly propylene), PE (polyethylene), etc. Water, carbon dioxide, inorganic compounds, or biomass are the major products formed by the decomposition of biodegradable plastics (S. Shaikh *et al.* 2021) [33].

Biodegradable food packaging has been one of a number of new alternatives developed to counter the plastic waste problem. One promising approach for developing such biodegradable materials involves utilizing organic waste. Through targeted microbial pathways and metabolic engineering, waste carbon can be efficiently converted into platform chemicals such as lactic acid, succinic acid, muconic acid, and biopolymers like polyhydroxyalkanoates (PHAs) and bacterial cellulose (Jayasekara S. *et al.*, 2022) [21].

Furthermore, integrating polysaccharides, lipids, protein together into biodegradable film/ packaging significantly improves the mechanical strength, water resistance, and oxygen barrier performance of biodegradable packaging (Afzal R. *et al.*, 2025) [1]. Innovative biotechnological strategies, such as embedding essential oils, plant-derived components, and antimicrobial peptides into biodegradable films have been shown to extend food shelf life and reduce the risk of contamination. Additionally, Incorporation of, nanotechnology with antimicrobial and antioxidant agents into biodegradable film/ packaging can impart "smart" or "active" functionalities, enhancing their application potential. Driven by the need to lower environmental impacts and reduce dependence on fossil fuels, biopolymers are already widely applied in the food sector and are expanding into pharmaceutical and medical fields due to their unique functional properties (Baranwal J. *et al.*, 2022) [8]. The degradation of these polymers occurs primarily through enzymatic hydrolysis and other enzyme-catalyzed reactions, which break large polymer chains into smaller molecules. Under favorable environmental conditions, microbial activity completes the process, yielding non-toxic end products such as water, carbon dioxide, and biomass (Ali *et al.*, 2024) [3].

Biopolymers: Biopolymers are macromolecules formed by repeating units of identical or similar monomers. They can either be directly obtained from biological systems or synthesized using biological resources (Edo *et al.*, 2025) [16]. In the food industry, biopolymer-based packaging films are gaining attention due to their non-toxic nature and their ability to regulate the transmission of water vapor, oxygen, and fats. These features are essential for maintaining food quality, extending shelf life, and boosting the market potential of agricultural products (Ali *et al.*, 2024) [3]. One of the major advantages of biodegradable polymers is their ability to decompose under suitable environmental conditions, such as appropriate humidity, temperature, oxygen levels, and microbial activity. This degradation process does not release harmful residues, making them environmentally friendly. Depending on their origin, biodegradable and bio-based polymers are generally classified into three categories: natural, synthetic, and microbial biopolymers Fig. No.1 (Dirpan *et al.*, 2023) [14].

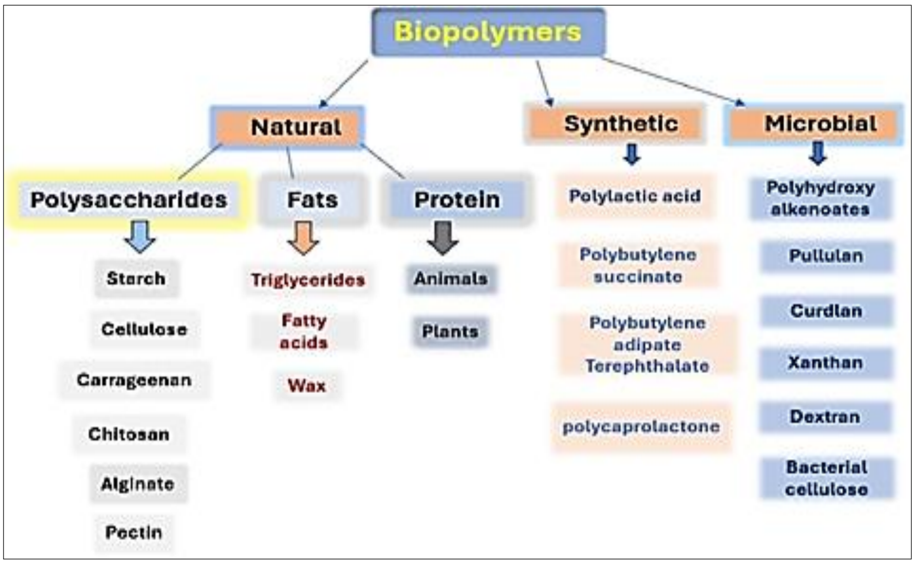

Fig 1: Biodegradable polymers classification (Ali M.Q. *et al.*, 2024) [3].

1. Natural biopolymers
These sourced are directly from nature, widely available, biodegradable, and non-toxic. They mainly include polysaccharides (e.g., pectin, cellulose, starch, chitosan), lipids (e.g., beeswax, resins, oils, fats), and proteins (e.g., casein, whey protein, soy, zein). Previous studies by (Chen *et al.*, 2019) [11] state that each category has unique advantages and limitations. For example, polysaccharides are low-cost, abundant, and easy to process but tend to have poor water vapor barrier properties due to their hydrophilic nature. Lipids, on the other hand, are hydrophobic and provide excellent resistance to water vapor but produce inelastic films, making them more suitable as coatings. Proteins stand out because of their strong film-forming ability, nutritional value, and superior gas barrier properties. Notably, soy protein-based films show oxygen permeability levels hundreds of times lower than those of methylcellulose, polyethylene, starch, and pectin. Protein-based films also outperform polysaccharide- and lipid-based films in terms of mechanical strength. Together, as composites, they can play a more effective role by improving the physical and functional properties of the film.

2. Synthetic biopolymers
They are chemically synthesized from biological monomers (Shaikh *et al.*, 2021) [33]. A common example is polylactic acid (PLA), an aliphatic polyester produced through ring-opening polymerization of lactide, which is itself derived from lactic acid obtained via fermentation of renewable resources like corn or sugar. PLA is sometimes also categorized under microbial biopolymers for this reason. Other examples include polyvinyl alcohol (PVA), a semi-crystalline polymer with mostly amorphous regions; polypropylene carbonate (PPC), produced through the copolymerization of CO_2 and propylene carbonate; and polycaprolactone (PCL), a semi-crystalline, low-cost, fossil-based polymer known for its biodegradability and ease of processing, though it takes about 9-12 months to degrade. These synthetic biopolymers generally exhibit strong mechanical and barrier properties.

3. Microbial biopolymers
They are produced by microorganisms, often with the help of genetic modification. A key example is polyhydroxyalkanoates (PHAs), which are polyesters synthesized by bacterial fermentation of sugars and lipids. PHAs are fully biodegradable, biocompatible, and derived from renewable feedstocks (Dirpan *et al.*, 2023) [14]. Their insolubility in water makes them attractive for food packaging, though they suffer from thermal instability. For instance, in polymers like poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), the melting temperature is higher than the decomposition temperature, which reduces molecular weight during high-temperature processing. Despite this challenge, PHAs can still be composted and processed with minimal adjustments to existing machinery, and hydrolytic enzymes can be used to support controlled degradation.

Manufacturing process for biodegradable packaging

Manufacturing process of biodegradable plastics uses combination of definite raw materials depending upon plastic to be produced. According to (Indpro.com.2022) [19] certain steps are common which involves the process of handling, mixing, extrusion and cooling. Pneumatic conveying systems and other bulk material handling systems are used as a starting point in the manufacturing of biodegradable plastics for the purpose of unloading and storing the raw material such as starch/ polymer pellets and additives used to make plastic. Second step include using certain technology of blenders for mixing and blending different ingredients in the plastic formulation, ensuring that the ingredients are evenly distributed and final product has the desired properties in the complete batch. Additionally uniformly blended raw material is then extruded and cooled to a desired shape through a pelletizer /molder. Finally Packaging and storage the final packing can be done using an automatic or semi-automatic machine to pack it into small bags or jumbo bags to dispatch.

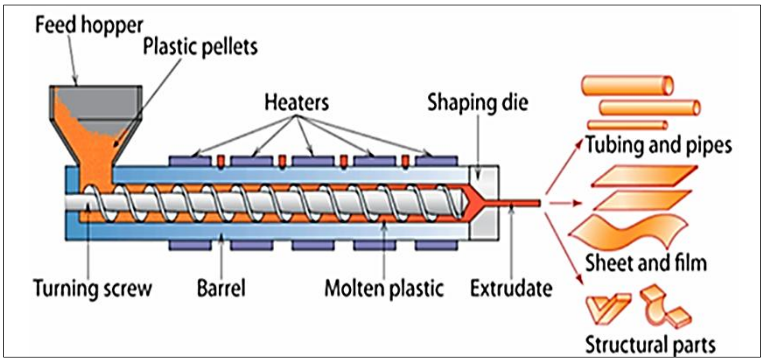

Fig 2: Mechanism of dry casting techniques (Prakoso *et al.* 2023) [30]

The basic idea behind Extrusion or dry process from the method by (Prakoso *et al.* 2023) [30] is illustrated in Figure 2. The polymer pellets are added in the hooper followed by compressing using a revolving screw, which facilitates uniform and homogeneous mixing. Plasticizer is added to enhance film flexibility and durability heat treatment is given for a specified amount of time at temperatures between 75 and 100℃. The heat and the rotating screw convert the mixture into a molten state that can be shaped into thin films. The screw speed must be carefully adjusted, as higher rotation rates can weaken the mechanical properties of biopolymers films. Once formed, the films require conditioning to enhance their quality, either by heating at 60 °C for two hours or by storing at 56.7% relative humidity for seven days. The advantageous of extrusion compared to wet casting, which needs about 12 hours of drying, extrusion offers a faster process, lower production cost, and the ability to manufacture a larger quantity of films, making it highly suitable for commercial applications.

Innovative advances of biodegradable packaging materials

1. Nanocellulose/Cellulose Nanofibers: Cellulose nanofibers (CNFs) are elongated fibers, typically several micrometers in length and 5-20 nm in width. While insoluble in water, they can be uniformly dispersed to form a viscous suspension. These fibers exhibit anisotropic physical properties, making them valuable in food packaging applications. CNFs can help extend food shelf life, preserve quality, and prevent spoilage by acting as an oxygen barrier. They also provide an eco-friendly alternative to polystyrene-based foams in packaging materials (Kouzegaran, 2022) [38]. Lignin's aryl ether (β-O-4) bonds can be oxidized to yield white-colored cellulose. For example, Nano cellulose derived from corn husks exhibits a particle size below 150 nm with a polyanionic surface charge. Additionally, cellulose films infused with eugenol have shown enhanced thermal stability up to 400 °C, along with promising antibacterial and antifungal properties (Chawla *et al.*, 2023) [31].

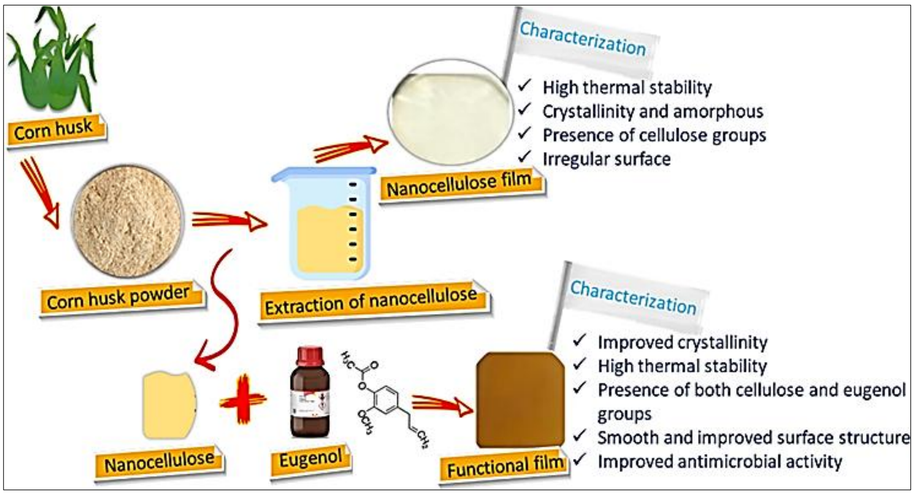

Fig 3: Nanocellulose (corn husk) -antimicrobial biodegradable packaging (P. Chawla *et al.* 2023) [31]

2. Algae-Based Plastics: Algae-based plastics are bioplastics manufactured from algae biomass a fast-growing, renewable resource that thrives in aquatic environments using sunlight and carbon dioxide. The harvested biomass is processed into polymers suitable for packaging applications. These plastics are fully biodegradable and can be used for compostable takeout containers, biodegradable produce packaging, single-use utensils, and eco-friendly wrapping for dry goods, offering a sustainable alternative to petroleum-based plastics (SGS Digicomply 2024) [40].

a)

b)

Fig 4: A. Environmentally Friendly Bottles Out of Seaweeds (AriJónsson.2016.cleanthesky.com) B. Bioplastics made from algae and seafood shells. (Natashah Hitti.2019) [28].

As indicate in Fig. no. 4(A) Environmentally Friendly Bottles from seaweeds developed by Ari Jónsson.2016 [5] state that the bottle can retain its shape and solidness while contain remains inside and when it gets empty. It can be consumed or eaten if person desired also the bottle begins to compose turning into natural waste mitigating environmental impact. Fig. no. (B) by. (Natashah Hitti.2019) [28] defines that the material for bioplastic consists of a mixture of vinegar and a biopolymer called chitin, from the exoskeleton of crustaceans and the cell walls of fungi. The material has been applied for anti-bacterial blister packaging, food-safe carrier bags and self-fertilizing plant pots.

3. Microbial Synthesis of Bioplastic: It is an innovative and sustainable biodegradable food packaging material synthesis by using certain microorganisms. de Souza *et al.* (2024) [12] state that microorganisms such as fungi and bacteria are capable of synthesizing a plethora of polymers, including polysaccharides, polyesters, polyamides and even polyphosphates, transforming food and agricultural waste. They are valued for being biodegradable, biocompatible and strong in both mechanical and chemical terms, which makes them wide-ranging applications in packaging, cosmetics, pharmaceuticals, medicine and agriculture. Two most used Bioplastic Synthesis by Microbial are:

3.1 Polyhydroxyalkanoates (PHAs): PHAs are a family of microbial polyesters produced by bacteria such as *Cupriavidus necator* and *Pseudomonas putida*. Through genetic modifications, these microbes can achieve high polymer yields. PHAs offer excellent mechanical strength and durability, making them suitable for medical devices and food packaging while remaining biodegradable (Atarés *et al.*, 2024; Indpro.com, 2022) [6, 19]. Bacteria convert the fatty acids or other precursors into polymers through enzymes like PHA synthase. These polymers accumulate as granules inside the cells and can later be extracted as bioplastic. Their yield depends on factors such as nutrients, temperature, and pH, and the exact pathway varies with the microorganism and type of PHA produced (S. M. BHATT. 2023). Furthermore, previous research showed that, when PHA was blended with zein a good barrier property film was obtained. There was an increase of 39-48% and 27-35% was seen in the water vapor permeation coefficient and oxygen permeation coefficient respectively (S. Shaikh *et al.* 2021) [32, 33].

Fig 5: A. PHA Sustainable Packaging (Carla Colwell. 2025) B. PLA Flexible films (Hyfpack.com.2025) [10, 18]

3.2 Polylactic Acid (PLA): PLA is produced via the fermentation of agricultural waste by *Lactobacillus* species and is considered one of the most environmentally friendly biopolymer production methods. Derived from renewable resources such as corn starch and sugarcane, PLA is biodegradable, compostable, and widely used in the food industry as an alternative to petroleum-based plastics (Awasthi *et al.*, 2022; Hyfpack.com, 2025) [18]. PLA has become one of the most widely used biodegradable and renewable, thermoplastic biopolymer across sectors such as packaging, agriculture, and the automotive industry. It is typically produced through microbial fermentation, where sugars from renewable resources are converted into lactic acid and then polymerized to form PLA (S. M. BHATT. 2023) [7, 32].

4. Edible Packaging: Edible packaging is an innovative, eco-friendly solution made from biopolymers including polysaccharides, proteins, and lipids. It can either be applied directly as a coating on food or shaped into standalone films and wraps. Coatings are applied in liquid form, whereas films are prepared separately and then used to encase food. This approach not only reduces waste but can also enhance product preservation (Janowicz, 2023) [20]. Chitosan-based edible film was developed by reinforcing pomegranate peel extract. With different concentrations by (Kumar, *et al.* 2021) the work demonstrate that pomegranate peel extract in chitosan film holds indispensable potential for the increase in biological activities in terms of antioxidant and antimicrobial behavior.

Fig 6: Edible films and Edible cups (designwanted.com & qz.com)

5. Mushroom-Based Packaging: Mushroom-based packaging is created from mycelium, the root-like structure of fungi composed of fine white filaments. Mycelium rapidly grows and binds agricultural residues such as corn stalks or husks into a strong, moldable material. The resulting packaging is fully biodegradable and compostable, breaking down naturally within weeks without releasing harmful residues (Kumari, 2025) [27]. By product like Tableware, Packaging box, bags can be obtain, which helps in serving and packing of food product. Mushroom-Based Packaging is making entry into several industries gaining interest due to its sustainable packaging solutions. As a consequence, Scientists are finding new ways to make Mycelium materials stronger and more versatile (SGS Digicomply 2025) [40] Researchers in Japan create a clean extract "mycelia pulp" a fine mycelium fibers from mushroom using sunlight to bleach the fibers and gentle ultrasonic treatment, making paper-like or leather-like materials for flexible packaging formats. Another study mixed oyster mushroom mycelium with pineapple leaf fibers, producing a stronger and more water-resistant reducing brittleness and moisture sensitivity.

Fig 7: Mushroom-Based Packagin (Shweta Kumari 2025) [27].

Decomposition of biodegradable product

Biodegradable packaging derived from bio-based sources has gained significant attention due to its ability to decompose naturally, reducing environmental impact. For instance, Polyhydroxyalkanoates (PHAs) represent a versatile family of naturally occurring biopolymers that serve as carbon and energy reserves in microorganisms. They are fully biodegradable not only in industrial composting facilities but also in soil, freshwater, and marine environments, a property shared only with starch-based plastics. For instance, PHA-based bottles can disintegrate in soil within two months, yet remain intact during use until disposal Fig. 8A (Diederik van der Hoeven.2016) [13].

Other composite biodegradable films have also shown promising potential. Fig. 8B blends of (1) polylactic acid (PLA) with crude palm oil (PV), (2) glycerol with crude palm oil (AV), and (3) PLA, glycerol, and crude palm oil (PAV) have been formulated and studied for their structural and functional properties. Among these, the PAV film exhibited the highest thermal stability, with 50% decomposition occurring at 330 °C. Its biodegradability was confirmed using soil burial tests and microbial culture assays, where microorganisms used the film as a carbon source. (Krishnamurthy *et al.* 2019) [24] In another study, (Shanbhag *et al.* 2023) [36] evaluated the rate of biodegradation in different film formulations over 22 days.

Fig 8: A. Biodegradable PHA bottles (Diederik van der Hoeven. 2016). B. Biodegradable films (Krishnamurthy *et al.* 2019 [13, 24]

Results showed that "Film C" degraded faster than the other variants, highlighting the importance of assessing biodegradable films across various environmental conditions, such as soil, to understand their complete ecological impact.

Challenge in biodegradable packaging material

Although biodegradable packaging material has various advantages, problem still exist. Biopolymers Packaging are generally more expensive due to raw materials, manufacturing and processing technologies. However successful implementation can overcome this challenge. Besides, it can degrade under heat, moisture, or UV exposure, limiting Storage and transport stability. In response research and scientist are coming up with blending different biopolymers along with active ingredients. Other challenges like Consumer Acceptance Issue as Innovative packaging like edible packaging may face hesitation or rejection due to unfamiliarity, Infrastructure Limitation and Performance Trade-offs as it May not always match the properties such as mechanical strength, flexibility and barrier properties.

Conclusion

Packaging plays an essential role in maintaining food quality, safety, and shelf life, yet conventional plastic packaging poses significant environmental and health challenges. The development of biodegradable packaging offers a viable and sustainable packaging alternative, combining functionality with reduced ecological impact. Advances in materials science, biotechnology, and nanotechnology have enabled the creation of biodegradable films and containers with enhanced mechanical strength, barrier properties, and active functionalities, while still allowing safe decomposition under appropriate conditions. Innovative solutions such as Nano-cellulose, algae-based plastics, microbial biopolymers, edible films, and mushroom-based materials demonstrate the potential to replace petroleum-based plastics in diverse applications. As the industry moves toward eco-friendly materials, careful consideration of production processes, cost-effectiveness, and performance will be essential to ensure widespread adoption. Additionally, collaborating with industry will significantly assist in advancing biodegradable plastic technology. Ultimately, the future of food packaging lies in systems that protect product integrity, extend shelf life, and align with global sustainability goals while minimizing harm to human health and the environment.

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