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**ARTICLE**

# Shelf Life Extension Technologies and Quality Maintenance of 3D-Printed Plant-Based Foods

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**ABSTRACT**

The rapid development of 3D printing technology has promoted the industrialization process of personalized plant-based foods, but the short shelf life and easy quality deterioration of 3D-printed products have become key bottlenecks restricting their commercialization. This study systematically reviews the shelf life limiting factors of 3D-printed plant-based foods, focuses on the application of shelf life extension technologies (including modified atmosphere packaging, active packaging, non-thermal processing, and formulation optimization), and explores the mechanisms of these technologies in maintaining the nutritional quality, sensory properties, and microbial safety of 3D-printed plant-based foods. The interactions between 3D printing processes and shelf life extension technologies are analyzed, and the existing challenges and future development directions are discussed. Research results show that the combination of multiple shelf life extension technologies can synergistically improve the storage stability of 3D-printed plant-based foods. This review provides theoretical support and technical reference for solving the quality maintenance problems of 3D-printed plant-based foods during storage, and promotes the sustainable development of the 3D-printed plant-based food industry.

***Keywords:*** 3D-Printed Plant-Based Foods; Shelf Life Extension; Quality Maintenance; Modified Atmosphere Packaging; Non-Thermal Processing; Microbial Safety

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# 1. Introduction

## 1.1 Background

With the deepening of global attention to food sustainability and personal health, 3D-printed plant-based foods have become a research hotspot in the food industry due to their advantages of personalized customization, precise nutrition, and resource saving (Williams et al., 2024). However, compared with traditional plant-based foods, 3D-printed plant-based foods have unique structural characteristics (such as high porosity, large specific surface area) and processing characteristics (such as layer-by-layer accumulation, extrusion shear), which make them more prone to quality deterioration during storage, including microbial contamination, oxidative rancidity, moisture loss or migration, and sensory quality degradation (Rodriguez et al., 2024). These problems lead to a short shelf life of 3D-printed plant-based foods, which seriously restricts their large-scale production, transportation, and market popularization.

The shelf life of 3D-printed plant-based foods is affected by multiple factors. On the one hand, the porous structure formed during 3D printing increases the contact area between the product and oxygen, accelerating the oxidation of lipids and vitamins (Sharma et al., 2024). On the other hand, the extrusion process may damage the cell structure of plant raw materials, leading to the release of endogenous enzymes (such as lipoxygenase, polyphenol oxidase), which further promotes the deterioration of product quality (Thompson et al., 2024). In addition, the personalized formulation of 3D-printed plant-based foods (such as high protein, high moisture content) may provide favorable conditions for the growth and reproduction of microorganisms, increasing the risk of microbial contamination (Zhang et al., 2024). Therefore, exploring effective shelf life extension technologies and quality maintenance strategies is crucial to promoting the industrialization and commercialization of 3D-printed plant-based foods.

In recent years, various shelf life extension technologies have been applied to food storage, such as modified atmosphere packaging (MAP), active packaging, non-thermal processing (ultrasound, high-pressure processing, cold plasma), and formulation optimization (adding antioxidants, preservatives) (Li et al., 2024). However, the application of these technologies in 3D-printed plant-based foods is still in the initial stage. Due to the unique structural and compositional characteristics of 3D-printed plant-based foods, the effectiveness and applicability of traditional shelf life extension technologies need to be re-evaluated and optimized (Wang et al., 2024). For example, the porous structure of 3D-printed products may affect the gas barrier property of packaging materials, and the high shear force during 3D printing may change the sensitivity of food components to non-thermal processing. Therefore, it is necessary to systematically study the shelf life extension technologies suitable for 3D-printed plant-based foods.

## 1.2 Research Objectives and Scope

This study aims to comprehensively review the shelf life limiting factors of 3D-printed plant-based foods, summarize the application progress of shelf life extension technologies in 3D-printed plant-based foods, analyze the mechanisms of these technologies in maintaining product quality, and discuss the interactions between 3D printing processes and shelf life extension technologies. The specific objectives are: (1) to clarify the main factors affecting the shelf life of 3D-printed plant-based foods (microbial factors, oxidative factors, moisture factors, etc.); (2) to review the application of typical shelf life extension technologies in 3D-printed plant-based foods and their effectiveness; (3) to explore the mechanisms of shelf life extension technologies in maintaining nutritional quality, sensory properties, and microbial safety; (4) to analyze the influence of 3D printing parameters (nozzle diameter, printing speed, filling density) on the effectiveness of shelf life extension technologies; (5) to point out the existing challenges and propose future development directions of shelf life extension technologies for 3D-printed plant-based foods.

The scope of this study covers 3D-printed plant-based foods (including plant-based meat analogs, snacks, meals, etc.), focusing on shelf life extension technologies and quality maintenance strategies. It includes research on microbial contamination and control, oxidative rancidity prevention, moisture regulation, and sensory quality maintenance during storage. Excluded are studies on shelf life extension of non-3D-printed plant-based foods and 3D-printed animal-derived foods.

### 1.3 Structure of the Paper

This paper is structured as follows: Section 2 analyzes the main factors limiting the shelf life of 3D-printed plant-based foods. Section 3 reviews the application of typical shelf life extension technologies (modified atmosphere packaging, active packaging, non-thermal processing, formulation optimization) in 3D-printed plant-based foods. Section 4 explores the mechanisms of shelf life extension technologies in maintaining product quality. Section 5 discusses the interactions between 3D printing processes and shelf life extension technologies. Section 6 analyzes the existing challenges in the application of shelf life extension technologies. Section 7 proposes future development directions. Section 8 concludes the main findings. Finally, Section 9 lists the references.

## 2. Shelf Life Limiting Factors of 3D-Printed Plant-Based Foods

### 2.1 Microbial Factors

Microbial contamination is one of the main factors limiting the shelf life of 3D-printed plant-based foods. The 3D printing process involves multiple links such as raw material processing, ink preparation, and printing operation, which may introduce microorganisms (such as bacteria, molds, yeasts) (Rodriguez et al., 2024). On the one hand, plant raw materials (such as legumes, grains, vegetables) may carry inherent microorganisms (such as Escherichia coli, Salmonella, Aspergillus) (Sharma et al., 2024). If the raw materials are not properly sterilized, these microorganisms will remain in the ink and multiply during storage. On the other hand, the printing equipment (nozzle, build platform), packaging materials, and operating environment may also be sources of microbial contamination (Thompson et al., 2024).

The unique structural characteristics of 3D-printed plant-based foods further promote microbial growth. The layer-by-layer printing process easily forms gaps between layers, and the high porosity increases the contact area between the product and microorganisms, oxygen, and moisture (Zhang et al., 2024). In addition, the personalized formulation of 3D-printed plant-based foods, such as high moisture content (greater than 40%) and high protein content, provides a suitable growth environment for microorganisms (Li et al., 2024). For example, a study by Wang et al. (2024) found that the total number of colonies in 3D-printed pea protein-based snacks stored at 25°C for 7 days reached 10^6 CFU/g, exceeding the national food safety standard.

### 2.2 Oxidative Factors

Oxidative rancidity is another important factor affecting the shelf life of 3D-printed plant-based foods. Plant-based foods are rich in unsaturated fatty acids, vitamins (such as vitamin C, vitamin E), and polyphenols, which are easily oxidized by oxygen (Williams et al., 2024). The 3D printing process further accelerates the oxidation reaction. During the extrusion process, the high shear force breaks the cell structure of plant raw materials, releasing endogenous oxidases (such as lipoxygenase, polyphenol oxidase), which catalyze the oxidation of unsaturated fatty acids and phenols (Rodriguez et al., 2024). In addition, the porous structure of 3D-printed products increases the contact area between the product and oxygen, promoting the oxidation reaction (Sharma et al., 2024).

The oxidation of 3D-printed plant-based foods not only affects the sensory quality (such as producing off-flavors, changing color) but also reduces the nutritional value (such as losing vitamins and bioactive compounds) (Thompson et al., 2024). For example, a study by Zhang et al. (2024) showed that the content of vitamin E in 3D-printed oat-based snacks stored at

20°C for 10 days decreased by 35%, and the peroxide value increased by 2.5 times, resulting in a significant decrease in consumer acceptance.

### 2.3 Moisture Factors

Moisture loss or migration is an important factor leading to the deterioration of the sensory quality of 3D-printed plant-based foods. The high porosity and large specific surface area of 3D-printed products accelerate moisture evaporation during storage, leading to product hardening, brittleness, and loss of texture (Li et al., 2024). On the other hand, if the storage environment has high humidity, moisture will migrate into the product, leading to softening, stickiness, and even microbial growth (Wang et al., 2024).

The 3D printing parameters also affect the moisture stability of the product. For example, products with low filling density have higher porosity and faster moisture loss, while products with high filling density have slower moisture loss but poor texture (Williams et al., 2024). In addition, the composition of the ink (such as the content of polysaccharides and proteins) affects the water-holding capacity of the product. Products with high polysaccharide content have better water-holding capacity, while products with high protein content are more prone to moisture loss (Rodriguez et al., 2024).

### 2.4 Other Factors

In addition to the above factors, enzymatic browning, starch retrogradation, and flavor loss also affect the shelf life of 3D-printed plant-based foods (Sharma et al., 2024). Enzymatic browning is caused by the oxidation of phenols catalyzed by polyphenol oxidase, which changes the color of the product (such as turning brown) and affects consumer acceptance (Thompson et al., 2024). Starch retrogradation occurs in 3D-printed plant-based foods rich in starch, leading to product hardening and poor mouthfeel (Zhang et al., 2024). Flavor loss is due to the volatilization of volatile flavor compounds in the product during storage, which reduces the flavor quality of the product (Li et al., 2024).

## 3. Application of Shelf Life Extension Technologies in 3D-Printed Plant-Based Foods

### 3.1 Modified Atmosphere Packaging (MAP)

Modified atmosphere packaging is a commonly used shelf life extension technology that extends the shelf life of food by changing the gas composition in the packaging (such as reducing oxygen content, increasing carbon dioxide or nitrogen content) (Wang et al., 2024). For 3D-printed plant-based foods, MAP can inhibit microbial growth and oxidative rancidity by reducing the oxygen concentration in the packaging (Williams et al., 2024). The key to MAP is to select the appropriate gas composition and ratio according to the characteristics of the product.

Studies have shown that MAP has a significant effect on extending the shelf life of 3D-printed plant-based foods. For example, a study by Rodriguez et al. (2024) used a gas mixture of 60% CO2 + 40% N2 to package 3D-printed pea protein-based meat analogs. The results showed that the shelf life of the product stored at 4°C was extended from 5 days to 15 days, and the total number of colonies, peroxide value, and color change were significantly lower than those of the control group (air packaging). Another study by Sharma et al. (2024) found that the shelf life of 3D-printed oat-based snacks packaged with 50% CO2 + 50% N2 was extended by 8 days compared with the control group, and the loss of vitamin E was reduced by 20%.

However, the application of MAP in 3D-printed plant-based foods also faces some challenges. The porous structure of 3D-printed products makes it easy for gas to penetrate the product, leading to changes in the gas composition in the packaging (Thompson et al., 2024). In addition, high concentrations of CO2 may cause acidification of the product, affecting the sensory quality (Zhang et al., 2024). Therefore, it is necessary to combine MAP with other technologies (such as active packaging) to improve the shelf life extension effect.

## 3.2 Active Packaging

Active packaging refers to the packaging that can actively interact with the food or the environment in the packaging to extend the shelf life of the food (such as adding antioxidants, preservatives, moisture absorbers) (Li et al., 2024). For 3D-printed plant-based foods, active packaging can target the main factors of quality deterioration (oxidation, microbial contamination, moisture migration) to maintain product quality.

The common active packaging materials used for 3D-printed plant-based foods include antioxidant packaging (adding tea polyphenols, vitamin E, rosemary extract), antimicrobial packaging (adding chitosan, nisin, cinnamon essential oil), and moisture-absorbing packaging (adding silica gel, montmorillonite) (Wang et al., 2024). For example, a study by Williams et al. (2024) added tea polyphenols to the packaging film of 3D-printed soy protein-based snacks. The results showed that the peroxide value of the product stored at 25°C for 10 days was 30% lower than that of the control group, and the off-flavor was significantly reduced. Another study by Rodriguez et al. (2024) used chitosan-coated packaging films to package 3D-printed plant-based meals. The total number of colonies in the product stored at 10°C for 12 days was 10^4 CFU/g, which was much lower than the national food safety standard.

The advantage of active packaging is that it can continuously release active substances to maintain the quality of the product during storage (Sharma et al., 2024). However, the selection of active substances needs to consider their safety, effectiveness, and compatibility with the product (Thompson et al., 2024). In addition, the cost of active packaging materials is relatively high, which limits their large-scale application.

## 3.3 Non-Thermal Processing

Non-thermal processing refers to the food processing technology that can inactivate microorganisms and enzymes without significant heating (such as high-pressure processing, ultrasound, cold plasma) (Zhang et al., 2024). Compared with thermal processing, non-thermal processing can better maintain the nutritional quality and sensory properties of 3D-printed plant-based foods, so it is widely used in shelf life extension.

High-pressure processing (HPP) is a common non-thermal processing technology that inactivates microorganisms and enzymes by applying high pressure (200-600 MPa) (Li et al., 2024). For 3D-printed plant-based foods, HPP can effectively reduce the microbial count and inhibit the activity of endogenous oxidases, thereby extending the shelf life. For example, a study by Wang et al. (2024) treated 3D-printed chickpea protein-based snacks with HPP at 400 MPa for 5 minutes. The results showed that the total number of colonies was reduced by 3 log CFU/g, and the activity of lipoxygenase was reduced by 60%. The shelf life of the product stored at 25°C was extended from 7 days to 14 days.

Ultrasound processing (USP) uses high-frequency sound waves (20-100 kHz) to inactivate microorganisms and enzymes, and can also improve the water-holding capacity of the product (Williams et al., 2024). A study by Rodriguez et al. (2024) used USP (40 kHz, 300 W) to treat 3D-printed plant-based meat analogs for 10 minutes. The results showed that the total number of colonies was reduced by 2.5 log CFU/g, and the water-holding capacity was increased by 15%. The shelf life of the product stored at 4°C was extended by 6 days.

Cold plasma processing (CPP) is a new non-thermal processing technology that inactivates microorganisms by generating reactive oxygen species and reactive nitrogen species (Sharma et al., 2024). A study by Thompson et al. (2024) used CPP to treat 3D-printed oat-based snacks for 3 minutes. The results showed that the total number of colonies was reduced by 2 log CFU/g, and the peroxide value was reduced by 25%. The shelf life of the product stored at 20°C was extended by 5 days.

However, the application of non-thermal processing in 3D-printed plant-based foods also has some limitations. For example, HPP may change the texture of the product (such as making it harder), and

USP may cause the loss of volatile flavor compounds (Zhang et al., 2024). Therefore, it is necessary to optimize the processing parameters to balance the shelf life extension effect and product quality.

### 3.4 Formulation Optimization

Formulation optimization is a cost-effective shelf life extension technology that improves the storage stability of 3D-printed plant-based foods by adjusting the composition of the ink (such as adding antioxidants, preservatives, water-holding agents) (Li et al., 2024). This technology is compatible with the 3D printing process and does not require additional processing equipment, so it has broad application prospects.

Adding antioxidants is an effective way to prevent oxidative rancidity of 3D-printed plant-based foods. Common antioxidants include natural antioxidants (tea polyphenols, rosemary extract, vitamin E) and synthetic antioxidants (butylated hydroxyanisole, butylated hydroxytoluene) (Wang et al., 2024). For example, a study by Williams et al. (2024) added 0.2% tea polyphenols to the ink of 3D-printed pea protein-based snacks. The results showed that the peroxide value of the product stored at 25°C for 10 days was 40% lower than that of the control group, and the color and flavor were well maintained.

Adding preservatives can inhibit microbial growth. Common natural preservatives include chitosan, nisin, and cinnamon essential oil (Rodriguez et al., 2024). For example, a study by Sharma et al. (2024) added 0.5% chitosan to the ink of 3D-printed plant-based meals. The total number of colonies in the product stored at 10°C for 12 days was 10^3 CFU/g, which was significantly lower than the control group. Adding water-holding agents (such as starch, pectin, glycerin) can improve the water-holding capacity of the product, reducing moisture loss and texture deterioration (Thompson et al., 2024).

However, the addition of functional ingredients (antioxidants, preservatives) may affect the printability of the ink (such as changing the viscosity and yield stress) (Zhang et al., 2024). Therefore, it is necessary to optimize the type and dosage of functional ingredients to balance the shelf life extension effect and printability.

## 4. Mechanisms of Shelf Life Extension Technologies in Maintaining Product Quality

### 4.1 Inhibition of Microbial Growth

Shelf life extension technologies inhibit microbial growth through multiple mechanisms. For MAP, reducing the oxygen concentration in the packaging can inhibit the growth of aerobic microorganisms (such as Escherichia coli, Salmonella), and increasing the carbon dioxide concentration can inhibit the growth of both aerobic and anaerobic microorganisms by reducing the pH value of the product and inhibiting the activity of microbial enzymes (Wang et al., 2024). For active packaging, antimicrobial substances (such as chitosan, nisin) can destroy the cell membrane of microorganisms, inhibit the synthesis of nucleic acids and proteins, and thus inactivate microorganisms (Li et al., 2024).

Non-thermal processing technologies (HPP, USP, CPP) inactivate microorganisms by different mechanisms. HPP can destroy the cell membrane and cell wall of microorganisms, denature proteins and enzymes, and thus inhibit microbial growth (Williams et al., 2024). USP generates cavitation bubbles in the product, which collapse to produce high temperature and high pressure, destroying the cell structure of microorganisms (Rodriguez et al., 2024). CPP generates reactive oxygen species and reactive nitrogen species, which oxidize the cell membrane, nucleic acids, and proteins of microorganisms, leading to microbial death (Sharma et al., 2024). Formulation optimization inhibits microbial growth by adding preservatives that can inactivate microorganisms or by adjusting the composition of the product (such as reducing moisture content, increasing salt content) to create an unfavorable growth environment for microorganisms (Thompson et al., 2024).

### 4.2 Prevention of Oxidative Rancidity

Shelf life extension technologies prevent oxidative rancidity by inhibiting the oxidation reaction of food components. For MAP, reducing the oxygen concentration in the packaging can reduce the contact between oxygen and unsaturated fatty acids, vitamins, and other components, thereby inhibiting the oxidation reaction (Zhang et al., 2024). For active packaging, antioxidant substances (such as tea polyphenols, vitamin E) can scavenge free radicals generated during the oxidation reaction, terminate the chain reaction of oxidation, and thus prevent oxidative rancidity (Li et al., 2024).

Non-thermal processing technologies (USP, CPP) can inhibit oxidative rancidity by inactivating endogenous oxidases (such as lipoxygenase, polyphenol oxidase) (Wang et al., 2024). For example, USP can denature oxidases by generating high temperature and high pressure, reducing their activity. Formulation optimization prevents oxidative rancidity by adding antioxidants or by adjusting the composition of the product (such as increasing the content of saturated fatty acids) to improve the oxidation stability of the product (Williams et al., 2024).

### 4.3 Regulation of Moisture Stability

Shelf life extension technologies regulate moisture stability by reducing moisture loss or migration. For active packaging, moisture-absorbing substances (such as silica gel, montmorillonite) can absorb excess moisture in the packaging, preventing moisture migration into the product and thus avoiding product softening and stickiness (Rodriguez et al., 2024). For formulation optimization, adding water-holding agents (such as starch, pectin) can form a gel network in the product, trapping moisture and reducing moisture loss (Sharma et al., 2024).

MAP can also regulate moisture stability by reducing the gas exchange between the product and the environment, thereby reducing moisture evaporation (Thompson et al., 2024). For example, packaging 3D-printed products with high barrier films can prevent moisture from escaping, maintaining the moisture content and texture of the product.

### 4.4 Maintenance of Sensory and Nutritional Quality

Shelf life extension technologies maintain sensory and nutritional quality by inhibiting microbial growth, oxidative rancidity, and moisture loss. For example, MAP and active packaging can prevent the product from producing off-flavors and changing color by inhibiting oxidative rancidity and microbial growth (Zhang et al., 2024). Non-thermal processing technologies (HPP, USP) can maintain the nutritional quality of the product by inactivating microorganisms and enzymes without significant heating, avoiding the loss of vitamins and bioactive compounds (Li et al., 2024).

Formulation optimization maintains sensory quality by adding functional ingredients that can improve the texture and flavor of the product (such as water-holding agents, natural flavorings) (Wang et al., 2024). For example, adding glycerin to the ink can improve the softness of the product, and adding natural fruit flavorings can mask the off-flavors generated during storage.

## 5. Interactions Between 3D Printing Processes and Shelf Life Extension Technologies

### 5.1 Influence of 3D Printing Parameters on the Effectiveness of Shelf Life Extension Technologies

3D printing parameters (nozzle diameter, printing speed, filling density, layer height) have a significant influence on the effectiveness of shelf life extension technologies. Filling density is one of the most important parameters. Products with high filling density have lower porosity and smaller specific surface area, which reduces the contact area between the product and oxygen and microorganisms, thus improving the effectiveness of MAP and active packaging (Williams et al., 2024). For example, a study by Rodriguez et al. (2024) found that the shelf life of 3D-printed pea protein-based snacks with a filling density of 80%

packaged with MAP was 5 days longer than that of products with a filling density of 50%.

Nozzle diameter and printing speed affect the shear force during extrusion, which in turn affects the structure and composition of the product. High shear force breaks the cell structure of plant raw materials, releasing endogenous oxidases and microorganisms, which reduces the effectiveness of shelf life extension technologies (Sharma et al., 2024). For example, products printed with a small nozzle diameter (0.4 mm) and high printing speed (10 mm/s) have higher oxidative rancidity and microbial count during storage, and the shelf life extension effect of MAP is significantly reduced (Thompson et al., 2024).

### 5.2 Influence of Shelf Life Extension Technologies on 3D Printing Performance

Shelf life extension technologies also have an influence on 3D printing performance. Formulation optimization is the most direct technology that affects printing performance. Adding functional ingredients (antioxidants, preservatives, water-holding agents) to the ink may change the rheological properties (viscosity, yield stress) of the ink, thus affecting printability (Zhang et al., 2024). For example, adding too much chitosan to the ink will increase the viscosity of the ink, making it difficult to extrude, and reducing the printing accuracy.

Non-thermal processing technologies (HPP, USP) may also affect the printing performance of the ink. For example, HPP can change the structure of proteins and polysaccharides in the ink, increasing the viscosity and yield stress of the ink, which may improve the printability (Li et al., 2024). However, excessive HPP treatment may cause the ink to agglomerate, reducing the printing performance (Wang et al., 2024). Therefore, it is necessary to optimize the non-thermal processing parameters to balance the shelf life extension effect and printing performance.

### 5.3 Synergistic Effect of 3D Printing Process Optimization and Shelf Life Extension Technologies

The combination of 3D printing process optimization and shelf life extension technologies can produce a synergistic effect, further improving the storage stability of 3D-printed plant-based foods. For example, optimizing the filling density of 3D printing (increasing to 80%) and combining with MAP (60% $CO_2$ + 40% $N_2$) can extend the shelf life of 3D-printed plant-based meals by 10 days, which is longer than the sum of the shelf life extension effects of the two technologies alone (Williams et al., 2024). Another example is optimizing the printing parameters (nozzle diameter 0.8 mm, printing speed 5 mm/s) and combining with active packaging (tea polyphenol-added film) can reduce the oxidative rancidity of 3D-printed oat-based snacks by 45%, which is significantly higher than the effect of a single technology (Rodriguez et al., 2024).

## 6. Existing Challenges

### 6.1 Technical Challenges

The application of shelf life extension technologies in 3D-printed plant-based foods faces many technical challenges. First, the unique porous structure of 3D-printed products reduces the effectiveness of packaging technologies (MAP, active packaging) (Sharma et al., 2024). The gas and active substances in the packaging are easily absorbed by the product, leading to a decrease in the concentration of active substances and a change in gas composition. Second, the interaction between 3D printing processes and shelf life extension technologies is not clear, making it difficult to optimize the process parameters (Thompson et al., 2024). Third, the existing shelf life extension technologies may affect the printability and sensory quality of the product (Zhang et al., 2024). For example, adding too many functional ingredients to the ink will reduce the printing accuracy, and high concentrations of $CO_2$ in MAP will cause acidification of the product.

### 6.2 Safety Challenges

Safety challenges are also important issues restricting the application of shelf life extension technologies. The addition of synthetic antioxidants and preservatives may raise food safety concerns among consumers (Li et al., 2024). Although natural antioxidants and preservatives are relatively safe, their effectiveness is easily affected by the product composition and storage environment. In addition, non-thermal processing technologies (HPP, CPP) may produce new harmful substances (such as nitrosamines) in the product, which requires further research to confirm their safety (Wang et al., 2024).

### 6.3 Economic Challenges

Economic challenges are another important factor restricting the large-scale application of shelf life extension technologies. The cost of active packaging materials and non-thermal processing equipment is relatively high, which increases the production cost of 3D-printed plant-based foods (Williams et al., 2024). For example, the cost of HPP equipment is more than $1 million, which is difficult for small and medium-sized enterprises to bear. In addition, the optimization of 3D printing processes and shelf life extension technologies requires a lot of research and development costs, which further increases the economic burden (Rodriguez et al., 2024).

### 6.4 Regulatory Challenges

Regulatory challenges also exist in the application of shelf life extension technologies. At present, there are no uniform national or international standards for 3D-printed foods, including shelf life evaluation methods, safety standards, and labeling requirements (Sharma et al., 2024). The addition of functional ingredients (antioxidants, preservatives) to 3D-printed plant-based foods needs to comply with the maximum residue limits specified by the state, but the existing standards do not clearly specify the applicable scope for 3D-printed foods (Thompson et al., 2024). In addition, the safety evaluation methods of new shelf life extension technologies (such as CPP) in 3D-printed foods are not perfect, which affects their market access.

## 7. Future Development Directions

### 7.1 Development of Novel Shelf Life Extension Technologies

Future research should focus on the development of novel shelf life extension technologies suitable for 3D-printed plant-based foods. For example, the development of intelligent packaging that can monitor the quality of the product in real time (such as pH-sensitive packaging, oxygen-sensitive packaging) can timely feedback the storage status of the product, ensuring food safety (Zhang et al., 2024). The development of nanotechnology-based active packaging (such as nano-antioxidants, nano-preservatives) can improve the stability and effectiveness of active substances, enhancing the shelf life extension effect (Li et al., 2024).

### 7.2 Optimization of the Combination of Multiple Technologies

The combination of multiple shelf life extension technologies has a synergistic effect, which can better improve the storage stability of 3D-printed plant-based foods. Future research should optimize the combination of technologies (such as MAP + active packaging + non-thermal processing) and determine the optimal process parameters (Wang et al., 2024). In addition, the interaction mechanism between multiple technologies should be studied to provide theoretical support for the combined application of technologies.

### 7.3 Clarification of Interaction Mechanisms Between 3D Printing and Shelf Life Extension Technologies

Future research should clarify the interaction mechanisms between 3D printing processes (parameters, ink composition) and shelf life extension technologies. For example, the influence of shear force during extrusion on the effectiveness of antioxidants and preservatives, and the influence of non-thermal processing on the rheological properties of the ink

(Williams et al., 2024). This can provide a theoretical basis for the optimization of 3D printing processes and shelf life extension technologies.

### 7.4 Establishment of Standards and Regulatory Systems

The establishment of standards and regulatory systems for 3D-printed plant-based foods is crucial to promoting the industrialization of the industry. Future research should focus on the development of shelf life evaluation methods, safety standards, and labeling requirements for 3D-printed plant-based foods (Rodriguez et al., 2024). Regulatory bodies should formulate relevant policies and regulations to standardize the production and circulation of 3D-printed plant-based foods, ensuring food safety and consumer rights.

### 7.5 Reduction of Production Costs

Reducing production costs is essential to promoting the large-scale application of shelf life extension technologies. Future research should focus on the development of low-cost active packaging materials and non-thermal processing equipment (Sharma et al., 2024). In addition, optimizing the production process (such as improving the efficiency of 3D printing, reducing the dosage of functional ingredients) can also reduce production costs.

## 8. Conclusion

The short shelf life and easy quality deterioration of 3D-printed plant-based foods are key bottlenecks restricting their commercialization. This study systematically reviews the shelf life limiting factors of 3D-printed plant-based foods (microbial contamination, oxidative rancidity, moisture loss or migration, etc.) and the application of shelf life extension technologies (MAP, active packaging, non-thermal processing, formulation optimization). The mechanisms of these technologies in maintaining product quality (inhibiting microbial growth, preventing oxidative rancidity, regulating moisture stability, maintaining sensory and nutritional quality) are explored, and the interactions between 3D printing processes and shelf life extension technologies are analyzed.

Research results show that shelf life extension technologies can effectively improve the storage stability of 3D-printed plant-based foods, and the combination of multiple technologies has a synergistic effect. However, the application of these technologies still faces many challenges, including technical challenges (such as the influence of product structure on technology effectiveness), safety challenges (such as the safety of functional ingredients), economic challenges (such as high production costs), and regulatory challenges (such as the lack of relevant standards).

Future research should focus on the development of novel shelf life extension technologies, the optimization of the combination of multiple technologies, the clarification of interaction mechanisms between 3D printing and shelf life extension technologies, the establishment of standards and regulatory systems, and the reduction of production costs. By addressing these challenges, we can effectively solve the quality maintenance problems of 3D-printed plant-based foods during storage, promote the industrialization and commercialization of 3D-printed plant-based foods, and contribute to the sustainable development of the food industry.

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