

Optimization of the 3D printing process of chicken meat products through response surface methods approach

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Abstract. This study explores how key operational settings of a food 3D printer affect the formation of printed structures using minced chicken paste. The printing material was prepared by blending chilled chicken breast with table salt and then cooled prior to use. To evaluate the impact of printing parameters, three output metrics were analyzed: printing time, product weight, and visual quality of the printed product. Among the studied parameters, nozzle movement speed and infill density were found to primarily influence the printing time – higher speeds and lower infill levels reduced the time. Product weight was most sensitive to flow rate and infill density, both contributing to an increase in weight as their values rose. Print quality benefited from higher flow rate and infill density, while excessive nozzle speed and diameter led to quality deterioration. The optimal parameters combination was determined as follows: nozzle speed of 58.7 mm/s, flow rate of 54.7 mm³/s, nozzle diameter of 1.2 mm, and infill density of 50%, achieving a desirability score of 0.89. These findings can support the fine-tuning of food 3D printing systems for producing customized meat-based products with improved process efficiency and product consistency.

1 Introduction

Today, the issues of improving quality of life and extending its duration are of particular relevance. Many chronic diseases are often linked to poor nutrition. Each individual requires a specific set of nutrients and vitamins to maintain health and high performance. In this regard, the concept of personalized nutrition has gained increasing popularity in recent years [1, 2, 3].

A novel approach in the food industry is the use of 3D printing technology, which enables the creation of complex geometric structures from food ingredients. The rapid development of robotics and its integration into the process of food 3D printing has the potential to significantly expand production technologies, particularly in the field of personalized nutrition [4]. Beyond improving flavor characteristics, it also becomes possible to easily adjust the nutritional content of food products in accordance with individual needs [5]. For people with special dietary requirements, such as children, the elderly, or patients with chronic illnesses, 3D printing allows for the creation of foods with precisely tailored nutrient compositions, adjustable in real time.

Consumer demand for foods with unique shapes and textures often requires the development of specialized product designs with intricate internal structures [6]. The production of such models by traditional molding methods can take more than a day, whereas 3D printing enables their fabrication within minutes. Extrusion-based 3D printing involves the deposition of paste-like

material under pressure through a nozzle to create three-dimensional structures layer by layer [7].

Due to its steadily increasing production rates, chicken meat holds a leading position in the global structure of processed livestock meat products [8]. Currently, the main chicken meat products on the market are minced semi-finished goods such as meatballs, breaded products like nuggets, and sausages. Due to their uniform appearance and limited variety, these products are gradually losing popularity among consumers [9]. The use of 3D printing technology can meet the demand for personalized chicken-based products. Chicken meat paste is well-suited for extrusion and post-processing, offering broad possibilities for manufacturing high-quality 3D-printed food products.

However, the complex composition of meat products presents challenges for their 3D printing. For this reason, it is crucial to determine the appropriate process parameters that ensure the desired sensory characteristics of the printed products after cooking. 3D printing technology provides particular advantages in producing foods with modified textures, making them easier to swallow, and in developing new flavors and aromas.

Research in 3D printing of foods from animal-based raw materials is expanding rapidly. For instance, the authors of [10] used transglutaminase to alter the texture of 3D-printed “combs” and “meat paste” from turkey, demonstrating the potential of 3D printing to create complex structures that transform the appearance of traditional dishes. In the work [11], a food 3D printer

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was used to print meat paste with food additives for the elderly. There are also reports on printing surimi paste with added table salt to modify its rheological properties [12]. Researchers in [13] added 8% sweet potato starch by weight as a structural modifier to achieve stable constructions printed from fish gel. Future possibilities for creating novel meat products with intricate internal structures from multiple materials for personalized diets are highlighted in a study on 3D-printed meat products. In another study by the same authors [14], various combinations of post-printing cooking methods were tested on beef-based 3D-printed foods with modified internal and external structures. That study varied infill percentages and fat content between layers. The experiments showed that the density of the food material was proportional to its water-holding capacity, hardness, and chewiness, while fat content was proportional to cooking losses, shrinkage, and cohesiveness of the 3D-printed product. Another study, focused on the effects of hydrocolloids on the printability of pork paste-based products, provides valuable insights for developing food for people with dysphagia [15]. The authors evaluated the effects of xanthan gum, including in combination with guar gum, on the textural, microstructural, and rheological properties of 3D-printed pork paste products.

Numerous factors influence the food 3D printing process, so a well-designed experimental plan is essential for parameters optimization. However, due to the high number of influencing parameters, predicting and achieving the desired textural properties of 3D-printed foods remains a complex challenge.

The primary objective of this study is to investigate the influence of various food 3D printer control parameters on the print quality of chicken meat paste products and to determine their optimal values.

2 Materials and methods

2.1 Preparation of chicken meat paste

To prepare the chicken meat paste, chilled chicken breast (moisture content $63.56 \pm 0.18\%$) and table salt were used. Visible areas of connective tissue and fat were removed from the meat, which was then cut into small pieces and blended for 2 min. The minced chicken was mixed with salt in a blender for an additional minute. The prepared paste, containing 1% salt by weight, was cooled to a temperature of 4 °C and held for 6 hours before being used for 3D printing.

2.2 3D printing process

For the experimental study of extrusion-based 3D printing of chicken meat paste, a custom setup was developed based on the Magnum Creative 2 UNI 3D printer (Irwin, Russia). The cartridge (30 mL volume) was filled with the prepared meat paste, sealed with a plunger, and installed in the print head. The 3D printing process involved extruding the paste from the cartridge via the plunger at a temperature of 25 °C. A virtual 3D model of the product was created using the T-Flex 3D

modeling software (Top Systems JSC, Russia) and represented an octopus with a length of 90 mm and a height of 25 mm. The exported STL file was converted into G-code using Repetier-Host software, which controlled the movement of the 3D printer's print head.

2.3 Experimental design

This study used a central composite rotatable design based on response surface methodology (RSM), consisting of 30 different combinations with 6 center points. The following key factors affecting the 3D printing process were selected: v (X_1) – nozzle movement speed, mm/s; V (X_2) – material flow rate (chicken meat paste), mm³/s; D_n (X_3) – nozzle diameter, mm, indicating the internal diameter of the nozzle outlet, which determines the thickness of the extruded lines; φ (X_4) – infill density, %, a factor characterizing the internal structure of the printed model and influencing its strength and weight. The printing factors were adjusted in the Repetier-Host software. Conical Luer-Lock fittings were used to vary the nozzle diameter. The limits of variation of the studied factors are given in Table 1.

Table 1. Range of different factors studied in the design.

Levels	Factors			
	Nozzle movement speed (mm/s)	Material flow rate (mm ³ /s)	Nozzle diameter (mm)	Infill density (%)
Central (0)	50	55	1.4	40
High (+1)	60	60	1.6	50
Low (-1)	40	50	1.2	30
α (+2)	70	65	1.8	60
α (-2)	30	45	1	20

To assess the influence of different factors on the extrusion-based 3D printing process, the following response criteria were selected: τ (Y_1) – product printing time, s; m (Y_2) – product weight, g; q (Y_3) – quality of printed product, units. Printing time was recorded in Repetier-Host software; printed product weight was measured on a scale. Images of the printed models were captured using a digital single-lens camera for visual assessment. Each product was rated on a scale from 0 to 10 based on visual inspection. Evaluation criteria included smoothness of lines, presence of gaps and irregularities, consistency of infill, and filament diameter stability. A perfect print received a score of 10, while a failed print was rated 0 [16].

2.4 Statistical Analysis

Experimental data was analyzed using Design expert 12 (Statease, USA) using one-way ANOVA to determine the significant differences among the means at 95% confidence level. For statistical analysis, actual factor values were converted into coded values using the following Eq. 1 and 2:

$$X_i = (D - D_0)/l_i; \quad (1)$$

$$D = X_i l_i + D_0, \quad (2)$$

where:

- X_i - coded value of the factor;
- D - actual value of the factor;
- D_0 - central point in actual units; and,
- l_i - variation interval of the factor in actual units.

The analysis of variance (ANOVA) tables were generated to check the adequacy and accuracy of the fitted models. The significance of all the terms, i.e., linear, quadratic, interaction in the mathematical model, was judged statistically. To visualize the relationship between the responses and independent variables, surface response and contour plots of the fitted polynomial regression equations were generated using the same software.

2.5 Optimization of printer parameters

The optimal printing parameters were determined using RSM, which was also employed to evaluate the relationships between variables and to generate data for constructing a predictive linear regression model. The optimum values of processing parameters were evaluated through desirability tool. Desirability approach was used to optimize the process parameters; solution having maximum desirability was selected as optimum conditions. This method [17] allows the values of multiple output optimization variables Y_i to be expressed through a single desirability function d , which ranges from 0 to 1 and is defined by the following Eq.3:

$$d = \left| \frac{Y-L}{U-L} \right|^\alpha, \quad (3)$$

where:

- Y - response function value;
- L, U - lower and upper bounds for the response function; and,
- α - weight reflecting the importance of the variable.

3 Results and Discussion

Printed products with the highest and lowest quality under different printing parameters are shown in Figures 1 and 2, respectively.



Fig. 1. Printed product at $v=50$ mm/s,
 $V=55$ mm³/s, $D_n=1,4$ mm, $\phi=60\%$



Fig. 2. Printed product at $v=60$ mm/s,
 $V=50$ mm³/s, $D_n=1,6$ mm, $\phi=30\%$

3.1 Effect of printer control parameters on the quality of the printed product

The mathematical model developed using multiple regression analysis is presented in the form of an Eq.4:

$$Y_3=8,33-0,33X_1+0,5X_2-0,417X_3+0,917X_4 \quad (4)$$

Quadratic terms for all parameters were excluded from Eq.4 due to their low significance in this process. As seen from the resulting equation, all linear terms have a significant impact on the quality of the printed product. The most influential parameters affecting the quality of the printed product are the material flow rate (X_2) and infill density (X_4). The developed model demonstrated a high coefficient of determination ($R^2 = 0.883$), indicating a good fit with the experimental data. The influence of the parameters on print quality is visualized in the response surface plots (Figures 3 and 4).

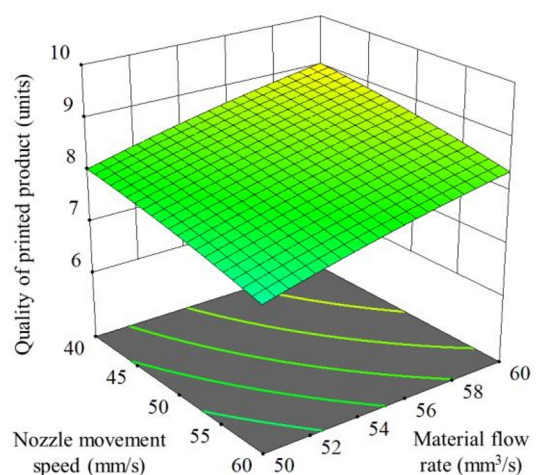


Fig. 3. Dependence quality of printed product on material flow rate and nozzle movement speed at a nozzle diameter of 1.4 mm and infill density of 40%

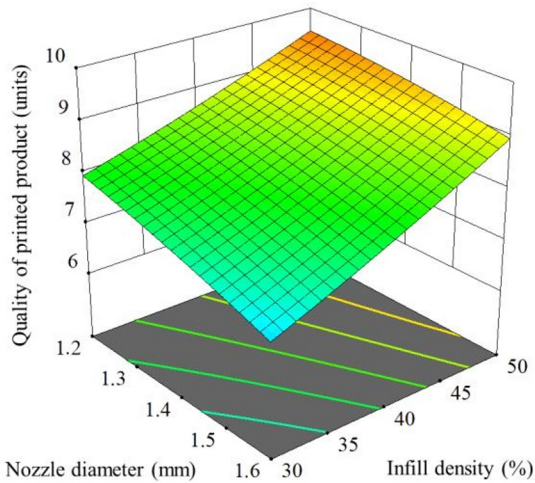


Fig. 4. Dependence quality of printed product on nozzle diameter and infill density at a nozzle movement speed of 50 mm/s and material flow rate of 55 mm³/s

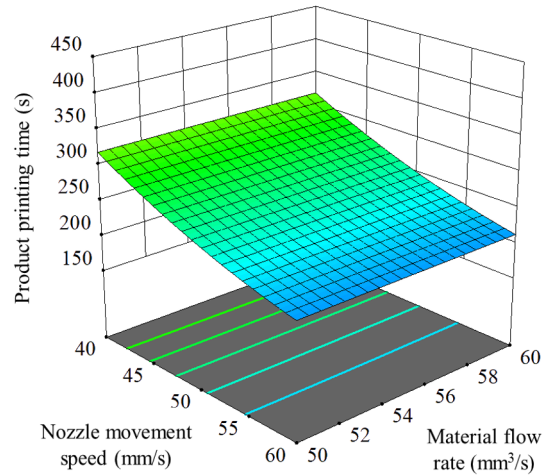


Fig. 5. Dependence of product printing time on material flow rate and nozzle movement speed at a nozzle diameter of 1.4 mm and an infill density of 40%

An increase in nozzle movement speed (X_1) leads to a reduction in print quality. This can be attributed to vibrations of the print head mechanism at high speeds, as well as abrupt changes in its movement direction, which result in smudged surfaces and inconsistent layer thickness. At high speeds, layer separation may also occur due to the extrusion rate lagging behind the movement of the print head. In contrast, an increase in both the material flow rate (X_2) and infill density (X_4) contributes to improved quality of printed product. This is likely due to the sufficient supply of material, which provides structural stability and eliminates hollow zones within the product. An increase in nozzle diameter (X_3) negatively affects the final quality of printed product, causing surface bulging and spreading of the chicken meat paste beyond the intended print path.

3.2 Effect of printer control parameters on product printing time

The mathematical model developed using multiple regression analysis is presented in the form of an Eq.5:

$$Y_1 = 255 - 53,25X_1 - 33,58X_3 + 24,58X_4 + 6,63X_1X_3 - 4,88X_1X_4 - 3,63X_3X_4 + 11,31X_1^2 + 5,56X_3^2, \quad (5)$$

The negative signs preceding the coefficients indicate a decrease in printing time as the corresponding input factors increase. This result is supported by the studies of [16], who reported that nozzle movement speed is inversely related to printing time. The nozzle movement speed was found to have the greatest influence on the printing time as reported by [18]. Linear and quadratic terms involving X_2 (material flow rate) were excluded from the model due to their low statistical significance in this process. The resulting model demonstrated a high coefficient of determination ($R^2 = 0.997$), indicating excellent fit. The influence of the varied parameters on printing time is illustrated in the response surface plots (Figures 5 and 6).

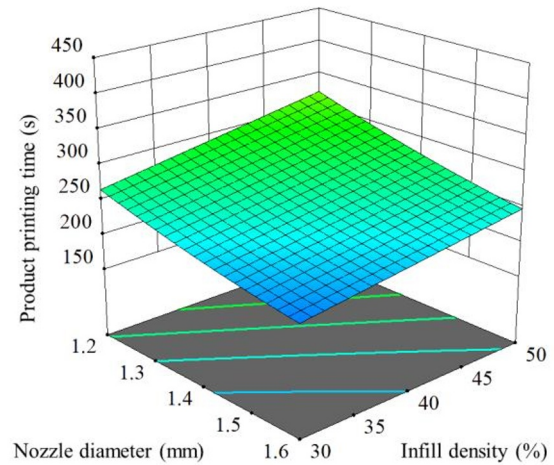


Fig. 6. Dependence of product printing time on nozzle diameter and infill density at a nozzle movement speed of 50 mm/s and a material flow rate of 55 mm³/s

Several conclusions can be drawn from the obtained equation. An increase in nozzle movement speed (X_1) reduces the product printing time, as indicated by the negative coefficient of the linear term in Eq.5. An increase in nozzle diameter (X_3) also decreases product printing time, which can be attributed to the reduced number of layers required to reach the desired product height, since the layer height was set equal to the nozzle diameter. Conversely, increasing the infill density (X_4) prolongs product printing time, due to the greater number of print head movements required within each layer.

3.3 Effect of printer control parameters on product weight

The mathematical model developed using multiple regression analysis is presented in the form of an Eq.6:

$$Y_2 = 21,945 + 2,35X_2 + 2,27X_4 - 0,259X_2X_4 + 0,246X_2^2 \quad (6)$$

From Eq.6 it is evident that the most influential parameters affecting the weight of the printed product are the material flow rate (X_2) and infill density (X_4). The resulting model showed a high coefficient of determination ($R^2 = 0.999$), indicating a strong fit between the model and the experimental data. As the material flow rate (X_2) increases, a greater amount of chicken meat paste is extruded through the nozzle, resulting in a higher product weight. Similarly, increasing the infill density (X_4) leads to a greater number of movements within each layer, which in turn causes more material to be extruded, thereby increasing the weight of the product. The influence of the process parameters on product weight is illustrated in the response surface plots (Figures 7 and 8).

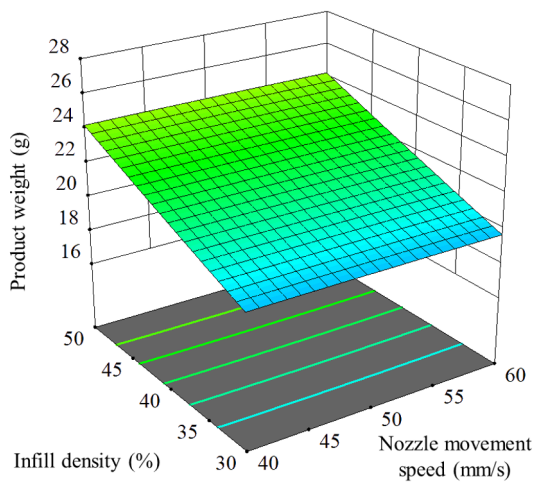


Fig. 7. Dependence of product weight on infill density and nozzle movement speed at a material flow rate of $55 \text{ mm}^3/\text{s}$ and nozzle diameter of 1.4 mm

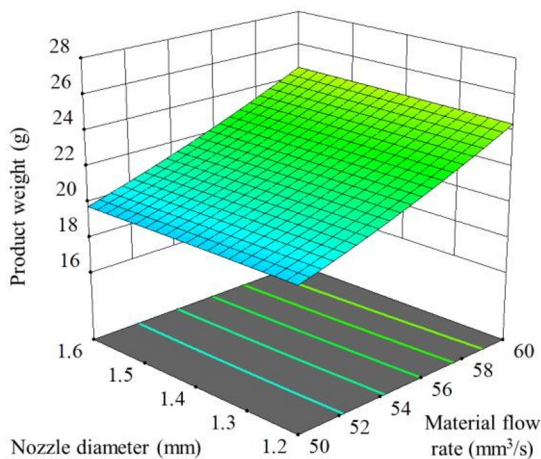


Fig. 8. Dependence of product weight on material flow rate and nozzle diameter at a nozzle movement speed of 50 mm/s and infill density of 40%

Following the development and validation of the regression models, optimization criteria were established to determine the optimal printing parameters for chicken meat paste. The objective of the optimization process was to achieve the highest possible print quality in the shortest possible time, while targeting a product weight close to 24 g , which

corresponds to the theoretical weight of the digital 3D model.

The optimization of the 3D printing process showed that a maximum desirability of 0.89 could be achieved at the following parameters values: $D_n = 1.2 \text{ mm}$, $\varphi = 50\%$, $V = 54.7 \text{ mm}^3/\text{s}$, and $v = 58.7 \text{ mm/s}$. Under these conditions, the product printing time was $\tau = 274.4 \text{ s}$, the product weight was $m = 24 \text{ g}$, and the quality of printed product was $q = 9.29$ units.

4 Conclusions

The influence of 3D printer control parameters – including nozzle movement speed and diameter, material flow rate (chicken meat paste), and infill density – on product printing time, product weight, and quality of printed product was investigated. Nozzle movement speed had the most significant impact on product printing time, while material flow rate showed no measurable effect. As the material flow rate and infill density increased, the weight of the printed product also increased. All studied parameters significantly affected quality of printed product. Specifically, higher material flow rate and infill density improved the quality of the printed products, whereas increases in nozzle movement speed and diameter led to a decline in print quality. Optimal values for the printer control parameters were determined as follows: nozzle movement speed of 58.7 mm/s , material flow rate of $54.7 \text{ mm}^3/\text{s}$, nozzle diameter of 1.2 mm , and infill density of 50% , achieving a desirability score of 0.89 . The results of this study are of practical relevance for tuning the parameters of a 3D printer when printing products from comminuted meat materials.

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