The Future of Food Preservation: Active Packaging with Controlled Release Systems

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Abstract. This report provides an overview of active packaging with a focus on controlled release packaging (CRP) technologies, which have been developed to improve the shelf life of food products. Active packaging systems incorporate various functional components such as antimicrobial agents or oxygen scavengers into package material to maintain product quality during storage. CRP technology involves encapsulating bioactive compounds within a carrier matrix that can be released in a controlled manner over time. The paper compares these two promising technologies and highlights their advantages for extending shelf life while maintaining product quality. While active packaging is more suitable for short-term preservation due to non-controllable active agent release, CRP has potential applications in long-term preservation due to its ability to provide sustained release of bioactive compounds. Future prospects include developing a blend of CRP and intelligent food packaging. However, challenges remain including the sustainable release rate of the active agents from the packaging into the headspace or food surface. Overall, this review provides insights into the current state-of-the-art research on CRP technologies while highlighting future directions for improving food safety through innovative approaches aimed at preserving freshness while minimizing waste generation from expired products.

Keyword. Active agents, Active packaging, Antioxidants, Controlled release, Encapsulation, Polymer matrix

1 Introduction

Before millennia, clay pots and wooden barrels were used to store and transport food products. These traditional methods of packaging are often more expensive compared to modern plastic-based alternatives. However, since it can be reused repeatedly, it is a more sustainable choice in longer-term whereas plastic food packaging is the main source of solid waste [1]. This emphasizes how crucial it is to reduce the use of single-use plastics for food packaging in order to preserve the environment from further contamination driven by plastics ending up in landfills or oceans after being thrown away after a single use. Thus, there are still ways to minimize reliance on single-use plastics when comes to determining the type of material used for food packaging, despite traditional approaches that may not always be feasible or economical.

Recent developments in food packaging have focused on the use and promotion of active or biodegradable food packaging, due to their environmental benefits. Traditional petroleum-based packaging materials are still commonly used because it is convenient and affordable, although it pollutes the environment [2]. Films and coatings made of biopolymers provide an option that is both biodegradable and capable of preserving the quality of food over time. Active packaging regulates the environment inside the packaged material and guards against spoiling brought by external forces such as physical, chemical and biological factors. Some packaging can even assist in keeping nutrients in food products intact for a longer period of time. Overall, incorporating biopolymer-based additives pose a solution for sustainable food packaging with numerous advantages compared to traditional methods [3].

The aim of this report is to showcase the new innovative food packaging technology known as active food packaging (AP) with a focus on controlled release food packaging (CRP). A comprehensive literature review was carried out to compare active and controlled release packaging, as well as review different methods to achieving sustained diffusion of active components and the challenges and future prospects of CRP. The

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importance of this research lays in understanding how to prolong the shelf life of food without compromising food safety and human health.

2 Active packaging associated with controlled released

Active packaging (AP) is a novel technology used in food preservation and storage that contains active agents such as antioxidants and antimicrobial components in the film to efficiently combat the build-up of bacteria that lead to food spoilage. This helps limit bacterial growth, food oxidation and decomposition of foods to prolong storage life. The mode of action is dependent on the volatility of the active ingredient, with non-volatile active agents diffusing through the packaging directly to the food surface [4]. Research into this type of AP has progressed through three phases, with the latest involving controlled-release packages that are designed to match up with food deterioration over time. By controlling when and concentration of active ingredients released onto the food surface, it helps maintain optimal concentrations for maximum safety and quality by preventing spoilage or oxidation from occurring. Control release active packaging technology improves numerous properties of packaging, such as gas and moisture permeability, UV protection and mechanical characteristic [5].

It is well understood that the release rate of active compounds from packaging into the food system is the primary factor that influences food quality. For instance, the release rate of antioxidants from packaging into food formulation is rapid, hence exceeding the authorized amount in food, and resulting in the production of pro-oxidants due to high concentrations of antioxidants [6]. Whereas the sustainable release rate of antioxidants has the advantage of inhibiting oxidation, hence resolving the issue of exceeding the authorized concentration level of antioxidants. Besides, the level of antioxidants efficiently diffused into the food is an essential phenomenon for designing CRP [7]. As an organic additive for meat products, edible oils, cereals, bakery goods, and fried meals, bamboo leaf extract (BLE) was permitted in China [8]. Table 1 summarizes the difference between control release packaging and active packaging.

3 Latest development

Active packaging development has been accelerated by incorporating nanocomposites [9]. Nanomaterials present a huge opportunity to overcome the obstacles associated with the production of active packaging. Minimizing the film thickness of polymer-based packaging has been made possible by nanomaterials resulting in cheaper transportation costs due to lower weight [10]. The incorporation of nanomaterials such as nanofibers and particles can serve as stabilizers to enhance the mechanical characteristics of biopolymers, thus eliminating the need for additional additives to achieve high and desirable characterizations [11]. In addition, it improves tensile strength, antioxidant and antibacterial properties [10,12].

Table 1. Comparison between control release packaging (CRP) and active packaging (AP)

Control Release Packaging (CRP)	**Active Packaging (AP)**
Involves the gradual active components diffusion over a period of time.	Fast release of active agent.
Straightforward addition of agents to the polymer or encapsulating the agents before addition to the polymer to achieve controlled release methods.	May use these same methods but also relies on natural active agents for its functionality
	Designed to respond to certain stimuli or conditions

For active packaging, nanocomposites such as antimicrobial nanocomposites and barrier-enhancing nanocomposites are a potential class of materials to use owing to their distinctive characteristics and activities [13-15]. Antimicrobial nanocomposites emit antibacterial substances or develop physical barriers that stop the spread of microbes [16]. Because of their broad spectrum of antibacterial activity, low cytotoxicity and prolonged shelf life of packaged foods, antimicrobial nanocomposites such as silver nanoparticles and zinc oxide nanoparticles are frequently used in the development of nanopackaging materials [17,18]. However, eco-friendly biological techniques, often known as green techniques, that include microbes, enzymes and plant extracts are becoming more popular at the current stage [19]. For instance, the zinc oxide nanoparticles synthesized via thyme extract demonstrated antifungal properties, making them a suitable alternative for food packaging [20]. While for barrier-enhancing nanocomposites, clay and graphene oxide nanoparticles can be introduced into polymers to improve their barrier performance by restricting oxygen or moisture from penetrating [14].

Recent advances in active food packaging have focused on the exclusive use of biodegradable and biocompatible materials, as well as natural compounds to enhance sustainability and sensory properties [21]. This shift has been driven by consumer preference for natural additives over synthetic ones due to their perceived health benefits. Technologies such as packaging with a controlled atmosphere and vacuum sealing are not effective at eliminating oxygen or moisture or protecting food from light. Active-release packaging technology could overcome this as it involves incorporating an active component within the polymer, which eliminates possible leakage onto packaged food items [12]. Examples of these agents include oxygen scavengers (iron oxidation or glucose oxidase, CO_2 and ethanol emitters), antioxidants agents (extracts, polyphenols and tocopherols) and antimicrobials components (organic acids, essential oils, bacteriocins chitosan derivatives) was the potential alternative agent used [22]. To be effective at preserving food, these components must be released in a controlled and sustained manner when needed [23]. The active agents used in food packaging were chosen based on the specific application, desired functionality, compatibility with the packaging materials and product, regulatory considerations and safety requirements [22].

Table 2. Advantages and disadvantages of control release food packaging

Advantages	Disadvantages
Provides protection from environmental stress like light, oxygen, moisture, etc.	Strict safety regulations must be adhered to when using active agents in packaging materials
Can be tailored to specific needs and conditions	Costly materials may be required for production which can increase the cost of packaging products
Reduces food waste by extending shelf life	

Controlled release (CR) active packaging has recently received wide attention, due to its pro-oxidation and regulatory maximum allowable concentration compliance compared to the traditional packaging [24]. Table 2 summarized the advantages and drawback of control release food packaging. In this regard, the controlled release of antioxidants from the packaging has been widely investigated to sustain food quality during transportation and storage. In addition, CR-based food packaging systems are intended to ensure the effective amount of active agent is disbursed into the food from the polymeric carrier to slow down the deterioration of food [25]. This reduces waste from spoiled foods and decreases reliance on single-use plastics for short-term storage solutions. Additionally, biodegradable polymers used in CRP systems are derived from renewable resources instead of nonrenewable petroleum sources like traditional plastics, making them a more environmentally friendly option with less potential for toxic compounds to be released into the environment.

Figure 1 summarizes 4 different techniques to facilitate the controlled and slower release of active agents. Multilayer active packaging is composed of several layers, including a layer that regulates the release of active agents and another to prevent their loss. Microencapsulation of active agents within a porous carrier material has been effectively developed for controlled-release packaging films [25]. Mesoporous silica materials, MCM-41 silica is an effective carrier material due to its strong textural properties, which can be used to encapsulate a wide range of natural compounds [26]. Reactive extrusion is a process in which two or more polymers are mixed and then heated to form a homogeneous blend. This process can be used to incorporate active substances into the polymer matrix, allowing for better control over release rates [27]. Polymer mixing can be used to provide control release of active packaging by adjusting the ratio of different polymers in a composite film. Nano clay and other particles were added to increase the tortuosity of the antioxidant diffusion path resulting in a slower release rate thus preserving the food for a longer period [28]. Surface coating can be used to control dispersion of active agent. For instance, natural antimicrobial agents encapsulated in fiber carrier was effective at controlling and releasing the agents and could be applied to various types of food applications [29]

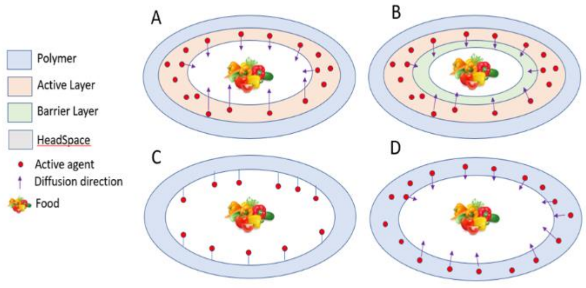

Fig. 1. (A) active layer applied by lamination, (B) Multiple layer Film, (C) covalently attaching molecules to the polymer surface, and (D) incorporating them directly into the polymer matrix which may involve encapsulating them.

The other recent development in packaging which caught the public attention includes edible packaging and intelligent packaging. Edible packaging refers to packaging materials or containers that are safe for consumption along with the product they contain. These materials are designed to be consumed or easily biodegradable, reducing waste and environmental impact. Edible packaging can be made from various natural sources, such as plant-based materials, seaweed, edible films, or even edible coatings [30]. Intelligent or smart packaging integrates technologies like sensors, indicators, and tracking systems to monitor and provide real-time information about product quality, freshness, and integrity. This enables improved quality control, supply chain transparency, and consumer engagement [31].

4 Current challenges and future prospect

CRP can be difficult to control and predict the rate at which active compounds are released from a package, as it differs based on pH levels, moisture content in the air and temperature. This unpredictability in release rates leads to inconsistent performance over time, making it difficult for manufacturers to guarantee food safety standards [32]. To overcome this challenge newly developed method for polymer matrix modification allow more precise control over active compounds released from packages. Testing methods have been developed to better understand how modified polymers interact with different foods and environments with their performance can be accurately assessed before use [23].

The future prospects for controlled release packaging (CRP) are very promising, with research suggesting that it could extend shelf-life up to five times more than traditional methods while also providing additional safety benefits due to its ability to interact with the environment around it [32]. One of the main trends in CRP is the development of intelligent or smart packaging (IOSP), which includes time–temperature indicators (TTIs), gas indicators, radiofrequency identification (RFID), and others which provide further information about handling foods safely and conveniently for consumers [23]. This demonstrates how CRPs can be used not only as a way of preserving food quality but also as a tool for providing useful data on food handling and storage conditions. In short, controlled release packaging offers great potential when it comes to maintain food safety whilst increasing convenience for consumers through extended shelf-life periods.

However, there are still challenges in the current packaging industry that need to be further studied, especially in understanding how nanomaterials interact with living things. It is important to take into account their migration behavior, which is still unknown in the current research field. The use of nanomaterials at a commercial scale in the food technology industry is constrained by conflicting evidence regarding cytotoxicity and a lack of comprehensive risk assessment and management studies. Additionally, the development of a sizable market for food applications based on nanotechnology must take into account customer acceptance.

5 Conclusion

In conclusion, active packaging and controlled release packaging technologies aim to prolong the storage life of food products by incorporating active agents such as antioxidants, antimicrobial components and oxygen scavengers**.** Future prospects include developing an intelligent food packaging system for better food storage and handling systems that could be beneficial to the community**.** However, the challenges regarding the release rate of active agents from packages into headspace or onto food surfaces needed to be further studied**.**

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