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ASSESSING THE ROLE OF COMPUTATIONAL FLUID DYNAMICS IN PREDICTING 3D PRINTABILITY OF MEATBALL FORMULATIONS

Elvan Gökçen Topbaş [1], Kezban Candoğan [1*]

[1] Ankara University, Faculty of Engineering, Department of Food Engineering, Ankara, Türkiye.

*Corresponding author email: candogan@eng.ankara.edu.tr

I. INTRODUCTION

Emerging technologies are opening up new avenues for process optimization and product innovation as the food industry continues to grow rapidly. Among the most remarkable developments in recent years, 3D food printing holds significant potential for the meat industry. This technology allows the creation of complex designs by precisely controlling the texture and structure of food products to meet increasing demand for personalized foods [1]. However, the integration of 3D printing technology into the meat sector faces significant technical challenges, primarily due to the heterogeneous structure and variable flow characteristics of meat-based products. To overcome these challenges, hydrocolloids are incorporated into the formulations to enhance mechanical properties and network structure, thereby improving printing performance [2]. Computational Fluid Dynamics (CFD) has been applied in various areas of the food industry, such as bread baking, beef roast cooling, 3D printing, and spray drying, to scale up, optimize, and design processes [3]. The primary objective of this study was to evaluate the potential of CFD analysis as a practical and cost-effective method for predicting the feasibility of 3D printing meatball formulations by incorporating varying concentrations of gelatin to enhance 3D printing performance. This was achieved through the characterization of rheological properties and the analysis of flow behavior, ultimately providing valuable insights to the meat industry and eliminating the need for time-consuming physical trials.

II. MATERIALS AND METHODS

Eleven meatball formulations with varying concentrations of gelatin were prepared with the ingredient levels demonstrated in Figure 1. Following refrigeration at 4°C for 10 minutes, each formulation was placed in the syringe and 3D printed for validation.

No.	Minced beef	Salt	Black pepper	Cumin	Onion powder	Olive oil	Bovine gelatin	Water
1	70	0.8	0.3	0.3	3.6	5	0	20
2	70	0.8	0.3	0.3	3.6	5	0.5	19.5
3	70	0.8	0.3	0.3	3.6	5	1	19
4	70	0.8	0.3	0.3	3.6	5	1.5	18.5
5	70	0.8	0.3	0.3	3.6	5	2	18
6	70	0.8	0.3	0.3	3.6	5	2.5	17.5
7	70	0.8	0.3	0.3	3.6	5	3	17
8	70	0.8	0.3	0.3	3.6	5	3.5	16.5
9	70	0.8	0.3	0.3	3.6	5	4	16
10	70	0.8	0.3	0.3	3.6	5	4.5	15.5
11	70	0.8	0.3	0.3	3.6	5	5	15

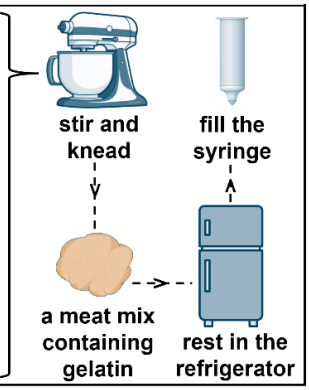


Figure 1. Preparation of formulations

Dynamic and static rheological properties of the formulations were analyzed using a Kinexus Lab+ Rheometer (Malvern, UK). A 20 mm parallel plate geometry with a 1 mm gap was used for all measurements. Oscillatory tests at 25°C (0.15% strain, 0.1–100 Hz) recorded storage (G') and loss modulus (G"). Static rheological tests (0.01–100 s^{-1}) were used to determine apparent viscosity against shear rate. The Carreau's model [4] was applied to fit the experimental data, as described by the following equation (1):

$$\eta(\dot{\gamma}) = \eta_\infty + (\eta_0 - \eta_\infty)[1 + (\lambda\dot{\gamma})^2]^{(n-1)/2} \quad (1)$$

where $\eta(\dot{\gamma})$ is the apparent viscosity (Pa·s), η_∞ is the viscosity at infinite shear rate (Pa·s), η_0 is the viscosity at zero shear rate (Pa·s), λ is the relaxation time (s), $\dot{\gamma}$ is the shear rate (s^{-1}), and n is the rheological index [4]. The CAD model of the syringe was created and after meshing the syringe CAD model, the extrusion process was simulated using the Finite Volume Method (FVM) in the ANSYS Fluent 2024 (ANSYS, USA). The Navier-Stokes equations were solved using a pressure-based model with absolute velocity formulation and steady time setting. Laminar flow

was assumed, with a printing speed of 0.02 m/s as the inlet velocity and zero gauge pressure at the outlet. Energy equations were neglected, and 100 iterations were performed. For validation, 3D printing was performed using a 3D Food Printer (ArtıBoyut G2, Türkiye) with a 1.8 mm nozzle. The printing parameters were set as follows: printing speed of 20 mm/s, shell thickness of 1.2 mm, printing height of 1 mm, layer height of 1.4 mm, and flow rate of 100%. The maximum pressure exerted by the piston, referred to as the “critical pressure”, was calculated based on the 36 kg load capacity of the printer's stepper motor. These experimental results were compared with the simulation outputs to evaluate the printability of the formulations under realistic operating conditions.

III. RESULTS AND DISCUSSION

For all formulations, the storage modulus (G') was consistently higher than the loss modulus (G"), indicating that the formulations exhibit solid-like behavior. Moreover, a decrease in viscosity was observed with increasing shear rate, confirming the pseudoplastic (shear-thinning) nature of the formulations. This rheological behavior is particularly advantageous for 3D printing as it facilitates smooth extrusion through the nozzle while maintaining structural integrity post-deposition. The critical pressure value was calculated as 187.93 kPa. Among the eleven formulations, the first eight were successfully printed while the remaining three formulations failed due to insufficient extrusion pressure. A gelatin content of 3.5% was found to be optimal for maintaining shape retention and facilitating extrusion after 3D printing. To assess the accuracy of the simulation, 3D printing experiments were conducted for all formulations. The strong agreement between the validation experiments and CFD simulations confirms the reliability of CFD as a predictive tool for assessing 3D printability of meat-based formulations (Figure 2).

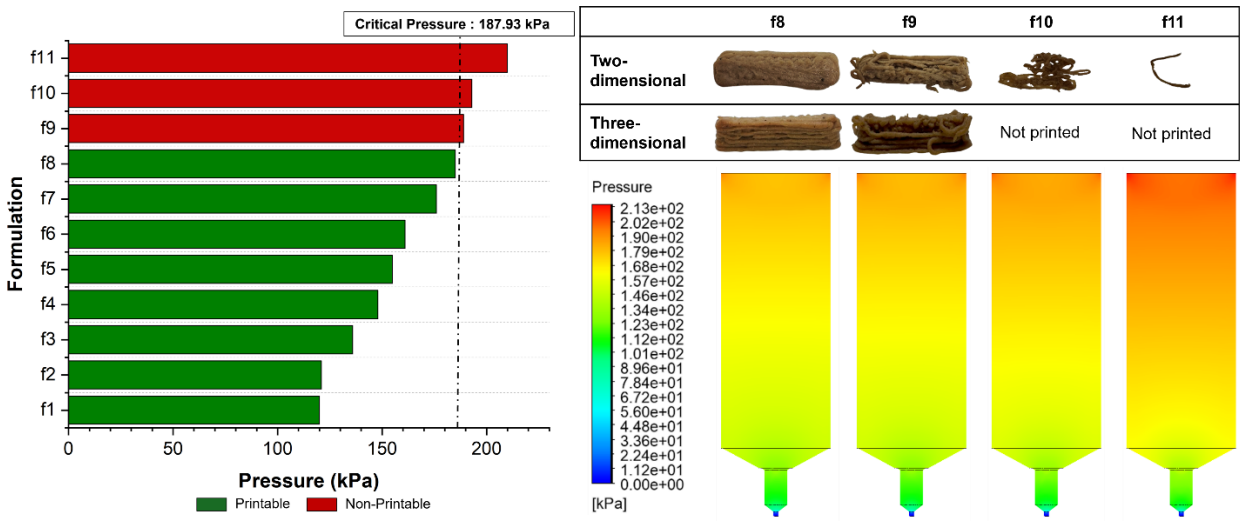


Figure 2. Comparison of 3D Printability and Simulation Results

IV. CONCLUSION

This study demonstrates the effective application of CFD in predicting the printability and 3D extrusion performance of meatball formulations. CFD simulations accurately predicted the critical pressure of 187.93 kPa—within the load capacity of the printer's stepper motor—and successfully identified the formulations suitable for 3D printing. A gelatin concentration of 3.5% was found to be optimal, significantly enhancing both shape retention and extrudability. The findings obtained from this study highlight the potential of CFD as an efficient and cost-effective approach, particularly for the 3D printing of meat-based products, by reducing the reliance on time-consuming and costly physical trials, especially relevant given the high production costs in the meat industry.

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