Appropriate Parameters of 3D Food Printing from Gelatin-Based Mixtures

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Abstract

3D Printing (3DP) technology, an additive manufacturing part layer by layer, has been widely used in various industries for prototype fabrication. In this project, the 3DP was utilized to investigate appropriate parameters for food fabrication. The objective was to determine processing factors that affected the quality of 3D printed specimens using the design of experiments (DOE). Gelatin-based food, one of the food mixtures commonly used in 3D food printing, was chosen as a case study. Independent variables consisting of print speed, flow rate, and printing temperature determined their contributions to specimen variation in weight and dimension. The result indicated that all these key factors significantly affect weight accuracy. However, only print speed and temperature affect the dimension accuracy of the printed food specimen. Furthermore, the optimal dimensions and weight accuracy conditions were found at 11.21 mm/s of print speed, 43.65 mm^3/s of flow rate, and printing temperature at 35°C, resulting in 0% error on weight and volume of the 3D printed food product.

Keywords
3D Food Printing, Print Speed, Flow Rate, Printing Temperature, Design of Experiment (DOE).

1. Introduction
3DP technology, known as the additive manufacturing process, has been widely acknowledged and applied in several industries. The process has many benefits, such as less material wastage in production, saving time, accuracy, high efficiency, and accessible design (Chen et al. 2019). Furthermore, the 3DP principles integrate a means of adding layer by layer to manufacture three-dimensional products with customized design, shape, taste, texture, color, and nutrition contents (Sun et al. 2015). Therefore, this technology can be extensively applicable to the food and pharmaceutical industries. In addition, 3DP can be used to create food products by controlling nutrition contents appropriate for each individual or specific consumer group, called personalization, including senior citizens, pregnant women, children, and athletes.

In the 3D food printing process, hydrocolloid is a general mixture that forms a printable food, sometimes referred to as food ink. Hydrocolloids such as gelatin can play a crucial role in food ink properties by thickening, gelling, stabilizing, or emulsifying the food characteristics. However, these various food characteristics can affect 3DP quality; it is necessary to study processing parameters in 3DP that contribute to a better quality of the printed product.

1.1 Objectives
This research aims to study the factors that impact food dimension and weight accuracy after being fabricated by 3DP technology. These factors include print speed, flow rate, and printing temperature. The weight and dimension

accuracy of the 3D printed food is characterized, and optimal process parameters are evaluated based on the experimental design**.**

2. Literature Review

2.1 Food Printing Material and Rheology property

In 3D food printing, many edible and flowable materials can be employed, such as potato starch, gelatin, xanthan gum, sodium alginate, and methylcellulose. However, these materials cannot be processed with the same printing parameter because of their different rheology properties. Many researchers mentioned that the rheology property of food affects 3D food printed products. For example, Ketel, et al. stated that the rheological properties of the solution, including yield stress, viscosity, storage modulus, strain, can lead to the accuracy of the geometric properties of the printed specimen (Ketel et al. 2019). Other researchers also presented that when the food temperature was increased, the product's viscosity increased, leading to the deformation of product shape during 3D food printing (Gomez-Diaz and Navaza 2002).

This research proposed the study of relationship between printing parameters on the quality of gelatin-based food printing. Gelatin is one of the common food materials for 3DP because it has been successfully printed in multiple layers with good dimensional accuracy (Chow et al. 2021). Furthermore, gelatin is mainly composed of protein, which benefits elderly patients in a hospital.

To successfully print gelatin into an accurate dimension of a 3D printed product, some factors such as print speed, nozzle diameter, nozzle high, extrusion rate, and printing temperature impact the quality of the product. For example, the study of 3DP of surimi gels by Wang et al., 2018 shows that the print speed affects the shape of the 3D printed product. Moreover, the study of Yang et al., 2018 recommended that the nozzle height and nozzle diameter should be the same to produce good quality of the 3D food printed product. This result is consistent with the study by Dick et al., 2019, studying the 3D printed of meat such as pork, chicken, fish, and beef using fused deposition modeling. In addition, the study shows that the nozzle high and nozzle movement speed affected the dimension of the workpiece as the expansion of the workpiece in the X-axis and Y-axis.

2.2 Statistical analysis

In part of statistical analysis, the 95% ($P < 0.05$) confidence interval is enough for analyzing the experiment data (Shi, Zhang, and Bhandari, 2021). Furthermore, this research used Minitab18 to design and analyze the data based on the 2^k factorial design with a center point at the 95% confidence interval to optimize the fabrication parameter.

3. Methods

3.1 Material preparation

From our preliminary study, a prototype diet has been developed aimed at the end-user of the hospital in the elderly population. Furthermore, food characteristics such as texture, taste, and smell were the sensory responses to determine proper composition. As a result, the ingredient of chosen material for this 3DP mixture is 10.00 g of gelatin (% w/w), and 20.25 g of syrups (% w/w), 25.00 g of soy protein (% w/w), and 75.00 g of coconut milk (%w/w).

3.2 3D Printer and accessory

Fused Deposition Modeling (FDM) printer was modified and employed in this study. The nozzle diameter and nozzle height were set at 1.50 mm, and 50-ml syringe was used to feed the gelatin-based food for the experiment. In addition, Simplify3D is the program used for model slicing and code generation.

3.3 Experimental design

The experimental design based on a 2^k factorial design with a center point was chosen to study the effect of processing parameters on the quality of the printed product. The scope of the experimental setup is shown in Table 1.

Table 1. Design of Experiments

Factors	Units	Level			Symbol
		High(+)	Center Poin	Low(-)	
Print Speed	mm/s	15.7	13	10.3	A
Flow rate	mm^3/s	57	48	39	B
Printing Temperature	°C	55	45	35	C

3.4 Accuracy analysis

VMM – 3020, a Video Measuring Machine, was implemented to evaluate the geometry accuracy of the printed specimen from the study. VMM – 3020 can display the image as a realistic or virtual level with micron-scale resolution. Thus, the device measured product dimension in both X and Y axis and the height. In the meantime, the weight evaluation was performed on the weight scale with a one-digit resolution (Figure 1 and figure 2).

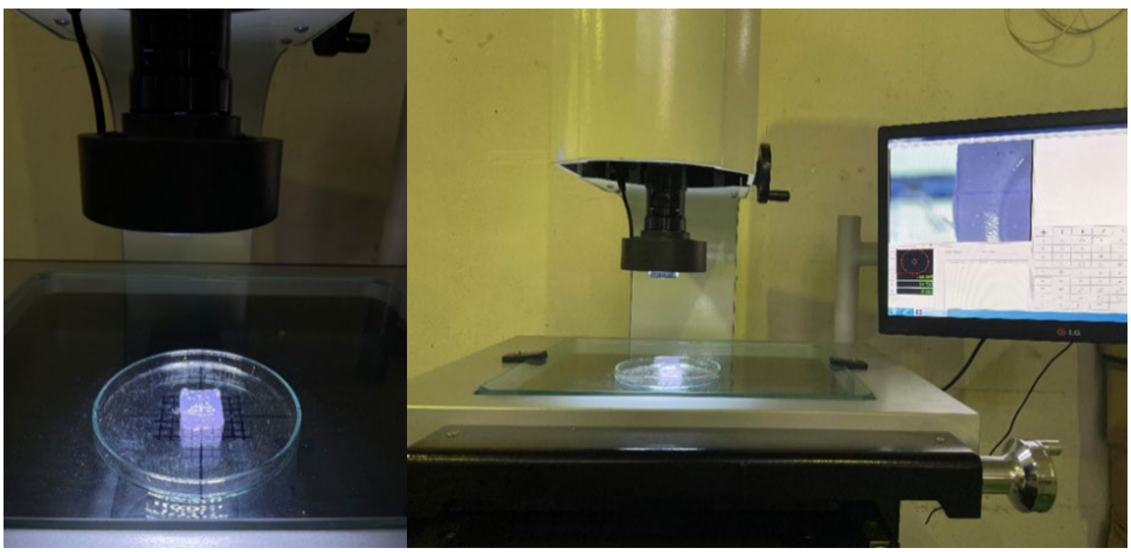


Figure 1. Evaluation of dimension by using VMM – 3020 Video Measuring Machine

Figure 2. Evaluation of dimension by using a one-digit weight scale

4. Results and Discussion

Table 2 presents the results from a total of 33 experimental runs. The geometry accuracy and weight consistency results are illustrated as an Error of weight and Volume (percentage). The Error of weight was calculated from the actual weight of the product minus the theoretical weight from the design. In the meantime, the Error of Volume was calculated from the different between the measured product Volume and the theoretical value from the 3D modeling program.

Table 2. Error of weight and Volume from the experimental results

Print speed (mm/s)	Flow rate (mm^3/s)	Printing Temperature (C)	Error of Volume (%)			Error of weight (%)		
			Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
40	39	35	-1.31	-15.59	-8.98	-7.98	-7.98	-7.98
80	39	35	-0.22	0.30	0.83	-5.08	-2.18	3.63
40	57	35	30.90	27.55	36.58	26.85	29.75	32.66
80	57	35	-1.60	-2.07	1.75	-5.08	0.73	6.53
40	39	55	-1.94	1.60	4.61	-2.18	0.73	6.53
80	39	55	-4.84	-11.01	-3.52	-7.98	-7.98	-5.08
40	57	55	14.77	31.80	41.58	26.85	32.66	35.56
80	57	55	26.28	29.91	37.26	26.85	32.66	32.66
60	48	45	3.01	5.23	4.52	-2.18	3.63	6.53
60	48	45	0.90	0.20	4.58	6.53	3.63	9.43
60	48	45	5.40	1.27	3.63	-2.18	3.63	3.63
SD			15.33			14.94		

Table 3 shows the statistical significance level of 0.05 from ANAVA. As can be seen, the print speed flow rate and temperature have a significant effect on the weight accuracy. Then, a regression analysis equation can be stated to show the relationship between the Error of weight as a function of printing speed, flow rate, and printing temperature as Equation 1.

The Error of Weight *= -665 + 51.21 A + 14.72 B + 11.80 C - 1.152 A*B - 1.017 A*C - 0.2522 B*C + 0.02240 A*B*C* (1)

Table 3. Analysis of weight variance

Term	F-Value	P-Value
Print speed (A)	16.00	0.000
Flow rate (B)	181.05	0.000
Printing Temperature (C)	20.12	0.000
A*B	12.36	0.002
A*C	2.48	0.128
B*C	12.36	0.002
A*B*C	29.76	0.000

Table 4 presents the volume analysis, showing that the print speed, flow rate, and temperature significantly affect dimensional accuracy. This is similar to the previous study of Ansari and Kamil, 2021, which showed that print speed and extrusion temperature affected the dimensional quality. In addition, a regression analysis equation as shown in Equation 2 can be stated to establish the relationship between the Error of volume and print speed, flow rate, and temperature.

Table 4. Analysis of volume variance

Term	F-Value	P-Value
Print speed (A)	8.57	0.007
Flow rate (B)	108.45	0.000
Printing Temperature (C)	10.59	0.003
A*B	9.83	0.004
A*C	2.94	0.099
B*C	6.76	0.015
A*B*C	25.52	0.000

The Error of Volume *= -774 + 59.4 A + 17.25 B + 13.96 C - 1.341 A*B - 1.177 A*C - 0.3040 B*C + 0.02618 A*B*C* (2)

Table 5 shows the contour plots of the Error in Volume and weight of the fabricated specimen. As can be seen from the graphs, all factors impact the accuracy of the printed product. The higher the flow rate, the larger Error of both weight and volume. In the meantime, printing temperature has a correlation with the print speed. Therefore, when printing temperature is high, the print speed should be increased. On the other hand, if the printing temperature was low, the print speed should be increased to cooperate into the proper dimension and weight of the printed specimen. These results comply with Gomez-Diaz and Navaza (2002) that the printing parameter causes the change in product's viscosity. Providing too much temperature to the printing material may cause the collapse of the product structure, leading to more Error on weight and dimension. In addition, the main effect plot of all printing parameters on both Error responses is illustrated in Table 6.

Table 5. Contour plots of printing parameters on the quality of 3D printed specimens

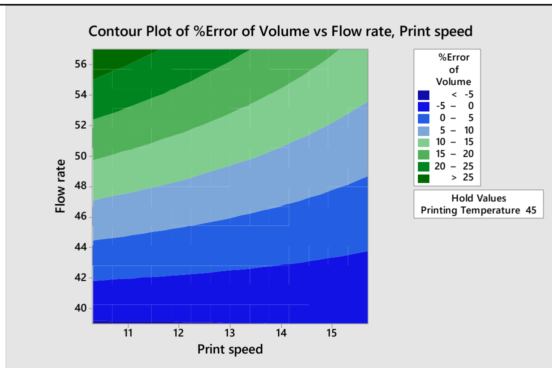
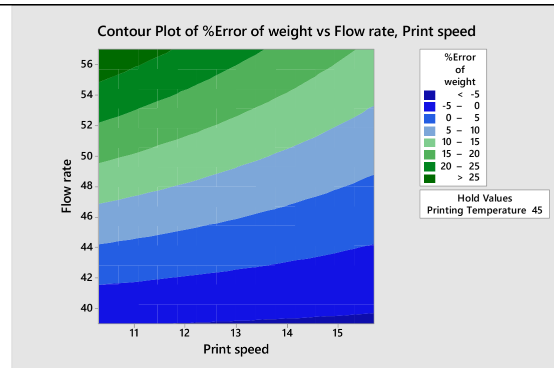
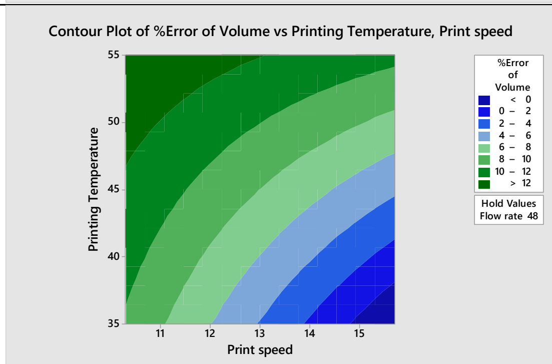
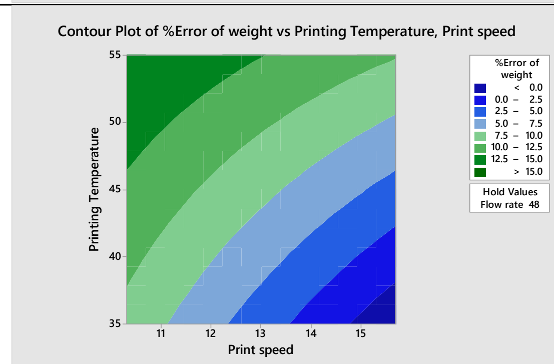
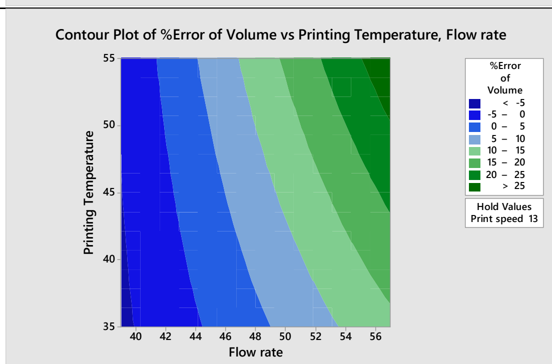
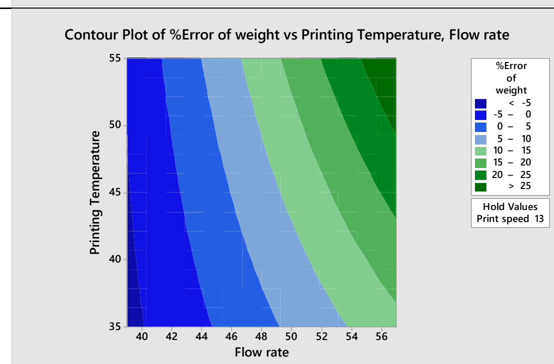
Term	Contour plot of Error of Volume	Contour plot of Error of weight
Print speed (A) and Flow rate (B)		
Print speed (A) and Printing temperature (C)		
Flow rate (B) and Printing Temperature (C)		

Table 6. Comparison of main effect plot between interactive factors.

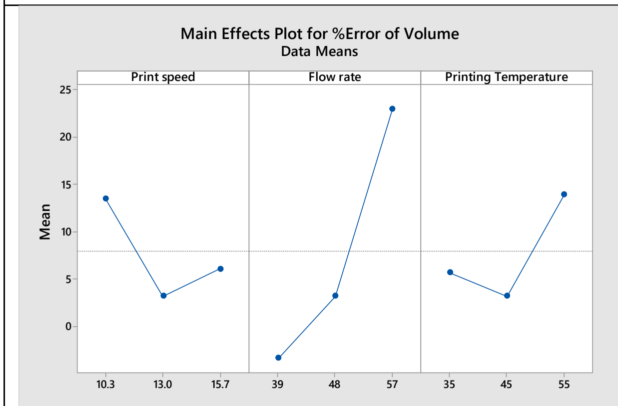
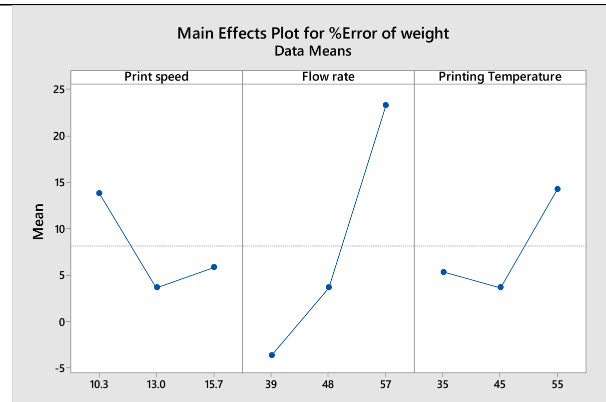
%Error of volume	%Error of weight
	

Figure 3 presents the response optimizer plot from the Minitab program. The result shows that an accurate 3D printed product can be obtained when setting the printing speed at 11.22 mm/s, the flow rate at 43.65 mm^3/s, and the printing temperature at 35 °C. Finally, fabricated the product with the optimum value shown in Figure 4.

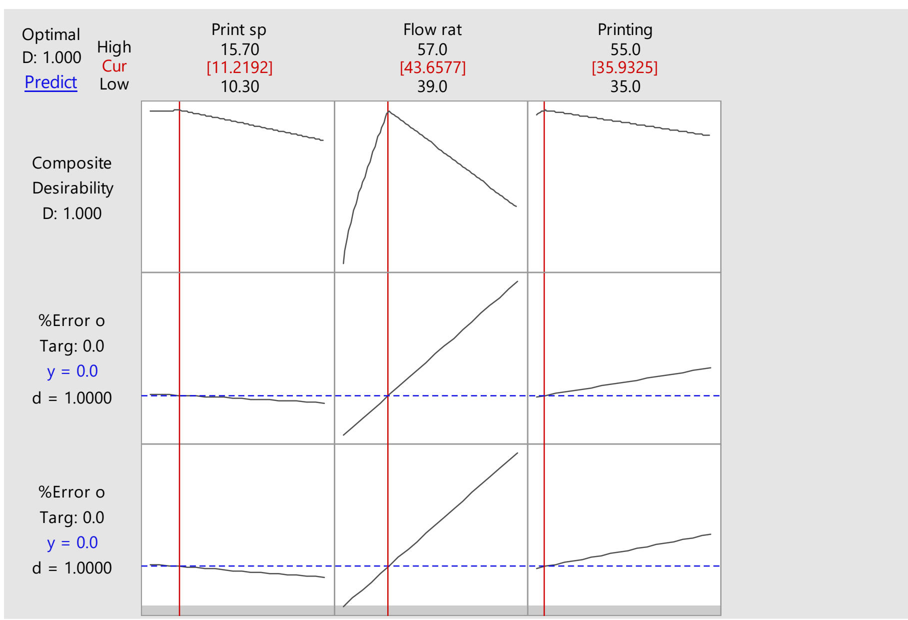


Figure 3. Optimization Plot of Gelatin-Based using Response optimizer function

Figure 4. The product is fabricated with recommended printing conditions.

5. Conclusion

From this study, 3DP technology can be successfully employed for food processing. The gelatin-based material was used as a printed food, containing 10.00 grams of gelatin, 25.00 g of water, 20.25 g of sweetener, 20.00 g of soy protein, 0.50 g of sodium alginate, and 75.00 g of coconut milk. With this material, the optimal printing speed was found at 11.22 mm/s, flow rate equals 43.66 mm^3/s, and printing temperature equals 35.93 °C where the food product had a standard deviation in weight and volume was 14.94 and 15.33, respectively. These fabrication parameters indicated the weight and volume errors equal to 0%. However, considering each dimension along the X Y and Z axis showed that the printed product has a lower value on height (Z-axis), while the size on the X Y plane is larger. The collapse of material could be the reason of this inaccuracy in product geometry. Further investigation to verify proper printing conditions and the rheology property of food prining materials were pursued to develop a 3D food printing system with accurate dimensions and volume.

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References

Ansari, A. A., and Kamil, M. Effect of print speed and extrusion temperature on properties of 3D printed PLA using fused deposition modeling process. Materials Today: Proceedings, 45, 5462-5468, 2021.

Chow, C. Y., Thybo, C. D., Sager, V. F., Riantiningtyas, R. R., Bredie, W. L. P., and Ahrné, L). Printability, stability and sensory properties of protein-enriched 3D-printed lemon mousse for personalised in-between meals. Food Hydrocolloids, 120, 2021.

Chen, J., Mu, T., Goffin, D., Blecker, C., Richard, G., Richel, A., and Haubruge, E,. Application of soy protein isolate and hydrocolloids based mixtures as promising food material in 3D food printing. *Journal of Food Engineering,* 261, 76-86, 2019.

Dick, A., Bhandari, B., and Prakash, S., 3D printing of meat. Meat Science, vol. 153, pp. 35-44, 2019.

Gomez-Diaz, G. and Navaza, J. (2002). Rheology of aqueous solutions of food additives Effect of concentration, temperature and blending. *Journal of Food Engineering,* vol. 56, pp. 387-392. ,2002.

Ketel, S., Falzone, G., Wang, B., Washburn, N., and Sant, G. (2019). A printability index for linking slurry rheology to the geometrical attributes of 3D-printed components. *Cement and Concrete Composites, vol.*101, pp. 32-2018.

Shi, Y., Zhang, M., and Bhandari, B., Effect of addition of beeswax based oleogel on 3D printing of potato starch-protein system. Food Structure, pp. 27, 2021.

Sun, J., Zhou, W., Huang, D., Fuh, J. Y. H., and Hong, G. S., An Overview of 3D Printing Technologies for Food Fabrication. *Food and Bioprocess Technology, vol.* 8, no. 8, pp. 1605-1615, 2015.

Wang, L., Zhang, M., Bhandari, B., and Yang, C. (2018). Investigation on fish surimi gel as promising food material for 3D printing. *Journal of Food Engineering,* 220, 101-108, 2018.

Yang, F., Zhang, M., Bhandari, B., and Liu, Y.,Investigation on lemon juice gel as food material for 3D printing and optimization of printing parameters. *LWT, vol.* 87, pp. 67-76, 2018.

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