An Overview of the Use of Plant Extracts in Antimicrobial Packaging

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Abstract. Antimicrobial packaging is a critical innovation in enhancing food safety by integrating substances that can inhibit or kill microorganisms directly in the packaging material. In this article, we reviewed common antimicrobial mechanisms, application of plant extracts in antimicrobial packaging, packaging materials, and methods of incorporation of antimicrobial agents into packaging material. Antimicrobial packaging can disrupt the cell membranes of microorganisms, interfere with enzyme activity, and hinder DNA replication and protein synthesis, thus providing a multifaceted approach to microbial control. The effectiveness of antimicrobial packaging is further amplified by its ability to disrupt the biofilm matrix on food surfaces, which is a common protective mechanism employed by microorganisms to withstand conventional cleaning methods. Plant extracts, known for their natural antimicrobial properties, have become a focal point in developing these advanced packaging materials. Incorporating these extracts into packaging can be achieved through various methods, including surface coating, solvent casting, extrusion, electrospinning, layer-by-layer assembly, and encapsulation. Advancements in antimicrobial packaging not only extend the shelf life of food products but also ensure safer consumption by reducing the risk of foodborne illnesses. The integration of plant extracts into packaging materials represents a sustainable and effective approach to addressing microbial contamination in the food industry.

Keywords: Antimicrobial Packaging, Food, Plant Extract; Packaging Materials.

1.0 Introduction

Harmful microorganisms, including bacteria, viruses, and protozoan parasites, can contaminate food-contact surfaces [1], leading to the formation of biofilms—structured communities of microbes encased in a self-produced matrix that adhere to surfaces [2-4]. These biofilms provide a protective barrier that makes the microorganisms more resistant to antibiotics and disinfection efforts [5]. When biofilms form on food-contact surfaces, they can persistently harbour pathogens that contaminate food products, thereby increasing the risk of disease transmission to consumers [6]. This contamination can result in foodborne illnesses, which are a significant public health concern due to the difficulty in eradicating biofilms once established. Biofilms pose a significant challenge in food packaging due to their

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resistance to conventional cleaning and sanitization methods [7]. Antimicrobial packaging addresses this issue by incorporating substances that inhibit or kill microorganisms, thereby preventing biofilm formation on packaging surfaces.

Antimicrobial packaging is a revolutionary innovation in the food packaging industry aimed at enhancing food safety and extending the shelf life of perishable products [8]. The primary function of antimicrobial packaging is to inhibit or kill pathogenic microorganisms that can spoil food and cause foodborne illnesses. This technology incorporates antimicrobial agents into packaging materials, creating an active defence against microbial contamination [9]. The significance of antimicrobial packaging in food safety cannot be overstated, as it addresses a critical challenge in the food supply chain: maintaining the quality and safety of food products from production to consumption. Food safety is a paramount concern for consumers, producers, and regulators alike [10]. Contaminated food can lead to severe health issues, ranging from mild gastroenteritis to life-threatening conditions. Traditional packaging methods primarily serve as barriers that protect food from external contamination. However, they do not actively combat the growth of microorganisms that may already be present in the food. Antimicrobial packaging fills this gap by providing an additional layer of protection.

Plant extracts are increasingly recognized for their potent antimicrobial properties and are being incorporated into food packaging to enhance food safety [8]. Studies have shown that phenolic extracts and essential oils from plants exhibit significant antimicrobial activity against foodborne pathogens, making them effective natural alternatives to synthetic preservatives. This mini review summarizes the potential use of plant extracts in food packaging.

1.1 Mechanisms of Antimicrobial Packaging

Antimicrobial packaging works through various mechanisms depending on the type of antimicrobial agents used. These agents can be integrated into the packaging material, coated on the surface, or embedded in a carrier matrix. The active agents then migrate to the surface of the packaging or the food product, where they exert their antimicrobial effects [11]. Common mechanisms include the disruption of microbial cell membranes, interference with cellular metabolism, and inhibition of DNA replication (Figure 1).

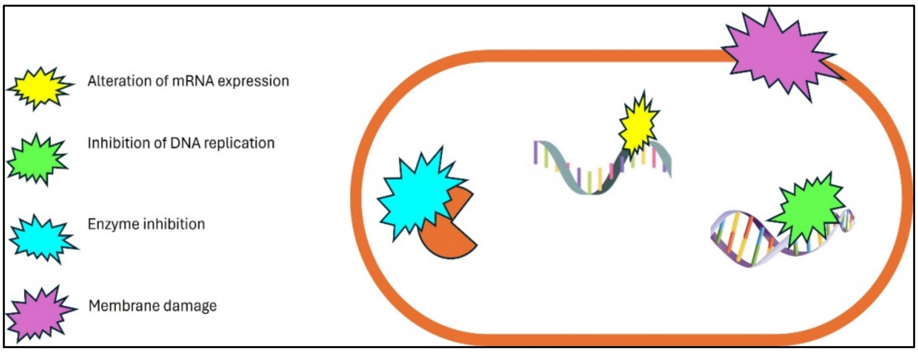

Fig. 1. Common antimicrobial mechanisms.

One of the primary mechanisms by which antimicrobial agents' function is by disrupting the cell membranes of microorganisms. This disruption can cause cell lysis, leakage of cellular contents, and ultimately, cell death. For instance, essential oils such as those derived from oregano and thyme contain compounds like carvacrol and thymol, which have been shown to insert themselves into microbial cell membranes, creating pores that lead to cell leakage and death [12-14].

Antimicrobial agents can interfere with the metabolic processes of microorganisms. This inhibition can occur through the disruption of enzyme activity, interference with nutrient uptake, or disruption of ATP synthesis. Silver nanoparticles, for example, can bind to thiol groups in enzymes and proteins, inhibiting their function and leading to the disruption of cellular respiration and other metabolic activities [15]. This mechanism is particularly effective against a broad spectrum of bacteria, including antibiotic-resistant strains.

Another significant mechanism is the interference with DNA replication and protein synthesis. Some antimicrobial agents can bind to DNA or RNA, preventing the replication and transcription processes necessary for cell division and function. Chitosan, a natural polymer derived from chitin, has been shown to bind to bacterial DNA, inhibiting its replication and leading to cell death [16]. This mechanism is particularly useful in targeting rapidly dividing cells, such as bacteria in the lag phase of growth.

Antimicrobial agents can also disrupt the biofilm matrix on food surfaces by various mechanisms that target the structural integrity and functionality of biofilms. These agents can inhibit biofilm formation by preventing bacterial adhesion and growth, dismantling the extracellular matrix, or disrupting multiple biological pathways [17-20]. Natural antimicrobial compounds like usnic acid inhibit bacterial biofilm formation on polymer surfaces by interfering with the biofilm slime matrix [21].

1.2 Plant Extracts in Antimicrobial Packaging

Among the various antimicrobial agents used in packaging, plant extracts have garnered significant attention due to their natural origin and potent antifungal, antibacterial, and antibiofilm properties [20, 23, 24]. Plant extracts, especially essential oils and polyphenols are rich in bioactive compounds that can inhibit a broad spectrum of microorganisms. These natural agents are preferred over synthetic chemicals because they are biodegradable, non-toxic, and generally recognized as safe (GRAS) by regulatory authorities.

Essential oils derived from plants such as oregano, thyme, and clove are known for their strong antimicrobial activity. These oils contain compounds like carvacrol, thymol, and eugenol, which have been proven to disrupt microbial cell walls and interfere with their metabolic processes. Studies have shown that packaging films incorporated with essential oils can effectively inhibit the growth of pathogens microorganisms [25]. Polyphenols are another group of plant-derived compounds with significant antimicrobial properties. Tannins, flavonoids, and phenolic acids can damage microbial cell membranes and bind to microbial proteins, leading to the inhibition of enzyme activity and biofilm formation [26]. Packaging materials infused with polyphenols from sources like green tea, grapes, and olives have demonstrated effectiveness in prolonging the shelf life of food products by preventing microbial growth [27].

Jailani et al. [28] examined the capacity of tannic acid, a compound commonly found in woody plants, to selectively hinder the growth and generation of biofilms by Agrobacterium tumefaciens. Tannic acid exhibited antibacterial properties and effectively decreased the production of biofilm on both polystyrene surfaces and the roots of Raphanus sativus, as confirmed by 3D bright-field and scanning electron microscopy (SEM) pictures. In addition, tannic acid exhibited a dose-dependent effect in decreasing the virulence characteristics of A. tumefaciens, including swimming motility, exopolysaccharide synthesis, protease production, and cell surface hydrophobicity. Cells that were exposed to tannic acid for 24 hours at a temperature of 30 °C were analysed to study gene expression. The results indicated that tannic acid had a strong downregulating effect on the exoR gene, which is essential for the adherence of cells to surfaces.

Zhao et al. [29] investigated how tea catechin extracts affected the growth of three different MRSA strains as well as the formation of biofilms on their surfaces. According to the findings, tea catechin extracts were able to effectively inhibit the growth of MRSA strains, and the minimum inhibitory concentration of tea catechin extracts against these MRSA strains was 0.1 g/L. -en, tea catechin extracts prevented the development of biofilms by these strains in a dose-dependent manner, which was assessed using a colorimetric approach. Additionally, the inhibitory effect was demonstrated by an assay using scanning electron microscopy. As an additional point of interest, the adhesin genes biofilm-associated protein (bap), bone sialoprotein-binding protein (bbp), collagen-binding protein (cna), clumping factors A (clfA), fibronectin binding protein A and B (fnbA and fnbB), and intercellular adhesion gene BC (icaBC) were analysed, and the findings revealed that fnbA and icaBC were present in these three strains. Additionally, the expression of fnbA and icaBC was reduced in the strains when tea catechin extracts were used. As a result, the downregulation of fnbA and icaBC expression in these strains was probably connected with the suppression of biofilm formation that was caused by tea catechin extracts.

1.3 Packaging materials

Food packaging materials play a crucial role in preserving the quality and safety of food products. Among the most commonly used materials are plastics, metals, glass, and paper, each offering unique properties and benefits for various applications. According to Marsh and Bugusu [30], traditional food packaging materials include glass, metals such as aluminium, tinplate, and tin-free steel, which are valued for their excellent barrier properties against moisture, gases, and light, thereby extending the shelf life of food products significantly.

Plastics are widely used due to their versatility, light weight, and cost-effectiveness. They can be tailored to provide specific barrier properties and mechanical strengths. However, the environmental impact of plastic waste has driven research towards more sustainable options. Common types include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). Recent studies highlight the use of biodegradable and bio-based plastics, which decompose under natural conditions and reduce the environmental footprint. Jiang et al. [31] discussed the advancements in active materials for food packaging, including oxygen scavengers and antimicrobial agents incorporated into plastic matrices, which actively enhance the preservation of food by inhibiting microbial growth and reducing oxidation.

Glass remains a preferred material for packaging beverages and certain food products due to its inert nature, impermeability, and recyclability. It does not react with food contents, ensuring the preservation of flavour and quality. Metals, particularly aluminium and steel, are used extensively in cans and foil packaging. They provide strong barrier properties and are highly durable, making them suitable for long-term storage of food and beverages. The research by Deshwal et al. [32] emphasized the role of paper and paperboard in food packaging, highlighting their biodegradability and recyclability. These materials are often used for packaging dry food products, offering a balance between protection and environmental sustainability.

Clamshell packaging, a type of packaging that consists of two halves joined by a hinge, is widely used for its convenience and protective properties. It is commonly made from plastic materials such as polyethylene terephthalate (PET) and polyvinyl chloride (PVC), which offer clarity and durability. Clamshells are used for fresh produce, bakery items, and ready-to-eat meals due to their convenience and protection. A key study by Kao et al. [33] investigated the incorporation of calcined waste clamshell (CCS) powder into polyethylene (PE) bags to enhance their bacteriostatic properties. The findings revealed that the addition of CCS powder prolonged the shelf life of the packaged food by retaining its CaO bacteriostatic efficacy. This innovative approach highlights the potential of using waste materials to improve the functionality of clamshell packaging, particularly in the food industry

1.4 Methods of Incorporation

The integration of plant materials into packaging material is a rapidly advancing field aimed at developing sustainable and eco-friendly alternatives to traditional plastic packaging. These methods focus on incorporating natural compounds and fibers derived from plants to enhance the antimicrobial properties, biodegradability, and overall functionality of packaging materials. The incorporation of plant extracts into packaging materials can be achieved through several methods including surface coating, solvent casting, extrusion, electrospinning, layer by layer and encapsulation [34, 35]. Figure 2 summarizes those common methods.

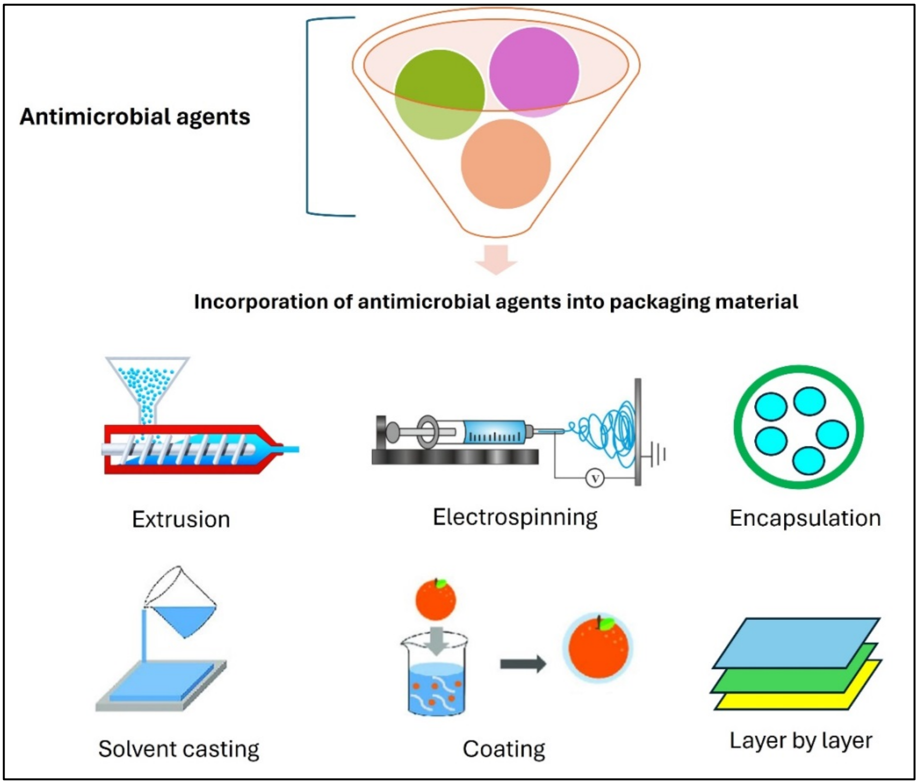

Fig. 2. Different methods commonly used for incorporating antimicrobial agents into packaging material for food packaging application.

Plant extracts can be applied as a coating on the surface of packaging materials. Surface coating method is particularly useful for creating a strong antimicrobial surface layer that can come into direct contact with the food product [36]. Encapsulation techniques, such as nanoencapsulation, can be used to protect plant extracts from degradation and control their release over time. This method enhances the stability and efficacy of antimicrobial agents [11]. Extrusion is a widely used method for incorporating plant materials into packaging. This process involves melting and shaping materials through a dye, allowing uniform distribution of antimicrobial agents within the polymer matrix [35]. Solvent casting is another common technique where plant extracts are dissolved in a solvent and mixed with a polymer solution. The mixture is then cast onto a surface and allowed to evaporate, forming a thin film. This method is particularly useful for incorporating heat-sensitive plant extracts that might degrade during extrusion. Electrospinning is a technique that uses electrical forces to produce fine fibers from a polymer solution [34]. Plant extracts can be incorporated into these fibers, creating packaging materials with enhanced functionalities. This method is particularly advantageous for creating nanoscale fibers with high surface area, which can improve the release and effectiveness of the antimicrobial agents. Layer-by-layer (LbL) assembly is a more advanced method where multiple layers of plant extracts and polymers are alternately deposited to build a multilayer structure [37].

In 2019, Radusin and colleagues [38] developed innovative active films composed of polylactide (PLA) with a 10 wt% extract of *Allium ursinum* L. (AU), commonly known as wild garlic, using electrospinning technology. The electrospinning process produced fibers within the 1–2 μm range, displaying a beaded morphology, indicating that the AU extract was predominantly encapsulated in specific fiber regions. These electrospun mats were subsequently annealed at 135 °C to form continuous films suitable for active packaging applications. Examination of the film cross-sections showed that the AU extract was embedded within the PLA matrix as micro-sized droplets. The addition of the AU extract was found to plasticize the PLA matrix and reduce its degree of crystallinity by interfering with the PLA chains' ability to fold into a crystalline structure. The electrospun PLA films containing the AU extract exhibited significant antimicrobial activity against foodborne bacteria.

Ordon et al. [39] developed active low-density polyethylene (LDPE) films incorporating a blend of CO2 extracts from rosemary, raspberry, and pomegranate using an extrusion process. The study demonstrated that these LDPE films inhibited the growth of *Staphylococcus aureus* and *Bacillus subtilis*. The integration of CO2 extracts into the polymer matrix altered its mechanical properties and enhanced its UV radiation barrier capabilities. These modified PE/CO2 extract films are promising candidates for functional food packaging materials due to their antibacterial and antiviral properties.

1.5 Future Trends and Smart packaging

Future research in antimicrobial packaging is likely to focus on optimizing the incorporation methods of plant extracts to enhance their stability and efficacy. Exploring new plant sources and bioactive compounds can expand the range of antimicrobial agents available for use in packaging. Innovations such as the development of smart packaging materials that can respond to environmental changes and release antimicrobial agents on demand are promising. Song et al. [40] provided insights into bio-based smart active packaging, which incorporates antibacterial agents, antioxidants, and other active compounds into biodegradable materials. These packaging materials not only respond to environmental changes but also enhance the sustainability of packaging solutions. The incorporation of bio-based agents ensures that the packaging is environmentally friendly while maintaining its antimicrobial properties.

2.0 Conclusion

In conclusion, antimicrobial packaging is a critical advancement in ensuring food safety and extending the shelf life of food products. The use of plant extracts as antimicrobial agents offers a natural and effective solution to combat microbial contamination. Despite the challenges, ongoing research and innovation hold great potential for the development of more efficient and consumer-friendly antimicrobial packaging solutions. The integration of these technologies into the food industry can lead to significant improvements in food safety, quality, and sustainability.

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Conflict of Interest. The authors have no competing interests to declare that are relevant to the content of this article.

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