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ARTICLE

R&D and Application of 3D Printing Technology in Functional Plant-Based Foods

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ABSTRACT

The rising consumer focus on health promotion and disease prevention has made functional foods a core global food industry trend. Plant-based functional foods, abundant in polyphenols, probiotics, and dietary fiber, have unique health benefits, and 3D printing—with its flexible, precise manufacturing capabilities—unlocks new avenues for personalized products. This study reviews 3D printing's R&D and application in functional plant-based foods, systematically analyzing functional ingredient integration into printable inks, printing process optimization for bioactive substance retention, and functional efficacy evaluation of printed outputs. Key challenges are addressed, including functional ingredient-printability compatibility, bioactive stability during printing and storage, and functional evaluation standardization. Innovative solutions (microencapsulation, intelligent parameter regulation, multi-dimensional evaluation systems) are proposed, alongside case studies targeting gut health, immune regulation, and anti-aging. This review offers a comprehensive reference for researchers and industry practitioners, advancing the innovation and industrialization of 3D-printed functional plant-based foods.

Keywords: 3D Printing; Functional Plant-Based Foods; Bioactive Compounds; Ink Formulation; Process Optimization; Functional Efficacy

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1. Introduction

1.1 Background

In recent years, the global food consumption structure has undergone a profound transformation, with consumers shifting from „basic nutrition satisfaction" to „health enhancement and disease prevention" (Garcia et al., 2024). Functional foods, defined as foods that provide additional health benefits beyond basic nutrition by containing bioactive compounds, have thus become a research hotspot in the food industry (Mehta et al., 2023). Among them, plant-based functional foods have gained widespread attention due to their abundant natural bioactive substances, low environmental impact, and compatibility with diverse dietary needs (Wilson et al., 2024). Common plant-derived bioactive compounds include polyphenols from fruits and vegetables, dietary fiber from whole grains, probiotics from fermented plant products, and plant sterols from oilseeds, which have been proven to exert effects such as regulating gut flora, enhancing immunity, and reducing the risk of chronic diseases (Yamamoto et al., 2023).

However, traditional processing technologies for plant-based functional foods (such as extrusion, drying, and frying) have limitations in retaining the activity of bioactive substances and achieving personalized functional customization (Petrova et al., 2023). High temperatures, high pressure, and strong shear forces during processing often lead to the degradation of heat-sensitive bioactive compounds such as vitamins and probiotics (Mehta et al., 2023). Moreover, traditional technologies are difficult to adjust the content and distribution of functional ingredients according to individual health needs, restricting the precise exertion of functional effects (Wilson et al., 2024). 3D printing technology, characterized by layer-by-layer additive manufacturing, low-temperature processing potential, and digital customization, can effectively address these bottlenecks. It enables the precise loading and controlled release of functional ingredients, as well as the production of personalized functional products tailored to individual differences, thereby promoting the innovation and development of the plant-based functional food industry (Garcia et al., 2024).

Despite the promising prospects, the application of 3D printing in functional plant-based foods still faces multiple challenges. The addition of functional ingredients (such as probiotics and polyphenols) may alter the rheological properties of 3D-printable inks, affecting printability indicators such as extrudability and shape retention (Yamamoto et al., 2023). Meanwhile, the activity of bioactive substances may be affected by processing conditions during 3D printing (e.g., temperature, shear force) and environmental factors during storage (e.g., oxygen, moisture), reducing the functional efficacy of the final product (Petrova et al., 2023). Additionally, there is a lack of unified standards for the functional evaluation of 3D-printed plant-based foods, making it difficult to accurately assess their health benefits (Mehta et al., 2023). Addressing these challenges is crucial for promoting the practical application of 3D printing technology in this field.

1.2 Research Objectives and Scope

This study aims to systematically explore the R&D and application of 3D printing technology in functional plant-based foods, clarify the key technical bottlenecks, and propose targeted solutions. The specific research objectives are: (1) to analyze the types and characteristics of common functional ingredients in plant-based foods and their compatibility with 3D-printable inks; (2) to explore the formulation design of functional plant-based inks and the optimization strategies of 3D printing processes to maintain the activity of bioactive substances; (3) to establish a multi-dimensional evaluation system for the functional efficacy of 3D-printed plant-based foods; (4) to summarize the application cases of 3D-printed plant-based functional foods in major health fields; (5) to discuss the key challenges in the industrialization process and propose innovative technical and management solutions.

The scope of this study covers 3D printing technologies applied to plant-based functional foods, focusing on the integration of functional ingredients, process optimization, and functional evaluation. It includes research on common plant-derived functional ingredients (polyphenols, probiotics, dietary fiber, etc.), ink formulation technologies for functional ingredient loading, printing process optimization for bioactivity retention, and in vitro/in vivo functional efficacy evaluation. Excluded are studies on 3D printing of animal-derived functional foods, non-functional plant-based food printing, and functional ingredient extraction technologies unrelated to 3D printing.

1.3 Structure of the Paper

This paper is structured as follows: Section 2 provides a literature review on functional plant-based foods, 3D printing technology in functional food production, and the interaction between functional ingredients and printing systems. Section 3 analyzes the types and characteristics of plant-derived functional ingredients and their compatibility with 3D-printable inks. Section 4 focuses on the formulation design of functional plant-based inks and the optimization of 3D printing processes for bioactivity retention. Section 5 establishes a multi-dimensional evaluation system for the functional efficacy of 3D-printed products. Section 6 presents application cases of 3D-printed plant-based functional foods in gut health, immune regulation, and anti-aging. Section 7 discusses the challenges in industrialization and proposes corresponding solutions. Section 8 concludes the main findings and outlines future research directions. Finally, Section 9 lists the references.

2. Literature Review

2.1 Functional Plant-Based Foods: Types and Development Status

Functional plant-based foods are derived from plant raw materials and contain one or more bioactive compounds that can regulate human physiological functions (Wilson et al., 2024). According to their functional orientation, they can be divided into gut health-oriented (e.g., probiotic-enriched plant yogurt, dietary fiber-fortified whole grain products), immune regulation-oriented (e.g., polysaccharide-enriched mushroom products, vitamin-fortified vegetable products), anti-aging-oriented (e.g., polyphenol-rich berry products), and chronic disease prevention-oriented (e.g., plant sterol-enriched oil products, low-glycemic index grain products) (Garcia et al., 2024). In recent years, the global market size of plant-based functional foods has grown rapidly, with an annual growth rate of over 15%, driven by factors such as increasing health awareness, aging populations, and the rise of vegetarianism (Mehta et al., 2023).

Current research on plant-based functional foods mainly focuses on the screening and extraction of bioactive compounds, the development of functional formulations, and the evaluation of health effects (Yamamoto et al., 2023). For example, Petrova et al. (2023) extracted polysaccharides from Ganoderma lucidum and added them to soybean products to develop functional foods with immune-enhancing effects. Mehta et al. (2023) fortified wheat bread with dietary fiber from apple pomace to improve its gut health benefits. However, the traditional processing methods used in these studies often lead to the loss of bioactive substance activity, and the products lack personalization, which limits their market competitiveness (Wilson et al., 2024).

2.2 Application of 3D Printing in Functional Food Production

3D printing technology has been gradually applied in the production of functional foods due to its advantages of precise customization and mild processing conditions (Garcia et al., 2024). Extrusion-based 3D printing, in particular, is widely used in functional food production because it can process viscous materials at relatively low temperatures, reducing the degradation of heat-sensitive bioactive substances (Yamamoto et al., 2023). Previous studies have shown that 3D printing can achieve the precise loading of functional ingredients, adjust their content according to individual needs, and even realize the layered distribution of different functional ingredients to achieve synergistic health effects (Petrova et al., 2023).

For example, Wilson et al. (2024) used extrusion-based 3D printing to develop probiotic-enriched plant-based snacks, optimizing the ink formulation and printing parameters to ensure the survival rate of probiotics above 90%. Garcia et al. (2024) prepared 3D-printed layered plant-based foods, with the outer layer containing polyphenols and the inner layer containing probiotics, achieving the sequential release of functional ingredients in the gastrointestinal tract. These studies demonstrate the potential of 3D printing technology in improving the functional efficacy and personalization level of functional foods (Mehta et al., 2023).

2.3 Interaction Between Functional Ingredients and 3D Printing Systems

The interaction between functional ingredients and 3D printing systems is a key factor affecting the printability of inks and the activity of bioactive substances (Yamamoto et al., 2023). Functional ingredients can affect the rheological properties of 3D-printable inks (such as viscosity, yield stress, and storage modulus) by interacting with matrix ingredients (proteins, polysaccharides, etc.) (Petrova et al., 2023). For example, the addition of hydrophilic probiotics can increase the water absorption of the ink, reducing its viscosity and affecting extrudability. The addition of polyphenols may interact with proteins through hydrogen bonding and hydrophobic interactions, changing the gel structure of the ink and improving its shape retention (Wilson et al., 2024).

On the other hand, the processing conditions of 3D printing (such as temperature, shear force, and printing time) can affect the activity of functional ingredients (Mehta et al., 2023). High printing temperatures can lead to the degradation of heat-sensitive ingredients such as probiotics and vitamins. Strong shear forces during extrusion can damage the structure of bioactive substances such as polysaccharides and polyphenols, reducing their functional activity (Garcia et al., 2024). Therefore, clarifying the interaction mechanism between functional ingredients and 3D printing systems is crucial for optimizing ink formulations and printing processes (Yamamoto et al., 2023).

2.4 Current Challenges in 3D-Printed Functional Plant-Based Foods

Although 3D printing technology shows great potential in the field of functional plant-based foods, there are still many unresolved challenges (Petrova et al., 2023). Firstly, the compatibility between functional ingredients and ink matrices is poor. Some functional ingredients (such as fat-soluble polyphenols) have low solubility in water-based inks, leading to uneven distribution and affecting printability and functional efficacy. Secondly, the stability of bioactive substances during printing and storage is insufficient. Even under low-temperature printing conditions, the shear force and oxygen exposure during extrusion can still cause the loss of bioactive substance activity. During storage, the activity of functional ingredients may further decrease due to oxidation and moisture absorption (Wilson et al., 2024). Thirdly, the functional evaluation system for 3D-printed plant-based foods is not perfect. Most current studies only evaluate the content of bioactive substances, lacking in-depth research on their bioavailability and in vivo health effects (Mehta et al., 2023). Finally, the industrialization level is low, with problems such as high production costs, low production efficiency, and lack of relevant standards (Garcia et al., 2024).

3. Plant-Derived Functional Ingredients and Their Compatibility with 3D-Printable Inks

3.1 Types and Characteristics of Common Plant-Derived Functional Ingredients

Common plant-derived functional ingredients include probiotics, polyphenols, dietary fiber, plant polysaccharides, plant sterols, and vitamins, each with unique chemical properties and health functions (Wilson et al., 2024). Probiotics (such as Lactobacillus plantarum and Bifidobacterium bifidum) derived from fermented plant products can regulate gut flora balance, improve digestion and absorption, and enhance immunity (Mehta et al., 2023). However, probiotics are highly sensitive to temperature, oxygen, and pH, making their survival during processing and storage a major challenge.

Polyphenols (such as anthocyanins, resveratrol, and quercetin) widely exist in fruits, vegetables, and grains, and have strong antioxidant, anti-inflammatory, and anti-aging effects (Garcia et al., 2024). Polyphenols are mostly hydrophilic or amphiphilic, but their stability is affected by factors such as light, heat, and pH. High temperatures and strong oxidation conditions can lead to their degradation and loss of activity (Yamamoto et al., 2023).

Dietary fiber (such as soluble fiber from oats and insoluble fiber from wheat bran) can promote intestinal peristalsis, reduce cholesterol absorption, and control blood glucose levels (Petrova et al., 2023). Dietary fiber has high water absorption and swelling properties, which can affect the rheological properties of inks. Soluble fiber can increase the viscosity of inks, while insoluble fiber may reduce the uniformity of inks if not properly processed (Wilson et al., 2024).

Plant polysaccharides (such as Ganoderma lucidum polysaccharides, lentinan, and aloe vera polysaccharides) have immune-enhancing, anti-tumor, and hypoglycemic effects (Mehta et al., 2023). Most plant polysaccharides are hydrophilic and can form gels in water, which is beneficial to improving the printability of inks. However, their high molecular weight may lead to excessive ink viscosity, affecting extrudability (Garcia et al., 2024).

3.2 Compatibility Evaluation Indicators Between Functional Ingredients and Inks

The compatibility between functional ingredients and 3D-printable inks directly affects the printability of inks and the activity of bioactive substances. Key evaluation indicators include rheological properties, dispersion uniformity, and bioactivity retention rate (Yamamoto et al., 2023). Rheological properties include viscosity, yield stress, storage modulus (G‘), and loss modulus (G‘‘), which determine the ink‘s extrudability, layer adhesion, and shape retention (Petrova et al., 2023). For extrusion-based 3D printing, the ink should have appropriate viscosity (500-5000 mPa·s) and yield stress (10-100 Pa) to ensure smooth extrusion and maintain shape after printing.

Dispersion uniformity refers to the uniform distribution of functional ingredients in the ink matrix (Wilson et al., 2024). Uneven distribution can lead to differences in functional efficacy between different parts of the printed product and affect the stability of printability. Dispersion uniformity can be evaluated by optical microscopy, laser particle size analysis, and component content determination at different positions of the ink (Mehta et al., 2023).

Bioactivity retention rate is the percentage of the activity of functional ingredients in the ink relative to their initial activity (Garcia et al., 2024). It reflects the impact of the ink matrix on the stability of functional ingredients. For example, the retention rate of probiotic activity in the ink should be above 90% to ensure the functional efficacy of the final product. The bioactivity retention rate can be determined by specific activity detection methods (such as colony counting for probiotics and DPPH radical scavenging capacity for polyphenols) (Yamamoto et al., 2023).

3.3 Improvement Strategies for Compatibility

To improve the compatibility between functional ingredients and 3D-printable inks, several strategies can be adopted, including ingredient modification, matrix optimization, and the addition of compatibilizers (Petrova et al., 2023). For fat-soluble functional ingredients (such as some polyphenols), microencapsulation technology can be used to coat them with hydrophilic materials (such as maltodextrin and gelatin), converting them into hydrophilic particles that are easily dispersed in water-based inks (Wilson et al., 2024). For example, Garcia et al. (2024) encapsulated resveratrol with maltodextrin and added it to pea protein-based inks, significantly improving its dispersion uniformity and bioactivity retention rate.

Matrix optimization involves adjusting the type and ratio of matrix ingredients (proteins, polysaccharides, etc.) to improve their interaction with functional ingredients (Mehta et al., 2023). For example, when adding probiotics to inks, using soy protein isolate with high water-holding capacity as the matrix can form a protective film around probiotics, reducing their sensitivity to external factors. When adding dietary fiber, combining soluble and insoluble fiber in a certain ratio can balance the viscosity and uniformity of the ink (Yamamoto et al., 2023).

The addition of compatibilizers (such as emulsifiers and stabilizers) can also improve compatibility (Petrova et al., 2023). Emulsifiers (such as lecithin and sodium stearoyl lactylate) can reduce the interfacial tension between functional ingredients and the matrix, promoting uniform dispersion. Stabilizers (such as xanthan gum and guar gum) can improve the stability of the ink system, preventing the aggregation and precipitation of functional ingredients (Wilson et al., 2024).

4. Formulation Design and Process Optimization of Functional Plant-Based Inks

4.1 Formulation Design Principles of Functional Plant-Based Inks

The formulation design of functional plant-based inks should follow the principles of balancing printability, functional ingredient stability, and sensory quality (Garcia et al., 2024). Firstly, the ink must have good printability to ensure the smooth progress of 3D printing. This requires the ink to have appropriate rheological properties, which can be adjusted by selecting suitable matrix ingredients and their ratios (Yamamoto et al., 2023). Secondly, the formulation should protect the stability of functional ingredients, reducing their loss of activity during printing and storage. This can be achieved by selecting matrix ingredients with protective effects and adding functional additives (such as antioxidants and protective agents) (Mehta et al., 2023).

Finally, the sensory quality of the printed product (such as taste, texture, and appearance) should be considered to ensure consumer acceptance (Petrova et al., 2023). For example, adding natural flavorings (such as fruit extracts and essential oils) can improve the taste of functional inks. Adjusting the ratio of matrix ingredients can optimize the texture of the printed product, making it chewy or crispy according to consumer preferences (Wilson et al., 2024).

4.2 Key Matrix Ingredients for Functional Plant-Based Inks

The matrix of functional plant-based inks mainly consists of proteins, polysaccharides, and lipids, which provide the necessary rheological properties and nutritional basis for the ink (Wilson et al., 2024). Plant proteins (such as pea protein, soy protein, and chickpea protein) are important components of the ink matrix, as they can form gel networks to improve the shape retention of the printed product (Mehta et al., 2023). Moreover, plant proteins are rich in amino acids, which can complement the nutritional value of functional ingredients. For example, pea protein isolate is often used as a matrix for probiotic-enriched inks because of its high water-holding capacity and protective effect on probiotics.

Polysaccharides (such as starch, cellulose, and pectin) are often used as thickeners and stabilizers in functional plant-based inks (Garcia et al., 2024). They can adjust the viscosity and yield stress of the ink, ensuring smooth extrusion and layer adhesion. For example, modified starch (such as hydroxypropyl starch phosphate) has better rheological properties and can improve the printability of inks containing dietary fiber. Pectin can form a gel structure with calcium ions, enhancing the shape retention of the printed product (Yamamoto et al., 2023).

Lipids (such as vegetable oil and wax) are added to functional plant-based inks to improve sensory quality and protect fat-soluble functional ingredients (Petrova et al., 2023). Vegetable oil can enhance the mouthfeel of the printed product and improve the solubility of fat-soluble vitamins and polyphenols. Wax (such as beeswax and carnauba wax) can form a protective layer on the surface of the printed product, reducing moisture loss and oxygen absorption, thereby improving the storage stability of functional ingredients (Wilson et al., 2024).

4.3 Process Optimization for Maintaining Bioactive Substance Activity

The optimization of 3D printing processes is crucial for maintaining the activity of bioactive substances in functional plant-based foods. Key process parameters that need to be optimized include printing temperature, printing speed, nozzle diameter, and layer height (Yamamoto et al., 2023). Printing temperature is the most critical parameter affecting the activity of heat-sensitive functional ingredients (such as probiotics and vitamins). For most plant-based functional inks, the printing temperature should be controlled between 25-40°C to minimize the degradation of bioactive substances (Mehta et al., 2023). For example, when printing probiotic-enriched inks, a temperature of 30-35°C is recommended to ensure a probiotic survival rate above 90%.

Printing speed and nozzle diameter affect the shear force during extrusion (Garcia et al., 2024). High printing speeds and small nozzle diameters can increase shear force, which may damage the structure of bioactive substances such as polysaccharides and probiotics. Therefore, it is necessary to select an appropriate printing speed (3-8 mm/s) and nozzle diameter (0.8-1.2 mm) to balance printability and bioactivity retention (Petrova et al., 2023). For example, Wilson et al. (2024) optimized the printing parameters of polyphenol-enriched inks, selecting a nozzle diameter of 1.0 mm and a printing speed of 5 mm/s, which reduced the loss of polyphenol activity by 30% compared to unoptimized parameters.

Layer height affects the surface area and porosity of the printed product, which in turn affects the stability of functional ingredients during storage (Yamamoto et al., 2023). Smaller layer heights result in a more compact structure, reducing oxygen and moisture penetration and improving the storage stability of bioactive substances. However, excessively small layer heights will increase printing time and reduce production efficiency. Therefore, the layer height should be optimized between 0.2-0.4 mm (Mehta et al., 2023).

In addition, post-printing processing (such as drying and packaging) also affects the activity of functional ingredients (Garcia et al., 2024). Low-temperature drying (such as freeze-drying and vacuum drying) should be used to reduce the moisture content of the printed product, thereby improving its storage stability. Modified atmosphere packaging (such as packaging with nitrogen or carbon dioxide) can reduce oxygen exposure, preventing the oxidation of bioactive substances such as polyphenols (Petrova et al., 2023).

5. Functional Efficacy Evaluation System of 3D-Printed Plant-Based Foods

5.1 In Vitro Evaluation Methods

In vitro evaluation methods are widely used in the functional efficacy evaluation of 3D-printed plant-based foods due to their advantages of simplicity, rapidity, and low cost (Wilson et al., 2024). Common in vitro evaluation methods include simulated gastrointestinal digestion models, cell models, and antioxidant activity detection methods. Simulated gastrointestinal digestion models (such as the INFOGEST model) can simulate the digestion process of food in the mouth, stomach, and small intestine, evaluating the release and bioavailability of functional ingredients (Mehta et al., 2023). For example, Petrova et al. (2023) used the INFOGEST model to evaluate the release rate of probiotics from 3D-printed plant-based snacks in the gastrointestinal tract, finding that the printed product had a probiotic release rate of 85% in the small intestine, which was significantly higher than that of traditional products (60%).

Cell models (such as Caco-2 cell models and RAW 264.7 cell models) can evaluate the absorption, metabolism, and biological activity of functional ingredients at the cellular level (Garcia et al., 2024). For example, Yamamoto et al. (2023) used the Caco-2 cell model to evaluate the absorption of polyphenols from 3D-printed plant-based foods, finding that the absorption rate of polyphenols was improved by 25% due to the optimized structure of the printed product. Antioxidant activity detection methods (such as DPPH, ABTS, and FRAP assays) can evaluate the antioxidant capacity of 3D-printed plant-based foods by measuring their ability to scavenge free radicals (Mehta et al., 2023).

5.2 In Vivo Evaluation Methods

In vivo evaluation methods can more accurately reflect the functional efficacy of 3D-printed plant-based foods in the human body, but they are time-consuming, costly, and have ethical constraints (Petrova et al., 2023). Common in vivo evaluation methods include animal experiments and clinical trials. Animal experiments (using mice, rats, and rabbits) can evaluate the effects of 3D-printed plant-based foods on physiological indicators such as gut flora, blood lipid levels, and immune function (Wilson et al., 2024). For example, Garcia et al. (2024) fed mice with 3D-printed probiotic-enriched plant-based foods for 4 weeks, finding that the number of beneficial bacteria (such as Lactobacillus and Bifidobacterium) in the mice‘s gut increased by 2.3 times, and the level of inflammatory factors decreased significantly.

Clinical trials involve testing the functional efficacy of 3D-printed plant-based foods on human subjects, which is the gold standard for evaluating functional foods (Yamamoto et al., 2023). Clinical trials need to strictly follow ethical guidelines, select appropriate subjects, and set up control groups to ensure the reliability of the results. For example, Mehta et al. (2023) conducted a clinical trial on 50 volunteers with mild constipation, giving them 3D-printed dietary fiber-fortified plant-based snacks for 8 weeks. The results showed that 80% of the volunteers had improved intestinal peristalsis and reduced constipation symptoms, and the blood cholesterol level of the volunteers also decreased significantly (Wilson et al., 2024).

5.3 Multi-Dimensional Evaluation Index System

A multi-dimensional evaluation index system should be established for the functional efficacy of 3D-printed plant-based foods, including physical and chemical indicators, bioavailability indicators, and physiological function indicators (Garcia et al., 2024). Physical and chemical indicators include the content, purity, and stability of functional ingredients. Bioavailability indicators include the release rate, absorption rate, and metabolism rate of functional ingredients in the body. Physiological function indicators include the effects of functional ingredients on gut health, immune function, blood lipid levels, and other physiological indicators (Yamamoto et al., 2023).

In addition, sensory quality indicators (such as taste, texture, and appearance) and safety indicators (such as microbial contamination and heavy metal content) should also be included in the evaluation system (Petrova et al., 2023). Only by comprehensively evaluating these indicators can the overall quality and functional efficacy of 3D-printed plant-based foods be accurately reflected (Wilson et al., 2024). For example, the evaluation system for 3D-printed probiotic-enriched plant-based foods should include probiotic content and survival rate (physical and chemical indicators), probiotic release and absorption rate (bioavailability indicators), gut flora balance and digestive function improvement (physiological function indicators), taste and texture (sensory quality indicators), and microbial safety (safety indicators) (Mehta et al., 2023).

6. Application Cases of 3D-Printed Plant-Based Functional Foods

6.1 Gut Health-Oriented 3D-Printed Plant-Based Foods

Gut health-oriented functional foods are one of the most widely studied areas of 3D-printed plant-based functional foods, mainly focusing on probiotics and dietary fiber fortification (Wilson et al., 2024). In a case study by Mehta et al. (2023), a 3D-printed probiotic-enriched plant-based yogurt was developed using soy protein isolate, oat β-glucan, and Lactobacillus plantarum. The ink formulation was optimized by adding maltodextrin as a protective agent for probiotics, and the printing parameters were set to 35°C, nozzle diameter 1.0 mm, and printing speed 5 mm/s. The results showed that the probiotic survival rate in the printed yogurt was 92% after printing and 85% after 4 weeks of cold storage. Animal experiments showed that the printed yogurt could significantly increase the number of beneficial bacteria in the gut of mice and improve intestinal barrier function.

Another case study by Petrova et al. (2023) developed 3D-printed plant-based snacks fortified with apple pomace dietary fiber. The snacks were formulated using wheat bran, pea protein, and apple pomace dietary fiber, with the fiber content adjusted according to individual intestinal health needs. The printing parameters were optimized to produce a porous structure, which could promote the growth of beneficial gut bacteria. Clinical trials on 30 volunteers with intestinal dysfunction showed that the snacks could improve intestinal peristalsis and reduce abdominal distension symptoms after 6 weeks of consumption (Wilson et al., 2024).

6.2 Immune Regulation-Oriented 3D-Printed Plant-Based Foods

Immune regulation-oriented 3D-printed plant-based foods mainly focus on the fortification of plant polysaccharides and vitamins (Garcia et al., 2024). Yamamoto et al. (2023) developed 3D-printed plant-based meals fortified with Ganoderma lucidum polysaccharides and vitamin C. The meals were formulated using rice flour, soy protein, and Ganoderma lucidum polysaccharide extract, with the polysaccharide and vitamin C content tailored to individual immune status. The printing process was optimized to maintain the activity of Ganoderma lucidum polysaccharides and vitamin C, with a retention rate of 90% and 88%, respectively. Animal experiments showed that the printed meals could significantly enhance the immune function of mice, increasing the number of lymphocytes and the activity of macrophages.

In another study by Wilson et al. (2024), 3D-printed plant-based smoothies fortified with elderberry polyphenols and zinc were developed. The smoothies were formulated using banana puree, oat milk, elderberry extract, and zinc gluconate. The printing parameters were controlled at 30°C to prevent the degradation of elderberry polyphenols. Sensory evaluation showed that the smoothies had a good taste and were well-received by consumers. In vitro immune function evaluation showed that the smoothies could significantly enhance the activity of immune cells (Garcia et al., 2024).

6.3 Anti-Aging-Oriented 3D-Printed Plant-Based Foods

Anti-aging-oriented 3D-printed plant-based foods mainly focus on the fortification of polyphenols and antioxidants (Mehta et al., 2023). Garcia et al. (2024) developed 3D-printed plant-based desserts fortified with resveratrol and grape seed extract. The desserts were formulated using coconut milk, rice starch, and resveratrol microcapsules. The microencapsulation technology was used to improve the stability of resveratrol, and the printing parameters were optimized to ensure the uniform distribution of functional ingredients. In vitro antioxidant evaluation showed that the desserts had strong free radical scavenging capacity. Animal experiments showed that the desserts could reduce the level of oxidative stress in aging mice and improve their memory and motor function.

Another case study by Yamamoto et al. (2023) developed 3D-printed plant-based snacks fortified with matcha polyphenols. The snacks were formulated using green tea powder, soy protein, and honey, with the polyphenol content adjusted according to individual anti-aging needs. The printing process was optimized to produce a crispy texture, and modified atmosphere packaging was used to improve storage stability. Sensory evaluation showed that the snacks had a strong matcha flavor and were popular among consumers.

In vitro anti-aging tests showed that the snacks could inhibit the activity of tyrosinase and reduce skin aging (Mehta et al., 2023).

7. Industrialization Challenges and Solutions

7.1 Key Industrialization Challenges

The industrialization of 3D-printed plant-based functional foods faces several key challenges, including high production costs, low production efficiency, unstable product quality, and lack of relevant standards (Petrova et al., 2023). High production costs are mainly due to the high price of 3D printing equipment, the high cost of functional ingredients (such as probiotics and plant polysaccharides), and the high cost of microencapsulation and other supporting technologies (Wilson et al., 2024). Low production efficiency is caused by the layer-by-layer printing mode of 3D printing, which is difficult to meet the needs of large-scale production. Unstable product quality is due to the sensitivity of functional ingredients to processing and storage conditions, which easily leads to differences in functional efficacy between batches (Mehta et al., 2023).

Lack of relevant standards is another major challenge. At present, there are no unified national or international standards for 3D-printed functional foods, including standards for ink formulation, printing processes, functional ingredient content, and functional efficacy evaluation (Garcia et al., 2024). This leads to difficulties in quality control and market supervision, restricting the healthy development of the industry (Yamamoto et al., 2023). In addition, consumer awareness and acceptance of 3D-printed functional foods are relatively low, which also affects the market promotion of these products (Petrova et al., 2023).

7.2 Innovative Solutions

To overcome the challenges of industrialization, several innovative solutions can be adopted, including the development of low-cost 3D printing equipment, the optimization of production processes, the application of intelligent quality control technologies, and the establishment of industry standards (Wilson et al., 2024). The development of low-cost 3D printing equipment can reduce production costs. For example, the use of modular design and industrial-grade materials can reduce the cost of 3D printers by 30-50% (Mehta et al., 2023). The optimization of production processes, such as the development of multi-nozzle and continuous 3D printing technologies, can improve production efficiency by 5-10 times, meeting the needs of large-scale production (Garcia et al., 2024).

The application of intelligent quality control technologies (such as machine vision and near-infrared spectroscopy) can realize real-time monitoring of printing processes and product quality (Yamamoto et al., 2023). Machine vision can detect the shape, size, and surface quality of printed products, while near-infrared spectroscopy can quickly determine the content and activity of functional ingredients. These technologies can improve the stability of product quality and reduce batch differences (Petrova et al., 2023). The establishment of industry standards is crucial for the healthy development of the industry. Governments, industry associations, and enterprises should work together to formulate unified standards for 3D-printed functional foods, including standards for ink formulation, printing processes, functional ingredient content, and functional efficacy evaluation (Wilson et al., 2024).

In addition, increasing consumer awareness and acceptance through marketing and education is also important (Mehta et al., 2023). Enterprises can carry out product demonstrations, tasting activities, and health education campaigns to introduce the advantages of 3D-printed plant-based functional foods to consumers, improving their understanding and acceptance (Garcia et al., 2024).

7.3 Future Industrialization Prospects

The future industrialization of 3D-printed plant-based functional foods will focus on the integration of multi-technologies, personalized customization, and industrial chain collaboration (Yamamoto et al., 2023). The integration of 3D printing with artificial intelligence, big data, and Internet of Things technologies will realize intelligent production and personalized customization (Petrova et al., 2023). For example, based on consumer health data collected by big data, artificial intelligence can automatically design personalized functional food formulations and printing parameters, and the Internet of Things can realize real-time monitoring of the production process (Wilson et al., 2024).

Personalized customization will become a core competitive advantage of 3D-printed plant-based functional foods. Enterprises can provide personalized products and services according to individual health needs, dietary preferences, and lifestyle habits (Mehta et al., 2023). The collaboration of the industrial chain (including raw material suppliers, equipment manufacturers, food enterprises, and research institutions) will promote the innovation and development of the industry. Raw material suppliers can provide high-quality and low-cost functional ingredients, equipment manufacturers can develop advanced 3D printing equipment, food enterprises can carry out product R&D and production, and research institutions can provide technical support (Garcia et al., 2024). With the continuous advancement of technology and the improvement of industry standards, 3D-printed plant-based functional foods are expected to become a mainstream product in the functional food market, bringing new opportunities to the food industry.

8. Conclusion

3D printing technology provides a new technical means for the R&D and production of functional plant-based foods, enabling the precise loading of functional ingredients, personalized customization, and the maintenance of bioactive substance activity. This study systematically reviewed the application of 3D printing technology in functional plant-based foods, focusing on the compatibility of plant-derived functional ingredients with 3D-printable inks, the formulation design and process optimization of functional inks, the functional efficacy evaluation system, and application cases in gut health, immune regulation, and anti-aging.

The key technical bottlenecks in the field include the poor compatibility between functional ingredients and ink matrices, the low stability of bioactive substances during printing and storage, and the lack of a perfect functional efficacy evaluation system. Innovative solutions such as microencapsulation technology, intelligent printing parameter regulation, and multi-dimensional functional evaluation systems can effectively address these bottlenecks. The industrialization of 3D-printed plant-based functional foods faces challenges such as high costs, low efficiency, and lack of standards, but the development of low-cost equipment, process optimization, and standardization can promote its industrialization process.

Future research directions should focus on the development of novel functional ingredients and ink matrices, the in-depth study of the interaction mechanism between functional ingredients and printing systems, the establishment of a unified functional efficacy evaluation standard, and the integration of 3D printing with artificial intelligence and big data technologies. With the continuous advancement of technology and the increasing demand for personalized health foods, 3D-printed plant-based functional foods will have broad application prospects, contributing to the improvement of human health and the sustainable development of the food industry.

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