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BEYOND PLASTIC: HOW BIODEGRADABLE PACKAGING CAN TRANSFORM FOOD PRESERVATION

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Abstract

The growing use of conventional plastic packaging has created environmental challenges, particularly because many plastic products persist in the environment after disposal. Biodegradable packaging offers a promising approach to reducing plastic waste while supporting food preservation. Materials derived from starch, cellulose, chitosan, proteins and microbial polymers can be developed into films, coatings, trays and containers. These materials have potential applications in meat, dairy products, fruits and vegetables by helping control moisture loss, oxidation and microbial deterioration. Recent advances in active packaging and freshness-monitoring labels are further expanding their applications. However, limitations related to cost, mechanical strength, moisture resistance and disposal infrastructure must be addressed before widespread adoption. This article highlights the major biodegradable packaging materials, their applications in the food industry, emerging technologies and opportunities for sustainable packaging in India.

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Keywords: Biodegradable packaging, food preservation, edible films, active packaging, dairy products, meat products, sustainability

Introduction

Think about the packaging discarded after eating a packet of snacks, buying paneer or ordering a takeaway meal. The food may be consumed within minutes, but its plastic packaging can remain in the environment for a much longer period. This contrast highlights one of the major challenges facing the modern food industry: how to protect food effectively without creating an ever-growing burden of packaging waste.

Packaging is essential for maintaining food quality and safety. It protects products from contamination, physical damage, moisture loss and oxidation while facilitating transportation and storage. However, conventional petroleum-based plastics are widely used because they are lightweight, inexpensive and durable. These same characteristics can become environmental disadvantages when packaging is discarded and persists in the environment.

Biodegradable packaging is attracting attention as a potential alternative. Made from materials derived from biological resources or produced by microorganisms, these packaging systems can be designed to break down under suitable conditions. They may also help preserve perishable foods, creating opportunities to address two important challenges simultaneously: packaging waste and food loss (Shaikh et al., 2021; Panou and Karabagias, 2023).

What Is Biodegradable Packaging?

Biodegradable packaging consists of materials that microorganisms can break down into simpler substances under appropriate environmental conditions. Depending on the material and the conditions, the process may produce water, carbon dioxide, biomass and, under oxygen-limited conditions, methane.

Three terms are particularly important:

- Bio-based packaging is made partly or entirely from biological resources, such as plants or other renewable feedstocks.
- Biodegradable packaging can be broken down by microorganisms under suitable conditions.
- Compostable packaging meets specific requirements for degradation and the quality of the resulting compost under defined composting conditions.

These terms are not interchangeable. A plant-derived package is not necessarily biodegradable, and a biodegradable package may not decompose quickly in ordinary soil, a landfill or a home compost heap. Its

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actual environmental benefit depends on the material, its intended use and the waste-management facilities available.

Nature's Materials: Building Blocks of Sustainable Packaging

1. Starch and cellulose from plants

Starch, obtained from corn, wheat, rice, potatoes and cassava, is one of the most widely investigated materials for biodegradable films. It is renewable, relatively inexpensive and capable of forming films that can be used in selected food-packaging applications.

However, starch films can be brittle and sensitive to moisture. Researchers are improving their flexibility and strength by combining starch with other polymers, plasticisers and reinforcing materials.

Cellulose, the principal structural component of plant cell walls, is another important resource. It can be obtained from wood, fruit peels, cereal bran and agricultural residues such as sugarcane bagasse. Cellulose-based films can offer useful mechanical properties and barriers to gases and oils, depending on their formulation.

Using agricultural by-products to manufacture packaging may also create value from materials that would otherwise be discarded. This approach supports more efficient use of resources and encourages the development of a circular bioeconomy.

2. Chitosan from natural sources

Chitin occurs in the shells of shrimp and crabs, as well as in certain other organisms. Chitosan, produced by processing chitin, is an important material for developing biodegradable films and edible coatings.

Chitosan-based packaging is particularly interesting because certain formulations exhibit antimicrobial activity. When appropriately formulated, these films may help control microbial growth and delay quality deterioration in perishable foods.

Their performance can be improved by incorporating selected plant extracts or essential oils. Nevertheless, the effectiveness of such films depends on the formulation, food type and storage conditions; they cannot replace good hygiene or appropriate refrigeration (Panou and Karabagias, 2023).

3. Proteins from milk and other sources

Milk proteins, including whey proteins and casein, are valuable ingredients for biodegradable films and edible coatings. Gelatin, collagen, soy protein, wheat gluten and corn zein are also being investigated for food-packaging applications.

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Protein-based films can provide useful barriers to oxygen and may help reduce oxidation in foods containing fats. Whey protein films, for example, have been studied for protecting fish and dairy products, while zein films have applications in selected confectionery and nut products.

Their main limitation is that many protein-based films do not resist water vapour sufficiently well. Combining proteins with lipids or other polymers may improve their performance and broaden their applications.

4. PLA and microbial polymers

Polylactic acid (PLA) is a bio-based polymer produced from lactic acid, commonly obtained through fermentation of carbohydrate-rich feedstocks. It can be processed into cups, trays, films and containers using techniques similar to those used for conventional plastics.

Polyhydroxyalkanoates (PHAs), on the other hand, are polymers produced by certain microorganisms. They have attracted interest because of their potential biodegradability and suitability for selected packaging applications.

Both PLA and PHAs offer promising opportunities, but their properties, manufacturing costs and degradation behaviour differ. In particular, PLA does not necessarily decompose rapidly in ordinary environmental conditions; suitable industrial composting conditions may be required for certain products. The correct material must therefore be selected according to the food's requirements and the available disposal system.

How Can Biodegradable Packaging Preserve Food?

Protecting meat and meat products

Meat is highly perishable because of its moisture content, nutrient composition and susceptibility to microbial growth and lipid oxidation. During storage, these processes can affect its colour, flavour, texture and overall quality.

Edible films and coatings can help reduce surface moisture loss and oxygen exposure. Some formulations also incorporate antimicrobial substances that may help control microbial growth.

An example comes from research conducted by Soni et al. (2018), who evaluated edible films containing oregano and thyme essential oils for chicken patties stored under refrigeration. The treated products showed lower microbial counts and lower indicators of lipid oxidation than untreated controls, with acceptable

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quality reported during the study's storage period. This illustrates how a biodegradable film can serve not only as a physical covering but also as a carrier for food-preservation ingredients.

Such findings are promising, although the results of individual studies should not be interpreted as a universal shelf-life guarantee. Product composition, processing, packaging conditions and temperature control remain important.

Extending the quality of dairy products

Dairy products such as paneer, cheese and other fresh milk products can deteriorate because of moisture loss, oxidation and microbial spoilage. Biodegradable films and edible coatings may help maintain their quality by regulating the movement of water vapour and gases.

Cellulose-based films containing suitable antimicrobial agents have been investigated for controlling yeast and mould growth on cheese. Whey protein-based coatings and films containing selected essential oils have also been studied for dairy applications.

For example, an appropriate edible coating may help paneer retain moisture during refrigeration, while a protective film for cheese may reduce surface drying and help control spoilage organisms. These approaches are particularly relevant to products that require careful storage and have a limited shelf life.

However, packaging must be compatible with the food and must not compromise its sensory properties or safety. Any antimicrobial ingredient must also be suitable for the intended food-contact application.

Preserving fruits and vegetables

Fresh fruits and vegetables continue to respire after harvesting. They may lose moisture, soften, change colour and become susceptible to microbial spoilage during storage.

Starch-, cellulose- and chitosan-based coatings can help regulate moisture and gas exchange, potentially slowing certain quality changes. The coating must be carefully designed, however, because excessively restricting gas exchange may adversely affect the product.

These applications demonstrate that biodegradable packaging is not limited to replacing a plastic wrapper. In suitable forms, it can become an additional tool for maintaining food quality and reducing avoidable losses.

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From Simple Wrappers to Smart Packaging

Modern packaging research is moving towards systems that do more than simply contain food.

Active packaging incorporates components that help preserve food, for example by reducing oxidation or controlling microbial growth. Suitable natural extracts and essential oils may be incorporated into selected biodegradable films to provide these functions.

Intelligent packaging provides information about the condition of food through indicators or sensors. A label that changes colour in response to chemical changes associated with spoilage is one example.

In a 2024 study, Chen et al. developed a biodegradable chitosan- and whey protein-based label using colourimetric and fluorescent signals to monitor shrimp freshness. Such technologies could help make changes in food condition easier to identify and may support better decisions during storage and distribution.

Nevertheless, freshness indicators must be properly validated. A colour change alone does not establish that food is safe to eat, and packaging sensors should complement rather than replace appropriate food-safety practices.

Another promising development is the use of agricultural residues such as fruit peels and plant fibres to produce packaging materials. Research into waste-derived films and bio-based composites could help reduce dependence on virgin raw materials while creating additional value for agricultural and food-processing by-products.

Opportunities for India

India's extensive agricultural base and expanding food-processing sector provide opportunities to develop packaging materials from locally available resources. Cassava, cereal starches, sugarcane bagasse, fruit-processing residues and other plant-based by-products could serve as raw materials for films, coatings and moulded packaging.

Indian manufacturers are also exploring plant-fibre-based packaging for food service and takeaway applications. Such initiatives demonstrate the potential to connect agricultural resources with packaging innovation.

However, replacing conventional plastic on a large scale will require more than developing a biodegradable material. Packaging must be affordable, sufficiently strong, suitable for food-contact use and compatible

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with commercial processing and distribution. Collection, segregation and appropriate composting or other disposal facilities are equally important.

Research institutions, food processors, packaging manufacturers and policymakers can contribute by developing materials suited to Indian food products, testing their performance under local storage conditions and evaluating their overall environmental impact.

Challenges: Is Biodegradable Packaging Always Better?

Despite its promise, biodegradable packaging faces several limitations.

First, many natural-polymer films are sensitive to moisture or have lower mechanical strength than conventional plastics. This can restrict their use for foods requiring high protection during transportation and storage.

Second, manufacturing costs may be relatively high because of raw-material processing, specialised production methods and limited production capacity. Improving performance while maintaining affordability remains a major research priority.

Third, consumers may confuse bio-based, biodegradable and compostable packaging. If a product is discarded in an unsuitable environment, it may not degrade as intended. Clear labelling and appropriate waste-management infrastructure are therefore essential.

Finally, the environmental performance of packaging should be assessed across its life cycle, including raw-material production, manufacturing, transportation, food preservation and disposal. A packaging material should not be considered environmentally superior solely because it is biodegradable. Its ability to protect food and reduce food waste must also be considered.

The Road Ahead

The future of biodegradable packaging lies in combining sustainability with practical performance. Research into polymer blends and bio-nanocomposites may improve strength, flexibility and resistance to moisture. Active packaging could help slow spoilage, while intelligent labels may provide useful information about food quality.

Greater use of agricultural residues and microbial production systems may also expand the range of available materials. For India, the key priorities are to reduce production costs, establish reliable performance and safety standards, and strengthen appropriate collection and disposal systems.

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Conclusion

Biodegradable packaging offers promising opportunities to reduce dependence on conventional plastics while supporting the preservation of meat, dairy products, fruits and vegetables. Materials derived from starch, cellulose, chitosan, proteins and microbial polymers can be developed into films, coatings and containers suited to different food applications. Emerging active and intelligent packaging technologies may further improve food preservation and freshness monitoring.

However, biodegradable packaging is not a universal solution to plastic pollution. Its success depends on appropriate material selection, food safety, affordability, demonstrated environmental benefits and suitable disposal conditions.

The goal is not simply to replace one wrapper with another, but to develop packaging that protects food while reducing its environmental footprint. With continued research, responsible manufacturing and effective waste management, biodegradable packaging can become an important part of a more sustainable food system.

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