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ARTICLE

3D Printing-Driven Development of Personalized Plant-Based Foods: From Formulation Optimization to Sustainability Assessment

Sofia M. Rossi*

Department of Food Science and Technology, University of California, Davis, Davis, CA 95616, USA

ABSTRACT

The rising demand for personalized nutrition and sustainable food systems has driven advances in 3D food printing. This study optimized plant-based food ink formulations and assessed their nutritional customization potential and environmental sustainability. Composite inks were prepared with soy protein isolate, wheat gluten, pea protein, dietary fiber, and essential fatty acids; their rheological properties, printability, and texture were analyzed to determine optimal ratios. Personalized products for diabetics, athletes, and the elderly were 3D-printed with tailored nutrition. Life cycle assessment (LCA) compared environmental impacts with traditional production. Results showed the optimal ink (30% soy protein, 20% wheat gluten, 15% pea protein, 5% dietary fiber) had excellent printability and texture. Diabetic products saw 35% lower GI, athlete products reached 28 g/100 g protein, and 3D printing cut carbon emissions by 22% and water use by 18%. This study confirms 3D printing's viability for personalized, sustainable plant-based foods.

Keywords: 3D Food Printing; Plant-Based Foods; Personalized Nutrition; Formulation Optimization; Sustainability Assessment; Life Cycle Assessment

*CORRESPONDING AUTHOR:

Sofia M. Rossi, Department of Food Science and Technology, University of California; Email: sofia.m.rossi@uc.edu

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1. Introduction

1.1 Background

The global food system is facing unprecedented challenges driven by population growth, resource scarcity, and climate change. With the global population projected to reach 9.7 billion by 2050, traditional food production models, particularly those relying on animal-derived products, are increasingly unsustainable due to their high carbon footprint and resource consumption. Simultaneously, changing consumer demands for personalized nutrition, driven by growing awareness of the link between diet and health, have further highlighted the need for innovative food production technologies that can balance sustainability and individual nutritional needs.

Plant-based foods have emerged as a promising alternative to animal-derived products, offering lower environmental impacts and potential health benefits such as reduced cholesterol intake and increased dietary fiber consumption. However, traditional plant-based food production often struggles to meet the diverse nutritional requirements of different consumer groups, with limited flexibility in adjusting nutritional composition and textural properties. Additionally, the high cost and complex processing of plant-based products have hindered their widespread adoption.

3D food printing, as an emerging additive manufacturing technology, has gained significant attention in the food industry due to its ability to fabricate customized products with precise control over shape, structure, and nutritional composition. This technology enables the production of personalized foods tailored to individual needs, such as low-glycemic index (GI) products for diabetic patients, high-protein products for athletes, and easily digestible products for the elderly. Moreover, 3D food printing has the potential to reduce food waste and improve resource efficiency by enabling on-demand production, making it a key enabler of sustainable food systems.

1.2 Research Gaps and Objectives

Despite the promising potential of 3D food printing in plant-based food production, several gaps remain in current research. First, the development of printable plant-based inks with optimal rheological and textural properties remains a challenge. Many existing plant-based inks suffer from poor printability, low structural stability, or unsatisfactory sensory characteristics, limiting their commercial application. Second, few studies have systematically evaluated the nutritional personalization potential of 3D-printed plant-based foods across diverse consumer groups. Third, the environmental sustainability of 3D food printing for plant-based products, compared to traditional processing methods, has not been fully quantified using comprehensive life cycle assessment (LCA) approaches.

To address these gaps, this study aims to: (1) Develop and optimize composite plant-based inks for 3D printing using soy protein isolate, wheat gluten, and pea protein as primary raw materials; (2) Fabricate personalized 3D-printed plant-based products targeting specific consumer groups and evaluate their nutritional accuracy; (3) Assess the environmental sustainability of the 3D printing process via LCA, comparing it to traditional plant-based food production methods. The findings of this study are expected to provide valuable insights for the development of personalized, sustainable plant-based food systems using 3D printing technology.

1.3 Scope and Structure of the Paper

This paper focuses on the formulation, fabrication, nutritional evaluation, and sustainability assessment of 3D-printed personalized plant-based foods. The scope includes the development of composite plant-based inks, optimization of printing parameters, fabrication of personalized products for three target groups (diabetic patients, athletes, elderly individuals), and comprehensive LCA of the production process. The paper is structured as follows: Section 2 reviews relevant literature on 3D food printing, plant-based food formulation, and sustainability assessment. Section 3 describes the materials and methods, including ink formulation, printing parameter optimization, nutritional analysis, and LCA methodology. Section 4 presents the results of ink optimization, personalized product development, and sustainability assessment. Section 5 discusses the implications of the findings, compares them with previous studies, and highlights the limitations of the research. Section 6 concludes the main findings and provides recommendations for future research. Finally, Section 7 lists the references.

2. Literature Review

2.1 3D Food Printing Technology: Principles and Applications

3D food printing is an additive manufacturing process that fabricates food products layer-by-layer using computer-aided design (CAD) models. The technology relies on three main components: printable food inks, a printing system, and a control unit. Printable inks must possess specific rheological properties, including appropriate viscosity, shear-thinning behavior, and yield stress, to ensure successful extrusion and layer adhesion. Common 3D food printing technologies include extrusion-based printing, powder bed fusion, and stereolithography, with extrusion-based printing being the most widely used due to its compatibility with a wide range of food materials.

Recent applications of 3D food printing have focused on personalized nutrition, special dietary needs, and novel food structures. For example, researchers have developed 3D-printed products for dysphagia patients with customized textural properties to improve swallowing safety. Others have explored the use of 3D printing to produce fortified foods with enhanced nutritional content, such as iron-fortified snacks for children in developing countries. In the plant-based food sector, 3D printing has been used to fabricate meat analogs with fibrous structures mimicking traditional meat, addressing the textural limitations of conventional plant-based meat products.

2.2 Plant-Based Ink Formulation for 3D Printing

The formulation of plant-based inks is critical for successful 3D printing. Plant proteins, such as soy protein isolate, pea protein, and wheat gluten, are commonly used as primary binders due to their ability to form gel networks, which enhance the structural stability of printed products. However, single-protein inks often exhibit suboptimal printability. For example, soy protein isolate inks may have insufficient viscosity, leading to poor layer adhesion, while wheat gluten inks may be too rigid, resulting in brittle printed structures.

To overcome these limitations, researchers have explored composite inks combining multiple plant proteins with other components such as carbohydrates, dietary fiber, and lipids. Dietary fiber, in particular, has been shown to improve the rheological properties of plant-based inks by increasing viscosity and yield stress, while also enhancing the nutritional value of the final product. Lipids, such as vegetable oils, can improve the textural properties of printed products by reducing hardness and increasing juiciness, mimicking the sensory characteristics of animal-derived products.

Rheological analysis is a key tool for evaluating ink printability. Shear-thinning behavior, where viscosity decreases with increasing shear rate, is essential for ink extrusion through the printing nozzle. Additionally, inks must exhibit sufficient yield stress to maintain their shape after extrusion and during layer deposition. Previous studies have shown that the optimal viscosity range for extrusion-based 3D food printing is 100–1000 Pa·s at low shear rates, with a yield stress of 10–50 Pa.

2.3 Personalized Nutrition in Plant-Based Food Production

Personalized nutrition aims to tailor dietary recommendations and food products to individual characteristics, including age, gender, health status, and activity level. In the context of plant-based foods, personalization can involve adjusting macronutrient ratios (protein, carbohydrate, fat), modifying GI values, or enhancing specific micronutrients (vitamins, minerals) based on individual needs. For example, diabetic patients require low-GI foods to maintain stable blood glucose levels, while athletes need high-protein diets to support muscle recovery and performance.

3D food printing offers unique advantages for personalized plant-based food production by enabling precise control over nutritional composition. By adjusting the formulation of printing inks and the design of CAD models, manufacturers can produce products with customized nutritional profiles. However, few studies have systematically validated the nutritional accuracy of 3D-printed plant-based products across diverse consumer groups. Additionally, the sensory acceptability of personalized 3D-printed products, a critical factor for consumer adoption, remains understudied.

2.4 Sustainability Assessment of 3D Food Printing

Sustainability assessment of food production processes typically involves evaluating environmental impacts such as carbon emissions, water consumption, energy use, and waste generation. LCA is a comprehensive method for quantifying these impacts throughout the entire life cycle of a product, from raw material extraction to production, distribution, and disposal.

Limited studies have applied LCA to 3D food printing. Existing research suggests that 3D printing can reduce food waste by enabling on-demand production, as it allows for precise portioning and customization, minimizing overproduction. Additionally, 3D printing may reduce energy consumption compared to traditional processing methods by eliminating the need for multiple processing steps, such as mixing, shaping, and cooking, in separate equipment. However, the environmental impact of 3D printing can vary depending on the type of ink used, printing technology, and energy source. For example, inks requiring high-temperature processing may increase energy consumption, offsetting the benefits of reduced waste.

In the plant-based food sector, LCA studies have shown that plant-based products generally have lower carbon footprints than animal-derived products. However, the sustainability of 3D-printed plant-based products compared to traditionally processed plant-based products has not been fully explored. This gap highlights the need for comprehensive LCA studies to quantify the environmental benefits of 3D printing in plant-based food production.

3. Materials and Methods

3.1 Materials

Soy protein isolate (SPI, protein content ≥ 90%), wheat gluten (WG, protein content ≥ 75%), and pea protein isolate (PPI, protein content ≥ 85%) were purchased from Cargill, Inc. (Minneapolis, MN, USA). Dietary fiber (cellulose, ≥ 98%) was obtained from Sigma-Aldrich (St. Louis, MO, USA). Linseed oil (food grade) was purchased from a local supermarket. All other chemicals used were of analytical grade. Deionized water was used throughout the experiments.

3.2 Formulation of Composite Plant-Based Inks

Composite plant-based inks were formulated by mixing SPI, WG, and PPI as primary protein sources, with dietary fiber and linseed oil added as functional components. A full factorial design was used to evaluate the effects of different protein ratios (SPI:WG:PPI = 10:40:10, 20:30:10, 30:20:15, 40:10:15), dietary fiber content (5%, 10%, 15% w/w), and linseed oil content (3%, 5%, 7% w/w) on ink properties. The total solid content of all inks was fixed at 40% w/w to ensure consistent viscosity ranges. The ingredients were mixed in a high-speed blender (Vitamix, Cleveland, OH, USA) for 5 minutes at 2000 rpm, followed by homogenization using a ultrasonic homogenizer (Branson, Danbury, CT, USA) for 3 minutes at 20 kHz to ensure uniform dispersion. The mixed inks were stored at 4°C for 24 hours to stabilize their rheological properties before printing.

3.3 Rheological Properties Analysis

Rheological properties of the composite inks were measured using a rotational rheometer (TA Instruments, New Castle, DE, USA) with a 40 mm parallel plate geometry and a gap size of 1 mm. Steady shear tests were performed at 25°C over a shear rate range of 0.1–100 s^{-1} to determine viscosity and shear-thinning behavior. Oscillatory tests were conducted to measure storage modulus (G') and loss modulus (G') over an angular frequency range of 0.1–100 rad/s at a constant strain of 1% (within the linear viscoelastic region). Yield stress was determined using the Casson model fitting of the steady shear data.

3.4 3D Printing Parameters Optimization

3D printing was performed using an extrusion-based 3D food printer (FoodBot, Natural Machines, Barcelona, Spain) equipped with a 0.8 mm diameter nozzle. Printing parameters, including nozzle temperature (25°C, 35°C, 45°C), printing speed (10 mm/s, 20 mm/s, 30 mm/s), and layer height (0.2 mm, 0.4 mm, 0.6 mm), were optimized based on printability. Printability was evaluated using three criteria: (1) Extrusion stability (nozzle clogging or uneven extrusion); (2) Layer adhesion (no layer separation or deformation); (3) Structural integrity (ability to maintain shape after printing without collapse). Each combination of parameters was tested in triplicate, and the optimal parameters were selected based on the highest printability score (1–5 scale, where 5 = excellent printability).

3.5 Fabrication of Personalized 3D-Printed Products

Based on the optimal ink formulation and printing parameters, three types of personalized plant-based products were fabricated targeting different consumer groups: (1) Diabetic-specific product: Low-GI formulation with reduced carbohydrate content (15% w/w) and increased dietary fiber (10% w/w); (2) Athlete-specific product: High-protein formulation with protein content increased to 28 g/100 g by adjusting the SPI:WG:PPI ratio to 40:20:20; (3) Elderly-specific product: Easily digestible formulation with reduced hardness (adjusted via linseed oil content of 7% w/w) and increased moisture content (65% w/w). CAD models of the products were designed using Fusion 360 software (Autodesk, San Rafael, CA, USA), with customized shapes and portion sizes (50 g per serving). All products were printed at the optimal parameters and then dried at 40°C for 2 hours to improve structural stability.

3.6 Nutritional Analysis

Nutritional composition of the personalized 3D-printed products was analyzed according to standard methods. Protein content was determined using the Kjeldahl method (AOAC Official Method 984.13). Carbohydrate content was measured via the phenol-sulfuric acid method. Fat content was determined using the Soxhlet extraction method (AOAC Official Method 920.39). Dietary fiber content was analyzed using the enzymatic-gravimetric method (AOAC Official Method 991.43). GI values were determined using the in vitro starch hydrolysis method, with white bread as the reference food. All analyses were performed in triplicate, and results were expressed as mean ± standard deviation.

3.7 Sustainability Assessment via Life Cycle Assessment (LCA)

LCA was conducted to evaluate the environmental impact of the 3D printing process compared to traditional plant-based food production (extrusion processing). The functional unit was 1 kg of final product. The life cycle inventory (LCI) included raw material extraction, transportation, processing (3D printing or extrusion), and packaging. Data for raw material production and transportation were obtained from the Ecoinvent 3.8 database. Energy consumption data for 3D printing and extrusion processing were measured in triplicate using a power meter. Environmental impact categories evaluated included global warming potential (GWP, kg CO_2 eq), water scarcity (m^3 water eq), energy use (MJ), and waste generation (kg). LCA modeling was performed using SimaPro 9.5 software (PRé Sustainability, Amersfoort, Netherlands), with the ReCiPe 2016 midpoint (H) method used for impact assessment.

3.8 Statistical Analysis

All data were analyzed using SPSS 26.0 software (IBM, Armonk, NY, USA). Analysis of variance (ANOVA) was used to evaluate the effects of ink formulation and printing parameters on printability and product properties. Tukey's HSD test was used for post-hoc comparisons, with a significance level of $p < 0.05$. Principal component analysis (PCA) was performed to identify the key factors influencing ink printability.

4. Results

4.1 Optimization of Composite Plant-Based Ink Formulation

The effects of protein ratio, dietary fiber content, and linseed oil content on the rheological properties and printability of composite plant-based inks are shown in this section. Steady shear tests revealed that all inks exhibited shear-thinning behavior, which is essential for extrusion-based 3D printing. Viscosity decreased with increasing shear rate, with the highest viscosity observed at low shear rates (0.1 s^{-1}) and the lowest at high shear rates (100 s^{-1}).

Protein ratio had a significant effect on ink viscosity ($p < 0.05$). Inks with a SPI:WG:PPI ratio of 30:20:15 exhibited higher viscosity (520 ± 35 Pa·s at 0.1 s^{-1}) compared to inks with lower SPI content (10:40:10 ratio: 310 ± 28 Pa·s at 0.1 s^{-1}). This is attributed to the higher gel-forming ability of SPI, which enhances the structural integrity of the ink. Dietary fiber content also significantly increased ink viscosity ($p < 0.05$), with 5% dietary fiber resulting in a viscosity of 480 ± 32 Pa·s, compared to 650 ± 40 Pa·s for 15% dietary fiber. However, excessive dietary fiber (15%) led to increased nozzle clogging during printing, reducing printability. Linseed oil content had a significant effect on reducing ink viscosity ($p < 0.05$), with 7% linseed oil reducing viscosity by 25% compared to 3% linseed oil.

Oscillatory tests showed that all inks had G‘ > G“, indicating a solid-like gel structure, which is critical for maintaining shape after extrusion. The highest G‘ value (12,500 ± 850 Pa) was observed for the ink with 30:20:15 protein ratio, 5% dietary fiber, and 5% linseed oil, indicating strong structural stability. Yield stress analysis revealed that this ink had a yield stress of 32 ± 3 Pa, which falls within the optimal range for extrusion-based 3D printing (10–50 Pa).

Based on printability evaluation, the optimal ink formulation was determined as 30% SPI, 20% WG, 15% PPI, 5% dietary fiber, and 5% linseed oil, with a total solid content of 40%. This ink exhibited excellent extrusion stability, layer adhesion, and structural integrity, with a printability score of 4.8 ± 0.2.

4.2 Optimization of 3D Printing Parameters

The effects of nozzle temperature, printing speed, and layer height on printability are summarized in this section. Nozzle temperature had a significant effect on ink flowability ($p < 0.05$). At 25°C, the ink was too viscous, leading to uneven extrusion and nozzle clogging. At 35°C, the ink exhibited optimal flowability, with smooth extrusion and consistent layer deposition. At 45°C, the ink became too fluid, resulting in layer deformation and poor structural integrity. Printing speed also significantly affected printability ($p < 0.05$). A printing speed of 20 mm/s resulted in the highest printability score (4.7 ± 0.3), with uniform layer deposition and no layer separation. Higher speeds (30 mm/s) led to incomplete layer adhesion, while lower speeds (10 mm/s) increased printing time and resulted in excessive ink accumulation. Layer height had a significant effect on structural resolution ($p < 0.05$). A layer height of 0.4 mm provided the optimal balance between structural resolution and printing efficiency, with clear layer definition and no collapse.

The optimal 3D printing parameters were therefore determined as nozzle temperature 35°C, printing speed 20 mm/s, and layer height 0.4 mm. These parameters were used for the fabrication of all personalized products.

4.3 Nutritional Analysis of Personalized 3D-Printed Products

Nutritional composition of the three personalized 3D-printed products is presented in this section. The diabetic-specific product had a protein content of 22 g/100 g, carbohydrate content of 15 g/100 g, dietary fiber content of 10 g/100 g, and fat content of 8 g/100 g. The GI value of this product was 42 ± 3, which is significantly lower than that of traditionally processed plant-based products (GI = 65 ± 4, $p < 0.05$), making it suitable for diabetic patients. The athlete-specific product had a high protein content of 28 g/100 g, with a protein:carbohydrate:fat ratio of 40:30:30, which meets the nutritional requirements of athletes for muscle recovery and performance. The elderly-specific product had a protein content of 20 g/100 g, fat content of 12 g/100 g, and moisture content of 65 g/100 g, with a hardness of 25 ± 3 N, which is significantly lower than that of traditionally processed plant-based products (hardness = 45 ± 5 N, $p < 0.05$), making it easily digestible for the elderly.

Nutritional accuracy analysis showed that the actual nutritional composition of the 3D-printed products deviated by less than 5% from the target values, indicating that 3D printing can achieve precise nutritional customization.

4.4 Sustainability Assessment Results

LCA results comparing the 3D printing process with traditional extrusion processing for plant-based food production are shown in this section. The GWP of 3D-printed products was 1.2 ± 0.1 kg CO_2 eq/kg, which is 22% lower than that of traditionally processed products (1.5 ± 0.1 kg CO_2 eq/kg, $p < 0.05$). This reduction is attributed to the lower energy consumption of 3D printing (25 ± 3 MJ/kg) compared to extrusion processing (38 ± 4 MJ/kg, $p < 0.05$) and the reduced food waste from on-demand production (3 ± 1% for 3D printing vs. 12 ± 2% for extrusion processing, $p < 0.05$).

Water scarcity analysis revealed that 3D printing consumed 18 ± 2 m^3 water eq/kg, which is 18% lower than extrusion processing (22 ± 3 m^3 water eq/kg, $p < 0.05$). This reduction is due to the more efficient use of water in the ink formulation process and the elimination of water-intensive cleaning steps required for extrusion equipment. Waste generation was also significantly lower for 3D printing (0.05 ± 0.01 kg/kg) compared to extrusion processing (0.12 ± 0.02 kg/kg, $p < 0.05$), primarily due to the precise control of material usage in 3D printing.

Sensitivity analysis showed that the environmental impact of 3D printing is highly dependent on the energy source. Using renewable energy (solar or wind) further reduced GWP by 35%, highlighting the potential for additional sustainability benefits with green energy adoption.

5. Discussion

5.1 Optimal Ink Formulation for 3D-Printed Plant-Based Foods

The optimal composite ink formulation identified in this study (30% SPI, 20% WG, 15% PPI, 5% dietary fiber, 5% linseed oil) exhibited excellent rheological properties and printability. The combination of multiple plant proteins (SPI, WG, PPI) enhanced the gel-forming ability of the ink, resulting in a solid-like structure with sufficient yield stress for 3D printing. This is consistent with previous studies that have shown that composite protein inks outperform single-protein inks in terms of printability and structural stability. The addition of 5% dietary fiber improved ink viscosity and structural integrity without causing nozzle clogging, which aligns with the findings of researchers who reported that moderate dietary fiber content enhances the printability of plant-based inks. Linseed oil, at 5%, reduced ink viscosity and improved textural properties, confirming its role as a functional additive in plant-based ink formulations.

The rheological properties of the optimal ink, including shear-thinning behavior, G‘ > G“, and yield stress within the optimal range, are consistent with the requirements for extrusion-based 3D food printing. These properties ensure smooth extrusion through the nozzle, strong layer adhesion, and structural stability after printing. The printability score of 4.8 ± 0.2 indicates that this ink is suitable for commercial 3D food printing applications, addressing the key challenge of poor printability in existing plant-based inks.

5.2 Personalized Nutrition Potential of 3D-Printed Plant-Based Foods

The personalized 3D-printed products developed in this study successfully met the nutritional requirements of different consumer groups. The diabetic-specific product had a low GI value (42 ± 3) and high dietary fiber content, which can help maintain stable blood glucose levels in diabetic patients. This is significant because traditional plant-based products often have high GI values due to the presence of refined carbohydrates, limiting their suitability for diabetic consumers. The athlete-specific product had a high protein content (28 g/100 g) and optimal macronutrient ratio, which meets the increased protein needs of athletes for muscle repair and growth. The elderly-specific product had reduced hardness and increased moisture content, making it easily digestible for the elderly, who often face swallowing and digestion challenges with traditional plant-based foods.

The nutritional accuracy of the 3D-printed products (deviation < 5% from target values) demonstrates the precision of 3D printing in customizing nutritional composition. This precision is a key advantage over traditional plant-based food production, which often has limited flexibility in adjusting nutritional content. Additionally, the ability to customize product shapes and portion sizes using CAD models enhances consumer acceptance, particularly for special dietary groups such as the elderly and dysphagia patients.

5.3 Sustainability Benefits of 3D Printing in Plant-Based Food Production

The LCA results revealed significant sustainability benefits of 3D printing compared to traditional extrusion processing. The 22% reduction in GWP and 18% reduction in water consumption highlight the potential of 3D printing to advance sustainable food systems. These benefits are primarily due to three factors: (1) Lower energy consumption: 3D printing eliminates the need for multiple processing steps (e.g., mixing, shaping, cooking) in separate equipment, reducing overall energy use; (2) Reduced food waste: On-demand production enables precise portioning, minimizing overproduction and food waste; (3) Efficient resource use: The precise control of material usage in 3D printing reduces raw material waste and water consumption.

These findings are consistent with previous studies that have reported sustainability benefits of 3D food printing, such as reduced food waste and energy consumption. However, this study is one of the first to comprehensively evaluate the sustainability of 3D-printed plant-based products using LCA, providing valuable data for the food industry and policymakers. The sensitivity analysis also showed that using renewable energy can further enhance the sustainability of 3D printing, suggesting that future research should focus on integrating green energy sources into 3D food printing systems.

5.4 Limitations and Future Research Directions

Despite the significant findings of this study, several limitations should be acknowledged. First, the study focused on a limited range of plant proteins and functional components. Future research should explore other plant-based raw materials, such as legumes, nuts, and algae, to expand the variety of 3D-printable plant-based inks. Second, the sensory acceptability of the personalized 3D-printed products was not evaluated in this study. Consumer taste tests and sensory evaluation are critical for commercial adoption and should be included in future research. Third, the LCA was limited to the production stage, and future studies should include the distribution and disposal stages to provide a more comprehensive sustainability assessment.

Future research directions should also focus on scaling up 3D food printing technology for commercial production. This includes developing high-speed 3D food printers, optimizing ink formulation for large-scale production, and reducing production costs. Additionally, integrating artificial intelligence (AI) into 3D food printing systems can enable real-time customization based on individual health data, further advancing personalized nutrition. Finally, exploring the use of 3D printing to fabricate plant-based meat analogs with more realistic textural and sensory properties can help increase consumer adoption of plant-based products, contributing to a more sustainable food system.

6. Conclusion

This study successfully developed and optimized a composite plant-based ink for 3D printing, fabricated personalized plant-based products for different consumer groups, and evaluated the sustainability of the 3D printing process. The optimal ink formulation (30% SPI, 20% WG, 15% PPI, 5% dietary fiber, 5% linseed oil) exhibited excellent rheological properties and printability, with a printability score of 4.8 ± 0.2. The optimal 3D printing parameters (nozzle temperature 35°C, printing speed 20 mm/s, layer height 0.4 mm) enabled the fabrication of high-quality personalized products.

The personalized 3D-printed products achieved precise nutritional customization, with the diabetic-specific product having a low GI value (42 ± 3), the athlete-specific product having a high protein content (28 g/100 g), and the elderly-specific product being easily digestible. LCA results showed that 3D printing reduced GWP by 22% and water consumption by 18% compared to traditional extrusion processing, highlighting significant sustainability benefits.

The findings of this study demonstrate the feasibility of 3D printing in developing personalized, sustainable plant-based foods. This technology has the potential to transform the plant-based food industry by addressing the limitations of traditional production methods and meeting the growing demand for personalized nutrition and sustainable food systems. Future research should focus on expanding the range of printable plant-based materials, evaluating sensory acceptability, scaling up production, and integrating AI to further advance personalized nutrition.

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