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Novel Strategies Based on Bioactive Compounds And Biopolymer Coatings To Prevent Food Losses: A Sustainable Approach

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Abstract

Food wastage is a critical global issue, exacerbated by population growth and shifting consumption patterns. Despite advancements in sustainable food production, nearly one-third of all food crops produced are wasted, severely impacting environmental sustainability, economic stability, and public health. This wastage is particularly detrimental to farmers in underdeveloped nations, where spoilage leads to significant income losses. Food degradation occurs throughout the supply chain due to several factors such as high moisture content, poor storage conditions and microbial activity. The widespread use of chemical agents in agriculture and food industries raises concerns about environmental and human health risks, necessitating sustainable alternatives. Plant extracts, rich in bioactive compounds with antimicrobial and antioxidant properties, offer a promising natural approach to food preservation. Extracts from rosemary, clove, and thyme, among others, have shown potential in preventing spoilage, extending shelf life, and enhancing nutritional content. Additionally, emerging innovations such as nanotechnology and biopolymer coating provide further opportunities for sustainable food preservation. This review examines the causes of food spoilage, the efficacy of plant-based bioactive compounds, and novel preservation technologies, emphasizing the need for eco-friendly strategies to mitigate food waste and enhance global food security. By promoting sustainable food preservation, we can reduce environmental impact and support a more resilient food system.

Keywords: food wastage, post-harvest losses, phytoextracts, bioactive compounds, biofilms

1. Introduction

The rapid growth of the world's population has boosted food demand, prompting concerns about food deterioration and waste. The United Nations survey predicts that the world population will reach up to 9.7 billion by 2050, emphasizing the need for global food supplies. Despite developments in sustainable food production practices, over one-third of all food crops produced globally are lost or wasted, indicating a significant inefficiency in the food demand and supply system. This problem is detrimental in developing countries, where post-harvest losses have a direct impact on farmers' livelihoods, contribute to the country's economic instability, and worsen food poverty. Smallholder farmers, who frequently lack access to proper storage and transportation facilities, are extremely sensitive to food spoiling, which can drastically diminish their revenue and prolong cycles of poverty [1].

Degradation of food happens at multiple stages, from post-harvest storage to consumption, and is influenced by factors such as excessive moisture content, microbial contamination, enzymatic activity, and ineffective preservation measures. Furthermore, consumer behaviors such as over-purchasing and inappropriate home storage contribute greatly to food waste at both the retail and consumption levels. Foodborne infections, particularly in

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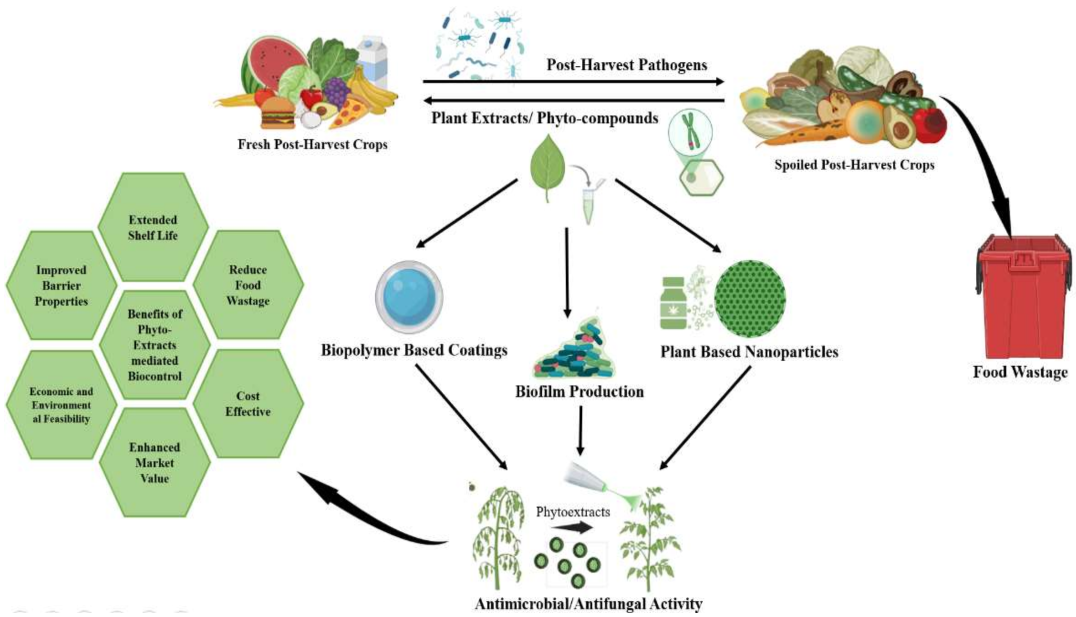

Fig. 1: Graphical Abstract illustration showing methods of plant extract application and benefits

developing countries, are a serious public health concern, with pathogenic bacteria including *Xanthomonas campestris* and *Fusarium spp.* playing important roles in post-harvest food contamination and deterioration. These microorganisms can cause a variety of ailments, from moderate gastrointestinal distress to serious, life-threatening infections, emphasizing the significance of good food preservation techniques [2].

Heat treatment, irradiation, modified atmosphere packaging (MAP), and chemical preservatives are all standard ways for preventing spoiling and extending shelf life. Heat treatments, such as pasteurization and sterilization, effectively kill or inactivate spoilage bacteria, but they can also degrade the nutritional and sensory properties of food products. Irradiation involves exposing food to ionizing radiation in order to destroy bacteria, molds, and insects, although there are issues about safety and customer acceptance. MAP alters the gaseous composition of food to delay respiration and reduce microbial growth, but it necessitates specialized packaging and precise atmospheric control. Chemical preservatives, such as synthetic antioxidants and antimicrobials, have been widely used in agriculture and the food industry, yet their long-term use raises environmental and health concerns, including microbial resistance, toxicity, and possible links to allergic reactions and endocrine disruption. These disadvantages have boosted the demand for safer, natural alternatives in food preservation [3].

Plant-based antimicrobials have emerged as appealing natural preservatives due to their bioactive components, which contain antimicrobial and antioxidant activity. Extracts from diverse plant components, such as leaves, stems, roots, and seeds, include bioactive substances such as essential oils, phenolic acids, flavonoids, alkaloids, and terpenoids, all of which have antibacterial and antioxidant properties. These phytoextracts have been shown to reduce food spoilage-causing bacteria, providing a sustainable and health-conscious method of food preservation. Furthermore, numerous

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unknown plant extracts could give unique methods for minimizing food spoilage, increasing shelf life, and improving food quality in an environmentally friendly way. Exploring these underutilized botanical resources could result in novel solutions for eliminating food waste and strengthening global food security[4].

This review focuses on the potential of plant-based extracts, the use of biopolymer-based coatings, and the formation of biofilms in food preservation. It analyzes their advantages over traditional chemical preservatives and proposes future research options in this area. This study aims to improve ecologically friendly and health-conscious techniques to minimize food waste and enhance global food security by encouraging the long-term use of plant extracts and biopolymers.

2. Causes of Food spoilage

Maintaining global food security is a challenge, given that food production ought to grow by 70% to meet the demands of projected 9.7 billion people by 2050. A major contribution to food security is post-harvest loss, including degradation of food quantity and quality from harvest to consumption. Reducing these losses in an effective and eco-friendly way would improve food security and give high returns. This food loss mostly occurs in the production, storage, and processing stages due to poor infrastructure, lack of technology and poor handling. The Food and Agriculture Organization (FAO) evaluates that post-harvest losses account for approximately 14% of global food production, representing a substantial waste of resources and economic value[5], [6]

Across India, millions of tons of cereals are lost annually. In Africa, 50% loss happens in perishable crops and dairy. In Europe, the UK wastes 6.7 billion tons of food yearly and in the USA, 30% of food is discarded annually. The post-harvest losses can be prevented at various stages including harvesting (loss due to improper maturity index, rough handling), Pre-harvest drying, transport (Poor infrastructure and lack of refrigerated transport), post-harvest drying, threshing, storage (Inadequate hygiene, pest-management), processing (limited technology for processing) and marketing [7].

The post-harvest losses can be prevented at various stages, including:

- **Harvesting:** Losses due to improper maturity index and rough handling can be minimized by implementing proper harvesting techniques and training farmers on optimal harvesting practices.
- **Pre-Harvest Drying:** Ensuring proper drying of crops before storage can reduce moisture content and prevent microbial growth.
- **Transport:** Poor infrastructure and a lack of refrigerated transport contribute to spoilage during transportation. Investing in improved infrastructure and refrigerated transport systems can significantly reduce these losses.
- **Post-Harvest Drying:** Adequate drying of crops after harvest is essential for preventing fungal contamination and spoilage.
- **Threshing:** Efficient threshing methods can minimize damage to grains and reduce losses during processing.
- **Storage:** Inadequate hygiene and pest management in storage facilities lead to significant losses. Implementing proper sanitation practices and pest control measures can prevent spoilage and protect stored crops.
- **Processing:** Limited technology for processing results in inefficiencies and losses. Investing in advanced processing technologies can improve efficiency and reduce waste.
- **Marketing:** Inefficient marketing systems can lead to spoilage and losses. Improving market access and distribution channels can help reduce food waste at the marketing stage.

Fruits are exceedingly susceptible to spoilage due to microbial contaminations, leading to economic losses and potential health hazards. Primary spoilage agents such as

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bacteria (*Xanthomonas campestris, Erwinia, Corynebacterium*) and Fungi (*Fusarium spp., Aspergillus spp., Cladosporium spp.*) enter the plant tissues through wounds, mechanical injuries and chilling damage causing toxic metabolite production, pectin degradation, lipid breakdown or protein degradation[8], [9].

Among these, *Xanthomonas* and *Fusarium* are two significant microbial threats to fresh fruits and vegetables. *Xanthomonas* is a bacterial pathogen that primarily causes leaf spots, blights, and wilting in crops. They usually spread through contaminated water, soil and plant debris. Similarly, *Fusarium spp.* is a fungal pathogen producing mycotoxins causing food spoilage. They usually contaminate potatoes and other underground crops by producing toxins such as diacetoxyscirpenol and deoxynivalenol. These mycotoxins not only adversely affect crops, they also cause carcinogenic and neurotoxic effects in humans. Table 1 highlights the different crops affected by *Xanthomonas spp.* and *Fusarium spp.* They are linked to detrimental yield and quality making them a major concern for crop production.

Effective control measures including proper field treatments, crop rotation, and storage under controlled conditions is required to control their growth and spread for proper agricultural and post-harvest practices [29].

3. Effect of Medicinal Plant Extracts in Post-Harvest Disease Management

Medicinal plant extracts provide bioactive secondary compounds demonstrating significant antibacterial and antifungal properties against *Xanthomonas spp.* and *Fusarium spp.* These major postharvest pathogens cause crop diseases, food contamination, yield losses, leading to food insecurity and high food costs. Even though several synthesis bactericides and fungicides are available in the market, they have negative environmental and health effects. In order to mitigate these negative effects, medicinal plant extracts provide a promising alternative. Choice of solvent also plays a crucial role in extraction efficiency with different solvents yielding alternate compounds[30]. Table 2 highlights the various plant extracts which have been studied so far in pathogen control along with their mechanisms.

Study of phytoextracts against *Xanthomonas spp.*

There has abundant research on *Xanthomonas spp.* and its effect on food crops. From past two decades, more scientists are indulged in applying natural sources such as plant extracts to control its growth. One such research done in Ethiopia focuses on controlling *Xanthomonas campestris* pv. where the scientists studied the efficacy of mustard and ginger rhizomes extracts, lemon juice, Atella as well as cow urine. The results show that seeds inoculated with *Xanthomonas* were treated with these extracts, showing promising antibacterial activity. Both ginger and mustard extracts were able to eliminate *Xanthomonas* within 24hr while maintaining good seed germination and vigor. This study provides a promising alternative treatment method prior to germination of various cultivars. Further field studies can be done to study practical agricultural application [31].

Similarly, research was done by using *Moringa oleifera* leaf extracts in inhibiting *Xanthomonas campestris* pv. on crucifers. They identified the effect of Methanolic, hydroalcoholic, and hydroalcoholic-maltodextrin extracts in bacteriostatic and bactericidal effects due to high flavonoids and phenolic acids. The leaf extract was able to alter bacterial membrane permeability, biofilm formation as well as disrupt ATP synthesis reducing necrosis in infected radishes. This might give an alternative bactericide to conventional methods offering a sustainable approach in controlling black rot in crucifers. The ability of *Moringa oleifera* leaf extract to disrupt bacterial membrane permeability and biofilm formation makes it a promising candidate for developing natural bactericides[32].

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Table 1: List of Crops effected by *Xanthomonas spp.* and *Fusarium spp.*

Crop	*Xanthomonas spp.*	*Fusarium spp.*	References
Rice	Bacterial Leaf Blight (*X oryzar pv. oryzae)*	Fusarium Wilt (*Fusarium oxysporum)*	[10]
Tomato	Bacterial Spot (*X. vesicatoria*)	Fusarium Wilt (*F. oxysporum f. sp. Lycopersici*)	[11]
Potato	Bacterial Wilt (*X. solanacearum)*	Dry Rot (*F. spp.)*	[12], [13]
Cotton	Bacterial Blight (*X. citri subsp. Malvacearum)*	Fusarium Wilt (*F. oxysporum f.sp. Vasinfectum)*	[14]
Banana	Xanthomonas Wilt *(X. campestris pv. musacearum*)	Panama Disease *(F. oxysporum f. sp. Cubense)*	[15]
Cabbage	Black Rot *(X. campestris pv. campestris)*	Fusarium Yellows (*F. oxysporum f. sp. Conglutinans*)	[16]
Wheat	Bacterial Leaf Streak *(X. translucens pv. undulosa)*	Fusarium Head Blight *(F. graminearum)*	[17]
Sugarcane	Leaf Scald (*X. albilineans*)	Pokkah Boeng (*F. moniliforme*)	[18]
Bean	Common Bacterial blight (*X. axonopodis pv. phaseoli)*	Fusarium Root Rot (*F. solani*)	[19]
Pepper	Bacterial spot (*X. campestris pv. vesicatoria)*	Fusarium Wilt (*F. oxysporum*)	[20]
Onion	Xanthomnas Leaf blight (*X. axonopodis pv. allii)*	Fusarium Basal Rot (*F. oxysporum f. sp. Cepae)*	[21]
Strawberry	Angular Leaf Spot (*X. fragariae)*	Fusarium Wilt (*F. oxysporum f. sp. Fragariae)*	[22]
Carrot	Bacterial blight (*X. hortorum pv. carotae)*	Fusarium Dry Rot (*Fusarioum spp.)*	[23]
Lettuce	Bacterial Leaf Spot *(Xanthomonas campestris pv. vitians)*	Fusarium Wilt (*F. oxysporum f. sp. Lactucae)*	[24]
Peanut	Bacterial Leaf Spot (*X. anopodis pv. arachidis)*	Fusarium Wilt (*F. oxysporum f. sp. Arachidis)*	[25]
Soybean	Bacterial Pustule (*X. axonopodis pv. glycines)*	Fusarium Root Rot (*F. solani f. sp. Glycines)*	[26]
Chili Pepper	Bacterial spot (*X. campestris pv. vesicatoria)*	Fusarium Wilt (*F. oxysporum)*	[20]
Sunflower	Bacterial Leaf Spot (*X. campestris pv. helianthi)*	Fusarium Wilt (*F. oxysporum f. sp. Helianthi)*	[27]
Cucumber	Angular Leaf Spot *(X. cucurbitae)*	Fusarium Wilt *(F. oxysporum f. sp. Cucumerinum)*	[28]

Study of phytoextracts against *Fusarium spp.*

Similarly, several scientists are trying to navigate the use of phytoextracts in mitigating the spread of *Fusarium spp.* in food crops. A study analyzed the composition of basil extract and identified major constituents as estragole and minor amounts of trans-α-bergamotene, eucalyptol, trans-ocimene, linalool, and methyl-eugenol. They further

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Table 2: List of Different plant extracts effective against various pathogen species and their mechanism of action

Plant Extract	Effective Against	Mechanism of Action	References
Moringa (*Moringa oleifera)*	*Xanthomonas campestris pv. campestris*	Disrupts the bacterial cell membrane and inhibits protein synthesis by bioactive compounds	[32]
Thyme (*Thymus vulgaris)*	*Xanthomonas spp.*	Destabilizes the bacterial membrane, causes leakage of cellular contents; Rich in thymol and carvacrol	[36]
Lavender (*Lavandula angustifolia)*	*Xanthomonas spp.*	Interfere with the bacterial cell wall development and disrupts energy metabolism; contains linalool and linalyl acetate.	[37]
Eucalyptus (*Eucalyptus spp.)*	*Xanthomonas campestris pv. campestris*	Disrupts bacterial cell membrane, inhibits essential enzymatic activity; contains several essential oils	[38]
Psoralea (*Psoralea corylefolia)*	*Xanthomonas citri*	Disrupts replication and transcription process by intercalating psoralen compound within DNA	[39]
Indian Gooseberry (*Emblica officinalis)*	*Xanthomonas citri*	Causes oxidative stress and protein precipitation; contains high tannins and vitamin c	[39]
Neem (*Azadirachta indica)*	*Fusarium oxysporum f. sp. Lycopersici*	Damages fungal cell wall synthesis, disrupts mitochondrial functions	[40]
Garlic (*Allium sativum)*	*Fusarium spp.*	Disrupts fungal metabolism and energy production; Allicin compound interfere with thiol-containing enzymes	[41]
Sage (*Salvia officinalis)*	*Fusarium spp.*	Disrupts fungal cell membrane, inhibit spore formation; contains phenolic acids and flavonoids	[42]
Yarrow (*Achillea millefolium)*	*Fusarium spp.*	Disrupt ergosterol biosynthesis, alter membrane fluidity and function; contain several essential oils	[43]
Tansy (*Tanacetum vulgare)*	*Fusarium spp.*	Reduce fungal protein synthesis and enzyme activity; contains sesquiterpene and lactones	[44]
Wormwood (*Artemisia absinthium)*	*Fusarium spp.*	Damage mitochondrial function, causes oxidative stress	[45]

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Clove (*Syzgium aromaticum)*	*Fusarium spp.*	Contains Eugenol; disrupts cell membrane, inhibits enzyme activity	[46]
Pomegranate (*Punica granatum)*	*Fusarium oxysporum*	Interfere with replication and cell wall integrity; contain punicalagins and ellagic acid	[47]
Tomato (*Lycopersicon esculentum)*	*Fusarium oxysporum.F. verticillioides F. graminearum*	Increase permeability for cell lysis, tomatine binds to sterol in fungal cell membrane	[48]
Betal Leaf (*Piper betle)*	*Fusarium oxysporum*	Fungicidal properties; Disrupts cell membrane; contains essential oils and phenolic compoundcitrus cankers	[49]
Cinnamon (*Cinnamomum verum)*	*Fusarium oxysporum F. solani, Geotrichum sp. Phytophthora capsici*	Disrupts fungal cell membrane integrity; contains cinnamaldehyde	[50]
Blak Sapote (*Diospyros digyna)*	*Fusarium oxysporum F. solani, Geotrichum sp. Phytophthora capsici*	Exhibit Antifungal activity	[51]
Wild Oregano (*Origanum elongatum)*	*Fusarium oxysporum*	Inhibits mycelial development; presence of bioactive compounds by methanol, hexane and chloroform extracts	[52]

studied the antifungal properties of these extracts against Fusarium oxysporum, F. proliferatum, F. subglutinans, and F. verticillioides. The basil extract was able to modify fungal morphology, causing hyphae deformations, fragmentation and reduced sporulation. As mentioned above, fusarium is a major contaminant in food products post-harvest, the antifungal action can serve as a natural preservative method to prevent fungal contamination in food and agriculture products. The ability of basil extract to inhibit fungal growth and sporulation highlights its potential as a natural preservative for preventing *Fusarium* contamination in food products [33].

In another research, *Capsicum baccatum* varieties were studied for their phytochemical content in analysis of their antifungal potential and ecotoxicity. These varieties contain highest concentrations of capsaicin, dihydrocapsaicin, and nordihydrocapsaicin offering antimicrobial and antioxidant benefits. These phytochemicals when applied to *Aspergillus niger* and *Fusarium oxysporum* displayed inhibitory effects on growth and alterations to morphology of fungal strains such as reduction in reproduction structures, pigmentation loss and fragile structure. They can alternate in plant disease management and natural preservative development [34].

[35]Evaluated the mechanism of action of cinnamon bark, clove buds, and avocado seeds on *Fusarium incarnatum*. All these three compounds have high levels of soluble phenolics, flavonoids, and lignin, showing promising antifungal properties against *Fusarium* spp. by enhancing the plant defense mechanism cascade. Application of these compounds led to increased activity of catalase, peroxidase, polyphenol oxidase and phenylalanine ammonia-lyase. Another advantage is reduced oxidative stress and less membrane damage. Cinnamon bark, clove buds and avocado seeds extracts serve as effective natural preservatives, improve potato tuber storage quality and enhance

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disease resistance. Overall, their optimized application in field conditions can be a potential biocontrol postharvest strategy in disease management.

Advantage over Synthetic pesticides

Many such studies demonstrate significant antibacterial and antifungal properties. The use of mustard, ginger, moringa, basil, capsicum, cinnamon, clove and avocado extracts show potential in managing post-harvest loss of food crop in a more environment friendly manner. However, there are certain challenges, including variability in assay methods, need for standardization and more in-vivo and field trials. Future research also needs to work on safe formulations, toxicity assessments, and regulatory approvals as a sustainable alternative to conventional methods.

Post-harvest losses in tropical and subtropical fruits are mainly due to inefficient management, poor training to the farmers and inadequate storage. In these conditions, farmers often rely on chemical pesticides for disease control and management. However, with growing awareness of environmental and health issues associated with chemical pesticides, there is prompted research into eco-friendly alternatives in managing such post-harvest diseases while minimizing negative impacts. The use of GRAS (Generally Recognized as Safe) compounds such as chitosan, essential oils, and salts show promising results for pathogen prevention and their efficacy can be enhanced with other technologies such as ultrasonic nebulization. Other alternatives also include application of Jasmonic Acid and Salicylic acid as induces of plant immunity, as these molecules induce a signal cascade in activating defense related proteins leading to production of antibacterial and antifungal compounds. Another recent alternative is use of plant extracts for controlling post-harvest decay in fruits. As mentioned above, many plant extracts possess antimicrobial activity making them suitable for disease management. These extracts have diverse applications including use for preservation, pre-treatment, post-harvest treatment or field application depending upon the requirement. They not only reduce bacterial and fungal growth post-harvest by inhibiting their growth but also increase shelf life of these crops reducing food wastage and reducing overall costs[53].

Overall, medicinal plant extracts offer an eco-friendly and sustainable alternative to other methods of management (Figure 2). As mentioned above, they demonstrate high potential in altering the growth of these microbes by making them a viable option. With some challenges in mind, if we focus on optimizing the extraction techniques, developing safe formulations, assessing toxicity and following secure regulatory guidelines, we can integrate this into a large-scale agriculture practice.

4. Significance of biopolymer-based coating and biofilms development in post-harvest Sustainability

Post-harvest characteristics and processes

Tropical fruits are a diverse group of fruits grown in warm and humid regions, including Asia, Africa, Central and South America, the Caribbean, and Oceania. Some common examples of these fruits include

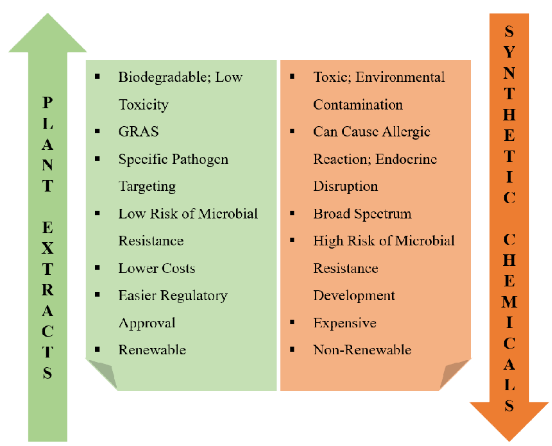

Fig. 2: Comparison between Plant Extracts and Synthetic Chemical Pesticides application for food preservation

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bananas, papayas, mangoes, pineapples, watermelons, muskmelons, oranges, durians, mangosteens, avocados, rambutans, guavas, jackfruits, pitayas, and passion fruits. These fruits are known for their unique flavors, aromas, shapes, and exotic appearances, as well as their rich nutritional content, which makes them highly popular among consumers[54].

The outer protective layer of tropical fruits, called the pericarp, is composed of epidermal cells. This layer acts as a barrier against environmental factors such as gases, microbes, and chemicals, helping to maintain fruit quality and freshness. Key structural components of the pericarp include cuticles, lenticels, epicuticular wax, cracks, and stomata, all of which influence how the fruit interacts with its surroundings. Openings such as stomata, lenticels, and cracks facilitate gas and water exchange, with stomata playing a crucial role in regulating these processes. However, excessive openings can weaken fruit firmness, leading to problems such as increased transpiration, susceptibility to pathogens, and rapid moisture loss. Meanwhile, the cuticle and epicuticular wax, primarily composed of lipid-based layers, help minimize water loss and regulate gas exchange. These layers also aid in surface protection by reducing wetting, reflecting UV light, maintaining a self-cleaning effect, altering surface chemistry, and influencing mechanical properties[55].

Many tropical fruits undergo climacteric ripening, meaning they can be harvested when physiologically mature but unripen and will continue ripening during storage and transportation. Fruits such as papayas ripen based on ethylene production, as this phytohormone is responsible for regulating the ripening process. Conversely, non-climacteric fruits like pineapples do not rely on ethylene; instead, their freshness is determined by external factors such as temperature, duration, color, and pH. As a result, these fruits are typically left on the plant to mature fully before being harvested[56].

Since tropical fruits grow in regions with high temperatures and humidity, it is essential to understand their ripening and post-harvest changes to develop suitable edible coatings. These coatings help in delaying ethylene production, reducing respiration rates, and preventing microbial growth, ultimately extending the shelf life of the fruits.

Postharvest metabolism encompasses biochemical activities in tropical fruits after harvest, driven mainly by respiration and transpiration. Respiration involves the oxidation of carbohydrates, consuming oxygen to produce carbon dioxide, water, and heat. This process depletes stored sugars and organic acids, directly impacting fruit weight, flavor, and quality. Elevated respiration rates also stimulate ethylene synthesis, a hormone that accelerates ripening and senescence. Transpiration, a passive water loss through the fruit’s surface, further reduces weight and freshness, leading to texture changes like shriveling and softening[57], [58].

The combined effects of these processes trigger physical and chemical deterioration, including color shifts, reduced acidity, and increased dissolved solids. These changes create a feedback loop that amplifies respiration and water loss, shortening shelf life.

Biopolymer-Based Edible Coatings

Biopolymer-basedcoatings are thin layers of edible materials applied on the surface of food products to improve their quality, safety, and shelf life. These coatings are usually produced from natural polymers such as polysaccharides, proteins, and lipids, which are biodegradable, biocompatible, and non-toxic. The use of edible coatings offers several advantages over conventional packaging materials, including improved barrier properties, reduced moisture loss, enhanced flavor retention, and the ability to incorporate functional ingredients such as antimicrobials and antioxidants. Table 3 shows certain biopolymer material based edible coatings along with their various properties.

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Table 3: Properties and applications of Biopolymer-based edible coatings and Biofilms in Food preservation

Material	Properties/Mechanism	Applications	Advantages	References
Chitosan Biopolymer	Antimicrobial, antifungal, film-forming, biocompatible	Fruits, vegetables, seafood	Extends shelf life, reduces microbial spoilage, enhances appearance	[70]
Alginate Biopolymer	Film-forming, gas barrier, biodegradable, non-toxic	Fruits, vegetables, dairy products	Reduces respiration rate, delays ripening, maintains firmness	[71]
Cellulose Biopolymer	Structural stability, antioxidant, film-forming, biodegradable	Meat, poultry, bakery products	Prevents lipid oxidation, maintains texture, extends shelf life	[72]
Starch Biopolymer	Biodegradable, hydrophobic, film-forming, readily available	Bakery products, confectionary	Prevents moisture absorption, maintains crispness, enhances texture	[73]
Whey Protein Biopolymer	Oxygen barrier, film-forming, edible, biodegradable	Cheese, processed meats, fruits	Prevents lipid oxidation, maintains color and flavor, extends shelf life	[74]
Antimicrobial Biofilms (Plant extracts, essential oils)	Inhibition of spoilage microorganisms, disruption of cell membranes	Fruits, vegetables, meat, poultry	Extends shelf life, prevents microbial spoilage, enhances food safety	[75]
Probiotic Biofilms (Lactobacillus, Bifidobacterium)	Production of antimicrobial compounds, competitive exclusion of pathogens	Fermented foods, dairy products, probiotics-enriched foods	Enhances gut health, improves food safety, increases nutritional value	[76]
Protective Biofilms (Food-grade microorganisms)	Formation of a physical barrier against spoilage organisms, reduction of oxygen levels	Fruits, vegetables, processed foods	Prevents spoilage, maintains texture and flavor, extends shelf life	[77]

a) **Polysaccharide-Based Coatings:** Polysaccharides such as chitosan, alginate, cellulose, and starch are commonly used as edible coating materials due to their film-forming ability, biocompatibility, and biodegradability. Chitosan coatings exhibit antimicrobial activity against a wide range of bacteria and fungi, making them effective for preventing microbial spoilage. Alginate coatings are effective barriers to gas

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exchange, reducing respiration rates and extending the shelf life of fruits and vegetables. Cellulose coatings provide structural stability and can be incorporated with antioxidants to prevent lipid oxidation. Starch coatings are biodegradable and hydrophobic, making them suitable for coating bakery products and preventing moisture absorption[59].

b) **Protein-Based Coatings:** Proteins such as whey protein, soy protein, and gelatin can be used to form edible coatings with excellent barrier properties. Whey protein coatings are effective barriers to oxygen, preventing lipid oxidation and preserving the color and flavor of food products. Soy protein coatings exhibit antioxidant activity and can be used to protect food products from oxidative damage. Gelatin coatings provide structural support and can be used to encapsulate flavors and aromas[54].

c) **Lipid-Based Coatings:** Lipids such as waxes, oils, and fats can be used to form edible coatings with excellent moisture barrier properties. Wax coatings are effective for preventing water loss from fruits and vegetables, extending their shelf life and maintaining their freshness. Oil coatings can be used to prevent lipid oxidation and preserve the flavor of food products. Fat coatings provide a smooth, glossy appearance and can be used to enhance the aesthetic appeal of food products[54].

The Role of Edible Coating Films in Overcoming Postharvest Challenges

Edible coating films (ECFs) serve as effective barriers, regulating the exchange of gases and moisture content between fruits and their environment. This control mechanism helps in slowing down respiration, retaining natural volatile flavor compounds, and delaying the ripening process. In addition to these benefits, ECFs are edible, health-supportive, biodegradable, and contribute to reducing waste while enabling preservative-free commercialization. Their application plays a key role in extending the postharvest shelf life of fruits by minimizing physicochemical changes and preventing physiological disorders[60].

Postharvest challenges in tropical fruits include cracking, water loss, infections, peel browning, chilling injuries, and logistical issues during distribution. These problems arise due to various internal and external factors, leading to accelerated aging and a shorter shelf life [61].

Characteristics of Effective Edible Coating Films (ECFs)

Edible coating films (ECFs) are thin, bioactive polymer layers applied to food products to enhance shelf life, preserve quality, and maintain food safety. These coatings act as protective barriers against moisture loss, gas exchange, and microbial contamination while also serving as carriers for additives such as antioxidants and antimicrobials.

- **Regulation of Barrier Properties:** The effectiveness of ECFs largely depends on their ability to control mass transfer between the fruit's internal structure and the external environment. This includes preventing water vapor loss, regulating gas exchange, and maintaining volatile compounds. Efficient coatings help prevent dehydration, shrinkage, and enzymatic degradation. Polysaccharide- and protein-based films provide strong gas barrier properties and transparency but may lack moisture retention. Lipid-based coatings, on the other hand, offer better moisture retention but higher oxygen permeability. Controlling the viscosity of coatings is essential, as excessively thick layers can block pores and hinder gas exchange, leading to carbon dioxide buildup. Ideally, ECFs should maintain proper gas diffusion while preventing volatile compound loss[62].
- **Material Composition and Structural Stability:** The structural stability of ECFs is influenced by their primary components, which can be proteins, polysaccharides, lipids, or composite materials. Polysaccharides, due to their hydrophilic nature, absorb moisture and may lead to water loss. To address this, researchers have incorporated hydrophobic

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agents like essential oils or mineral oils. Lipid-based coatings effectively prevent moisture loss but may cause surface defects such as browning or lesions in fruits. Nanotechnology-based enhancements, such as reducing droplet size or incorporating nanoparticles, have been explored to improve coating performance. Composite films, which blend different materials, offer improved protection and are increasingly used in food preservation. For example, garlic extract has been encapsulated using whey protein isolate and chitosan to create a protective film with antimicrobial properties[63].

- **Mechanical Durability:** The mechanical strength of ECFs determines their ability to protect fruits from physical damage while maintaining flexibility. Factors such as tensile strength, polymer cohesion, elongation properties, and plasticizer concentration influence film durability. Incorporating cellulose nanocrystals (CNCs) or cellulose nanofibers (CNFs) into chitosan films has been shown to enhance tensile strength significantly. Starch-based films, though promising for large-scale production, often lack durability. However, integrating chitosan nanoparticles (CNs) into tapioca starch coatings has improved tensile strength by 795.5% and elongation by 35%, making them suitable for food applications[54].
- **Surface Interaction and Adhesion:** Effective adhesion is crucial for an ECF to function properly. Wettability, or the ability of the coating to spread evenly over the fruit surface, is influenced by the interaction between the coating material and the fruit epidermis. To enhance adhesion, researchers incorporate surfactants (e.g., Tween 80), plasticizers, and crosslinking agents into coating formulations. Uniform distribution of nanoparticles within biopolymer films also improves surface interaction, ensuring better coverage and functionality[64].
- **Functional Bioactivity:** ECFs offer additional bioactive properties such as antimicrobial effects, antioxidant activity, and probiotic potential. These coatings help mitigate spoilage and physicochemical changes during storage while preventing post-harvest losses. Essential oils and plant extracts incorporated into coatings have shown antimicrobial properties against spoilage microorganisms. However, challenges such as strong flavors, hydrophobicity, and stability need to be addressed for widespread application[64].
- **Sensory Quality Maintenance:** Preserving sensory attributes like color, texture, aroma, and taste is a key consideration in ECF formulation. Consumers associate visual appeal with freshness and ripeness, and coatings should not negatively alter these perceptions. Studies indicate that sensory factors strongly influence purchasing decisions, especially for tropical fruits. ECFs must maintain glossiness, prevent off-flavors, and avoid undesirable textural changes such as sogginess[65].
- **Safety Considerations:** ECF materials must be classified as Generally Recognized as Safe (GRAS) and meet regulatory safety standards. However, not all GRAS-listed substances are safe in every application, necessitating rigorous evaluation. In addition to safety, ECFs should be biodegradable, non-toxic, cost-effective, and widely accessible. They must not interfere with fruit surfaces during storage while preserving nutritional value. Sustainable and eco-friendly formulations are gaining importance in the development of next-generation ECFs(Food and Drug Administration HHS)

Biofilm Development in Food Preservation

Biofilms are complex communities of microorganisms attached to a surface, encased in a self-produced matrix of extracellular polymeric substances (EPS). Biofilms can form on food processing equipment, packaging materials, and the surface of food products, leading to spoilage and contamination. However, the development of beneficial biofilms can be harnessed for food preservation[67]. In table 3, three different types of biofilm materials are described alongside their mechanism as well as applications and advantages.

a) **Antimicrobial Biofilms:** The incorporation of antimicrobial agents into

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edible coatings can create antimicrobial biofilms that inhibit the growth of spoilage microorganisms. Plant extracts, such as essential oils and phenolic compounds, can be incorporated into edible coatings to create antimicrobial biofilms that prevent microbial spoilage and extend the shelf life of food products.

b) **Probiotic Biofilms:** The application of probiotic bacteria to the surface of food products can create probiotic biofilms that enhance food safety and nutritional value. Probiotic biofilms can inhibit the growth of spoilage microorganisms, produce antimicrobial compounds, and improve the gut health of consumers.

c) **Protective Biofilms:** The formation of protective biofilms on the surface of food products can create a barrier against spoilage microorganisms and environmental factors. Edible coatings can be designed to promote the formation of protective biofilms that enhance the quality and shelf life of food products[68], [69].

5.Trends in Nanotechnology for Post-Harvest Food Conservation

Nanotechnology involves working with materials at a very small scale to develop new methods for managing fruits after harvest. Nanoparticles (NPs) are tiny spherical structures, typically ranging from 1 to 100 nm in laboratory settings and up to 1000 nm in industrial applications. These particles offer unique advantages due to their small size, high surface area-to-volume ratio, and distinctive structural properties compared to larger materials. Because of their nanoscale size, they can easily enter fruit epidermal pores, helping regulate mass transfer, improve coating adherence, and enhance biocompatibility. This ensures even distribution in edible coatings, reduces microbial contamination, and lowers overall postharvest handling costs[78].

In addition to directly protecting the outer layer of the fruit and maintaining freshness, nanotechnology has enabled real-time monitoring of fruit quality throughout storage and transportation. The use of nano sensors in intelligent packaging helps detect changes such as microbial growth, quality deterioration, swelling, pH shifts, temperature fluctuations, and humidity variations. These freshness indicators, often in the form of labels or visual signals, provide accurate information about the condition of the fruit and its storage environment.

Nanotechnology offers innovative solutions for improving food preservation techniques and enhancing food safety. Nanomaterials, such as nanoparticles, Nano emulsions, and nanocomposites, can be used to deliver antimicrobial agents, improve barrier properties, and enhance the functionality of edible coatings[64].

a) **Nanoparticles for Antimicrobial Delivery:** Nanoparticles can be used to encapsulate and deliver antimicrobial agents to the surface of food products, providing controlled release and targeted delivery. Silver nanoparticles, zinc oxide nanoparticles, and titanium dioxide nanoparticles exhibit antimicrobial activity against a wide range of bacteria and fungi, making them effective for preventing microbial spoilage.

b) **Nano emulsions for Improved Barrier Properties:**Nano emulsions are stable dispersions of oil and water phases with droplet sizes in the nanometer range. Nano emulsions can be used to improve the barrier properties of edible coatings, reducing moisture loss, gas exchange, and lipid oxidation.

c) **Nanocomposites for Enhanced Functionality:** Nanocomposites are materials consisting of a polymer matrix reinforced with nanoparticles. Nanocomposites can be used to enhance the mechanical strength, barrier properties, and antimicrobial activity of edible coatings[79].

Recent advancements have also led to the development of smart packaging systems incorporating active components like antioxidants, antimicrobial agents, and scavengers to further preserve fruit quality. Additionally, beta-chitosan nanoparticles have been combined with cellulose nanocrystals and beta-galactosidase to improve stability. These nanoparticles serve as non-toxic and

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effective carriers, with applications such as lactose intolerance treatment

6. Formulation Strategies for Plant-Based Antimicrobials

Once plant extracts with antimicrobial properties are obtained, their formulation is critical to enhance their stability, solubility, and delivery to the target site. Formulation strategies aim to protect the bioactive compounds from degradation, improve their bioavailability, and ensure their controlled release in food products. Various formulation approaches can be employed, including encapsulation, nano formulation, and the use of carrier systems.

Encapsulation Techniques

Encapsulation involves entrapping the plant extract within a protective matrix, which can be a polymer, lipid, or carbohydrate-based material. Encapsulation protects the bioactive compounds from degradation due to heat, light, oxygen, and pH changes. It also improves their dispersibility in aqueous media and allows for their controlled release over time.

a) **Microencapsulation:** This technique involves encapsulating the plant extract within micro-sized particles, typically ranging from 1 to 1000 µm in diameter. Microencapsulation can be achieved using various methods, including spray drying, emulsification, and coacervation. The choice of encapsulating material depends on the properties of the plant extract and the desired release characteristics. Common encapsulating materials include polysaccharides (e.g., alginate, chitosan, starch), proteins (e.g., whey protein, gelatin), and lipids (e.g., waxes, fats). Spray drying is a widely used technique for microencapsulation due to its simplicity, scalability, and cost-effectiveness. It involves dispersing the plant extract in a solution of the encapsulating material and then spraying the mixture into a hot air stream, causing the solvent to evaporate and the particles to solidify. Emulsification involves forming a stable emulsion of the plant extract and the encapsulating material, followed by solidification or cross-linking of the emulsion droplets. Coacervation involves the separation of a polymer solution into two phases, one of which encapsulates the plant extract[80].

b) **Nanoencapsulation:** Nanoencapsulation involves encapsulating the plant extract within nano-sized particles, typically ranging from 1 to 100 nm in diameter. Nanoencapsulation offers several advantages over microencapsulation, including improved stability, enhanced bioavailability, and controlled release. Nanoencapsulation can be achieved using various methods, including nanoprecipitation, nanoemulsification, and layer-by-layer assembly. Nanoprecipitation involves dissolving the plant extract and the encapsulating material in a solvent and then adding the solution to a non-solvent, causing the particles to precipitate. Nanoemulsification involves forming a stable nanoemulsion of the plant extract and the encapsulating material using high-pressure homogenization or micro-fluidization. Layer-by-layer assembly involves depositing alternating layers of oppositely charged polymers onto the surface of the plant extract, forming a multilayered coating[81].

c) Liposomes: Liposomes are spherical vesicles composed of lipid bilayers that can encapsulate plant extracts. Liposomes offer excellent biocompatibility, biodegradability, and the ability to deliver both hydrophilic and hydrophobic compounds. Liposomes can be prepared using various methods, including thin-film hydration, reverse-phase evaporation, and micro-fluidization. The size and composition of liposomes can be tailored to optimize their stability, encapsulation efficiency, and release characteristics. Liposomes can be used to deliver plant extracts to specific sites in the food product, enhancing their antimicrobial activity[82].

Nanoformulation Techniques

Nanoformulation involves incorporating the plant extract into nanoscale delivery systems, such as nanoemulsions, nanocapsules, and solid lipid nanoparticles. Nanoformulations enhance the solubility,

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Table 4: Nano formulation strategies

Formulation Strategy	Description	Advantages	Disadvantages	Applications	References
Microencapsulation	Encapsulation of plant extracts within micro-sized particles	Protection from degradation, improved dispersibility, controlled release	Potential for low encapsulation efficiency, limited bioavailabilit, particle size may affect texture	Food coatings, food additives, controlled release of antimicrobials	[84]
Nanoencapsulation	Encapsulation of plant extracts within nano-sized particles	Improved stability, enhanced bioavailability, controlled release, targeted delivery	High production cost, potential toxicity of nanomaterials, regulatory concerns	Food coatings, food additives, targeted delivery of antimicrobials	[85]
Liposomes	Encapsulation of plant extracts within lipid bilayers	Excellent biocompatibility, biodegradability, delivery of hydrophilic and hydrophobic compounds	Limited stability, potential for lipid oxidation, high production cost	Food coatings, drug delivery, cosmetic applications	[82]
Nano emulsions	Stable dispersions of oil and water phases with droplet sizes in the nanometre range	Enhanced stability, bioavailability, penetration into microbial cells, improved dispersibility of hydrophobic compounds	Potential for droplet coalescence, high production cost, regulatory concerns	Food coatings, delivery of lipophilic antimicrobials, flavourings, and antioxidants	[86]
Nano capsules	Core-shell structures consisting of a liquid or semi-solid core surrounded by a polymeric shell	Protection from degradation, controlled release, targeted delivery	High production cost, potential toxicity of polymers, regulatory concerns	Food coatings, delivery of antimicrobials, flavourings, and antioxidants	[87]
Solid Lipid Nanoparticles (SLNs)	Solid lipid matrices containing the	Excellent biocompatibility, biodegradability,	Limited drug loading, potential for	Food coatings, delivery of	[88]

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	plant extract	delivery of hydrophilic and hydrophobic compounds, protection from degradation, controlled release	particle aggregation, high production cost	antimicrobials, flavourings, and antioxidants	
Cyclodextrins	Cyclic oligosaccharides that form inclusion complexes with plant extracts	Enhanced solubility, stability, protection from degradation	Limited loading capacity, potential for complex dissociation, high cost	Delivery of hydrophobic antimicrobials, flavourings, and antioxidants	[89]
Proteins	Biomacromolecules that bind to plant extracts	Enhanced stability, solubility, protection from degradation, controlled release	Potential for allergic reactions, protein denaturation, high cost	Food coatings, delivery of antimicrobials, flavourings, and antioxidants	[90]
Polysaccharides	Biomacromolecules that form gels or films encapsulating plant extracts	Sustained release, protection from degradation, biocompatible, biodegradable, readily available	Potential for gel degradation, polysaccharide crosslinking, high cost	Food coatings, delivery of antimicrobials, flavourings, and antioxidants	[91]

stability, and bioavailability of the plant extract, improving its antimicrobial activity and prolonging its shelf life. Table 4 highlights the different nano-formulations along with their advantages, disadvantages and applications.

a) **Nanoemulsions:** Nanoemulsions are stable dispersions of oil and water phases with droplet sizes in the nanometer range. Nanoemulsions can be prepared using high-pressure homogenization, micro-fluidization, or spontaneous emulsification. The small droplet size of nanoemulsions enhances their stability, bioavailability, and penetration into microbial cells. Nanoemulsions can be used to deliver hydrophobic plant extracts to aqueous food systems, improving their dispersibility and antimicrobial activity.

b) **Nanocapsules:** Nanocapsules are core-shell structures consisting of a liquid or semi-solid core containing the plant extract, surrounded by a polymeric shell. The polymeric shell protects the plant extract from degradation and controls its release. Nanocapsules can be prepared using interfacial polymerization, solvent evaporation, or layer-by-layer assembly. The size and composition of nanocapsules can be tailored to optimize their stability, encapsulation efficiency, and release characteristics.

c) **Solid Lipid Nanoparticles (SLNs):** SLNs are solid lipid matrices containing the plant extract. SLNs offer excellent biocompatibility, biodegradability, and the ability to deliver both hydrophilic and hydrophobic compounds. SLNs can be prepared using high-pressure homogenization, micro-emulsification, or solvent emulsification-evaporation. The solid lipid matrix protects the plant extract from degradation and controls its release[83].

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7. Sensory, consumer acceptance, regulatory aspects and labelling requirements of Plant-Based Preservatives

The sensory properties of plant extracts, such as their flavor, odor, and color, can influence their acceptance by consumers. It is important to evaluate the sensory impact of plant extracts and optimize their concentration to achieve the desired antimicrobial effect without compromising the sensory quality of the food product.

Sensory Evaluation: Sensory evaluation involves using human senses to assess the appearance, odor, flavor, and texture of food products. Sensory evaluation can be conducted using descriptive analysis, preference tests, and acceptance tests.

Descriptive Analysis: Descriptive analysis involves using trained panelists to identify and quantify the sensory attributes of food products. The panelists use a standardized vocabulary to describe the intensity and quality of each sensory attribute. Descriptive analysis can be used to evaluate the impact of plant extracts on the sensory profile of food products.

Preference Tests: Preference tests involve asking consumers to indicate their preference for one or more food products. Preference tests can be used to determine whether consumers prefer food products containing plant extracts over those containing synthetic preservatives.

Acceptance Tests: Acceptance tests involve asking consumers to rate their overall liking of food products on a scale. Acceptance tests can be used to determine whether consumers find food products containing plant extracts to be acceptable.

Consumer Perception: Consumer perception refers to the attitudes, beliefs, and expectations that consumers have about food products. Consumer perception can influence the acceptance of plant-based preservatives. It is important to educate consumers about the benefits of plant-based preservatives and address any concerns they may have.

Health Benefits: Consumers are increasingly interested in food products that offer health benefits. Plant-based preservatives are perceived as being more natural and healthier than synthetic preservatives. Educating consumers about the health benefits of plant-based preservatives can increase their acceptance.

Safety Concerns: Some consumers have concerns about the safety of plant-based preservatives. It is important to provide consumers with information about the safety of plant-based preservatives and the regulatory approval process.

Environmental Impact: Consumers are increasingly concerned about the environmental impact of food production. Plant-based preservatives are perceived as being more environmentally friendly than synthetic preservatives. Educating consumers about the environmental benefits of plant-based preservatives can increase their acceptance.

The use of plant-based antimicrobials in food preservation is subject to regulatory oversight by government agencies such as the Food and Drug Administration (FDA) in the United States and the European Food Safety Authority (EFSA) in Europe. It is important to comply with all applicable regulations to ensure the safety and legality of plant-based preservatives[92], [93].

Regulatory Framework

The regulatory framework for plant-based antimicrobials varies depending on the country and the specific application. In general, plant extracts are considered to be food additives and are subject to pre-market approval requirements.

a) **GRAS Status:** Some plant extracts have been granted Generally Recognized as Safe (GRAS) status by the FDA. GRAS status means that the plant extract is considered to be safe for its intended use based on scientific data and expert opinion.

b) **Food Additive Petitions:** Plant extracts that do not have GRAS status may be approved for use as food additives through a food additive petition. A food additive

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petition must include scientific data demonstrating the safety and efficacy of the plant extract.

c) **EFSA Assessment:** In Europe, plant extracts are subject to assessment by the European Food Safety Authority (EFSA). EFSA evaluates the safety of plant extracts based on scientific data and provides recommendations to the European Commission[94].

Labeling Requirements

The labeling of food products containing plant-based antimicrobials must comply with applicable regulations. In general, the label must list the plant extract as an ingredient and indicate its function as a preservative.

a) **Ingredient List:** The ingredient list must list all ingredients in descending order of weight. Plant extracts must be listed by their common or usual name.

b) **Preservative Declaration:** The label must indicate that the plant extract is used as a preservative. This can be done by stating "Preserved with [plant extract]" or "To maintain freshness, [plant extract] has been added."[95]

8. Environmental and Economic Impacts

The use of plant extracts as food preservatives offers a range of potential environmental and economic benefits compared to synthetic alternatives. However, it is crucial to carefully evaluate these impacts to ensure that the adoption of plant-based preservatives contributes to a more sustainable and economically viable food system.

Environmental Impacts

Reduced Reliance on Synthetic Chemicals: The replacement of synthetic preservatives with plant extracts can significantly reduce the environmental burden associated with the production, use, and disposal of synthetic chemicals. Synthetic preservatives often require energy-intensive manufacturing processes, generate hazardous waste, and can persist in the environment, leading to pollution and ecological damage.

Biodegradability and Reduced Waste: Plant extracts are typically biodegradable and can be composted, reducing the amount of waste sent to landfills. In contrast, synthetic preservatives can contribute to plastic waste and require specialized disposal methods.

Sustainable Sourcing and Agricultural Practices: The cultivation of plants for extraction can promote sustainable agricultural practices, such as crop rotation, reduced pesticide use, and conservation of biodiversity. Sustainable sourcing of plant materials can also support local communities and promote fair trade.

Reduced Carbon Footprint: Plant-based preservatives can have a lower carbon footprint compared to synthetic preservatives, particularly if they are sourced locally and processed using renewable energy. The production and transportation of synthetic chemicals can contribute significantly to greenhouse gas emissions[96]

Economic Impacts

Cost Competitiveness: Plant extracts can be cost-competitive with synthetic preservatives, particularly if they are produced locally and extracted using efficient and sustainable methods. The cost of synthetic chemicals can fluctuate due to changes in raw material prices and energy costs.

Reduced Food Waste: By extending the shelf life of food products, plant-based preservatives can help reduce food waste, which translates into economic savings for consumers, retailers, and food manufacturers.

Enhanced Market Value: Food products preserved with plant extracts can command a premium price due to their perceived health benefits and environmental friendliness. Consumers are increasingly willing to pay more for natural and sustainable products.

Support for Local Economies: The

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production and processing of plant extracts can create economic opportunities in rural areas and support local communities. Sustainable sourcing of plant materials can also promote fair trade and improve the livelihoods of farmers[96]

9. Future Perspectives and Research Directions

The field of plant-based food preservation is rapidly advancing, driven by innovations in extraction technologies, formulation techniques, and regulatory frameworks. Future research should focus on multiple key areas to enhance the efficacy, stability, and consumer acceptance of plant-based preservatives[97].

Novel Plant Sources: Exploring new plant sources for antimicrobial compounds can expand the range of effective natural preservatives. Research should focus on plants traditionally used in medicine or those with demonstrated antimicrobial properties in vitro. Identifying and characterizing novel bioactive compounds from underutilized plant species can enhance the natural preservation toolkit. High-throughput screening techniques and metabolomics can aid in discovering plants with strong antimicrobial potential.

Improved Extraction and Formulation Techniques: Enhancing extraction and formulation techniques can improve the yield, stability, and bioavailability of plant-based preservatives. Research should focus on optimizing extraction methods, encapsulation techniques, and delivery systems. The use of green solvents, such as supercritical CO_2 and ionic liquids, can reduce environmental impact. Additionally, nanoformulations can improve the stability and controlled release of plant-derived antimicrobials, ensuring more effective food preservation.

Combination Strategies: Integrating plant-based preservatives with other preservation methods can enhance their effectiveness and prolong food shelf life. Research should explore synergistic combinations with techniques such as modified atmosphere packaging, irradiation, and high-pressure processing. Additionally, studying interactions between plant extracts and other natural antimicrobials—such as bacteriophages and antimicrobial peptides—could lead to innovative preservation solutions.

Consumer Education and Market Acceptance: Consumer awareness and perception play a crucial role in the adoption of plant-based food preservatives. Research should focus on developing effective communication strategies to educate consumers about their safety, health benefits, and environmental advantages. Conducting consumer studies to assess attitudes, perceptions, and willingness to pay for foods preserved with plant extracts can guide marketing and labeling strategies, ultimately increasing consumer trust and demand.

Regulatory Harmonization: Standardizing regulations for plant-based preservatives can facilitate their global adoption and trade. Research should focus on developing consistent testing methods and risk assessment procedures to ensure efficacy and safety. Collaboration among regulatory agencies to establish common guidelines will promote the international use of plant-based antimicrobials, ensuring compliance across different markets and encouraging widespread application.

Conclusion

Plant-based preservatives represent a promising and sustainable alternative to synthetic additives, offering antimicrobial and antioxidant benefits that enhance food safety and extend shelf life. Their potential to reduce reliance on artificial preservatives aligns with growing consumer demand for natural and eco-friendly food preservation methods. However, widespread adoption requires overcoming key challenges, including optimizing sensory properties, improving formulation techniques, ensuring regulatory compliance, and fostering consumer

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acceptance.

Future research should focus on identifying novel plant sources, refining extraction and encapsulation technologies, and conducting rigorous safety and efficacy assessments. Additionally, harmonizing global regulatory standards and educating consumers on the benefits of plant-based preservatives will be essential for their successful integration into the food industry.

By addressing these challenges, plant-based preservatives can play a transformative role in food preservation, contributing to a safer, healthier, and more sustainable global food supply. Continued innovation and collaboration among researchers, food manufacturers, and policymakers will be key to unlocking their full potential.

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