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Future Foods and Technologies

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ARTICLE

Sensory Characteristics Optimization and Consumer Acceptance of 3D-Printed Plant-Based Foods: A Multidimensional Evaluation

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ABSTRACT

3D printing holds promise for personalized sustainable plant-based foods, yet commercialization is hindered by suboptimal sensory quality and uncertain consumer acceptance. This study optimized sensory traits (texture, flavor, color) of 3D-printed plant-based foods and assessed consumer acceptance via multidimensional methods. Chickpea protein isolate and oat β-glucan formed core ink materials, supplemented with sensory modifiers. Single-factor and response surface methodology optimized printing parameters (nozzle diameter, temperature, filling density). Evaluations included professional sensory panel tests, 200-participant hedonic/WTP surveys, and electronic nose/tongue analyses. Optimal products matched traditional plant-based meat analog texture, reached 82% real meat flavor similarity, and had natural color. 78% of consumers liked the product, with WTP ($5.2±0.3/100g) comparable to commercial alternatives. This work offers theoretical and technical support for 3D-printed plant-based food commercialization.

Keywords: 3D-Printed Plant-Based Foods; Sensory Optimization; Consumer Acceptance; Quantitative Descriptive Analysis; Electronic Nose; Electronic Tongue

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ARTICLE INFO

Received: 26 November 2025 | Revised: 2 December 2025 | Accepted: 12 December 2025 | Published Online: 19 December 2025

DOI: https://doi.org/10.55121/fft.v1i1.1069

CITATION

Rajesh K. Singh. 2025. Sensory Characteristics Optimization and Consumer Acceptance of 3D-Printed Plant-Based Foods: A Multidimensional Evaluation. Future Foods and Technologies . 1(1):26-36. DOI: https://doi.org/10.55121/fft.v1i1.1069

1. Introduction

1.1 Background

The global shift towards plant-based diets has accelerated the development of plant-based food products, driven by concerns about environmental sustainability, animal welfare, and human health. 3D food printing, as an innovative manufacturing technology, has been widely recognized for its ability to customize nutritional composition and product structure, making it a promising tool for plant-based food production. However, compared with traditionally processed plant-based foods, 3D-printed plant-based products often have obvious sensory defects, such as poor texture coordination, single flavor, and unnatural color, which significantly affect consumer acceptance and market promotion.

Sensory characteristics, including texture, flavor, and color, are crucial factors determining consumer preference and purchase behavior. For plant-based foods, especially meat analogs, mimicking the texture and flavor of animal-derived meat is the key to gaining consumer recognition. Traditional plant-based meat products usually achieve texture simulation through extrusion texturization, while 3D printing can fabricate more complex and meat-like fibrous structures by controlling layer deposition. However, the selection of printing materials and optimization of printing parameters often lead to texture deviations, such as excessive hardness or insufficient chewiness. In terms of flavor, plant-based raw materials (e.g., legume proteins) often have beany off-flavors, which are difficult to eliminate in 3D printing processes with simple processing steps. In addition, the color of 3D-printed products is usually determined by the raw materials themselves, which are mostly light-colored, lacking the natural color of meat, reducing the sensory appeal to consumers.

Consumer acceptance is the core criterion for the commercialization of 3D-printed plant-based foods. Previous studies on 3D-printed foods have mainly focused on formulation optimization and printability, while research on consumer acceptance is relatively scarce. Moreover, existing studies on consumer acceptance mostly use simple hedonic scaling, lacking comprehensive evaluations combining sensory perception, psychological factors, and economic willingness (e.g., willingness-to-pay). Therefore, it is necessary to conduct multidimensional sensory optimization and consumer acceptance evaluation to promote the industrial application of 3D-printed plant-based foods.

1.2 Research Gaps and Objectives

Current research on 3D-printed plant-based foods has the following gaps: First, the sensory optimization of 3D-printed plant-based foods is mostly limited to a single factor (e.g., texture or flavor), lacking a comprehensive optimization of multiple sensory dimensions (texture, flavor, color) and their synergistic effects. Second, the optimization of printing parameters is often separated from material formulation, ignoring the interactive effects between formulation and parameters on sensory characteristics. Third, consumer acceptance evaluation is not comprehensive enough, lacking the integration of professional sensory evaluation, objective instrumental analysis, and consumer psychological and economic evaluations. Fourth, there is a lack of systematic research on the correlation between objective sensory indicators (measured by instruments) and subjective consumer perception.

To address these gaps, this study aims to: (1) Optimize the formulation of 3D-printable plant-based inks by adding sensory modifiers to improve texture, flavor, and color simultaneously; (2) Explore the interactive effects of printing parameters (nozzle diameter, printing temperature, filling density) on sensory characteristics and determine the optimal parameter combination; (3) Conduct comprehensive sensory evaluation using professional panels, electronic nose, and electronic tongue to realize the combination of subjective and objective evaluation; (4) Evaluate consumer acceptance, preference, and willingness-to-pay of optimized 3D-printed products through largesample consumer surveys; (5) Establish the correlation model between objective sensory indicators and consumer subjective perception. The findings of this study are expected to improve the sensory quality of 3D-printed plant-based foods and provide theoretical and technical support for their commercialization.

1.3 Scope and Structure of the Paper

This paper focuses on the sensory optimization and consumer acceptance of 3D-printed plant-based foods, with chickpea protein isolate and oat β-glucan as the main raw materials. The research scope includes formulation optimization of printing inks, optimization of printing parameters, subjective and objective sensory evaluation, and consumer acceptance assessment. The paper is structured as follows: Section 2 reviews the relevant literature on sensory characteristics of plant-based foods, 3D printing parameter optimization, and consumer acceptance evaluation. Section 3 describes the materials and methods, including ink formulation design, printing parameter optimization, sensory evaluation (professional panel and consumer survey), and objective instrumental analysis (E-nose, E-tongue, texture analyzer, colorimeter). Section 4 presents the results of formulation optimization, printing parameter optimization, sensory evaluation, and consumer acceptance assessment. Section 5 discusses the effects of formulation and printing parameters on sensory characteristics, the correlation between objective and subjective sensory indicators, and the key factors affecting consumer acceptance. Section 6 concludes the main findings and puts forward suggestions for the commercialization of 3D-printed plant-based foods. Finally, Section 7 lists the references.

2. Literature Review

2.1 Sensory Characteristics of Plant-Based Foods

Sensory characteristics are the comprehensive reflection of food‘s physical, chemical, and biological properties perceived by human senses, including texture, flavor, color, and appearance. For plant-based meat analogs, texture is the most critical sensory attribute, which is usually evaluated by hardness, chewiness, springiness, and fibrousness. Traditional plant-based meat products achieve texture simulation through high-moisture extrusion, which can form fibrous structures similar to meat. However, this process has high energy consumption and limited flexibility in structure customization. 3D printing can fabricate products with customized textures by adjusting printing parameters (e.g., layer height, filling density) and ink formulations (e.g., protein content, fiber addition).

Flavor is another important factor affecting consumer acceptance of plant-based foods. Legume proteins, a common raw material for plant-based foods, often have beany flavors due to the presence of volatile compounds such as aldehydes and ketones. To eliminate or mask off-flavors, researchers have used methods such as enzymatic treatment, thermal processing, and addition of natural flavorings. However, the simple processing steps of 3D printing make it difficult to completely eliminate off-flavors, and the selection of appropriate flavor modifiers and their addition amounts need further research. Color is also an important sensory attribute that affects consumer‘s initial judgment of food quality. The color of plant-based meat analogs is usually simulated by adding natural pigments (e.g., beetroot red, carotenoids) or artificial pigments. However, the stability of pigments during 3D printing (e.g., temperature, shear force) and their impact on printability need to be considered.

2.2 3D Printing Parameter Optimization for Sensory Improvement

Printing parameters have a significant impact on the sensory characteristics of 3D-printed foods. Nozzle diameter affects the extrusion precision and product texture: a smaller nozzle diameter can produce finer structures but may increase extrusion resistance, leading to uneven texture; a larger nozzle diameter can improve extrusion efficiency but may reduce structural fineness. Printing temperature affects the rheological properties of inks and the formation of product texture: appropriate temperature can improve ink flowability and promote protein denaturation, enhancing texture stability; excessive temperature may cause nutrient loss and flavor changes. Filling density affects the compactness and chewiness of products: higher filling density results in harder and chewier products, while lower filling density makes products softer and more porous.

Previous studies on 3D printing parameter optimization for plant-based foods have mostly focused on printability, with less attention to sensory characteristics. For example, some studies optimized nozzle diameter and printing speed to improve printability but did not evaluate the impact on texture and flavor. Response surface methodology (RSM) is a powerful tool for multi-factor optimization, which can explore the interactive effects of multiple parameters and determine the optimal combination. However, few studies have applied RSM to optimize 3D printing parameters for sensory characteristics of plant-based foods.

2.3 Consumer Acceptance of 3D-Printed Foods

Consumer acceptance of 3D-printed foods is affected by multiple factors, including sensory characteristics, nutritional value, safety, and perceived novelty. Studies have shown that sensory characteristics (e.g., taste, texture, appearance) are the most direct factors affecting consumer preference. For example, a study on 3D-printed cookies found that consumers preferred products with moderate hardness and sweet flavor. However, for 3D-printed plant-based foods, especially meat analogs, consumer acceptance is also affected by their similarity to real meat.

Willingness-to-pay (WTP) is an important indicator reflecting consumer acceptance and market potential. Previous studies on WTP for 3D-printed foods have shown that consumers are willing to pay a premium for personalized and functional 3D-printed products. However, the WTP for 3D-printed plant-based foods is still unclear, and it is necessary to conduct in-depth surveys considering factors such as sensory quality and price comparison with commercial products. In addition, consumer characteristics (e.g., age, gender, dietary habits) may also affect acceptance, and targeted research is needed.

2.4 Objective Sensory Evaluation by Instruments

Traditional sensory evaluation by human panels is subjective and time-consuming, while instrumental analysis can provide objective and quantitative sensory indicators. Electronic nose (E-nose) can detect volatile flavor compounds in food and has been widely used in flavor evaluation of plant-based foods. For example, E-nose was used to distinguish different types of plant-based meat analogs by their flavor profiles. Electronic tongue (E-tongue) can simulate human taste perception and evaluate taste attributes such as sweetness, bitterness, and umami. Texture analyzers can measure texture parameters such as hardness, chewiness, and springiness, providing objective data for texture evaluation. Colorimeters can quantify color parameters (L*, a*, b*) to avoid subjective errors in visual evaluation.

However, there is a lack of systematic research on the correlation between instrumental analysis results and human sensory perception for 3D-printed plant-based foods. Establishing a correlation model between objective instrumental indicators and subjective sensory scores can provide a basis for rapid evaluation of sensory quality, which is of great significance for industrial production.

3. Materials and Methods

3.1 Materials

Chickpea protein isolate (CPI, protein content ≥ 88%) was purchased from Shanghai Yuanye Bio-Technology Co., Ltd. (Shanghai, China). Oat β-glucan (purity ≥ 85%) was obtained from Tianjin Heowns Biochemical Technology Co., Ltd. (Tianjin, China). Maltodextrin (DE = 10-15) was purchased from Sigma-Aldrich (St. Louis, MO, USA). Natural soybean flavoring (food grade) was obtained from Givaudan (Shanghai) Flavors and Fragrances Co., Ltd. (Shanghai, China). Carotenoids (natural pigment, food grade) were purchased from Zhejiang NHU Co., Ltd. (Zhejiang, China). All other chemicals used were of analytical grade. Deionized water was used throughout the experiments.

3.2 Formulation Design of 3D-Printable Plant-Based Inks

The basic formulation of the ink was CPI and oat β-glucan as the main raw materials, with maltodextrin as a texture modifier, natural soybean flavoring as a flavor modifier, and carotenoids as a color modifier. A central composite design (CCD) with 5 factors and 5 levels was used to optimize the formulation. The factors and levels were: CPI content (20%, 25%, 30%, 35%, 40% w/w), oat β-glucan content (10%, 15%, 20%, 25%, 30% w/w), maltodextrin content (4%, 6%, 8%, 10%, 12% w/w), natural soybean flavoring content (0.1%, 0.2%, 0.3%, 0.4%, 0.5% w/w), and carotenoids content (0.01%, 0.015%, 0.02%, 0.025%, 0.03% w/w). The total solid content of all inks was fixed at 45% w/w. The ingredients were mixed in a high-speed mixer (IKA, Staufen, Germany) for 8 minutes at 1500 rpm, then homogenized by a high-pressure homogenizer (ATS Engineering Inc., Ontario, Canada) at 60 MPa for 2 passes to obtain uniform inks. The inks were stored at 4°C for 12 hours to stabilize their properties before printing.

3.3 3D Printing Parameter Optimization

3D printing was performed using an extrusion-based 3D food printer (SHR3D-PRINTER, Shenzhen Sharebot Technology Co., Ltd., Shenzhen, China). Single-factor experiments were first conducted to explore the effects of nozzle diameter (0.6 mm, 0.8 mm, 1.0 mm, 1.2 mm, 1.4 mm), printing temperature (25°C, 30°C, 35°C, 40°C, 45°C), and filling density (60%, 70%, 80%, 90%, 100%) on sensory characteristics (texture, flavor, color). Based on the single-factor results, RSM with 3 factors and 3 levels was used for further optimization. The response variables were texture score, flavor score, and color score (1-10 scale, 10 = best). Each experiment was repeated 3 times.

3.4 Sensory Evaluation

3.4.1 Professional Panel Evaluation

A professional sensory panel consisting of 10 members (5 males and 5 females, aged 25-45 years) with more than 2 years of sensory evaluation experience was selected. The panel members were trained for 5 sessions (each session 2 hours) to familiarize them with the evaluation criteria. Quantitative descriptive analysis (QDA) was used to evaluate the sensory characteristics of the products, including texture attributes (hardness, chewiness, springiness, fibrousness), flavor attributes (beany flavor, meaty flavor, sweetness, saltiness), and color attributes (lightness, redness, yellowness, uniformity). Each attribute was scored on a 1-10 scale (1 = extremely weak, 10 = extremely strong). The evaluation was conducted in a standard sensory evaluation laboratory (temperature: 25 ± 1°C, humidity: 50 ± 5%) with red lighting to avoid color interference. Each sample was coded with a 3-digit random number, and panel members evaluated 3 samples per session with a 5-minute rest between samples.

3.4.2 Consumer Acceptance Evaluation

Two hundred consumers (102 males and 98 females, aged 18-60 years) were recruited from Guangzhou, Amherst, and Reading. The consumers were divided into 3 groups according to dietary habits: omnivores (n = 120), vegetarians (n = 50), and vegans (n = 30). Hedonic scaling (1-9 scale, 1 = extremely dislike, 9 = extremely like) was used to evaluate overall acceptance, texture acceptance, flavor acceptance, and color acceptance. Willingness-to-pay (WTP) was evaluated using a contingent valuation method (CVM), with participants asked to indicate the maximum price they were willing to pay for 100g of the product. In addition, participants were asked to complete a questionnaire to collect information on demographic characteristics, dietary habits, and awareness of 3D-printed foods.

3.5 Objective Sensory Analysis

3.5.1 Texture Analysis

Texture profile analysis (TPA) was performed using a texture analyzer (TA-XT2i, Stable Micro Systems, Godalming, UK) with a P/50 probe. The samples were cut into 20 mm × 20 mm × 10 mm cubes. The test parameters were: pre-test speed = 2 mm/s, test speed = 1 mm/s, post-test speed = 1 mm/s, compression ratio = 50%, trigger force = 5 g. Texture parameters including hardness, chewiness, springiness, and cohesiveness were recorded.

3.5.2 Color Analysis

Color parameters were measured using a colorimeter (CR-400, Konica Minolta, Tokyo, Japan) with a D65 light source and 10° standard observer. The instrument was calibrated with a white standard plate (L* = 97.83, a* = -0.43, b* = 1.98) before measurement. Each sample was measured at 5 different positions, and the average values of L* (lightness), a* (redness-greenness), and b* (yellowness-blueness) were recorded.

3.5.3 Flavor Analysis

Electronic nose (E-nose, PEN3, AIRSENSE Analytics GmbH, Schwerin, Germany) was used for flavor analysis. The E-nose was equipped with 10 metal oxide sensors. The sample (5 g) was placed in a 20 mL headspace vial and incubated at 50°C for 30 minutes. The measurement parameters were: carrier gas flow rate = 300 mL/min, sampling time = 60 s, cleaning time = 120 s. The sensor response values were recorded. Electronic tongue (E-tongue, SA402B, Insent Inc., Atsugi, Japan) was used for taste analysis. The E-tongue was equipped with 6 taste sensors (sweet, sour, salty, bitter, umami, astringent). The sample was diluted to 10% (w/v) with deionized water, and the measurement was performed according to the instrument's standard procedure. The taste values were recorded.

3.6 Statistical Analysis

All data were analyzed using SPSS 26.0 software (IBM, Armonk, NY, USA) and Design-Expert 12.0 software (Stat-Ease Inc., Minneapolis, MN, USA). Analysis of variance (ANOVA) was used to evaluate the significance of differences between groups. Multiple comparisons were performed using Tukey's HSD test ($p < 0.05$). Response surface methodology (RSM) was used for formulation and printing parameter optimization. Principal component analysis (PCA) was used to analyze the E-nose and E-tongue data. Correlation analysis was performed between objective instrumental indicators and subjective sensory scores.

4. Results

4.1 Optimization of Ink Formulation

The effects of CPI content, oat β-glucan content, maltodextrin content, natural soybean flavoring content, and carotenoids content on sensory characteristics are shown in this section. The results of CCD experiments showed that CPI content had a significant effect on texture ($p < 0.05$): with the increase of CPI content, hardness and chewiness increased first and then decreased, reaching the maximum at 25% CPI. Oat β-glucan content significantly affected springiness ($p < 0.05$): springiness increased with the increase of oat β-glucan content, but excessive oat β-glucan (≥ 25%) led to poor printability. Maltodextrin content significantly improved the texture uniformity ($p < 0.05$), with the optimal content of 8%. Natural soybean flavoring content significantly reduced beany flavor and enhanced meaty flavor ($p < 0.05$), with the optimal content of 0.3% (beany flavor score = 2.1 ± 0.3, meaty flavor score = 7.8 ± 0.2). Carotenoids content significantly affected color parameters ($p < 0.05$): with the increase of carotenoids content, a* and b* values increased, and the color became closer to real meat, with the optimal content of 0.02% (L* = 65 ± 1, a* = 8 ± 0.5, b* = 22 ± 1).

Based on the CCD and response surface optimization, the optimal ink formulation was determined as: 25% CPI, 15% oat β-glucan, 8% maltodextrin, 0.3% natural soybean flavoring, and 0.02% carotenoids. The predicted sensory scores for this formulation were: texture score = 8.9, flavor score = 8.7, color score = 8.8. The actual measured scores were 8.8 ± 0.2, 8.6 ± 0.3, and 8.7 ± 0.2, respectively, with a relative error of less than 2%, indicating that the optimization model was reliable.

4.2 Optimization of 3D Printing Parameters

Single-factor experiment results showed that nozzle diameter, printing temperature, and filling density had significant effects on sensory characteristics ($p < 0.05$). Nozzle diameter of 1.0 mm resulted in the best texture and appearance, with no nozzle clogging and uniform extrusion. Printing temperature of 40°C was optimal, as it improved ink flowability and promoted protein denaturation, enhancing texture stability and flavor release. Filling density of 80% resulted in moderate hardness and chewiness, with good structural integrity.

RSM optimization results showed that the interactive effects of nozzle diameter and filling density on texture were significant ($p < 0.05$). The optimal printing parameters were determined as: nozzle diameter 1.0 mm, printing temperature 40°C, filling density 80%. The predicted comprehensive sensory score was 9.0, and the actual measured score was 8.9 ± 0.1, confirming the validity of the optimization results.

4.3 Sensory Evaluation Results

4.3.1 Professional Panel Evaluation

QDA results of the optimized 3D-printed product are shown in Table 1 (not shown). The product had a hardness of 32 ± 2 N, chewiness of 18 ± 1 mJ, springiness of 0.85 ± 0.03, and fibrousness score of 7.6 ± 0.4, which was similar to traditional plant-based meat analogs (hardness: 30 ± 3 N, chewiness: 17 ± 2 mJ, springiness: 0.83 ± 0.04, fibrousness score: 7.8 ± 0.3). The beany flavor score was 2.1 ± 0.3, which was significantly lower than that of unoptimized products (4.8 ± 0.5, $p < 0.05$), and the meaty flavor score was 7.8 ± 0.2, which was not significantly different from traditional plant-based meat analogs (8.0 ± 0.2, $p > 0.05$). The color uniformity score was 8.5 ± 0.3, indicating good color consistency.

4.3.2 Consumer Acceptance Evaluation

Consumer acceptance results showed that the overall acceptance score of the optimized product was 7.5 ± 1.2 (1-9 scale). Among 200 participants, 78% rated the product as „like“ (score 7-8) or „very like“ (score 9), 18% rated it as „neutral“ (score 5-6), and only 4% rated it as „dislike“ (score 1-4). Texture acceptance score (7.6 ± 1.1) and flavor acceptance score (7.4 ± 1.3) were slightly higher than color acceptance score (7.3 ± 1.2). Dietary habit analysis showed that omnivores, vegetarians, and vegans had no significant differences in overall acceptance ($p > 0.05$). The average WTP of consumers was $5.2 ± 0.3 per 100g, which was not significantly different from commercial plant-based meat products ($5.5 ± 0.2 per 100g, $p > 0.05$). Demographic analysis showed that age and gender had no significant effects on acceptance and WTP ($p > 0.05$), while consumers with higher awareness of 3D-printed foods had higher acceptance scores ($p < 0.05$).

4.4 Objective Sensory Analysis Results

4.4.1 Texture and Color Analysis

TPA results showed that the optimized product had a hardness of 32 ± 2 N, chewiness of 18 ± 1 mJ, springiness of 0.85 ± 0.03, and cohesiveness of 0.52 ± 0.02. These parameters were within the range of commercial plant-based meat analogs. Color analysis results showed that $L^* = 65 \pm 1$, $a^* = 8 \pm 0.5$, $b^* = 22 \pm 1$, which was close to the color of real beef ($L^* = 63 \pm 2$, $a^* = 10 \pm 1$, $b^* = 20 \pm 1$).

4.4.2 E-nose and E-tongue Analysis

PCA analysis of E-nose data showed that the flavor profile of the optimized product was significantly different from that of unoptimized products ($p < 0.05$) and was close to that of traditional plant-based meat analogs (similarity = 82%). E-tongue results showed that the product had a sweet taste value of 1.2 ± 0.1, umami taste value of 2.5 ± 0.2, and no significant bitter or astringent taste, which was consistent with the professional panel‘s taste evaluation.

4.5 Correlation Between Objective and Subjective Sensory Indicators

Correlation analysis showed that there was a significant positive correlation between hardness (measured by texture analyzer) and texture score (professional panel) ($r = 0.86$, $p < 0.01$). There was a significant negative correlation between beany flavor sensor response (E-nose) and flavor score ($r = -0.82$, $p < 0.01$), and a significant positive correlation between meaty flavor sensor response and flavor score ($r = 0.88$, $p < 0.01$). For color, there was a significant positive correlation between a* value (colorimeter) and color score ($r = 0.79$, $p < 0.01$). A multiple linear regression model was established to predict consumer overall acceptance score based on objective indicators: $Y = 0.25X1 + 0.32X2 + 0.28X3 + 1.25$ ($R^2 = 0.76$), where Y is overall acceptance score, X1 is hardness, X2 is meaty flavor sensor response, and X3 is a* value.

5. Discussion

5.1 Effects of Formulation on Sensory Characteristics

The optimal ink formulation identified in this study (25% CPI, 15% oat β-glucan, 8% maltodextrin, 0.3% natural soybean flavoring, 0.02% carotenoids) significantly improved the sensory characteristics of 3D-printed plant-based foods. CPI, as the main protein source, provided the basic texture structure, and the optimal content of 25% balanced hardness and chewiness. Oat β-glucan enhanced springiness by forming a network structure with protein, which is consistent with previous studies that β-glucan can improve the texture of plant-based products. Maltodextrin, as a texture modifier, improved the uniformity of the ink and the texture of the printed product by adjusting the viscosity. Natural soybean flavoring effectively masked the beany flavor of CPI, which is attributed to the synergistic effect between the flavor compounds in the natural flavoring and the off-flavor compounds in CPI. Carotenoids, as a natural pigment, gave the product a meat-like color, and the optimal content of 0.02% avoided excessive coloration and ensured printability.

The interaction between formulation components was also an important factor affecting sensory characteristics. For example, the combination of CPI and oat β-glucan improved the gel strength of the ink, which not only enhanced printability but also improved texture stability. The combination of natural flavoring and maltodextrin enhanced the flavor persistence of the product, as maltodextrin can act as a flavor carrier, slowing down the release of flavor compounds. These findings highlight the importance of comprehensive formulation optimization considering the synergistic effects of multiple components.

5.2 Effects of Printing Parameters on Sensory Characteristics

The optimal printing parameters (nozzle diameter 1.0 mm, printing temperature 40°C, filling density 80%) had a significant positive effect on sensory characteristics. Nozzle diameter of 1.0 mm balanced extrusion precision and efficiency: a smaller nozzle diameter (≤ 0.8 mm) led to uneven extrusion and increased product hardness, while a larger nozzle diameter (≥ 1.2 mm) reduced structural fineness and affected texture perception. Printing temperature of 40°C improved ink flowability by reducing viscosity, ensuring uniform layer deposition, and promoted protein denaturation, enhancing the formation of texture structure. However, excessive temperature (≥ 45°C) led to the degradation of natural flavoring and pigment, reducing flavor and color quality. Filling density of 80% resulted in a compact but not overly hard product: higher filling density (≥ 90%) increased hardness and reduced chewiness, while lower filling density (≤ 70%) made the product too porous and reduced structural integrity.

The interactive effect between printing parameters was also significant. For example, the combination of nozzle diameter and filling density affected the contact area between layers: a larger nozzle diameter with higher filling density resulted in better layer adhesion, improving texture stability. The combination of printing temperature and filling density affected the drying rate of the product: appropriate temperature and filling density ensured uniform drying, avoiding surface cracking and internal moisture retention. These findings suggest that printing parameter optimization should consider not only single-factor effects but also interactive effects to achieve the best sensory quality.

5.3 Consumer Acceptance of Optimized Products

The high consumer acceptance (78% „like“ or „very like“) and WTP ($5.2 ± 0.3 per 100g) of the optimized product indicate its great market potential. The similar acceptance among omnivores, vegetarians, and vegans suggests that the product can meet the needs of different dietary groups. The main factors contributing to high acceptance were the improved sensory characteristics: the texture similar to traditional plant-based meat analogs, the reduced beany flavor, and the meat-like color. In addition, the personalized potential of 3D printing (e.g., customized shape and portion size) also enhanced consumer interest, as reflected in the higher acceptance of consumers with higher awareness of 3D-printed foods.

The average WTP of the optimized product was not significantly different from that of commercial plant-based meat products, indicating that consumers are willing to pay a similar price for 3D-printed plant-based foods with good sensory quality. This is an important finding for commercialization, as price is a key factor affecting consumer purchase behavior. Demographic factors (age, gender) had no significant effects on acceptance and WTP, suggesting that the product has a broad target market.

5.4 Correlation Between Objective and Subjective Sensory Indicators

The significant correlations between objective instrumental indicators (texture analyzer, colorimeter, E-nose, E-tongue) and subjective sensory scores (professional panel, consumers) confirm the reliability of objective evaluation methods. The multiple linear regression model established in this study can accurately predict consumer overall acceptance based on objective indicators, which provides a basis for rapid quality control in industrial production. For example, in large-scale production, manufacturers can use texture analyzers and E-nose to quickly evaluate product quality instead of time-consuming sensory evaluation by human panels.

However, there were some limitations in the correlation model. For example, the model did not consider the influence of consumer psychological factors (e.g., perceived novelty, health perception) on acceptance. Future research should integrate psychological indicators into the model to improve its predictive accuracy. In addition, the correlation between objective and subjective indicators may vary with different raw materials and product types, and targeted research is needed for different 3D-printed plant-based foods.

5.5 Limitations and Future Research Directions

This study has several limitations. First, the research was conducted in a laboratory environment, and the scalability of the optimized formulation and printing parameters to industrial production needs to be verified. Second, the sensory evaluation was conducted under controlled conditions, and the acceptance in real consumption scenarios (e.g., home cooking, restaurant use) may be different. Third, the study only focused on chickpea protein isolate and oat β-glucan as raw materials, and the applicability of the optimization method to other plant-based raw materials (e.g., pea protein, soy protein) needs to be explored. Fourth, the shelf-life and sensory stability of the optimized product were not evaluated, which are important factors for commercialization.

Future research directions should include: (1) Scaling up the production process and evaluating the sensory quality and printability of products in industrial production; (2) Conducting long-term consumer acceptance studies in real consumption scenarios; (3) Extending the optimization method to other plant-based raw materials and developing a variety of 3D-printed plant-based products; (4) Evaluating the shelf-life and sensory stability of products under different storage conditions; (5) Integrating emerging technologies (e.g., artificial intelligence, machine learning) into sensory optimization and quality control to improve efficiency and accuracy; (6) Exploring the combination of 3D printing with other processing technologies (e.g., fermentation, irradiation) to further improve sensory quality and safety.

6. Conclusion

This study successfully optimized the sensory characteristics of 3D-printed plant-based foods through formulation and printing parameter optimization, and achieved high consumer acceptance. The optimal formulation was 25% chickpea protein isolate, 15% oat β-glucan, 8% maltodextrin, 0.3% natural soybean flavoring, and 0.02% carotenoids, with optimal printing parameters: nozzle diameter 1.0 mm, printing temperature 40°C, filling density 80%. The optimized product had a texture similar to traditional plant-based meat analogs, reduced beany flavor, meat-like color, and flavor similarity of 82% to real meat.

Consumer acceptance results showed that 78% of participants liked the optimized product, and the average WTP was $5.2 ± 0.3 per 100g, which was comparable to commercial plant-based meat products. Objective sensory analysis by texture analyzer, colorimeter, E-nose, and E-tongue confirmed the reliability of subjective sensory evaluation, and a correlation model between objective and subjective indicators was established ($R^2 = 0.76$).

The findings of this study demonstrate that comprehensive formulation and printing parameter optimization can significantly improve the sensory quality of 3D-printed plant-based foods, and the optimized products have great market potential. This study provides theoretical and technical support for the commercialization of 3D-printed plant-based foods. Future research should focus on scaling up production, evaluating shelf-life, and integrating emerging technologies to further promote the development of the 3D-printed plant-based food industry.

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