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Review Article

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Preserving Freshness in Bell Peppers: Innovative Packaging Solutions to Prolonged Shelf Life

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ABSTRACT

Every year, a significant portion of the vegetable harvest is lost due to improper packaging conditions, resulting in extensive economic, food security and environmental losses. Without proper packaging, fresh produce is vulnerable to spoilage before it reaches consumers, leading to waste and financial losses for farmers. Due to their high nutritional value, bell peppers are a popular and commercially valuable produce. Their phytochemical content, including flavonoids, carotenoids, and vitamin C, contribute to health benefits, driving strong consumer demand. Bell peppers are consumed in various forms, including whole, sliced, and dried. This review illustrates various strategies to prevent the spoilage of bell peppers, including pre-and post-packaging treatments, novel packaging materials, modified atmosphere packaging (MAP), active packaging, packaging with antimicrobial agents, and the potential of nanotechnology and chitosan coatings to extend shelf life. These techniques promise to increase food safety and reduce waste in Iran's bell pepper industry.

Keywords: Bell pepper,Bell pepper shelf-life, Food security, long-lasting packaging, Vegetable packaging

Introduction

The preservation of food quality during transportation to the end consumer is a significant challenge for the agricultural industry and food producers, particularly given the increasing demand for food due to population growth. As a result, the development of effective packaging techniques and the implementation of innovative technologies to maintain the freshness of food products, such as fruits and vegetables, have become critical priorities for stakeholders in this field. Effective food packaging should possess a variety of characteristics, including non-toxicity, hygiene, resistance to light, moisture, fats, and gases, lightweight and ease of transport, easy-to-open packaging closures, and recyclability and minimal environmental impact [1-2]. Materials commonly used in food packaging today include plastics, petroleum-based substances, glass, metals, and paper. However, the quest for more environmentally friendly and sustainable packaging solutions is an ongoing area of research and development in the food industry [3].

Polyethylene (PE) is the most used plastic in food packaging, having been commercialized in the 1950s and maintaining its dominant position as a packaging material for food and beverages ever since. PE's popularity in food packaging can be largely attributed to its relatively low cost, versatile properties, ease of fabrication and processing, and flexibility in catering to the diverse packaging needs of the food industry [4].
Amongst vegetables, bell peppers are particularly commercially significant horticultural commodities due to their high content of flavonoids, carotenoids, and vitamin C. These phytochemicals impart valuable nutritional and health benefits, contributing to the strong consumer demand for this particular vegetable variety [5].
Bell peppers have specific storage requirements that depend on factors such as temperature, relative humidity within packaging, transportation methods, and exposure to light. To meet these requirements, various packaging methods are employed, including partial pasteurization,

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unwashed or sliced fruits, modified atmosphere packaging, vacuum packaging, smart or active packaging, the use of edible polymers, petroleum-based or biodegradable materials, and the incorporation of antimicrobial agents [6-11].
Numerous studies have explored various techniques to extend the shelf life of bell peppers both pre- and post-harvest, utilizing a range of polymers for packaging. However, only some of these studies have been adopted on a global scale. In Iran specifically, specialized packaging for bell peppers is not available, leaving farmers and distributors without effective methods to improve shelf life. This paper compiles significant research that has substantially increased the shelf life of bell peppers, aiming to serve as a resource for enhancing post-harvest handling and packaging processes for fresh bell peppers in Iran. By synthesizing existing knowledge, this study seeks to promote sustainable practices that maintain the quality and freshness of bell peppers, benefiting both producers and consumers in Iran and beyond.

Packaging of Bell Peppers

Extensive research has been conducted to identify appropriate packaging methods for bell peppers. Below, several studies that have demonstrated success in preserving bell peppers are discussed.

Pre-package treatment

Various pre-packaging treatments have been identified, including the use of UV and gamma radiation, chemical agents such as chitosan, thyme essential oil, lemon leaf oil, calcium chloride, ozonation, hot water washing, and biological materials. These treatments have demonstrated the potential to enhance the shelf life of bell peppers prior to packaging [12-18]. Chlorine-based solutions, such as chlorine (10–200 ppm), have demonstrated significant efficacy in reducing microbial contamination on bell peppers when employed as a simple washing procedure [19]. A study investigating the efficacy of various washing solutions on bell peppers in greenhouses revealed that a combination of salicylic acid (8 mM), citric acid (30 mM), and clove or olive oil (5 mL/L) effectively reduced the growth of Botrytis cinerea during cold storage. Salicylic acid demonstrated the highest effectiveness in inhibiting fungal growth, completely preventing mycelial growth at concentrations of 4 and 8 mM [18]. The control of post-harvest fruit rot caused by B. cinerea and other pathogens has been the subject of significant research, with numerous microorganisms demonstrating potential efficacy. Despite this, specific focus on post-harvest fruit rot control remains somewhat limited. Microbial agents can be applied both pre-and post-harvest, either as single or combination treatments. For instance, Bacillus amyloliquefaciens has demonstrated efficacy in controlling gray mold in tomatoes. When applied to bell pepper plants as a foliar spray, B. amyloliquefaciens exhibits plant growth-promoting rhizobacteria (PGPR) properties, enhancing the antioxidant capacity of the fruit [20]. Moreover, the endophytic fungus Beauveria bassiana has shown potential as a control agent for B. cinerea in both tomato and chili pepper crops. When applied to the roots of these plants, B. bassiana provides protection against penetration by the pathogen [21]. Within the Iranian context, studies have focused on the application of pre-treatments to improve the shelf life and quality of bell peppers. One such study examined the synergistic effects of ultrasound and Thymus vulgaris essential oil nanoemulsion when employed as a pre-packaging washing treatment for sliced bell peppers. The results indicated significant antibacterial activity and preservation efficacy, as demonstrated by the ability to maintain the quality of the bell peppers at 5°C for up to 10 days. The application of Thymus vulgaris essential oil offeres potential as an environmentally-friendly and safe alternative for preserving the freshness and safety of produce [22].An alternative approach for mitigating chilling injuries in bell peppers involves the application of a gibberellic acid and calcium chloride solution as a pre-harvest washing treatment. In this method, the solution is sprayed onto the bell peppers prior to harvest, with the aim of enhancing their resilience to the adverse effects of low-temperature storage. Research has demonstrated that this technique effectively enhances the quality of bell peppers during cold storage, potentially offering a viable strategy for improving the post-harvest handling and preservation of this produce [23]. Pre-packaging methods are not limited to washing solutions and irradiation techniques. A study explored pre-harvest fertilization using calcium and potassium thiosulfate to extend bell peppers' shelf life. This method significantly increased self-life by up to 20 days compared to untreated controls, indicating that pre-harvest interventions can improve the produce quality and reduce spoilage. These findings highlight the potential of innovative techniques for optimizing post-harvest quality and reducing food waste in bell pepper production [24].

post-packaging treatment

post-packaging treatments primarily involve the optimization of storage temperatures, which is a critical factor in extending the shelf life of packaged bell peppers. The optimal storage temperature for bell peppers is between 8°C and 10°C, which can effectively reduce the microbial and enzymatic activities of the produce. However, it may also facilitate the growth of psychrophilic microorganisms, including B. cinerea, which can cause gray mold [19].

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Storing bell peppers at temperatures below 8°C can lead to chilling injury, which negatively impacts the fruit quality and renders it unfit for consumption. This emphasizes the importance of maintaining optimal storage temperatures to ensure the preservation of the quality and integrity of the produce [13].

Petroleum-Based packaging

Low-density polyethylene (LDPE) films are effective in prolonging the shelf life of yellow bell peppers when paired with oxygen absorbers. Packaging yellow bell peppers in LDPE 150 films along with 2 grams of oxygen absorbers has been shown to significantly extend the shelf life of the produce at a low temperature of 10°C [25]. Packaging bell peppers with heat shrinkable film (15µ) and cling film (15µ) has been found to significantly slow down product degradation and spoilage in both supermarket conditions (18–20°C; 90–95% RH) and ordinary market conditions (28–30°C; 60–65% RH). This method of packaging offers a viable solution for extending the shelf life of bell peppers under a range of environmental conditions [26].The Xtend® (XF) plastic-based packaging combined with modified atmosphere has demonstrated enhanced preservation of bell peppers at a range of temperatures, including 1.5, 7, and 17°C. This method of packaging outperformed polyethylene in terms of preserving product quality and extending shelf life when stored at 7°C [5].

In another study, three packaging films (LDPEe60, MDPEe30, and PVC) were tested at two storage temperatures, 5°C and 10°C, in combination with modified atmosphere packaging (MAP). The results revealed that polyethylene-derived packaging at both 10°C and 5°C significantly reduced the incidence of chilling injury compared to unpackaged storage [27].

A study comparing the effectiveness of different polymers for modified atmosphere packaging revealed that among PELD, polyolefin, and anti-fog films, bell peppers stored with anti-fog film had superior physicochemical properties and stability during storage. This improved stability was maintained for up to 28 days compared to the control sample [28].

In a study comparing three packaging films (LDPEe60, MDPEe30, and PVC) at two storage temperatures (5°C and 10°C), it was found that bell peppers packaged with polyethylene films (LDPEe60 and MDPEe30) retained a stable ascorbic acid content during storage . Furthermore, these peppers showed reduced gas exchange compared to PVC packaging. Bell peppers packaged with LDPEe60 film at 5°C could be stored for up to two weeks with minimal quality loss, while peppers stored in the same temperature conditions with PVC film showed significant quality loss. These findings indicate the suitability of polyethylene films for maintaining the quality of bell peppers during storage [27].

Biodegradable Materials

In response to concerns about pollution caused by traditional biopolymers, there has been a shift in focus towards the utilization of biodegradable materials in packaging applications. These materials offer a more sustainable and environmentally-friendly alternative, which has garnered significant interest among researchers and industry players alike [29].

Biodegradable edible packaging, which is designed to be consumed along with the food product, encompasses two categories: edible films and edible coatings. Edible films are produced as thin layers, serving a similar function to synthetic polymers in food packaging. They are typically applied prior to storage or transportation, creating a protective barrier that enhances the shelf life and quality of the packaged food item [30]. Edible coatings, in contrast, are formed directly on the surface of the food product. These coatings, like edible films, offer numerous advantages, including biodegradability, reduced gas exchange, control of respiration in fruits and vegetables, resistance to flavor and aroma loss, and protection against mechanical damage. These advantages render edible films and coatings a highly effective and sustainable solution for food packaging, particularly for fruits and vegetables [31].

Edible packaging

To study the effects of chitosan and aloe vera gel coatings on postharvest quality, red bell peppers (Capsicum annuum L.) were subjected to two coating treatments: 1.5% and 2% solutions of chitosan or aloe vera gel. The coated surface was then dried using a high-speed air fan, and the treated peppers were stored in paper cartons under ambient conditions (25 ± 2°C and 55 ± 5% RH) .The effectiveness of the coatings in preserving the post-harvest quality of bell peppers was evaluated through several measurements, including respiration rate, ethylene production, fruit firmness, weight loss, external color change, beta-carotene content, ascorbic acid content, pH, incidence of fungal rot, and sensory quality. Uncoated peppers developed fungal decay by day 6, while those treated with 1.5% chitosan demonstrated signs of decay by day. Coatings of 2% chitosan and aloe vera gel (AV) also extended the period before the development of fungal rot, with decay appearing on day 12 in treated peppers. Both AV and chitosan coatings were found to reduce respiration rate, weight loss, incidence of rot, and maintain fruit color, firmness, ascorbic acid content, and other quality attributes. These results indicate that coating treatments with chitosan or AV gel effectively delayed the onset of decay in bell peppers, whether due to aging or microbial attack [32].

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Significant research has been conducted in Iran on innovative packaging methods for bell peppers. One notable study assessed the efficacy of Arabic gum in preserving bell peppers at 8°C. The findings demonstrated that bell peppers coated with a 12% Arabic gum solution could be effectively preserved for up to 28 days. This research indicates that the application of Arabic gum as an edible coating can significantly extend the shelf life of bell peppers, likely due to its ability to create a barrier against moisture loss and microbial contamination [33].

Another related study investigated the effects of combining Arabic gum with silver nanoparticles as a novel packaging intervention for bell peppers. The results indicated that this combination effectively maintained the visual quality of bell peppers and inhibited microbial contamination throughout 21 days of storage at both 20°C and 7°C. This finding highlights the potential synergistic effects of Arabic gum, which provides a protective barrier, and silver nanoparticles, which possess potent antimicrobial properties [34].

Indeed, research has demonstrated the potential of gum tragacanth as an effective edible coating for bell peppers. This natural substance can be applied either on its own or in combination with other compounds, such as aloe vera, to extend the shelf life of bell peppers to 28-30 days when stored at low temperatures. The application of gum tragacanth has been shown to maintain the quality, antioxidant capacity, and overall freshness of bell peppers during storage, highlighting its potential as a viable packaging solution for this popular vegetable [35-36].

Non-edible packaging

Non-edible coating: Unlike edible coatings, these treatments are intended to be removed prior to consumption. Non-edible coating can be applied to fruits and vegetables, and they are designed to be easily removable, while still providing a protective barrier during storage and transportation.

The efficacy of ethanol-extracted propolis wax (EEP) as a coating for bell peppers was investigated for its potential to inhibit the growth of Colletotrichum capsici mycelium and preserve the post-harvest quality of bell peppers. The study aimed to evaluate the effectiveness of this natural compound as an alternative to conventional food preservatives, particularly for preventing fungal growth and decay in bell peppers .The ability of EEP to inhibit the growth of C. capsici mycelium, the causal agent of anthracnose in bell peppers, was evaluated under both in vitro and in vivo conditions. For the in vivo study, bell peppers were artificially inoculated with C. capsici and stored at 10°C and 90% RH for 28 days, using EEP at 1%, 5%, and 10% concentrations .This highlights the potential of EEP as an effective natural preservative against anthracnose in bell peppers, while also maintaining the quality and freshness of the fruit [37].

Modified Atmosphere Packaging (MAP)

MAP involves regulating the gas composition inside the packaging to influence the rate of respiration of the packaged product. This is achieved through two methods:

1. Active Packaging: Involves the use of oxygen scavengers or other systems that actively regulate gas exchange.
2. Passive Packaging: Relies on the natural gas exchange through the packaging material, which is designed to have a controlled permeability to oxygen, carbon dioxide, and other gases [38].

A study was conducted to compare the effectiveness of Active Modified Atmosphere Packaging (AMAP) and Passive Modified Atmosphere Packaging (PMAP) on the quality and shelf life of yellow bell peppers. The results showed that AMAP packages reached steady-state gas compositions (4.8% O_2 and 7.1% CO_2) by the fourth day of storage, while PMAP packages failed to achieve a stable gas composition even after 12 days of storage. The quality of bell peppers was better preserved in the AMAP packages compared to the PMAP packages .Moreover, the shelf life of actively packaged bell peppers was found to be 28 days, significantly longer than the 12-day shelf life of passively packaged fruits. Oxygen absorbers were included in the AMAP as indicators, while the same packaging polymer was used for both the active and passive methods. These results suggest that active packaging is a more effective approach for preserving the quality and extending the shelf life of bell peppers compared to passive packaging [25].

In another study, ethylene absorbers were added to demonstrate the effectiveness of active and passive modified atmosphere packaging for preserving bell peppers. Low-density polyethylene (LDPE) films were used as the packaging material, and 5 grams of potassium permanganate (KMnO4) sachets were included as ethylene absorbers. Bell peppers were stored under modified atmosphere conditions of 10°C ± 1°C and 95% ± 5% RH, with a gas mixture of 5% O_2 and 5% CO_2 filled inside the bags .Both active and passive modified atmosphere packaging (MAP) effectively preserved the physicochemical quality of bell peppers compared to the control samples. However, the results showed that passive MAP was more successful in maintaining the antioxidant content, except for total phenol and cysteine, and antioxidant activity. Furthermore, the inclusion of ethylene absorbers within the MAP system had a positive impact on the bioactive content of the peppers, further improving their quality and freshness [39].

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Passive Atmosphere Packaging

In this method, the air inside the packaging is removed using a vacuum or replaced with a modified atmosphere containing specific ratios of oxygen, carbon dioxide, and nitrogen. Once sealed, the gas mixture remains stable inside the packaging until it is opened, ensuring the preservation of the product's quality and freshness without the need for active intervention [40].

A study examining the efficacy of vacuum and modified atmosphere packaging (MAP) found that MAP can significantly extend the shelf life of fresh-cut peppers. When stored at 10°C, the shelf life of MAP-packaged peppers was extended to 14 days, while at 5°C, the shelf life increased to 21 days [41]. These findings are particularly important considering the current commercial shelf life of fresh-cut bell peppers, which ranges from 9 to 14 days. When peppers are stored at 5°C with a modified atmosphere composition of 10% O_2 and 45% CO_2, MAP packaging can increase the shelf life by at least 3 days, resulting in a 20% extension. This extension of shelf life can have a significant impact on food waste reduction and overall food security [42].

A study investigated the effects of different concentrations of carbon dioxide (CO_2) and oxygen (O_2) on maintaining the quality of green and red pepper slices. The results showed that air with 15 kPa CO_2 caused physiological damage in both green and red peppers, regardless of the ripening stage. Additionally, red pepper slices were more sensitive to CO_2 enrichment, exhibiting damage in the 5–10 kPa range .Fully ripened fresh-cut peppers were also sensitive to low oxygen levels below 5 kPa. The optimal atmosphere for maintaining the quality of both green and red peppers was found to be 5 kPa O_2 and 5 kPa CO_2. Storage in modified atmosphere at this composition effectively maintained the firmness and resistance to bending of the pepper slices. Moreover, the spoilage, dehydration, and ion leakage of the slices were reduced when stored in modified atmosphere, while the color, acidity, sugars, and antioxidants remained unchanged .This packaging not only maintained the quality and firmness of the pepper slices but also effectively controlled the growth of microorganisms. Mesophilic bacteria, yeasts, and molds were significantly reduced in ripe red pepper slices stored in MAP, further extending their shelf life and ensuring safety for consumption [43].

In another study, the shelf life of green bell peppers was extended through the use of Passive Modified Atmosphere Packaging (PMAP) in combination with gamma irradiation at various dose levels of 0.1, 0.25, and 0.5 kGy. This combination of treatments was found to be effective in preserving the quality and safety of green bell peppers. The significant reduction in physiological and biochemical changes observed in green peppers treated with MAP and gamma irradiation at 0.25 and 0.5 kGy resulted in an enhanced shelf life of up to 42 days at 8°C ± 1°C. These findings suggest that the combined treatment of PMAP and gamma irradiation could be an effective strategy for extending the shelf life of fresh green peppers and preserving their quality and nutritional value [13].

Active Atmosphere Packaging

In contrast to passive atmosphere packaging, active atmosphere packaging involves the continuous regulation of atmospheric conditions inside the packaging after the replacement of air. This is achieved by adding active compounds such as O_2, CO_2, ethylene, methanol, water, or antimicrobial agents, which can be absorbed or removed as needed [44].

Since the atmospheric conditions inside the packaging are continuously altered to maintain the optimal environment for preserving the product quality, this method is referred to as Active Modified Atmosphere Packaging (AMAP) [45].

In a study evaluating the impact of Active Modified Atmosphere Packaging (AMAP) with air composition of either 4.7% O_2 and 7.5% CO_2 or 4.5% O_2 and 7.8% CO_2, the addition of a single silica gel moisture absorber extended the shelf life of bell peppers stored at 8°C by 7 days. This means that when using AMAP in combination with a moisture absorber, the bell peppers remained fresh and of good quality for 28 days, compared to the original 21-day shelf life in controlled conditions [12].

Active Packaging

In this approach, active components or materials are placed within the packaging, which actively interact with the components inside the package to preserve the quality and extend the shelf life of the product. The active components can include a variety of substances, such as antimicrobial agents to inhibit microbial growth, intelligent indicators to monitor changes in temperature or humidity, and various types of absorbers to remove excess moisture, oxygen, or other gases.

• Antimicrobial packaging: Several factors play a crucial role in the successful design of an active antimicrobial packaging system, as the efficacy of the packaging depends on the characteristics of the antimicrobial agent, the packaged food product, and the target microorganisms. By considering the properties and conditions of all three elements, it is possible to create an effective active packaging system that effectively inhibits the growth of microorganisms and product spoilage without compromising the organoleptic and nutritional qualities of the product.

The use of encapsulated essential oils (EOs) in active packaging has proven to be an effective means of prolonging the shelf life of bell peppers.

The controlled release of the EOs in the vapor phase from the active packaging significantly increases the antimicrobial activity against spoilage microorganisms, extending the shelf life of green, red, and yellow peppers to a minimum of 18 days when stored at 8°C. This demonstrates that active packaging containing EOs can be a powerful tool for maintaining the freshness and quality of bell peppers during storage [46].

• Intelligent (Smart) Packaging: Smart packaging incorporates intelligent indicators or sensors that can monitor various environmental factors affecting the food product, such as temperature, oxygen levels, and pH. This information is then communicated to the consumer via visual indicators, such as color changes or electronic signals, thereby providing crucial insights into the product's quality and safety.

This type of packaging serves as a dynamic tool for consumers, allowing them to make well-informed decisions about the freshness, safety, and overall quality of the food .It is important to note that smart packaging does not directly extend the shelf life of food. Its primary function is to communicate information about the quality and safety of the food, thereby allowing the consumer to make more educated decisions about its consumption. In this way, smart packaging acts as a tool for informed decision-making and can potentially contribute to reduced food waste, as it allows consumers to avoid discarding food products prematurely or consuming them when they are no longer of optimal quality [47].

Given that bell peppers are particularly sensitive to the level of carbon dioxide (CO_2) inside the packaging, where high concentrations can lead to accelerated respiration and fermentation, a study was conducted to develop a smart CO_2 indicator. This indicator was designed to initially display a blue color when the packaging was sealed, but then change color in response to the presence of excess CO_2, providing an early warning to the consumer about the potential deterioration of the bell peppers. As the bell peppers aged, the produced CO_2 within the packaging penetrated the smart label and chemically reacted with the calcium hydroxide contained within the smart film. This reaction formed water, which subsequently absorbed additional CO_2 molecules and organic acid vapors that were also present in the packaging. These additional components served to neutralize the slightly basic mixture within the smart film, causing a visual change in the label, typically a color change, which could then be easily observed by the consumer. As the CO_2 concentration increased within the packaging, the pH of the indicator label changed, causing a shift in its color from blue to greenish-blue, and finally to greenish yellow as the peppers continued to age. This visual change in the label provided a reliable indication of the peppers' freshness and quality, allowing consumers to make informed decisions about when to consume the peppers for optimal flavor and safety [48].

A separate study utilized freshness indicators to monitor the changing pH levels of bell peppers. These indicators were created by mixing methyl red and bromothymol blue solutions in a 3:2 ratio at a concentration of 70 mL L^{-1}, which was then incorporated into an indicator film solution named Indicator b. As the bell peppers aged, the pH of the packaging environment shifted, causing a visible change in the indicator label's color As the peppers began to decay, the indicator label changed from yellow-green to orange, providing a clear visual warning to the consumer that the product was no longer fresh and should be consumed or discarded as soon as possible [49].

Antimicrobial Agents in Bell Pepper Packaging

To preserve the freshness and quality of bell peppers, various antimicrobial agents have been utilized in food packaging, including ethanol, carbon dioxide, silver ions, chlorine dioxide, antibiotics, bacteriocins, organic acids, nanomaterials, essential oils, and spices. Each of these substances can be driven from plants, animals and ,microorganisms and has distinct properties and mechanisms of action that can effectively inhibit the growth of spoilage microorganisms in the packaging environment [50-52].While the potential benefits of these various antimicrobial agents have been extensively studied, only a few have been industrialized for commercial use. Of these, silver-based antimicrobial materials are currently the most widely adopted, with many countries, including the United States and Japan, recognizing the efficacy and safety of these materials in food packaging [53]. Like many other fresh fruits and vegetables, bell peppers are susceptible to microbial spoilage during storage, transportation, and supermarket display. The major storage-related infections affecting bell peppers include Alternaria rot, commonly known as black mold, and gray mold rot. Alternaria rot, caused by Alternaria spp., penetrates through the stem end of the pepper, leading to the development of black mold inside the pepper. This infection can cause significant damage to the pepper's quality and shelf life .Gray mold rot, caused by Botrytis cinerea, is another major spoilage concern for bell peppers, particularly in humid and cool storage conditions. This pathogen thrives in these conditions and can rapidly spread through the pepper, causing soft rot and loss of texture and quality. The presence of these pathogens is a significant challenge for preserving the freshness and shelf life of bell peppers, making the use of effective storage and packaging methods crucial for maintaining their quality [19, 54].In an effort to combat these spoilage concerns, the use of plant-derived compounds, such as thymol and carvacrol, which are naturally found in thyme, has been investigated as an alternative to synthetic antimicrobials.

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These compounds have been approved by the FDA for use in food packaging and have demonstrated strong antifungal activity against spoilage fungi, making them promising candidates for protecting the freshness and quality of products during storage and transportation [55-56].

Harnessing Nanoparticles and Nanocoating to Preserve Freshness

Copper nanoparticles (CuNPs) have numerous applications across various industries due to their unique properties, including use as sensors, catalysts, surfactants, antimicrobials, and antifouling agents. Despite their widespread applications, concerns about potential toxicity, particularly for aquatic animals, have limited the use of copper in bio-nanocomposite films for food packaging [57].

To mitigate these concerns and explore alternative antimicrobial agents, researchers incorporated different proportions of copper nanoparticles into sodium alginate and nano whisker cellulose matrices, creating a range of antimicrobial films. One of these films, created by combining copper oxide nanoparticles (CuO NPs) with sodium alginate (SA), was designed to provide a flexible and effective barrier against microbial spoilage, while avoiding the potential toxicity issues associated with copper nanoparticles .The most effective antimicrobial film formulation was found to be the one containing CuO NPs at a 5 mM concentration. This film demonstrated significant inhibitory activity against a range of microorganisms, including Staphylococcus aureus (27.49 ± 0.91 mm), E. coli (12.12 ± 0.58 mm), Salmonella sp. (25.21 ± 1.05 mm), Candida albicans (23.35 ± 0.45 mm), and Trichoderma spp. (5.31 ± 1.16 mm). The CuO NP film was also found to preserve the freshness of freshly cut bell peppers for up to 7 days, significantly extending their shelf life and reducing spoilage. Furthermore, the presence of the CuO NPs in the films also improved the antioxidant activity of the peppers, potentially protecting them from oxidative damage and enhancing their nutritional value [58].

Recent research has explored the potential benefits of bio-composite films containing titanium dioxide nanoparticles (TiO_2NPs) in preserving the freshness of various fruits, such as tomatoes [59] and green bell peppers. The inclusion of TiO_2NPs in these films has shown promise for enhancing the shelf life of fruits through the degradation of ethylene, a naturally occurring hormone that accelerates ripening and hastens the spoilage process. In addition to their ethylene degradation capabilities, TiO_2NPs in bio-based composite films have demonstrated improved thermal stability, tensile strength, UV protection, and antimicrobial activity, as well as reduced water vapor permeability. In storage studies of green bell peppers, these films have exhibited significant resistance to weight loss and spoilage, suggesting that they may be a viable option for maintaining the freshness and quality of this fruit during storage and transportation [60].

Another recent study has demonstrated that combining copper oxide nanoparticles (CuO NPs) with nano whisker cellulose and chitosan nanofibers can result in a highly effective antimicrobial bio-based composite film. The incorporation of these nanomaterials into the film significantly increased its antimicrobial properties, providing a promising solution for extending the shelf life and preserving the freshness of food products, particularly bell peppers [61]. Furthermore, Saravanakumar et al. (2020) developed a bio-based composite film, combining copper oxide nanoparticles (CuO NPs) and cellulose nano-whiskers, for packaging freshly cut bell peppers. This film exhibited impressive antimicrobial activity against a range of microorganisms, including Staphylococcus aureus, Escherichia coli, Salmonella sp., Candida albicans, and Trichoderma spp. Additionally, the film effectively inhibited microbial growth in bell peppers for up to 7 days, improved antioxidant activity, and significantly reduced weight loss and spoilage during storage [58]. Further research in this area has revealed that coatings of polyvinyl pyrrolidone (PVP) embedded with silver nanoparticles (AgNPs) can also effectively prolong the shelf life of fresh-cut bell peppers. When applied to the peppers, this coating significantly increased the storage life to 12 days at 4°C, while maintaining the cellular and physicochemical properties of the produce [62].

Chitosan-Based Coatings

Recent studies have highlighted the potential of irradiated chitosan coatings as a natural solution to extend the shelf life of sweet bell peppers. In one investigation, researchers found that coating the bell peppers with solutions containing 0.5% and 1% irradiated chitosan, along with the application of polyethylene-wrapped nanocomposites, successfully preserved storage quality for up to 28 days at 8°C [14].

Another study evaluated the efficacy of thyme-chitosan essential oil coatings in preserving the quality of green bell peppers infected with Pectobacterium carotovorum. In this investigation, a 15% thyme-chitosan coating was found to be the most effective formulation, significantly minimizing disease incidence and CO_2 production, while preserving firmness and reducing weight loss in the infected bell peppers [15]. In another investigation, researchers studied the effects of nanochitosan-based coatings enriched with Byrsonima crassifolia extract on the shelf life of bell peppers. This pre-harvest treatment was found to completely suppress Alternaria alternata mold growth, preserve weight and color, enhance antioxidant properties, and reduce microbial activity by 85% over a 21-day storage period, demonstrating the potential of this natural coating as an effective tool for extending the shelf life of bell peppers [16].

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A similar study examined the effects of chitosan nanoparticles combined with lemon leaf oil on bell pepper storage quality. The findings revealed that the combination of chitosan nanoparticles and lemon leaf oil effectively reduced weight loss, slowed color changes, maintained firmness, and increased soluble solid concentrations in the bell peppers over a 21-day storage period, further reinforcing the potential of chitosan-based coatings in preserving the freshness and quality of bell peppers [17].In a study conducted in Iran, researchers employed two chitosan-based packaging methods to prolong the shelf life of bell peppers. The first approach involved the utilization of filter papers impregnated with Heracleum persicum essential oil (HPEO), and the second technique employed HPEO-loaded chitosan nanoparticles. The findings revealed that when these chitosan-based packaging solutions were applied to bell peppers stored at a temperature of 9°C, they effectively extended the shelf life by up to six days [63]. A subsequent study examined the impact of chitosan as an edible packaging material on the preservation of bell peppers. The results demonstrated that when chitosan was applied at a 2% concentration, it had the potential to maintain the quality of bell peppers for up to 28 days when stored at a temperature of 10°C. These findings highlight the efficacy of chitosan-based coatings in preserving the freshness and overall quality of bell peppers during storage, suggesting its utility as a sustainable packaging solution for this popular vegetable [64].

Figure 1. Colour changing of CO_2 indicator [48].

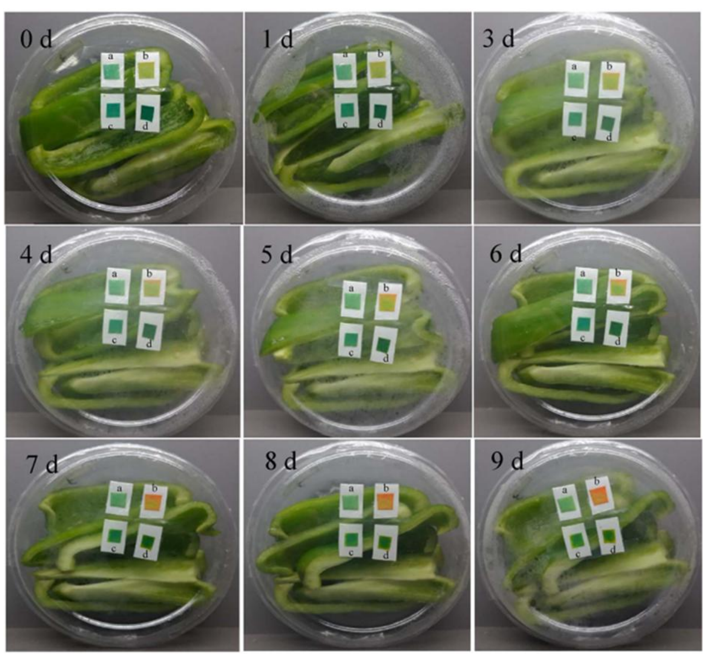

Figure 2. Indicator of pH. Indicator b shows how the product deteriorates after eight days [49].

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Conclusion

This review examines the range of packaging methods developed to date for bell peppers in order to prevent spoilage during storage. Packaging, whether simple or complex, can have a significant impact on spoilage prevention and thus reduce waste. However, factors such as cost, economic feasibility, and a lack of consumer awareness of the benefits of improved packaging have prevented the packaging of bell peppers in Iran from becoming industrialized, with little change in the past fifty years. The implementation of active food packaging systems in Iran is predicted to increase significantly in the near future. Such progress, coupled with the domestic production of advanced packaging technologies and a more comprehensive understanding of the mechanisms and effectiveness of these systems for bell peppers, with a particular focus on green packaging, will help to ensure food safety for this product and similar vegetables. This advancement will ultimately promote consumer health and contribute to food security in the region.

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