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Review

# Smart Packaging Based on Polylactic Acid: Effect of Antibacterial and Antioxidant Agents from Natural Extract on Physical-Mechanical Properties, Colony Reduction, and Perishable Food Shelf Life

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**Abstract:** The changes in consumer lifestyles have raised awareness of the variety of food options and packaging technologies. Active and smart packaging represents an innovative technology that serves to enhance the safety and quality of products. Smart packaging, as a subset of this technology, entails the integration of additives into packaging materials, thereby facilitating the preservation or extension of product quality and shelf life. This technological approach stimulates a heightened demand for safer food products with prolonged shelf life. Active packaging predominantly relies on the utilization of natural active substances. Therefore, the combination of active substances has a significant impact on the characteristics of active packaging particularly on polymeric blend like Polylactic acid (PLA) as a matrix. So, This review will summarize and explains how the addition of natural active agents influenced the properties related to the performance of active packaging through systematic analysis, providing new insights about the relationship between the types of active agents on physical-mechanical properties, bacterial colony reduction, and applications in foods packaging such as meat, fish, fruit, and vegetables. Through their integration, the market for active and smart packaging systems is expected to have a bright future.

**Keywords:** colony reduction; food shelf life; mechanical properties; natural additive; PLA; smart packaging

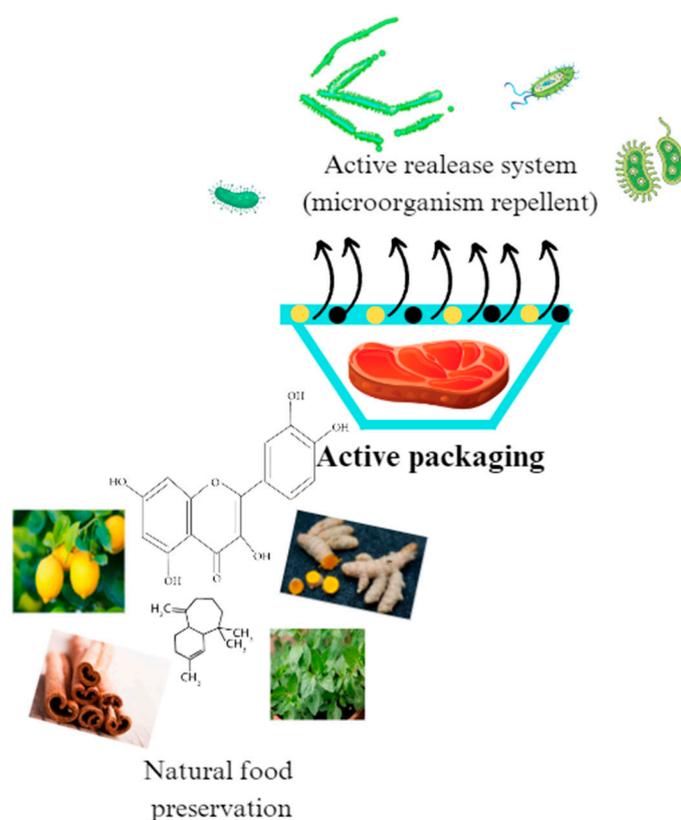
## 1. Introduction

The rise in plastic food packaging waste, due to the large number of industries involved in the production of fast food, led several countries to encourage their packaging industries to improve the efficiency of the food supply chain in order to reduce food spoilage and waste. To address this situation, incorporating active agents, such as antimicrobial and antioxidant compounds, into packaging materials has emerged as a viable solution for extending food shelf life, reducing food losses, and increasing food industry profitability (Ribeiro et al., 2021; Stanley et al., 2022; Deshmukh et al., 2022). Active packaging, also known as smart packaging, is designed to detect and alert to spoilage or other potential problems in packaged food (Pirsa et al., 2023; Osmolska et al., 2022; Khan et al., 2023). These systems, which are classified as direct (humidity, time-temperature, freshness, damage, and biosensor) and indirect (traceability and tracking), serve as quality indicators to ensure food safety (He et al., 2023; Firoozjah et al., 2023; Priyanka et al., 2023).

In order to maintain the product's nutrient, protection, and quality throughout the distribution chain and to ensure that it reaches consumers for final use and consumption, it is crucial to extend

the shelf life of food products through the control of microbial and chemical processes, both inside and on the product's surface (Khanna et al., 2022). Food can be stored and kept fresh for a long time in packaging with high barrier properties, which make it impermeable to gases and moisture (Olonisakin et al., 2023; Xue et al., 2023). High barrier properties also prevent chemical oxidation and lowers microbial spoilage, which is primarily caused by the presence of aerobic microorganisms. The microorganism activity provided information by the markers varies due to chemical differences, reactions, or microbiological development that occur as a result of time and processing. When metabolites produced by microbial growth interact with chemical compounds, they produce both a visual signal and information about degradation. (Dsouza et al., 2022; Das et al., 2023).

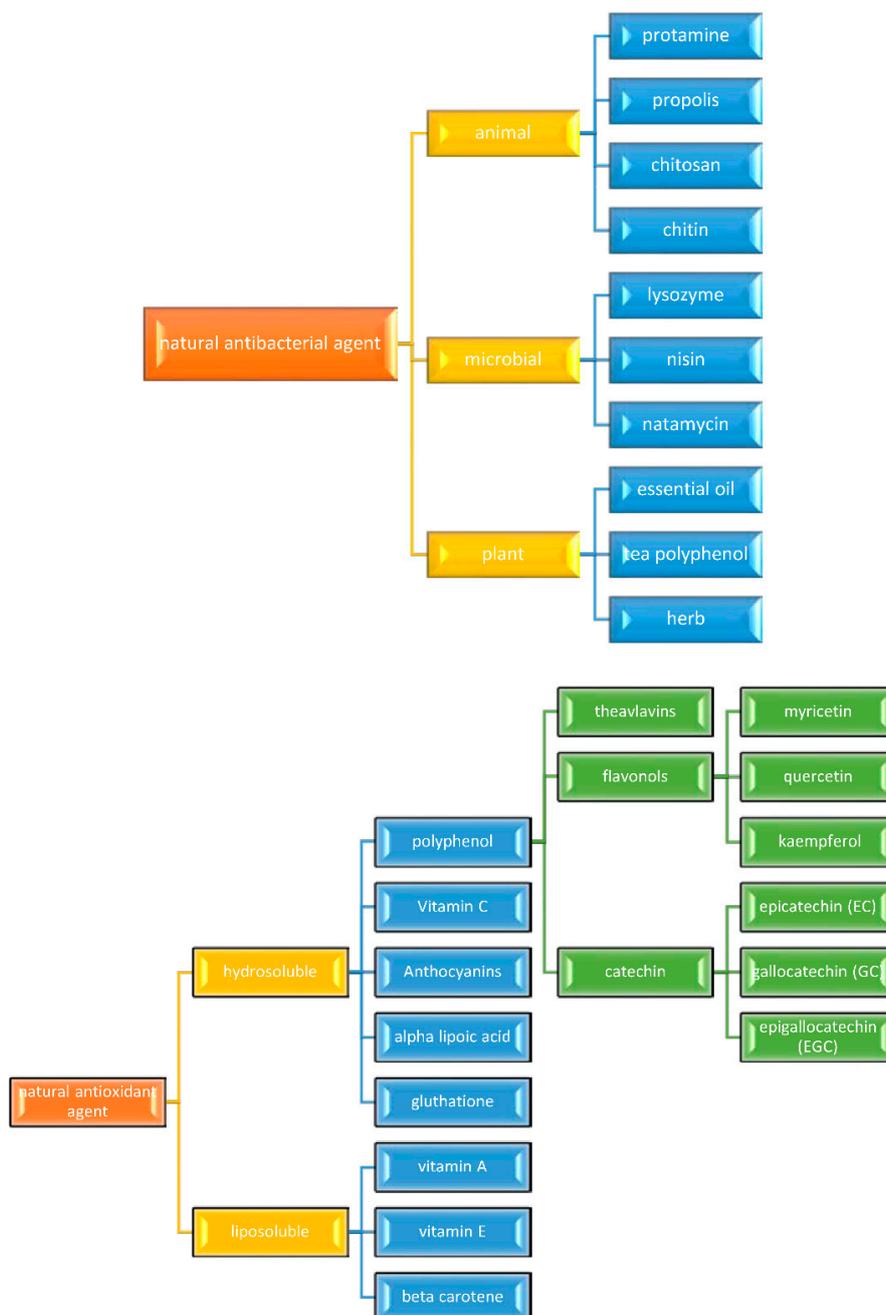
Utilizing plant extracts in active packaging systems presents a multifaceted approach to extending the shelf life of food ingredients. As shown in Figure 1 their antioxidant properties prevent oxidation, their antibacterial properties reduce microbial growth, and their active release mechanisms ensure a continuous protective effect. The anti-bacterial and anti-oxidant food packaging system is being developed to examine interactions between food components, packaging, and the environment in order to improve product quality, safety, and shelf life (Popescu et al., 2022; Rout et al., 2022; Thakur et al., 2023). However, the deployment of antimicrobial and antioxidant agents as packaging materials must adhere rigorously to established guidelines, particularly concerning toxicological repercussions. Antibacterial agents of various types, including organic synthetic antibacterial agents, inorganic antibacterial agents, and natural antibacterial agents, are now used in food preservation (Ahmed et al., 2022; Oyom et al., 2022; Wang et al., 2023). The three types of natural antibacterial agents are animal-derived antibacterial agents (such as protamine, propolis, and chitosan), microbial-derived antibacterial agents (such as lysozyme, nisin, and natamycin), and plant-derived antibacterial and anti-oxidant agents (such as plant essential oils, tea polyphenols, and Chinese herbal medicines) (Zhang et al; Jeong et al., 2023).



**Figure 1.** Active packaging system.

Natural antimicrobial and antioxidant agents are extracted and purified from raw natural sources, as depicted in Figure 2. This is due to their chemical constituents, encompassing compounds

like anthocyanins, catechins, vitamin A, and beta-carotene. Additionally, plant-derived materials mostly possess both antibacterial and antioxidant characteristics (Alonso et al; 2022; Zeng et al., 2022; Ailli et al., 2023). These constituents are frequently employed in the formulation of active packaging materials. As packaging systems with active features undergo diverse storage and processing circumstances, the degradation of food items within can lead to the creation of metabolites like volatile amines and organic acids thus, plant extracts are deemed safer compared to synthetically produced preservatives due to their origin as secondary metabolites within plants, as indicated in Table 1. Moreover, the robust antibacterial activity exhibited by plant extracts has been demonstrated, effectively inhibiting a range of foodborne pathogens such as *E. coli*, *Salmonella typhi*, *Staphylococcus aureus*, and *Bacillus cereus*. This serves to affirm their enhanced versatility across a spectrum of applications (Zhou et al., 2022; Bouslamti et al., 2022; Imade et al., 2022).



**Figure 2.** Sources of antibacterial and antioxidant agent.

**Table 1.** Common natural extract plant usually used to develop smart packaging.

Plant	Active components
Jamun	$\beta$ -humulen, $\alpha$ -guaiene, Caryophyllene, $\alpha$ -humulene, $\beta$ -elemene
Propolis	dihydrochrysin, pinostrobin, caryophyllene and chrysin
Green tea	epigallo-catechin gallate
Clove	eugenol, eugenyl acetate and caryophyllene
Turmeric	$\alpha$ -turmerone, $\beta$ -turmerone and ar-turmerone
Cinnamon	cinnamaldehyde, camphor, cinnamyl-acetate, caryophyllene, trans $\alpha$ -bergamotene, caryophyllene oxide, linalool, geraniol, bornyl acetate, eugenol, $\gamma$ -elemene, $\alpha$ -copaene, guaiol, and $\alpha$ -cubebene
Lemon	limonene, p-mentha-3,8-diene, $\beta$ -pinene, $\gamma$ -terpinene, myrcene, sabinene, myrcene, and geranial
Cymbopogon	myrcene, limonene, citral, geraniol, citronellol, geranyl acetate, neral, and nerol
Thymol	p-cymene, $\gamma$ -terpinene and thymol
Eucalyptus	1,8-cineol and $\alpha$ -pinene
Oregano	rosmarinic acid, linalool, thymol, carvacrol, tannins, flavonoids, triterpenes, phenol carvacrol, and thymol.
Syzygium aromaticum	eugenyl acetate, eugenol, and $\beta$ -caryophyllene

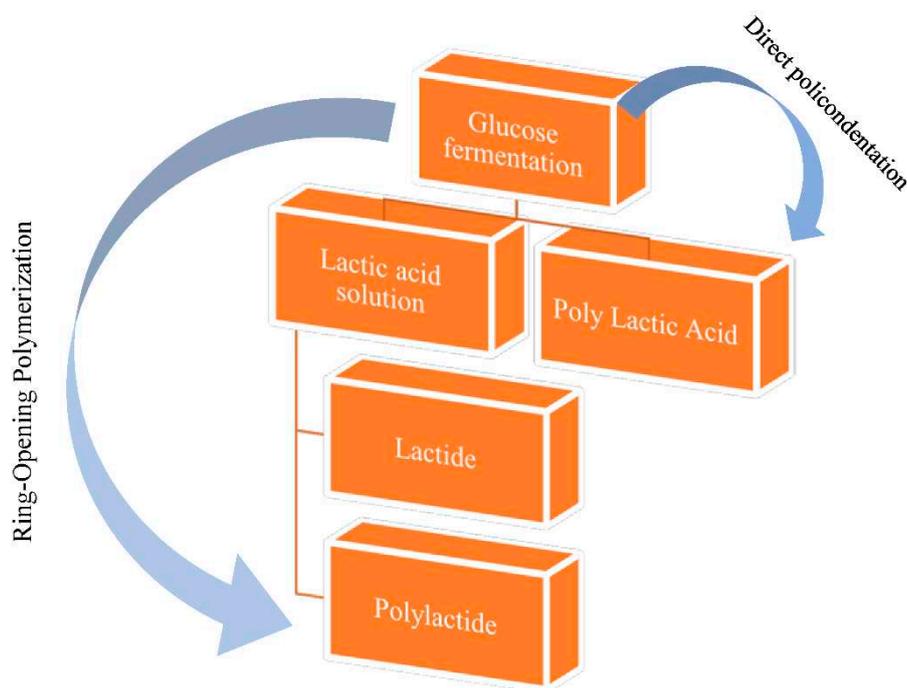
Nowadays, there is a high demand in the consumer market for healthy, organic, and wholesome products with a "clean" label. As a result, research into smart packaging to improve the quality and safety of food ingredients is critical. Therefore, food packaging has become part of modern civilization and developed using biopolymers materials. A biopolymer is an organic polymer contains of monomeric units of an organic substance that are covalently linked together. Posseses to biodegradability, means it can be broken down into the soil naturally by microorganisms, and it emits organic byproducts such as CO<sub>2</sub> and H<sub>2</sub>O that are beneficial to the environment.

In the context of active packaging, a range of polymers has been utilized as matrix for developing innovative solutions. Natural biopolymers, sourced from renewable materials, include starch, cellulose, chitosan, and proteins, known for their inherent biodegradability and compatibility with living systems. Conversely, synthetic polymers such as polyethylene, polypropylene, and polyethylene terephthalate offer adaptable mechanical properties and high barrier capabilities (Akshaykranth et al., 2022; Agrawal et al., 2022; Bonnenfant et al., 2022). Furthermore, chemically engineered synthetic biodegradable polymers like polylactic acid (PLA), polyhydroxyalkanoates (PHA), and polybutylene adipate terephthalate (PBAT), polyglycolic acid (PGA), polyvinyl alcohol (PVA) present customized degradation patterns, harmonizing ecological considerations with packaging effectiveness. This diverse array of polymers, encompassing both natural and synthetic origins, forms the cornerstone for active packaging systems endowed with a variety of functions aimed at augmenting product shelf life, ensuring safety, and addressing environmental concerns (Baranwal et al., 2022). Whereas the biopolymers are completely obtained from renewable resources, those are manufactured from non-renewable resources (fossil-sourced chemicals). Despite extensive efforts to enhance their properties using various techniques, biopolymer-derived materials

frequently lack the performance characteristics than traditional plastics, in term of strength, flexibility, and barrier qualities (Porta et al., 2020; Westlake et al., 2023).

PLA is one of the most promising biopolymers for a variety of food applications, and it can be converted into smart packaging through commercial manufacturing processes (Das et al., 2022). PLA is frequently suggested as a raw material for packaging and beverages because it offers better mechanical strength and durability with a good appearance compare with other polymers such as polyurethane, polystyrene, and polypropylene (Cvek et al., 2022; Marano et al., 2022). PLA has several desirable properties, including high transparency, clarity, and insoluble with air, ethanol, methanol, and aliphatic carbon (Freeland et al., 2022). The main disadvantages of PLA, especially for flexible food packaging applications, are its brittleness and heat distortion temperature, as well as its low water vapor barrier properties (Kumari et al., 2022; Bikiaris et al., 2023).

PLA can be made using two common methods as shown by Figure 3: Direct Polycondensation (DP) and Ring-Opening Polymerization (ROP) (Desai et al., 2023). Although DP is a simpler method for producing PLA than ROP, it can produce a brittle, low molecular weight form of PLA (Chong et al., 2022; Freland et al., 2022). Commonly, PLA produce by the sugar-based plant fermentation to produces lactic acid solution. After that, the lactic acid is converted to lactide, which is then converted to PLA. It should be noted that the lactic acid polymer is known by two different names: "Poly(lactic acid)" and "Polylactide". There is a scientific distinction because polylactide is produced via the ROP route, whereas PLA is produced via the DP route. The production and use of PLA results in significant energy savings and decreases in greenhouse gas emissions. Additionally, PLA degrades quickly and occurs within a few weeks in composting environments with high temperatures and high humidity (Mouhoubi et al., 2022).

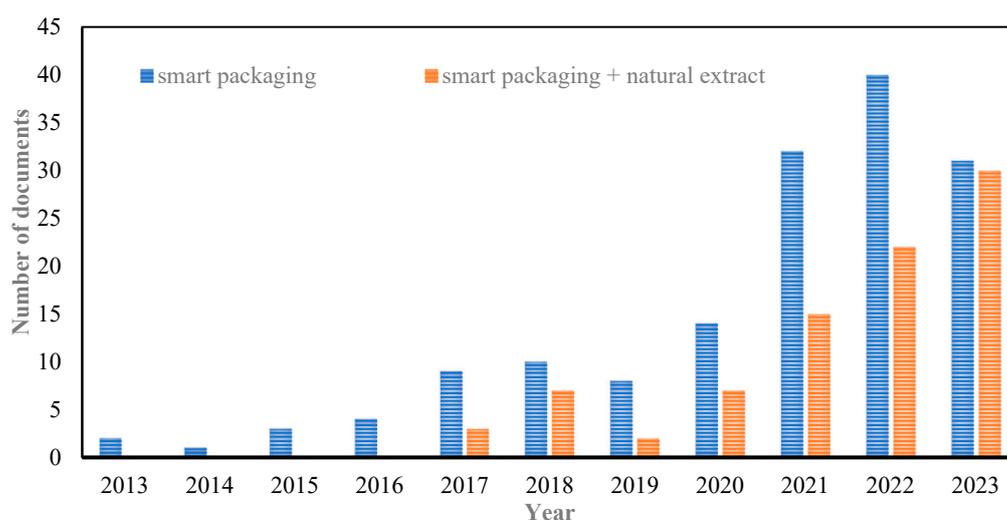


**Figure 3.** Methods to produce PLA.

Many researchers have previously investigated the development of active packaging based on PLA containing antioxidants and antimicrobials active agents. Study by Suwananamornlert et al., (2020) on PLA blends containing 3% and 6% thymol to produce smart packaging films. The films' in vitro antifungal activity against *Aspergillus spp.* and *Penicillium spp.* was evaluated. The addition of thymol significantly increased the thermal and barrier properties of the film, allowing it to extend the shelf life of bread packaging by up to 9 days compared to commercial polypropylene plastic. Zhang et al., (2021) also produced a different film that is UV-blocking and reduce microbial activity.

Modification was made by the addition of curcumin so that the packaging film showed significant antibacterial activity against *E. coli*. Packaging films also have strong UV inhibition capabilities and physical properties. Filipini et al., (2020) also produced active films using additives made from *syzygium cumini* peel extract. The 2,2-azinobis-3-Ethylbenzothiazoline-6-Sulfonic Acid (ABTS) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) methods were used to verify the samples' antioxidant activity. Due to the high concentration of phenolic hydroxyl groups in the film's structure and the addition more than 30% extract, the antioxidant properties of the film were increased, enable to scavenge free radicals by donating phenolic hydrogen atoms thus, improving food shelf life.

Drawing from the Scopus database based on Figure 4, it is evident that over the past decade, the field of smart packaging has evolved into a nascent discipline within the packaging development. This surge in interest within the smart packaging sector has surged by an impressive 140%. This advancement notably revolves around the exploration of natural extracts as term of "smart packaging + natural extract". However, up to the present, other studies that solely focus on the single properties of packaging materials or bioactive agents, but this review uniquely combines these elements to unravel a synergistic relationship. By investigating the intricate interplay between PLA and antibacterial-antioxidant agents derived from natural extracts, this paper delves into uncharted territory, exploring how the combined influence of these components not only influenced the physical-mechanical characteristics of the packaging material but also its efficacy in reducing microbial colonies and preserving perishable foods.



**Figure 4.** Scopus database from 2013-2023 with the keyword "Smart packaging" and "Smart packaging + natural extract".

The novelty of this review paper lies in its ability to present a holistic perspective, showcasing how the introduction of antibacterial and antioxidant agents from natural sources can multifaceted improvements to PLA-based smart packaging. This study underscores the profound impact of these agents on the packaging material's strength, flexibility, and barrier properties, while concurrently unveiling their potential to inhibit microbial growth and oxidative deterioration. Moreover, this review paper transcends traditional boundaries by pioneering a comprehensive examination of PLA-based smart packaging as an integrated ecosystem. As industries worldwide seek sustainable and effective packaging strategies, the findings and insights presented in this paper herald a significant advancement, setting a precedent for future research at the crossroads of materials science, biochemistry, and food technology.

## 2. Effect of the Antibacterial and Antioxidant Agent from Natural Extract on Physical-Mechanical Properties

### 2.1. Tensile Properties

The term "rough handling" emphasises the importance of tensile strength in the plastic packaging industry, which determining its ability to withstand and be safe from external pressure. Therefore, the tensile test is one of the most important parameters for evaluating the mechanical performance of polymer blends, particularly in the production of smart packaging. Tensile strength where the maximum force that a material can withstand and elongation at break where the material's extensibility. Among all biopolymers, PLA, an aliphatic polyester derived from renewable resources, specifically starch fermentation, caught the interest of researchers as a potential packaging material.

In spite of possessing commendable mechanical, thermal, and biodegradable characteristics, their practical applications encounter limitations stemming from inadequate flexibility, limited impact resilience, suboptimal barrier properties, and a constrained processing range. Attempts to enhance these characteristics have been undertaken through diverse methodologies, including blend with alternative biopolymers, chemical adaptations, and incorporation of responsive additives (Sharma et al., 2022; Shlush et al., 2022). As depicted in Table 2, variations in the tensile properties of intelligent packaging based on PLA hinge on the specific active agent employed. Typically, the tensile strength of PLA blends spans approximately 40 MPa to 70 MPa. Evidently showcased in Table 2 is the noteworthy decline in all resultant tensile strength values. The active agent which is from the essential oil group decreases the tensile strength value due to a heterogeneous internal structure with lower cohesiveness (Klinmalai et al., 2021; Maroufi et al., 2021). The tensile strength of the resulting film also decreases due to the plasticizing effect of essential oils. Essential oils are highly hydrophobic so they affect the hydrophilic/hydrophobic balance of the film (Suwanamornlert et al., 2020; Lukic et al., 2020). Based on the previous works, it can be concluded that the tensile properties of PLA smart packaging are influence by amount of active agent, type of active agent, and specific formulation of the PLA blend.

**Table 2.** Tensile Properties of PLA based Smart Packaging.

PLA/Active agent composition (%)	Active agent	Tensile strength (MPa)		Elongation at breaks (%)		Referencee
		a	b	a	b	
98/2	green tea extract	12.52	10.29	260.11	121.95	Andrade et al., 2023
95/5	carvacrol	26.8	16.4	267.3	194.9	Klinmalai et al., 2021
97/3	clove essential oil	43.30	11.8	2.60	30.7	Lu et al., 2021
98/2	mango peel extract	57.77	46.48	6.77	14.31	Cheng et al., 2021
99/1	thyme essential oil	2.90	3.90	11.33	23.19	Maroufi et al., 2021
95/5	mediterranean propolis extract	36.80	26.2	2.9	3.0	Ardjoum et al., 2021

91/9	thyme essential oil	64.16	49.81	3.08	175.99	Suwanamornlert et al., 2020
95/5	thymol	29.6	4.02	176.4	76.61	Lukic et al., 2020
98/2	rice straw extract	34	34	6	3.4	Freitas et al., 2020
99.5/0.5	pomegranate peel extract	88.7	67.92	47.3	69.04	Dai et al., 2022

<sup>a</sup> control sample, <sup>b</sup> sample with active agent.

Essential oils can also reduce the oxygen permeability of the film by forming a more porous microstructure. The mechanical properties of the film will be modified due to the development of structural discontinuities, which results in flexibility and lower resistance to cracking. Elongation at break shows a different pattern. The incorporation of PLA with essential oils into the film results in a slight increase in the data's average elongation at break value. Depending on the molecular structure of the substances, processing techniques, and operating conditions, the effect of active substances that function as antibacterial and antioxidant agents will also affect the mechanical properties of packaging films.

The increased elongation at break observed in the films is also a result of the essential oil loading's plasticizing effect, which reduces stiffness and increases film flexibility by allowing more chain mobility. However, essential oil concentrations greater than 10% by weight cause an antiplasticization phenomenon in which the interaction between the plasticizer and polymer molecules is stronger, inhibiting macromolecule mobility and leading to a very brittle film (Chen et al., 2022; Gunny et al., 2023; Cui et al., 2023). The addition of anthocyanin-rich plant extracts such as pomegranate also reduced the film's tensile strength, but only by 15-20% because it was able to maintain denser film through interfacial adhesion (Andrade et al., 2023; Dai et al., 2022; Ardjoum et al., 2021). Thus, when producing smart packaging, the chosen combination of polymeric materials and active agents must have similar properties in order to achieve better interfacial adhesion. Thus, using a hydrophilic polymer matrix and hydrophilic agents, or hydrophobic and hydrophobic, results in a strong bond between the materials (Mohammed et al., 2022). Matrix and active agents with similar properties also imply better dimensional stability and maintain their mechanical properties.

When running research, it might be challenging to figure out the appropriate quantity of active agent to add in order to achieve optimal interaction between the additive and the matrix while avoiding phase separation and filler particle agglomeration. Table 2 also shows that the addition of an active agent between 0.5% wt and 20% wt has plasticizing properties because it contains a lot of aromatic ring structures that inhibit the polymer network from being arranged closely, providing more flexibility and higher elongation at break value. By weakening the chain's structure, the plasticizing effect also reduces cohesiveness and increases deformability and flexibility, partially replacing the stronger polymer-polymer interactions. Unless nanofiber is added, which can lengthen polymer chains, as research by Maroufi et al., (2021) found, nanofiber which has outside forces such as rigidity and durability of the film, provide in situ polymerization and ends up in the formation of covalent bonds while monomers or polymer chains interact with the filler materials.

## 2.2. Water Vapour Transmission Rate (WVTR)

The WVTR value is a standard measure of how easily moisture can penetrate the film, the packaging's ability to withstand different humidity levels at different temperatures, and the ability to keep the quality of the food ingredients inside until it reaches the consumer. For food products, moisture migration can lead to undesirable texture changes or a loss of flavor. Controlling moisture through proper packaging helps preserve the product's sensory qualities. Moisture also causes packaging materials to warp, labels to detach, and colors to fade, affecting the overall appearance and appeal of the product; therefore, a consistent WVTR value ensures that products maintain a consistent weight, volume, and overall quality, helping manufacturers deliver products that meet consumer expectations. Typically for solid polymers, the transmission of water vapor follows a simple mechanism whereby water vapor penetrates the film by adsorbing on the surface, dissolving rapidly, thereby establishing an equilibrium that spreads through the film and desorption on the surface exits.

The use of films as a potential material for food packaging is greatly limited by the higher water vapor transmission rate (WVTR) of the films. Since PLA-based films indicate high WVTR based on previous studies, strengthening strategies using natural extracts and essential oils have been known to improve the barrier properties of PLA-based films. However, based on Table 3, the additive incorporation must be considered because it will change the balance of the film's hydrophilicity and hydrophobicity (Ordonez et al., 2022; Nasrollahi et al., 2022). The main factors that influence WVTR are differences in the physical properties of the matrix and additive, operating conditions, the diffusion coefficient, the solubility of water molecules, and the three-dimensional structure formed by hydrogen bonding (Ahari et al., 2022). The types of molecules and their compatibility of additives with the matrix are important factors affecting dispersion and physical and/or chemical interactions with the polymer matrix, along with chemical structure and polarity. The WVTR value in the film, however, is also influenced by others variables, including the crystallinity of the polymer, as well as the absorption of molecules inside in the matrix (Mohd aris et al., 2019; Palai et al., 2020; Srisa et al., 2020).

**Table 3.** Effect of different film composition on WVTR.

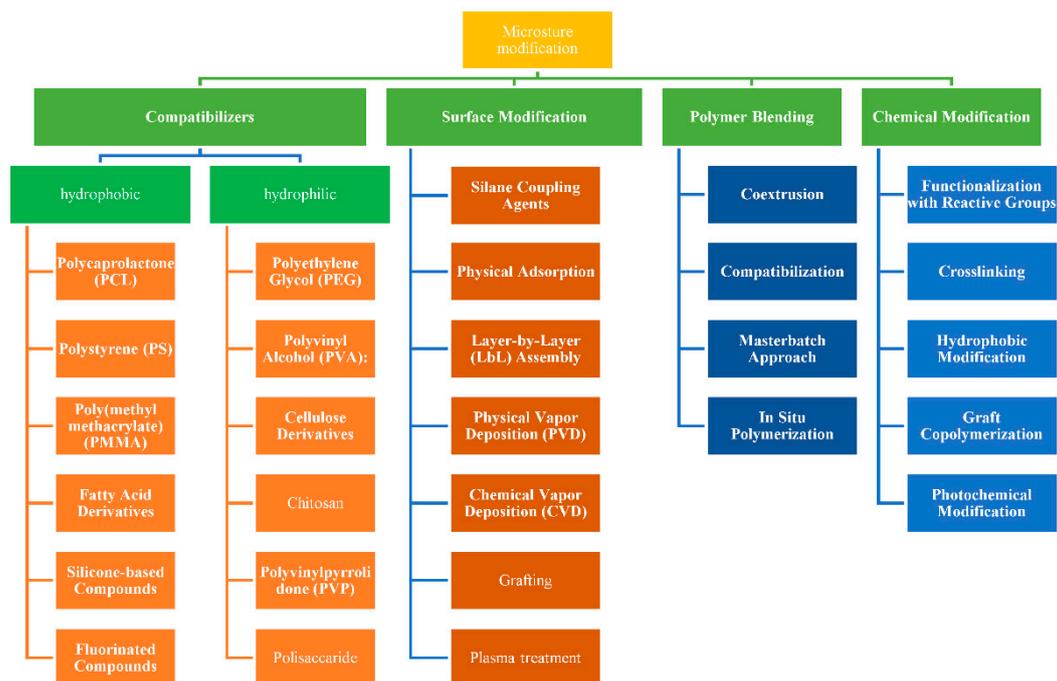
Film composition	WVTR (g/m <sup>2</sup> /s x 10 <sup>-4</sup> )		Effect on film properties	Reference
	a	b		
PLA-Cinnamon essential oil	0.345	0.793	• cinnamon essential oil is hydrophobic, creates pores that absorb more moisture	Aguilar et al., 2023
PLA- Betel leaf ethanolic extract	0.410	0.30	• betel Leaf Ethanolic Extract boosts molecular cross-linking, which reduces hydrophilic functional groups and slows water migration	Tagrida et al., 2022
PLA/PBAT-Peppermint essential oil	0.916	1.036	• peppermint essential oil reduces the structural cohesiveness of the mixed film, allowing moisture to pass through the film more easily	Gui et al., 2022
PLA-Rosemary essential oil	1.70	1.58	• the strong hydrophilicity of the biopolymer was attributed slight decreased in the water vapour barrier properties	Fiore et al., 2021
PLA-Carvacrol essential oil	0.045	0.043	• carvacrol essential oil (CEO is primarily made up of nonpolar hydrocarbon atoms (C-H) in the liquid phase, which makes	Laorenza et al., 2021

				nonpolar permeant molecules able to move around	
PLA-PEG	6.28	6.44	•	PEG is hydrophilic, as the contact angle value rises, the hydrophilic properties also rise proportionally, and the contact angle value decreases water permeability	Sundar et al., 2021
PLA/PBSA	0.175	0.129	•	PBSA crystallites to create diffusion pathways for oxygen gas molecules, thus increase films barrier	Palai et al., 2020
PLA/PBAT-Trans-cinnamaldehyde	0.154	0.169	•	PLA and trans-cinnamaldehyde have an intense interaction, leading to plasticizing effect and an increase in free volume, which increases WVTR	Srisa et al., 2020
PLA-Pea Starch	0.22	0.27	•	higher pea starch loading made it easier for water molecules to saturate the bilayer films' surface through the hydroxylated PS/PLA chains and then enter the films through the spaces between starch molecular chains	Zhou et al., 2019
PLA-Chitosan	3.75	0.085	•	chitosan is hydrophilic and has poor water vapour barrier properties, higher amount of it causes the WVTR to increase	Mohd aris at al., 2019
PLA/PHB-Cinnamaldehyde	0.26	0.69	•	cinnamaldehyde aldehyde group's hydrophilicity resulting higher WVTR	Ma et al., 2018
PLA-Oregano Essential Oil	0.112	0.135	•	WVTR of PLA composite films explained the presence of oregano essential oil made the average film pore size larger	Liu et al., 2016.

### 3. Effect of the Antibacterial and Antioxidant Agent from Natural Extract on Microstructure of Smart Packaging

The microstructure of smart packaging materials, can be engineered to create effective barriers against external factors such as moisture, oxygen, light, and contaminants (He et al., 2023). By carefully tailoring the microstructure, packaging materials can prevent the ingress of these detrimental elements, thereby safeguarding the sensory characteristics, nutritional value, and overall quality of the packaged food. This preservation is especially important for perishable and sensitive products. Smart packaging's microstructure can be designed to slow down the deterioration processes that occur in food over time (Janjarasskul et al., 2018). For instance, incorporating oxygen-absorbing or moisture-absorbing materials at the microstructural level can reduce the rate of oxidative reactions and microbial growth, effectively extending the shelf life of the product. This is not only economically beneficial but also contributes to reducing food waste.

Integrating active agents within the microstructure of smart packaging allows for controlled and targeted release. This is particularly advantageous when active compounds, such as antimicrobial agents or antioxidants, are incorporated. The microstructure can facilitate the gradual release of these compounds, providing continuous protection against spoilage microorganisms and oxidative reactions, thereby maintaining food safety and quality (Carpena et al., 2021). A common attempt has been used by previous researchers to enhance compatibility and facilitate interactions between polymeric blend in the production of smart packaging systems (Figure 5).



**Figure 5.** Microstructure modification of smart packaging based on PLA.

Microstructure modification also encompasses changing the configuration and characteristics of materials at the microscopic scale with the aim of attaining targeted enhancements in the functionality of food packaging. This process has the potential to augment properties such as barrier capabilities, adhesion, compatibility, and the holistic performance of the packaging system. The roles of compatibilizers, surface modification, polymer blending, and chemical modification are:

- **Compatibilizers** are additives used to improve the compatibility between two or more polymers with differing properties. In food packaging, where different polymers may need to work together, compatibilizers help create a cohesive structure and improve properties like adhesion, mechanical strength, and barrier performance. Compatibilizers achieve this by promoting interfacial interactions between polymers that would otherwise phase separate or have weak interactions.
- **Surface modification** encompasses the adjustment of material surface characteristics to amplify adhesion, wettability, and harmonization with additional substances. Surface modification assumes paramount significance in optimizing the interplay between packaging materials and the contents. Methodologies such as plasma treatment, Layer-by-Layer (LbL) Assembly, and chemical grafting engender the introduction of functional groups onto the surface, fostering an augmented propensity for adhesion or coating. This, in turn, elevates the packaging material's barrier properties, print quality, and holistic performance.
- **Polymeric blending** techniques offer effective ways to improve adhesion and compatibility between hydrophilic or hydrophobic polymer materials in smart packaging systems.
- **Chemical modification** involves changing the chemical structure of the polymer to achieve the desired properties. Functional groups can be introduced to improve compatibility, adhesion, or specific interactions. In food packaging, chemical modification can adapt the properties of the packaging material to meet specific requirements.

Surface modification has been extensively explored and applied in active packaging research, as evident from the existing paper publications (Kuai et al., 2022; Almasi et al., 2021; wu et al., 2022; Khuntia et al., 2022;). Surface modification techniques offer a wide range of applications in active packaging (enhancing barrier properties, incorporating functional groups for controlled release or antimicrobial effects, minimizes disruption to the overall structure while significantly improving

adhesion, and compatibility). Surface modification also complement other techniques, such as incorporating antimicrobial agents, antioxidants, or moisture absorbers. Otherwise, component selection and blending methods should be considerate to achieve the desired compatibility while maintaining the essential properties of the packaging material. In-depth characterization and testing are crucial to ensure the successful integration of blended polymers in functional packaging solutions.

#### 4. Effect of the Antibacterial and Antioxidant Agent from Natural Extract on Colony Reduction

The use of antibacterial agents is paramount in thwarting the formation of biofilms, intricate microbial communities that adhere to surfaces and are enveloped within a protective matrix. This multifaceted process initiates with the attachment of bacteria to a surface, setting the stage for biofilm development. Active components present in substances such as essential oils and plant extracts, for instance, possess the capability to modify the structural composition of bacterial cell membranes. Study by Loest et al., (2022) indicated that the transformative action renders of bacterial attachment to surfaces more challenging. Moreover, the biofilm matrix, comprising extracellular polymeric substances (EPS), furnishes a safeguarding shield for bacteria within the biofilm community. This defensive layer is susceptible to degradation or disruption by antibacterial agents, thereby compromising the biofilm's structural integrity and rendering it more vulnerable to removal.

*Staphylococcus aureus*, *Listeria monocytogenes*, *Escherichia coli* O157:H7, and *Salmonella Typhimurium* are sources of biofilm-forming behind global instances of foodborne illnesses (Isilva et al., 2023; Salimnejhad et al., 2023). These virulent microorganisms can contaminate a spectrum of foods, spanning from ready-to-eat vegetables to processed meat products. Their stature as enteric pathogens leads them to a mounting concern in public health circles (Melo et al., 2023). Associated with afflictions like diarrheal disease, peritonitis, colitis, bacteremia, infant mortality, and urinary tract infections worldwide, these pathogens inflict substantial economic burdens due to treatment costs. In the context of biofilm growth, where bacteria adhere to surfaces, an avenue to curtail the pathogenic influence of Gram-positive bacteria involves impeding their adherence to both living and non-living surfaces (Sedarat et al., 2022; Pandey et al., 2022).

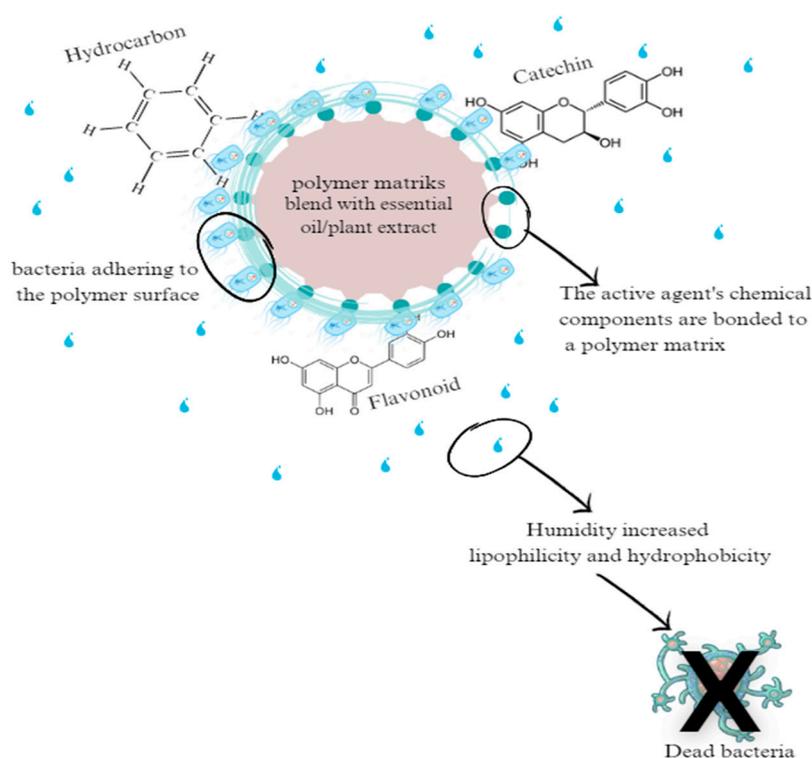


Figure 6. Dead cell mechanism.

Usually in food spoilage, an active agent is released into the *Staphylococcus aureus*, *Listeria monocytogenes*, *Escherichia coli* O157:H7, or *Salmonella typhimurium* membrane structure due to the presence of moisture in the air, which increases lipophilicity and hydrophobicity, which causes membrane expansion, increased membrane fluidity and permeability, disruption of membrane-embedded proteins, inhibition of respiration, and changes in bacterial ion transport processes. The active agent destroys the bacterial cell membrane and binds directly to DNA gyrase. DNA gyrase is an essential part of bacteria that plays an important role in the replication of DNA and chromosomal segregation. One of the most extensively investigated mechanisms for killing bacteria is the inhibition of DNA gyrase. The antibacterial activity of a group of chemical substances that consist of flavonoids, hydrocarbons, and catechins will interact with the outermost layer of the porin protein of bacteria, preventing the porin's primary function, specifically the transportation of small hydrophilic molecules such as glucose, thereby preventing its growth. Other study data has report that the flavonoid group adheres to the cell surface, potentially altering its properties and interfering with the interaction between the bacterial cell and the substrate surface (Silva et al., 2017; He et al., 2020).

Secondary metabolites such as alkaloids, flavonoids, steroids, saponins, terpenoids, and tannins are likely to be responsible for this antibacterial activity in plant extracts and essential oils (Fontes et al., 2023; Serna et al., 2023; Mao et al., 2022). Each plant extract and essential oil inhibits bacteria at a different level, which is probably due to the different active compounds found in each extract. Furthermore, the combination of compounds from different plant extracts, particularly flavonoids—an abundant group of secondary metabolites in plant tissues and essential oils—demonstrates a synergistic antibacterial effect. It is important to remember that the compatibility of hydrophilic compounds and hydrophobic matrices can influence the effectiveness of antimicrobial properties. As shown in Table 4, the incorporation of plant extracts prevails over essential oils in terms of bacterial colony reduction. Additionally, it was discovered that due to variations in the structure of the bacterial cell wall and outer membrane, Gram-positive bacteria were more susceptible to PLA films containing active essential agents than Gram-negative bacteria (Stoleru et al., 2021; Aziman et al., 2021; Pabo et al., 2021).

**Table 4.** Inhibitory effect of active agent addition on inhibitory effect.

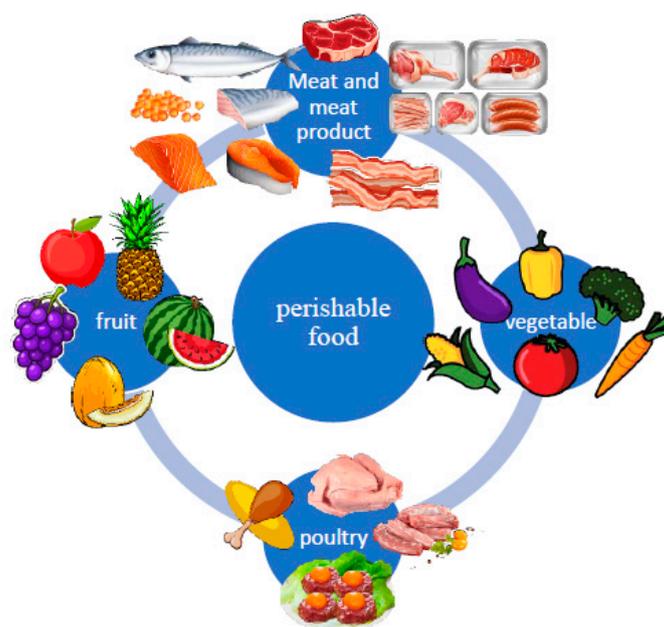
Polymers	Inhibitory effect	Reference
PLA- pink pepper essential oil	Pink pepper essential oil contains myrcene, which has antimicrobial action against <i>S. aureus</i> and <i>L. monocytogenes</i> , resulting in an inhibitory effect on day 21 of storage for <i>L. monocytogenes</i> and <i>S. aureus</i> were 30 and 62%, respectively.	Fontes et al., 2023
PLA-d-Limonene essential oil	Regardless of irradiation source or d-limonene loading, PLA/limonene films demonstrated 99.99% efficiency against <i>Escherichia coli</i> .	Serna et al., 2023
PLA-Polyphenols quarcetin	The antibacterial level of reducing bacterial colonies against <i>Escherichia coli</i> films based on PLA increased to 87.8% with the addition of the polyphenol quercetin.	Mao et al., 2022
PLA-Ginger Essential Oil	The bacterial growth of the PLA/Ginger Essential Oil composite film was gradually stopped because of the presence of $\alpha$ -zingiberene and $\beta$ -sesquiphellandrene.	Mohan et al., 2022

PLA-Carvacrol essential oil	Carvacrol-containing films inhibited the growth of <i>Rhizopus sp</i> and <i>Penicillium sp</i> .	Klinmalai et al., 2021
PLA-Argan essential oil	The addition of argan essential oil was able to reduce the bacterial colonies of <i>E. coli</i> (86.5%), <i>L. monocytogenes</i> (72.2%) and <i>S. Typhimurium</i> (81.9%).	Stoleru et al., 2021
PLA-Persicaria hydropiper extract	The antibacterial activity of the ethanol extract of Persicaria hydropiper was able to reduce the growth of <i>S. aureus</i> (12.5%) but was unable to reduce the growth of <i>E. coli</i> and <i>S. Typhimurium</i> .	Aziman et al., 2021
PLA-Oregano essential oil	The growth inhibition of <i>S. Typhimurium</i> , <i>E. coli</i> , and <i>L. monocytogenes</i> was up to 99%, after the addition of oregano oil stopped the growth of pathogenic bacteria in vitro.	Pabo et al., 2021
PLA-Thyme essential oil	<i>E. coli</i> growth was slightly inhibited by thyme oil film (2.76%).	Sharma et al., 2020
PLA-Allium ursinum extract	Antimicrobial activity of <i>Allium ursinum</i> extract reduced colony growth of <i>S. aureus</i> (53%) and <i>E. coli</i> (100%)	Radusin et al., 2019

## 5. Effect of the Antibacterial and Antioxidant Agent from Natural Perishable Food Shelf Life

Foods are perishable because they have a short shelf life and are extremely sensitive to factors like humidity, temperature, and other factors. The refrigerator has prolonged the shelf life of perishable food up until this point, but food deterioration is unavoidable. Nowadays, improving packaging systems has become essential for preserving the quality of food ingredients. Bacterial biofilm formation is regarded as a newly emerging microbial lifestyle that thrives on all types of surfaces and is present in both natural and artificial environments.

As shown in Figure 7, meat, poultry, egg products, salads, tuna, chicken, potatoes and macaroni are the main foods that are commonly infected with bacterias (Chowdhury et al., 2023). Foods rich in protein tend to be decomposed by bacteria. A Gram-positive bacterium that can attach to glass, metal, and plastic as an abiotic surface and host tissue as a biotic surface (Carrascosa et al., 2021). The attachment of those bacteria to surfaces depends on components of the bacterial microbial surface that recognize adhesive matrix molecules for proteins. To prevent the attachment to the surface through the matrix, the surface must be coated with anti-adhesion agents such as arylrhodamines, calcium chelators, essential oils, plant extracts, silver nanoparticles and chitosan (Partovi et al., 2020; Wang et al., 2021; Hojatoleslami et al., 2022).



**Figure 7.** Types of food that are susceptible to microorganisms.

Even when optimal conditions are provided during distribution, agricultural products have a short shelf life from the time of harvest due to quality degradation between harvest and consumption (Sangeetha et al; 2020; Ahmad et al., 2021). If the product is not handled properly, this loss in quality could be significant. Both for producers and consumers, quality is a key marketing component that is becoming more and more crucial. Therefore, quality management is crucial in the distribution of agricultural products. Definitions of quality have been developed in various research fields as a result of this growing significance. It is inevitable for foodborne pathogens to form biofilms, which can contaminate food (Chen et al., 2021). There have been numerous studies, as shown in Table 5, that investigate the use of natural ingredients as natural preservatives that are safe for use in packaging systems.

**Table 5.** The effect of active agent addition on perishable food shelf life quality.

Polymers	Methodology	Activity	References
PLA-Lemon extract	Lipid Oxidation Assays of almond including: Thiobarbituric acid-reactive substances (TBARS), Fat extraction, Peroxide value, <i>p</i> -Anidisine value	• The phenolic compounds in lemon extract improved the effectiveness of the film in preventing lipid oxidation in almonds kept at 40 °C for 30 days (83.33%).	Andrade et al., 2023
PLA-Olive Pomace Extract	Physicochemical parameters (hardness, weight loss, and color) were evaluated for 12 days of storage at 4 °C.	• olive pomace extract maintained or increased the fruit's total phenolic	Madureira et al., 2023

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		index and antioxidant potency while having no effect on firmness.	
PLA- Lippia citriodora essential oil	The Quality Index Method (QIM) was used to perform sensory analysis on the rainbow trout fillet skin appearance (shiny to dull), the color of the fillets (pink to dark pink), the odor (freshness, seaweed, sour and rancid), and the texture (firm, elastic, soft, and very soft)	• A score of "excellent" was given, and Lippia citriodora essential oil had no adverse effects on the sensory qualities of fish fillets.	Hojatoleslami et al., 2022
PLA-Perilla essential oil	Kjeldahl distillation was used to determine the TVB-N content of chicken breast fillets.	• This film increases the shelf life of chilled chicken by up to 12 days, as measured by a Total Volatile Base Nitrogen (TVB-N) 28.95 mg/100 mL	Wang et al., 2021
PLA- Marjoram essential oil	The total volatile base nitrogen (TVB-N) content of meat samples was determined using the AOAC (Association of Official Analytical Chemists) method.	• a reduction of 1 log CFU/g of bacteria in beef was observed between the group that used marjoram essential oil	Partovi et al., 2020
PLA- Oregano essential oil	TVC was calculated to track when minced fish began to deteriorate microbiologically (TVC > 7 log cfu/g). Thiobarbituric acid (TBA) based on Malondialdehyde (MDA) value and Sensory evaluation (acceptability test) was performed using hedonic scale point with 9 (most liked) and 1 (least liked) for minced fish.	• It concludes that after the sixth day of storage, the MDA value is useless because the TVC has reached or exceeded the limit value of 7 log cfu/g.	Zeid et al., 2019
PLA-Green tea extract	smoked salmon tested based on fat extraction to examine peroxide value, <i>p</i> -Anidisine value and TBARS.	• Aldehydes were present, as indicated by the <i>p</i> -anisidin value, and TBARS demonstrated a	Martins et al., 2018

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33% reduction in  
aldehyde.

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As can be seen in Table 5, the addition of active agents can increase the shelf life of food ingredients (33% TBARS reduction in aldehyde) in food samples packaged with active films for 12 days to 30 days since of the most important processes causing the deterioration of meat and meat products is lipid oxidation. Aldehydes, ketones, and alcohols are just a few of the volatile and nonvolatile compounds that are produced when the lipids in meat oxidize (Martins et al., 2018). These compounds provide meat its rancidity, taste, odor, and color loss. One of the most important indicators for assessing the freshness of meat and meat products is TVB-N content. TVB-N is primarily made up of ammonia (NH<sub>3</sub>), dimethylamine, trimethylamine, putrescine, and cadaverine, which are created when putrefactive microorganisms break down protein and non-protein nitrogen components like nucleic acids. Study by Wang et al., (2021) measured TVB-N 28.95 mg/100 mL and explained that active packaging can preserve the quality of chicken meat because, in accordance with TVBN standards, chicken breast should not contain more than 60 mg/100g of TVBN. Many factors can influence the migration of bioactive compounds from the film matrix to the food surface, including the amount of water in the food and the interaction between PLA and plant extracts or essential oils. Foods rich in water content can cause bioactive substances to migrate more quickly from the film matrix to the food surface (wang et al., 2021). Additional factors such as film thickness and hydrophilicity may impact the rate at which bioactive substances migrate from the film matrix to the food surface.

## 6. Future Trend of Smart Packaging System

Rice, poultry and poultry products, dairy, beverages, fruit, frozen foods, candy, and snacks are the most common food purchased. But, fresh meat, vegetables, and fruits are most popular among workers nowadays as a result of the need for new and natural products as well as changes in consumer lifestyles, particularly during a global epidemic. However, the food industry faces the challenge of preserving the freshness of those products over long periods of storage. Many countries around the world have adopted active packaging technologies to some extent. The adoption of active packaging is not limited to a specific country but rather depends on the industry, market demand, and technological advancements. Countries with advanced food and pharmaceutical industries, such as the United States, Japan, Germany, and South Korea, have been early adopters of active packaging solutions. These countries often prioritize research and development in packaging technologies to improve product safety, shelf life, and consumer experience. However, active packaging concepts have been embraced to varying degrees in numerous other countries as well. According to the compound annual growth rate (CAGR), the smart packaging market is projected to reach USD 18.67 billion by 2028, growing at a CAGR of 6.55% during the forecast period (2023-2028). In 2023, the market worth more than USD 13.59 billion. The need for smart and innovative packaging systems is not only limited to foodstuff. The cosmetic and skincare industry has also started to apply smart packaging for commercialized products. They focus on promoting product packaging that can be recycled at room temperature as a marketing strategy to attract consumer interest.

The production of smart packaging faces a common challenge, some of which are related to the kinetics of agent release, the compatibility of polymers and additives, and interactions between substances therefore, it can compete with the characteristics of conventional plastics. Moreover, the implementation of smart packaging also will face techno-economic challenges:

1. **Cost** Developing and incorporating smart packaging can be expensive, potentially increasing the overall cost of production and affecting product pricing.
2. **Compatibility:** Ensuring compatibility between different components of smart packaging, such as sensors and communication systems, can be challenging.
3. **Data Security:** Smart packaging often collects and transmits data, raising concerns about data security, privacy, and potential breaches.

4. Regulations: Compliance with regulatory standards and certifications can be intricate, especially in industries like pharmaceuticals and food where safety is crucial.
5. Consumer Acceptance: Introducing new technology to consumers may require education and demonstration to ensure their understanding and willingness to use smart packaging.
6. Sustainability: Balancing the integration of electronics with sustainable and recyclable packaging materials can be challenging.
7. Technical Reliability: Ensuring the reliability and accuracy of sensors and communication systems over the entire product lifecycle can be complex.

Addressing these challenges requires collaboration among researcher in smart packaging, experts, technologists, and manufacturers to develop cost-effective, reliable, and user-friendly smart packaging solutions.

## 7. Conclusions

The integration of smart technologies into PLA-based packaging enhances its functionality and value. Smart packaging can incorporate features like sensors, and indicators to monitor various aspects of the packaged product, such as temperature, freshness, and authenticity. These capabilities offer several benefits, including improved supply chain visibility, enhanced product safety, and reduced food waste. The influence of natural extracts and essential oils on PLA-based smart packaging can be examined through their impact on the material's physical, mechanical and structural properties, interfacial adhesion as well as their role in colony reduction. The efficacy of plant extracts, encompassing active agent amount, type, and PLA blend formulation will influence physical, mechanical, and colony reduction properties hinges on their chemical bond and interfacial adhesion with the PLA matrix. This interfacial adhesion can be optimized through techniques such as surface modification, compatibilizers, and encapsulation methods, ensuring a stable and controlled release of the active agents over time. Achieving effective chemical bonds and interfacial adhesion between the active agents and the PLA matrix is pivotal for unlocking the full potential of these enhancements and ensuring the sustained performance of the smart packaging system. Achieving a strong bond between the active agents and the PLA substrate is crucial for consistent and prolonged release of the bioactive compounds thus prolong the perishable food shelf-life. As the field of advanced materials continues to evolve, this integration holds significant promise for revolutionizing the packaging industry by providing sustainable, intelligent, and bioactive solutions.

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