Food Production, Processing and Nutrition

REVIEW Open Access

Effect of intelligent controlled release anti-microbial packaging in food preservation

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Abstract

Food packaging is intended to shield foods, provide necessary food details, and make food handling easier for delivery to customers. Packaging holds pivotal importance in the elongation of shelf-life, food, and quality. Controlled Release Packaging (CRP) is an innovative method that improves quality and safety of food products during storage. This technique involves the release of active ingredients in a controlled, regulated manner. Food preservation is greatly improved by the use of intelligent controlled release antimicrobial packaging, which uses responsive systems to release antimicrobial agents in response to environmental stimuli. This novel method prevents microbial development, extending the shelf life of perishable foods while simultaneously guaranteeing food safety. This paper elucidates a critical review of CRP. Additionally, it summarizes the difficulties and potential outcomes, as well as the present state of application in several food categories. An innovative and challenging packaging technique, CRP technology attempts to maximize the antibacterial effect and preserve the standard of food items by harmonizing the delivery of active ingredients with the need for food preservation using detecting input via a stimulus. In order to serve as a reference for future research on food preservation and food packaging, this review summarizes the uniqueness of CRP, active compounds, as well as its application in different foodstuff.

Keywords Intelligent packaging, Antibacterial, Quality, Controlled release packaging

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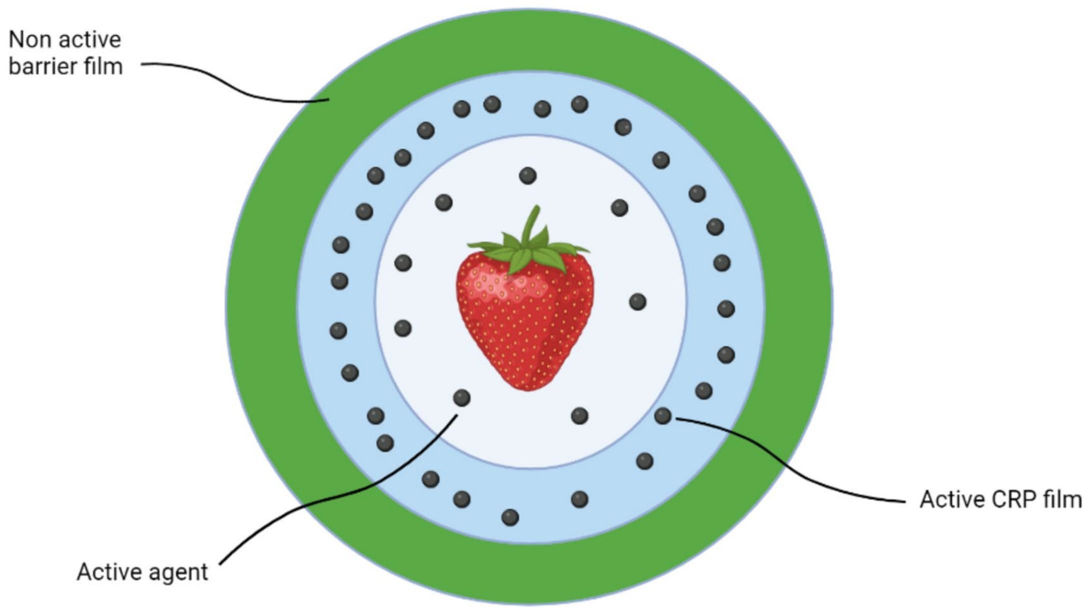
Graphical Abstract



Introduction

Consumers today are more mindful of the importance of healthy eating practices and are making a concerted effort to learn about the negative consequences of chemical-based food additives that are purposefully added to food products to prevent spoiling. Food safety hazards, shifting eating patterns, and the rising demand for minimally processed foods all have a continuous effect on food packaging systems. Foods with minimal processing are vulnerable to the development of dangerous microorganisms, which jeopardize their quality and safety (Fadiji et al., 2023). Researchers and the food industry are looking at innovative ways to stop microbiological growth in food while maintaining its safety and nutritional value in order to address this problem. Due to its potential to protect a variety of food products and its vast range of materials and application techniques, active packaging including antimicrobial packaging has drawn a significant interest in contemporary food packaging techniques (Malhotra et al., 2015). Exchanges between food and packaging can act as harmful agents to the optimal quality as well as safety of food items. Two significant issues can arise when food is stored in compound polymer packaging: the food's flavor may change due to the packaging absorbing its aroma, and unpleasant odors from the packaging may seep into the food. Active, intelligent packaging is intended to maximize shielding, product quality, and shelf life while minimizing unwanted changes. It is founded on an intentional interchanging of the packaging items with the food and elevates the quality as well as safety of food items (Motelica et al., 2020).

Researchers globally have demonstrated considerable interest in active packaging films for their capacity to extend food shelf life and improve food safety. The considerable environmental harm caused by the widespread use of conventional non-biodegradable petroleum-based packaging demands the immediate creation of biodegradable alternatives (Faba et al., 2024; Qiao et al., 2024). As a result, the development of active food packaging films derived from sustainable materials has become a significant topic in the field of food packaging (Wang et al., 2024). Active packaging has the intended impact on food, as shown by the improvements achieved through extended oxidation and monitored respiration rate, growth of microbial inhibiting agents, and moisture displacement, as well as the addition of carbon dioxide absorbers/emitters, odor absorbers, ethylene removers, and aroma emitters. Meanwhile, intelligent packaging includes time–temperature measures, maturity measures, biosensors, and Radio Frequency Identification (RFID) identification. The bioactive chemical is regulatedly delivered when there is an immediate link amongst the packing material, the environment, and the food being packaged, as in controlled-release packaging (CRP) (Siddiqui et al., 2023a, 2023b). As the final stage of the food production and processing, packaging plays a critical role. Antimicrobial packaging such as bacterial active packaging is an innovative elongation of standard packaging that offers enhanced food protection by preventing microbial contamination and oxidation (Wicochea-Rodriguez et al., 2019). However, the physiochemical characteristics of food and the environment have an impact on microbial growth and reproduction. In this regard, it is crucial to produce ecologically friendly controlled release antibacterial packaging.

Intelligent responsive packaging is a revolutionary advancement in the packaging industry that can respond when the environment stimulates it by monitoring changes in the ambient conditions both inside as well as outside the container (Brockgreitens & Abbas, 2016). An efficient strategy to address the increasing need for real-time information monitoring and assurance of quality among food items is to enhance food quality by timely release of active chemicals or real-time detection of active substances (Gao et al., 2019). Information-responsive and intelligent controlled release types of intelligent responsive packaging can be categorized based on their functionality. In order to act as an important component for future research on food preservation and food packaging, this review summarizes the distinctiveness of Controlled release packaging (CRP), active compounds, as well as its applicability in several food categories. This paper elucidates a critical review of controlled release packaging (CRP). Additionally, it summarizes the difficulties and potential outcomes, as well as the present state of application in several food categories. An innovative and challenging packaging technique, controlled release packaging (CRP) technology attempts to maximize the antibacterial effect and preserve the standard of food items by harmonizing the delivery of active ingredients with the need for food preservation by detecting input via a stimulus.

Controlled release packaging (CRP)

A relatively new definition, controlled release packaging (CRP), initially emerged in the documentation of research (LaCoste et al., 2005). Given that there was previously antimicrobial packaging and antioxidant packaging. One of the foremost explanations for this is the innovative concept of employing the product's container as a means of distribution that regulates the emission of biologically active compounds in order to enhance the quality and safety of food. This is completely independent from packaging that is antimicrobial and antioxidant packaging. Packaging that is antimicrobial merely comprises antimicrobials, compared to packaging that is antioxidant comprises solely of antioxidants (Chen et al., 2019).

The investigation in CRP is limited to releasing systems, with a particular emphasis on a thorough understanding of the dynamics and procedure of the chemically active substances unloading from the package. In the contrary, study on packaging with antibacterial and antioxidant qualities goes in addition to systems that rely on releases. It includes techniques that include grafting non-releasing antioxidants or antimicrobials inside packaging components. Non-releasing mechanisms incorporating absorbents of oxygen as well as free radical scavenging agents are also investigated (Gómez et al., 2014; Moudache et al., 2017; Moudache et al., 2016). Despite the fact that the idea of controlled release has been used in the distribution of drugs and other areas, its use in food packaging is distinct because of the needs of both the food and the package.

CRP differs from previous controlled release procedures in that it focuses on the kinetics and technique of controlled release, including what is to be released, whenever and in what manner to initiate the emission, the quantity to release, and the speed at which it must be released. For diverse target microbes, a controlled releases packaging system may contain two antimicrobials (Lee et al., 2003), or a controlled releases packaging system might have both an antioxidant and an antimicrobial to inhibit lipid oxidation and microbial growth (Lee et al., 2004). Mixtures of two or more active compounds may also be used in conjunction with one another in addition to single active compounds. The ideal moment is often right away following the packaging and food filling processes. Some CRP systems may employ moisture from meals, including fresh fruit, to start the release process (Rios et al., 2022). The release rate ought to be as similar to the kinetics of food degradation as possible. If the pace is too slow, there won't be enough active compounds to prevent food from deteriorating, and if it's too quick, there will be too many active compounds and too much loss from degradation (Drago et al., 2020a, 2020b). According to several studies, CRP systems may require far fewer active substances than immediate addition to have the same benefits on thwarting food degradation. The ability to have an extensive variety of "release rate profiles," which are graphs that display the rate of active component release versus time, is another distinguishing characteristic of controlled release packaging. The word "profile" implies that the rate of variation in the active compound's release from the package over time. Most CRP systems have irregular and variable release rates. As an illustration, when an ingredient that is active is added to a coating, its release is commonly controlled by the substance's transmission, in accordance with the characteristics of diffused-controlled flow rate, which is characterized by initially fast release with progressively slower discharge over the course of time (Chen et al., 2019) (Fig. 1).

Active compounds in controlled release packaging

Incorporating chemicals with intrinsic antioxidant and antibacterial properties into the packaging materials can provide active characteristics (Salević et al., 2019). Prominent active ingredients used in CRP comprise CO_2 emitters, oxygen or ethanol scavengers, antimicrobials for food protection, as well as antioxidants for providing high-quality food items.

Bioactive components in controlled release packaging

Clean-label foods are becoming more and more popular these days. Food manufacturers are therefore being forced to look for safer natural alternatives due to consumer demand for safe ingredients and concerns about the negative consequences of synthetic chemicals. Since food packaging protects against physical, chemical, and biological hazards at every stage of the production process, it is essential to modern food production (Vasile & Baican, 2021a, 2021b). During handling, storage, and transit until it is used, packaging protects the item. It prolongs the shelf life and preserves the nutritional value as well as the quality of food goods more effectively. People's desire for improved living conditions and their growing awareness of food quality and safety have led them to search for packaging materials that are biodegradable, recyclable, and safe. This is to ensure that no harmful chemicals contaminate their food supply (Ncube et al., 2020). The utilization of plastic for packaging has led to a substantial rise in both the production and utilization of plastic packaging materials. It provides several advantages, such as simplicity, cost-effectiveness, lightweight, durability, and flexibility, and is extensively used for food packaging (Macena et al., 2021). Plastics have significant environmental repercussions, despite their ability to enhance the longevity of food on store shelves, as they are rarely recyclable and biodegradable, particularly in single-use packaging. Scientists have endeavored to combine plant-based chemical extracts with organic polymers to remove harmful chemicals from food, as an alternative to using plastic packaging. Food packaging utilizes phytochemicals derived from various plants, fruits and vegetables, and herbs.

Polyphenols

Polyphenols, naturally occurring secondary bioactive compounds derived from plants, have drawn considerable attention for their extensive range of bioactivity that contributes to promoting safe food practices. These phytochemicals, structurally similar to phenolic compounds, are abundant in plants and can be classified into two types, namely flavonoids and non-flavonoids, based on their molecular makeup. The flavonoids are the primary group of compounds that have a shared structure called diphenylpropane, which consists of two aromatic rings connected by a three-carbon oxygenated heterocycle. Flavonoids can be classified into different subclasses based on the changes in the heterocyclic ring. The most significant subclasses include flavonols, flavones, the flavanones isoflavones, flavonoids, and anthocyanins (Ansari et al., 2019). The non-flavonoids consist primarily of phenolic acids, stilbenes, and lignans. These molecules exhibit substantial differences in terms of their bioavailability, structure, or biochemical characteristics (Arfaoui, 2021). They have gained significant popularity as a result of their utilization in the food industry. Furthermore, apart from their antioxidant capabilities, they may also exhibit crucial antibacterial actions, the mechanisms of which are still not completely understood (Panda & Duarte-Sierra, 2022). This process involves several

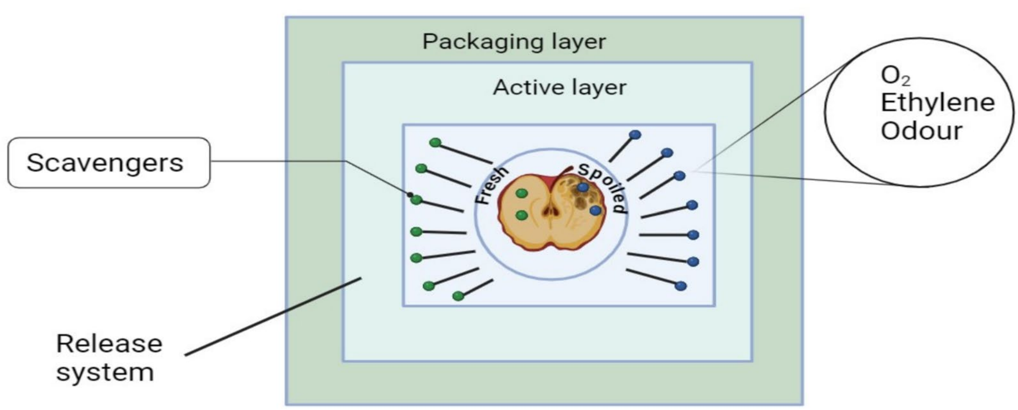


Fig. 1 Barrier properties of active packaging

mechanisms, such as alterations in cell membrane fluidity, modifications in intracellular processes related to the binding of phenolics to enzymes, and a reduction in cell wall stability caused by interactions with the membrane (Tsuchiya, 2015). Polyphenols are present in numerous plants and show promising promise as natural substitutes for traditional food preservation methods. Polyphenols possess the ability to impede the growth of bacteria and fungi, underscoring their significance in the realm of food production. It is crucial to comprehend the antibacterial capabilities of polyphenols because their effectiveness is affected by the sensitivity of pathogens and their chemical composition (Manso et al., 2021). Numerous bacteria, including Gram-positive and Gram-negative, as well as fungi, are susceptible to the antibacterial activity of polyphenols. Three possible mechanisms have been proposed for the antibacterial actions of polyphenols, particularly flavonoids: direct bacterial death, synergistic antibiotic activation, and mitigation of bacterial pathogenicity. More significantly, flavonoids have been demonstrated to inhibit β-lactamases and topoisomerase, destabilize the cytoplasmic membrane, and inactivate the efflux pump, all of which can stop bacteria from developing antibiotic resistance (Xie et al., 2017).

Plant extracts are frequently included in packaging products and integrated into films. Phenolic chemicals, particularly polyphenols and flavonoids, function as antioxidants and antimicrobials in plants. Phytochemicals in active packaging effectively prevent food contamination and degradation without direct touch with the food or compromising its nutritional value (Zhang et al., 2021). Plant-derived extracts containing polyphenols (such as flavonoids and non-flavonoids) and alkaloid compounds with antioxidant properties can be utilized as useful additives in food packaging (Yan et al., 2022). Bran, which is derived from grain milling, is a widely utilized by-product in the food sector. Bran is a cost-effective and easily accessible food that contains numerous advantageous qualities, such as anti-inflammatory and antioxidant characteristics, due to its high content of phenolic compounds, minerals, and fibers (Călinoiu & Vodnar, 2018). According to Wang et al., tea polyphenols have been identified as a promising method for creating biodegradable packaging films with high effectiveness (Wang et al., 2021a, 2021b). Due to their exceptional antioxidant and bactericidal characteristics, polyphenols have been employed to improve the chemical and physical characteristics of food packaging materials. A recent study explored the potential of combining polyphenols with synthetic polymers through grafting in order to enhance the performance of packaging materials, minimize the presence of harmful chemicals, and avoid the degradation of active compounds (Panzella & Napolitano, 2017).

However, due to their polyhydroxy nature, polyphenols are unstable during food processing and often break down and react with other ingredients. Numerous biochemical and chemical reactions determine the stability of polyphenols in food matrixes. These reactions are greatly influenced by factors such as pH, photo/light, temperature, oxygen availability, metal ions, enzymes, proteins, nitrite salt, sulfur dioxide, other antioxidants, and interactions with other food ingredients. It has been noted that the advantages of polyphenols depend on both their bioavailability and consumption (Zhang et al., 2022). Their bioactivity and health advantages are limited due to their limited availability and the possibility of major changes in their redox potential. Incorporating polyphenols into nanoparticles is one method of increasing their bioavailability. Particularly with the use of nanoencapsulation of bioactive chemicals for biological purposes, nanotechnology has been fast growing in the food and pharmaceutical industries in recent years (Rahim et al., 2019).

Carotenoids

Carotenoids are pigments that are widely produced by many organisms, including bacteria, algae, and fungi (Martínez-Cámara et al., 2021). In nature, carotenoids can be classified into two categories: xanthophylls, which are oxygenated compounds like lutein, cryptoxanthin, zeaxanthin, and fucoxanthin, and carotenes, which are hydrocarbon compounds such as lycopene, α-carotene, and β-carotene (Tan & Norhaizan, 2019). Carotenoids primarily function as antioxidants, working to neutralize reactive oxygen species (ROS). Furthermore, they have antibacterial, antihyperglycemic, and anti-inflammatory properties, which contribute to the prevention of cardiac and neurological diseases and enhancement of the immune system (Šimat et al., 2022). Carotenoids have been identified as a viable alternative to synthetic compounds, which are frequently associated with adverse effects (Meléndez-Martínez, 2019), due to their beneficial characteristics. Moreover, these pigments have the advantage of being valuable for the aim of enhancing the color of meals and enhancing their nutritional value (Silva et al., 2022). Carotenoids are present in a diverse range of vegetables and fruits, including tomatoes, carrots, watermelons, as well as specific fish species like salmon and crustaceans (Saini et al., 2022). Food packaging biofilms include carotenoids, including α-carotene, β-carotene, and lycopene. β-Carotene can serve as an active component in organic packaging sheets (Nemes et al., 2020). Stoll et al. investigated the effects of carotenoid extracts on the conservation of sunflower oil by using polylactic acid films. β-carotene, lycopene, and bixin were employed as antioxidants to inhibit the oxidation of sunflower oil (Stoll et al., 2019). Szabo et al. showed that the combination of carotenoids and phenolic chemicals with tomato by-product extraction in polyvinyl alcohol (Latos-Brozio & Masek, 2020) can yield highly effective smart and active packaging materials. Lycopene is categorized as a carotenoid phytochemical that has the potential to be utilized in active packaging (Rodriguez-Amaya, 2019).

Phytosterols

Plant sterols are compounds that have the same chemical composition and properties as cholesterol, but they come from plants. Vegetables contain plant sterols, although the human body does not synthesize them (Tolve et al., 2020). Phytosterols help preserve the integrity and stability of cell membranes, which is crucial for their functional and structural health (Poli et al., 2021). Phytosterols have a direct impact on membranes of cells and other vital processes. β-sitosterol, stigmasterol, and campesterol are the predominant phytosterols (Sharma et al., 2021). The benefits of phytosterols have sparked a greater interest in utilizing these substances to create food products that incorporate phytosterols for the purpose of preventing and treating cardiovascular diseases. Phytosterols serve as effective and secure choices for the prevention of coronary vascular disease when used as functional food components (Poli et al., 2021). These components are commonly present in numerous contemporary culinary products. Food manufacturers in affluent countries often produce functional foods that contain high levels of sterols and stanols. Plant sterols including stanols can be added to food products without affecting their flavor or consistency. Phytosterols are currently found in a diverse range of items, including bars, oils from plants, juice, meat, soups, dairy, and baked goods (Pereira et al., 2022).

However, recent studies have indicated that utilizing phytosterol coatings could enhance the barrier properties of packaging for food materials. The addition of phytosterols to polyethylene films was found to boost their oxygen barrier properties, which could potentially prolong the shelf life of products stored in these containers. Further investigation is necessary to determine the potential applications and limitations of using phytosterols as a material for food packaging.

Phytosterols and their metabolites can be found in fruits, legumes, cereal crops, and seeds (Witkowska et al., 2021). Phytosterols have been extensively studied for their ability to lower blood cholesterol levels. In 1995, Benecol margarine became the first food to be fortified with plant stanol fatty acid esters, which are loaded with phytosterols (Tolve et al., 2020). Phytosterol-enriched functional foods of diverse types have been manufactured and sold globally over the course of time. The solubility and bioavailability of phytosterols could be affected by other components present during food preparation (Alvarez-Sala et al., 2016). Developing dependable and precise methods for extracting and quantifying phytosterols is crucial to support the food sector and ensuring the precision of nutritional labeling (Tolve et al., 2020).

The choice of packaging for keeping a phytosterol-enriched meal might also impact its quality. It may be possible to maintain the nutritional properties of yogurt beverages containing phytosterols by reducing their exposure to light through packaging. Microencapsulation is a method that helps protect the bioactive chemicals in food, which are important for maintaining the proper composition and preventing interference from phytosterols during production or conservation (Mehta et al., 2022).

In addition, phytosterols are mostly utilized as dietary supplements along with food additives. They possess health-promoting features, such as their potential to manage cardiovascular health and lower cholesterol levels. The antioxidant and antibacterial properties of phytosterols are widely recognized. As far as we know, there are no published investigations that demonstrate the utilization of phytosterols for food packaging. Phytosterols, like other bioactive substances, can serve as antioxidant, antibacterial, and barrier agents in functional packaging for foods. Applying this technology to the creation of biodegradable innovative packaging for food materials, aimed at preserving the safety and quality of food, would be a novel and highly valuable solution in terms of sustainability and environmental friendliness, generating significant attention in the industrial sector.

Glucosinolates

Glucosinolates (GSL), a class of thioglucosides and their bioactive derivatives, isothiocyanates (ITC) and indoles, are recognised for their ability to influence cellular mechanisms critical for various benefits (Maycotte et al., 2024). They are secondary compounds in plants, primarily produced from glucose and sulphur-containing compounds present in dicotyledonous plant species. The Brassicaceae family contains the largest amounts of glucosinolates (Rhee et al., 2020). These molecules are readily accessible from a diverse range of plants, such as fruits, herbs, vegetables, and oil crops, which offer a wide array of essential nutrients (Cámara-Martos et al., 2022). These substances are predominantly found in cruciferous vegetables (Brassicas), such as broccoli, radishes, cabbages, kale, mustards, rocket and wasabi (Maycotte et al., 2024).Glucosinolate molecules are chemically stable and physiologically inactive until they are located within the plant's subcellular structures. Glucosinolates undertake metabolic reactions in vacuoles when plant cells are damaged by pathogens, harvesting methods, food preparation, consumption, or thermal deterioration (Maina et al., 2020). Glucosinolates can be classified as aliphatic or aromatic based on their unique side chains. To date, a total of 130 glucosinolates have been discovered (Nguyen et al., 2020). Isothiocyanates are a class of acrid chemical compounds found in mustard oils. The compounds derived from glucosinolates have undergone substantial investigation (Lietzow, 2021). Scientific research has proven that glucosinolates and their metabolites offer numerous health benefits. These include decreasing the probability of cancer, cardiovascular diseases, inflammatory conditions, and neurological disorders. They also help in managing asthma and diabetes, as well as maintaining healthy cholesterol levels (Alotaibi et al., 2021; Kamal et al., 2022). The acrid flavor of recently harvested consumable plant matter is a result of the enzymatic degradation of glucosinolates triggered by myrosinase. The enzyme is situated within the cytoplasm, whereas glucosinolates are kept within the vacuole (Lv et al., 2022). Glucosinolate levels can vary significantly within the same species, with different cultivars showing noticeable variations in both the amount and quality. The levels of glucosinolates differ across different parts of the same plant as a result of their particular distribution in tissues (Chhajed et al., 2020).

Bahmid et al. (2020) devised a controlled antimicrobial packaging technique that gradually releases allyl isothiocyanate (AITC) derived from mustard seed. The researchers conducted an analysis on how the fat content and size of ground mustard seed particles affect the generation and release of AITC. The study also highlighted the fundamental mechanisms involved. In addition, Duda-Chodack et al. identified other types of bioactive chemicals used in intelligent and dynamic packaging, such as antibacterial agents AITC.

Other bioactive compounds

Other bioactive compounds such as minerals, peptides, enzymes, vitamins, bacteriocins, and unsaturated fatty acids can be utilized in packaging for a wide range of food chains and products, including grain-based foods, dairy foods, fruits and vegetables, meat-based foods, and seafood (Dilucia et al., 2020). Vitamins, minerals, essential oils, lipids, and other bioactive molecules play a vital role in maintaining human health. Consuming a diet high in vitamins can have a positive impact on the immune system and the formation of antibodies, hence reducing the risk of ocular, respiratory, and gastrointestinal illnesses. Vitamins along with other bioactive components are also linked to qualities that reduce inflammation (Mironescu et al., 2021). Vitamins, which possess antioxidant properties, can be incorporated into the food production process as they protect against oxidative damage. Proteins are mostly made up of amino acid chains that are connected by peptide bonds (Siddiqui et al., 2023a, 2023b).

Proteins are primarily utilized in food packaging because of their exceptional physical and oxygen-blocking characteristics (Teixeira-Costa & Andrade, 2021). Furthermore, protein exhibits strong affinity for polar molecules and effectively inhibits the leakage of components and bioactive chemicals from their packaging system (Nogueira et al., 2020). Scientists have been working on creating bio-based packaging using edible films and materials made from bioactive chemicals (Filho & Egea, 2022). Antimicrobial peptides are suitable for use in the food packaging systems. They have the ability to effectively suppress pathogen replication and reduce infections with little amounts. As a result, meat products that contain these chemicals show reduced lipid oxidation (Liu et al., 2021) (Fig. 2).

Minerals, vitamins, bacteriocins, peptides, fatty acids and enzymes that are unsaturated are bioactive components which can be utilized in the production of bio-based and edible packaging materials. Enzymes and bacteriocins are examples of compounds that might be used as functional or active elements in packaging materials. Bacteria create antimicrobial peptides called bacteriocins, which can be used to inhibit the growth of harmful microbes in food packaging. Enzymes have the capacity to enhance the barrier properties or biodegradability of packaging materials, hence improving their overall performance. For instance, a biopolymer matrix composed of peptides and proteins can be employed to provide consumable packaging. Furthermore, unsaturated fatty acids have the ability to improve the flexibility as well as mechanical strength of biopolymer matrices. The specific roles performed by these bioactive compounds in packaging materials are determined by their chemical composition, physical properties, and interaction with other components of the packaging structure (Siddiqui et al., 2023a, 2023b).Unsaturated fatty acids are commonly used as additives in packaging materials due to their efficient oxygen elimination properties (Röcker et al., 2021).

Antimicrobial packaging plays a vital role in ensuring food safety and quality in the modern era. It effectively extends the shelf life of food goods and inhibits bacterial development on them. The current term for this practical packaging strategy is "active packaging". Hence, the active peptide enhances food safety by extending the lifespan of the item and increasing the sensory attributes of the food (Ambrosio et al., 2022). The need for this form of packaging is increasing since it has the ability to provide the market with nutritious, natural, and trustworthy food

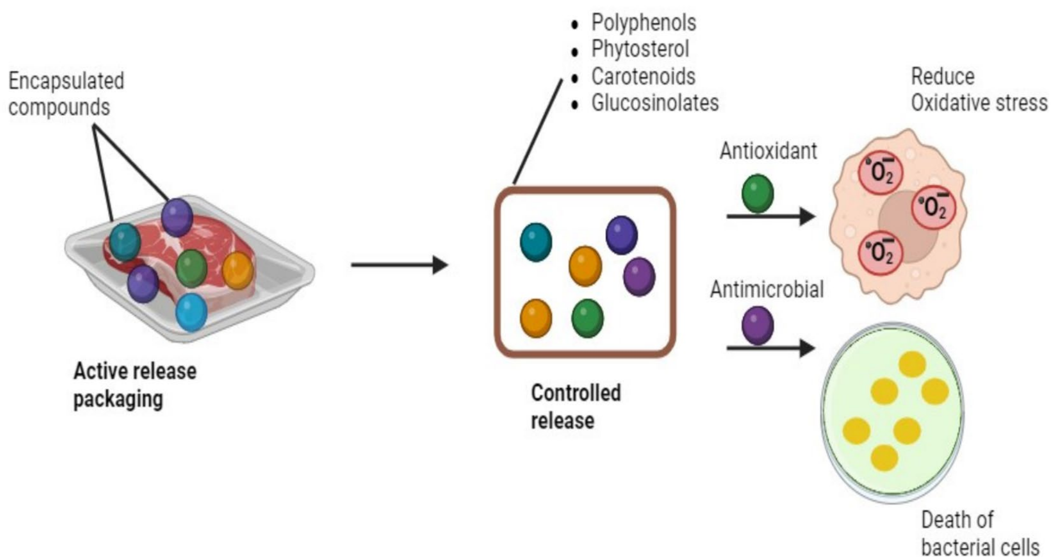


Fig. 2 Antimicrobial and antioxidant mechanism of active packaging

options (Pereira et al., 2022). By employing a systematic method that incorporates intelligent and active packaging methods, such as packaging that uses enzymes, we can enhance food safety and preservation while also addressing evolving cultural and economic needs (Lin et al., 2021).

Importance of antimicrobial substances in food packaging

An antimicrobial is a compound which has the ability to either eliminates or obstruct the development of bacteria. Antimicrobial substances have emerged as an alternative to conventional antibiotics and preservatives which is beneficial for environment due to its greater biodegradability (Li et al., 2024). By lowering hazardous bacteria activity in food, antimicrobial packaging serves to boost food safety, decrease food wastage, and extend the shelf life of food. Biobased antibacterial agents used in packaging increase consumer health safety (Sung et al., 2013). These agents prevent the growth of pathogens and spolage microorganisms. Antimicrobial substances are integrated into the packaging that inhibit targeted microbes such as opposing *Saccharomyces cerevisiae, Pseudomonas aeroginosa (MTCC 4676), Mycobacterium smegmatis (MTCC 943), Escherichia coli O157, Listeria monocytogenes, Salmonella, Staphylococcus aureus, Aspergillus niger, Clostridium perfringens, Bacillus cereus, Campylobacter* etc. The following are some of the most popular natural antimicrobials: organic acids (such ascorbic, and propionic acid, naturally produced polymers (such as chitosan and its byproducts), essential oils derived from plant sources (such as thyme, cinnamon, clove, basil, oregano, and rosemary), enzymes from animals (such as lactoferrin as well as lysozyme), bacteriocins from microbial elements which can be nisin or natamycin).

Over 1140 publications were published in 2014 that discussed the "antimicrobial activity" of chitosan, 740 of which were published after 2010. Chitosan undergoes quaternization acylation, alkylation, carboxylation, and processes to enhance its water solubility, pH responsiveness, and effectiveness in areas such as antibacterial action, prolonged controlled release, targeted delivery systems. Derivatives of chitosan exhibit exceptional antibacterial activity because the polymer backbone forms side bonds with nitrogen atoms and maintains a continuous positive charge (Wang et al., 2020; Martin et al., 2014; Goy et al., 2016). Alginates and carrageenan are two intriguing polysaccharides that are utilized in antimicrobial packaging (Cha, 2002). Researchers have used biopolymers such as chitosan, cellulose, and alginic acid to synthesize nano-formulations of silver nanoparticles for antibacterial applications (Alavi & Rai, 2019). The antibacterial properties of these polysaccharides are boosted by the addition of silver nanoparticles (NPs) as nanocomposite (NC).

They are affected by numerous intrinsic variables, such as oxygen content and pH, and extrinsic storage-related ones, such as time, temperature, and humidity. Plant growth hormones e.g. 1-methyl cyclopropane, probiotic, nutraceuticals, enzymes, aromas and bacteria and can also be included. Multifunctional active substances include several essential oils (EOs), which have antibacterial, antioxidant, and antifungal properties (Munteanu & Vasile, 2019; Vasile et al., 2017, 2019). Volatility, molecular structure, size, polarity, weight, and the inclusion of additional bioactive substances all affect how easily they come out of packaging (Chen et al., 2012; Nerin et al., 2016).

Organic antimicrobial agents encompass a range of substances including thyme essential oils clove and oregano, citric acid (naturally occurring in green tea), monoterpene hydrocarbons like terpinene and p-cymene, polymers such as chitosan and its derivatives, bacteriocins like nisin, organic acids like acetic acid, benzoic acid and lactic acid, and metal ions like zirconium and zinc oxide (Saadah & Mhd, 2019) (Fig. 3).

Given that it possesses strong mechanical, optical, and oxygen barrier qualities, Film technology based on proteins has become one of the food-packaging industry's most thoroughly explored technologies in recent years. The emission of additives and beneficial chemicals amongst the food-packaging system was effectively controlled by protein-based film, which also demonstrated high similarity to polar surfaces (Li et al., 2024). Due to its strong microbial activity suppression, antimicrobial food packaging has got attention since it increases food safety and shelf life while also strengthening the films functionality. They are decomposable as well. However, in order to provide more secure and authorized goods in accordance with the required food safety, chemical, toxicological, and other tests may also be necessary for bio composite protein-based packaging films created by including antimicrobial agents (Vasile et al., 2017).

Advances in antioxidants encapsulation for food preservation

Food items include antioxidants such as polyphenols, flavonoids (such as quercetin), resveratrol vitamins, curcumin, poly-unsaturated fatty acids, astaxanthin, catechins and others. They either function as antioxidants that break chains or as antioxidants that deactivate hydroperoxide. Reactive oxygen species as well as reactive oxygen-containing compounds participate in a variety of chemical processes (oxidative stress) and are involved in the breakdown of active biological components or biomolecules. They exhibit varying degrees of reactivity and oxidizing ability. Antioxidant (AC)-containing formulations are used to stop oxidative stress and shield other molecules from the damaging effects of reactive oxygen species (Ashok et al., 2022).

Whenever the functional components of the enclosed molecular structure and the encasing nanomaterial engage favorably, efficient encapsulation takes place. Antioxidant compounds and antimicrobial agents are produced using a variety of nanoencapsulation in techniques. These methods include lipid-based nanoencapsulation, colloid-based nanoincorporation, and encapsulation using polymeric nanocarriers derived from biological sources, encapsulation using polymeric nanocarriers derived from non-biological sources, electrospraying, cyclodextrin incorporation, nanocomposite encapsulation and electrospinning (Pisoschi et al., 2018).

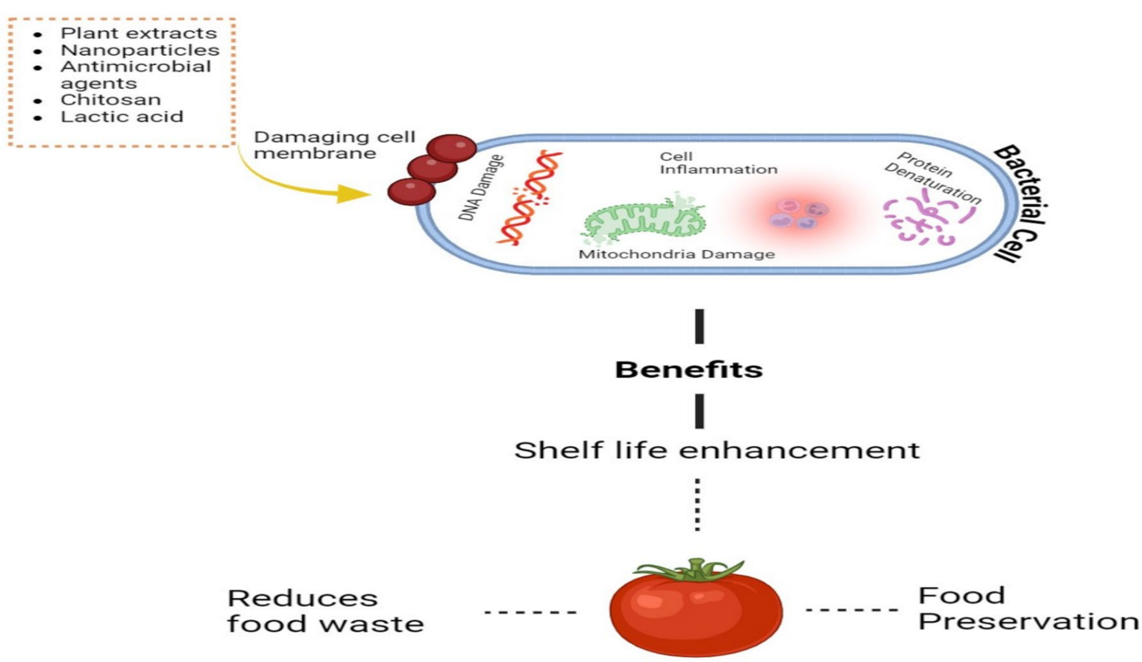


Fig. 3 Food packaging agent as a antimicrobial

Drying via freeze-drying or spray-drying can be followed by a number of nanoencapsulation techniques. By using various nanoencapsulations, such as amylose, inclusion complexes of yeast cells, carbon dots (CDs), nanogels, nanoparticles, natural concentrated extractions and hydrophobic food bioactive compounds may have improved solubility of fluid, antioxidant in vitro GI emission profile, and protect against ecologically unfavorable environments (Rezaei et al., 2019).

An example illustrating this concept is the utilization of nanostructured lipid carriers loaded with astaxanthin, which were mentioned earlier. These carriers have an average diameter of 94 nm and include antioxidants such as Ethylenediaminetetraacetic acid (EDTA) and α-tocopherol. They were incorporated with nonpasteurized CO_2-free brew at an approximate volume proportion of 3:97, maintained with Tween 80 and lecithin, and showed greater stability at a lower preservation temperature of 6 °C. (Tamjidi et al., 2018). The efficiency of their antioxidant capacity storage of > 50% of hydroxytyrosol and gastroresistance, an olive oil constituent with antioxidant properties, were demonstrated by the encapsulated ethyl cellulose microparticles (Paulo & Santos, 2018). This formulation may find use in foods, medications, and nutraceuticals.

Resveratrol (RES) from α-lactalbumin had 32-fold greater solubility in water than free RES, and the nano complexes significantly enhanced the endurance of the antioxidants chemically by the preservation process of introducing them to pH 8.0 and elevated temperature, as well as an exceptional experimental antioxidant efficacy, indicating that a-lactalbumin as a nanoscale carrier was capable of delivering lipophilic nutraceuticals in the functional food and a decreased phytosterols breakdown rate when weighed against digested large quantities oil, demonstrating a potential use for food production in the future (Cheong et al., 2016). Numerous spices and herbs, including natural extracts (NEs), sage extract, rosemary extract, oregano essential oil, and green tea extract (GTE) as well as inorganic and metal nanoparticles, are known to be sources of bioactive compounds that can stabilize free reactive radicals, stop oxidation activity and perform as an exceptional bactericidal agent (Souza et al., 2016) (Fig. 4).

Utilization of intelligent controlled release packaging preservation of food

After being harvested, vegetables and fruit keep breathing and existing as well as generating CO_2 and moisture, increasing the acidity of the air within the packing. Furthermore, as carbohydrates are degraded by bacteria during the rotting process, gases acidic in nature such as hydrogen sulphide and acetic acid are produced, lowering microenvironment's pH in the top place of package (Ghaani et al., 2016). As a consequence, the fresh keeping package of vegetables and fruits and may be engineered to adjust to pH and humidity and by using water and acid gas produced by metabolism when triggered. Antioxidants are used in formulations as AC to prevent oxidative stress and to shield other substances against the harm that reactive oxygen species (ROS) can cause.

Many researchers are currently developing freshness measure founded on the premise that metabolite CO_2 levels fluctuate during storage, influencing the pH of the surroundings. As previously said, these indicators may simply and intuitively transmit fluctuating information about vegetable and fruit quality through graphic alterations, although the bulk of them just serve the "indication" function. In the context of fruit and vegetable conservation, it is crucial to comprehend how to accomplish controlled release and lengthen the period of preservation of fruits and vegetables by making use of the features of pH and humidity changes (Mohd Ali & Hashim, 2021).

Pineapple exudate, freshly squeezed juice, and other mildly acidic liquids are also used as triggers for pH-sensitive systems. Heras-Mozos et al. (2022a) successfully suppressed *E. coli* and pineapple wild yeast using a modified chitosan formulation. This substance's bactericidal and fresh-keeping benefits were achieved by using the acidic elements of fruit and vegetables, which were based on the Schif-base framework and encouraged the synthesis of naturally occurring antibacterial aldehydes compounds. The nanofiber pad created by Wong et al. (2022) permitted for controlled delibery of carvacrol at various RH levels and showed exceptional encapsulation efficiency. The of the strawberry's shelf life increased by two days after the fibre mats were added to high humidity strawberry packaging. This was accomplished by lowering the mold and yeast populations on the strawberry's surface. Along with antimicrobial drugs, inhibitors of 1-MCP ethylene also aid in the preservation of fruit by lowering the respiratory power. In a unique fruit paper packaging system created by Ariyanto et al. (2019), The amount of relative humidity in moist air is associated with the 1-MCP release rate from laminated paper. The paper with coating reduced the amount of titratable acidity, preserved the freshness of the pulp, and reduced the amount of ethylene released during storage.

Importance of packaging materials in meat preservation

Although meat and meat products are perishable, they are excellent sources of high-quality protein. Because decay microbes such as *Filamentous Bacillus*, *Lactic*

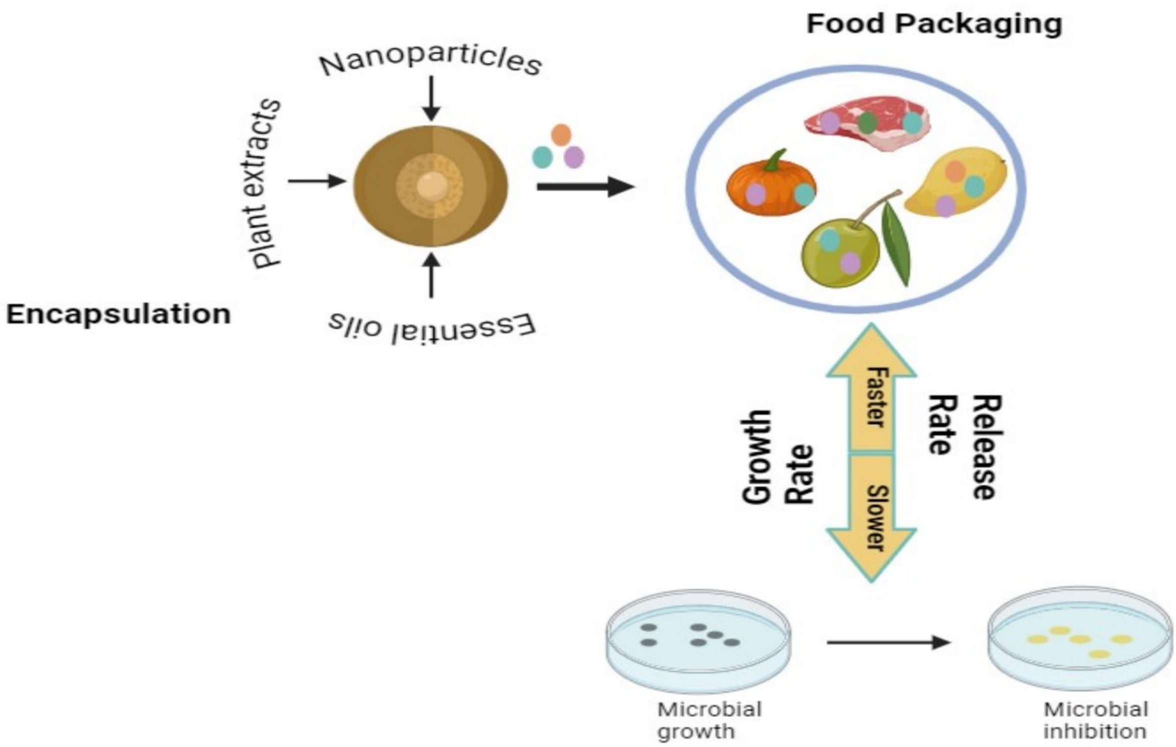


Fig. 4 Schematic diagram shows the role of active packaging for the reduction of microbial spoilage

Acid Bacillus Staphylococcus, *Pseudomonas* and may thrive in an acidic atmosphere with high water activity and readily available nutrients (Bhattacharya et al., 2022). By preventing the development of *Bacillus cereus* and *Pseudomonas*, the chitosan microspheres developed by Sriwattana et al. (2023) extended the duration of storage of chilled deli meat products from 7 to 24 days. This was accomplished by increasing the amount of antiseptic essential oil under high humidity conditions. Boyac and Yemenicioglu (2018) developed lysozyme-releasing pH-responsive packaging material for the mutton, smoked salmon and beef preservation by using the charge balance idea.

Customers stimulate the lysozyme with acidified lemon juice, which may effectively prevent listeria growth on meat product's surface, and this action regulates the film. As compared to, Zhang et al. (2023) utilized electrospinning to create nanofiber padding based on Eudragit L100 that may be used for the preservation of frozen meat without the requirement for human activation. Ammonia Cal compounds generated by protein breakdown and the deprotonation of the polymer's carboxyl groups were also linked to an intensification of pH, which boosted the generation of cinnamon essential oil and raised the molecular chain's repulsion. Staphylococcus aureus and Escherichia coli were effectively inhibited by the fibrous padding, extending the shelf life of fresh meat by three days.

Baked foods preservation

The oil content of baked items including bread, cakes, and moon cakes is high. Oil will become rancid when exposed to high temperatures and light, producing an unpleasant odor. In addition, baked foods must adhere to very tight moisture restrictions since moisture in packing can easily promote the development of yeast, bacteria, and mold, which reduces freshness (Qian et al., 2021). Wang et al. (2021a, 2021b) developed kappa-carrageenan hydrogels in particular that can control how quickly essential oil extracted from cinnamon releases based on relative humidity. The container drastically reduced the possibility of mold developing on the bread fragments. The amount of mold colonies on the bread surface after 3 days was only 22 CFU/g as opposed to 225 CFU/g in the control group, which is much more than the 105 CFU/g upper limit for bread that is still safe to consume.

Temperature and the rate of oxidation of dietary lipids are closely associated; elevated temperature ensures the faster the release of oxidation rancidity. As a consequence, temperature sensitive release packaging will increase baked item quality and reduce lipid oxidation. Some researchers believe that Cantonese mooncakes are wrapped with a temperature-sensitive TPSU-based film (Drago et al., 2020a, 2020b). In contrast to industrially available PE film, this particular coated layer exhibited enhanced preservation properties. The expected lifespan of mooncakes was increased to 28 days as a result of the packaging's ability to effectively limit the formation of peroxide value (an indicator of oxidation that shows fatty acids are rancid). However, when mooncakes were packaged in PE film, typically used for Cantonese mooncakes, their shelf life was restrained to 21 days. This was due to the rapid increase in peroxide value and total plate count, indicating a shorter period of freshness and quality maintenance (Table 1).

But like many packaged food, baked goods can deteriorate physically, chemically, and microbiologically. Refrigerating food can extend its shelf life by two to three weeks by preventing spoiling problems including the formation of mildew. All of these baked goods can be securely frozen indefinitely, but if they are kept frozen for more than two to three months (cookies 6 to 12 months), they will begin to lose their flavor and texture, among other quality issues (Vermelho et al., 2024).

Intelligent packaging concepts' advantages and drawbacks

Generally, intelligent packaging is simple to utilize and offers customers, food producers, and the entire food sector a variety of benefits. They provide a variety of characteristics depending on the system (Fuertes et al., 2016).

One can determine the present quality standard of a food item using indications and sensors. As a consequence, overall product safety increases, and there is less unnecessary food waste (Brünnagel, 2014; Verghese et al., 2015). This continuous quality monitoring also reduces the time duration as well as material expenditure involved with packaged food analysis methods (Vanderroost et al., 2014). Additional economic benefits emerge when creative packaging decreases food waste along the supply chain. These qualities could even be of greater importance in the biological disciplines, including the field of pharmaceuticals (Brünnagel, 2014).

Innovations in biopolymer-based materials and natural sensors are driving the increasingly promising sustainability prospects of intelligent food packaging. In addition to addressing the environmental issues raised by conventional plastics, these developments also improve food safety and cut waste. To drastically lessen the ecological impact of plastics derived from fossil fuels, biopolymers such as polylactic acid (PLA), poly(vinyl alcohol) (PVA), and chitosan are being developed as substitutes. Additionally, using agricultural waste, like cellulose from

Table 1 Application of controlled release antimicrobial packaging system in preservation of fruit and vegetable

Fruit and vegetables	Active agent	Triggers	Preservation effect	References
Strawberries	essential oil extracted from cinnamon	Humidity/ Moisture	When compared to the control, the decay rate was just 24%, 59% at the end of storage	Luo et al. (2022)
Pineapple	Salicylaldehyde	pH	The pineapple's exudate caused salicylaldehyde to be released and prevented the pineapple chunks' surfaces from oxidising	Heras-Mozos et al., (2022)
Apple	1-MCP	Moisture	Prolonged the expected lifespan of apples by minimising the generation of ethylene	Ariyanto et al. (2019)
Blackberry	Trans-2-hexenal	pH	Increased the expected lifespan of blackberries from 3 to more than 10 or 12 days and had strong antibacterial effects on Penicillium and Bostonia cinerea	Heras-Mozos et al. (2021)
Agaricus bisporus	Thymol	Humidity/ Moisture	The period during which that Agaricus bisporus could potentially be preserved was greatly extended by 5 days simply by keeping the degree of moisture in the packaging at 97%	Wu et al. (2022)
Avocado, dragon fruit	Curcumin	Moisture	On the sixth day, there was very little oxidation in the experimental group and no bacterial infection was seen	Liang et al. (2022)
Grape	Clove essential oil	Moisture	Mould development was initially noticed on the grape surface in the control group on day 21, but there was none in the experiment group	Sangsuwan and Sutthasupa (2019)

honeydew melon rind, produces biodegradable films that increase food shelf life and reduce waste.

Data reporters provide improved supply chain traceability. Owing to their minimal cost, ease of utilization, and benefits, barcodes and quick-response QR codes are becoming increasingly popular. Sensors and indicators, on the other hand, are scarce on the market. One aspect in this is the present high cost of development and manufacturing. A finished goods packaging expenses could add up 50% to 100% of the entire pricing. Actually, the packaging charges are limited to 10% of the product's value. Furthermore, the utilization of sensors and indicators may have a detrimental impact on client purchasing habits. Customers are more likely to opt for a good with a clear freshness sign than one that is stained. If a consumer observes labels for a specific brand of items with a diverging hue on a regular basis, he may lose trust in that brand (Müller et al., 2019). Furthermore, this practice may result in more food not being sold (Dainelli et al., 2008). On the opposite hand, smart packaging can support the traditional "first in-first out" rule. The store can prevent food waste by selling the commodities with the shorter shelf lives first if the true current qualitative status of the food is known.

It is necessary to ensure that the systems and the food under examination are compatible. Not all types of food can be packaged in new ways. As a result, it is necessary to specify the sensor or indication that is best for the particular product. Only when the inventive packaging enhances the dish is it useful. For MAP (Modified Atmosphere Packaging) packaged goods, an oxygen sensor, for instance, could prove helpful, but a time–temperature indicators (TTI) should be used for refrigerated and frozen goods (Kontominas et al., 2021). Packaging that is recyclable is a different issue that has to be addressed. Jute is used as a recyclable packaging agent as its cost effective and ecofriendly (Kumar, 2024). The extra waste produced by the installation and manufacture of intelligent packaging directly contradicts the purpose of decreasing food waste (Vanderroost, 2014).

Furthermore, while intelligent packaging might assist assure the highest quality of item available, misuse or system non-fulfillment might not be totally eliminated (Fang et al., 2017). A variety of factors might be blamed for the fall in quality. The quality of a product cannot be entirely established by monitoring simply one parameter. Furthermore, the technology may occasionally be negatively impacted by environmental factors such as temperature, light, and mechanical stress. On the other hand, this may contribute to the classification of products as safe for consumption even while they are not. On the other hand, this may result in a situation where a product's degradation is hidden. In the worst situation, ingesting the products may be harmful to the consumer's health. To summarize, it can be concluded that in order to maximize benefits, system resilience must be increased and separate packaging technologies should be combined (Sohail et al., 2018; Vanderroost et al., 2014).

Disadvantages of intelligent packaging systems

- It is not possible to rely solely on intelligent packaging equipment for the highest product quality because misuse and system failure can occasionally occur
- The development and production costs for sensors and time temperature indicators are high; and the cost of packing materials is also very high.
- A single constraint monitoring is insufficient to provide a comprehensive assessment of the product's quality status within the package.
- The technologies may also be negatively impacted by external environmental factors as sunshine, temperature, mechanical risks, and stress.

Contribution to advance knowledge

In contrast to previous reviews on intelligent controlled release anti-microbial packaging, which predominantly focused on the technical mechanisms or specific material properties this review is conducted to give a full review of the practical and functional elements of these systems in the context of food preservation. Previous reviews of intelligent controlled release antimicrobial packaging, which mostly concentrated on technical methods or specific material features, are contradicted by this finding. In contrast to past studies that concentrated on particular characteristics of antimicrobial agents or packaging technologies, this analysis takes into account these components within the context of a larger framework of growing trends in intelligent packaging, with a particular emphasis on recent advancements in controlled release systems. This presented a fresh perspective that integrates theoretical innovation to practical applications which in turn enhance the overall comprehension of the subject matter. Within the context of practical applications, this is achieved by establishing a connection between the effectiveness of preservation and variations.

Conclusion and future recommendations

The field of AP technology now exhibits numerous elements with potential futures. Future research on controlled-release materials has a strong chance of success, especially when it comes to nanomaterials and the widespread usage of encapsulating techniques. Furthermore, stimuli-responsive active packaging is one example of a synergistic technique that shows promise for the field's future research prospects. It could potentially be possible to produce a controlled discharge of the active chemical in such a circumstance by using mechanisms started by variations in temperature or activity from microbial cells. It is necessary to do more study to determine release rates suitable for a range of food packaging applications. To be employed in active packaging, biopolymers should be cost-effective compared to conventional plastics. Because of this, bioplastics have to be made from sustainable resources, have excellent mechanical and barrier properties, and be cost-effective to use. Examples of this review's examples demonstrate how likely it will be that this technology will replace petroleum-based polymers, which are currently quite popular. Future research must, however, address the challenges raised in order to successfully commercialize.

Acknowledgements
Authors are thankful to Government College University and NUR International University for providing literature collection facilities.

Authors' contributions
Samreen Latif, Original draft equal, Anam Latif, Supervision equal; Wisha Waheed, Formal Analysis equal; Ali Imran, Conceptualization equal; Muhammad Sadiq Naseer, data curation equal; Fatima Tariq, Editing equal; Fakhar Islam, Visualization equal; Abdela Befa Kinki, Supervision equal.

Funding
The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability
Even though adequate data has been given in the form of tables and figures, however, all authors declare that if more data is required then the data will be provided on a request basis.

Declarations

Ethics approval and consent to participate
This article does not contain any studies with human participants or animals performed by any of the authors.
Corresponding and all the co-authors are willing to participate in this manuscript.

Consent for publication
All authors are willing to publish this manuscript.

Competing interests
Authors declare that they have no conflict of interest.

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Received: 26 July 2024 Accepted: 8 March 2025
Published online: 07 May 2025

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