Development and Rheological Optimization of 3D-Printed Fish Protein Gel Structures

Abstract

Three-dimensional (3D) food printing has emerged as a transformative innovation in food engineering, enabling the fabrication of customized, nutrient-dense foods with controlled geometry and texture. Fish protein, recognized for its high biological value and essential amino acid composition, remains underutilized in structured food applications due to challenges in texture stability and consumer acceptance. This study explores the development and rheological optimization of fish protein gel formulations suitable for extrusion-based 3D printing. Rheological properties, including viscosity, shear-thinning behavior, storage modulus (G′), and loss modulus (G″), were evaluated to determine printability and structural integrity. Process parameters such as extrusion speed, nozzle diameter, and printing temperature were optimized to enhance dimensional accuracy and mechanical strength. The findings demonstrate that controlled rheological modification significantly improves print fidelity and structural stability. The study highlights the potential of integrating marine protein utilization with digital food fabrication to promote sustainable protein innovation and value-added seafood products.

1. Introduction

The global demand for sustainable and high-quality protein sources has intensified interest in marine-derived proteins. Fish protein is nutritionally superior due to its balanced amino acid profile, high digestibility, and presence of bioactive compounds (FAO, 2022). However, traditional fish products often face limitations in shelf life, texture variability, and limited diversification.

Three-dimensional food printing represents a novel approach that combines food engineering, material science, and digital fabrication to create customized food structures (Sun et al., 2015). Extrusion-based 3D printing is particularly suitable for protein-rich gels, as it enables layer-by-layer deposition of viscoelastic materials (Godoi et al., 2016). Successful printing depends heavily on rheological properties, especially shear-thinning behavior and gel strength (Liu et al., 2018).

2. Materials and Methods

2.1 Fish Protein Gel Preparation

Fish protein was extracted using standardized washing and homogenization techniques to obtain a concentrated protein matrix. Hydrocolloids were incorporated to enhance gel stability and viscosity suitable for extrusion.

2.2 Rheological Characterization

Rheological measurements were conducted using a rotational rheometer to determine apparent viscosity, shear-thinning index, storage modulus (G′), and loss modulus (G″). Shear-thinning behavior is essential for smooth extrusion while maintaining post-print structural integrity (Liu et al., 2018).

2.3 3D Printing Optimization

Extrusion-based 3D printing was performed by varying nozzle diameter, extrusion rate, printing temperature, and layer height. Print fidelity and dimensional stability were evaluated through structural analysis and compression testing.

3. Results and Discussion

The optimized fish protein gel exhibited non-Newtonian shear-thinning behavior, facilitating smooth extrusion. A higher storage modulus (G′ > G″) indicated dominant elastic properties, essential for structural retention after printing (Sun et al., 2015).

Optimization of extrusion speed and nozzle diameter significantly influenced layer adhesion and geometric precision. These findings align with previous studies emphasizing the critical role of rheology in 3D food printing performance (Godoi et al., 2016).

4. Conclusion

The study demonstrates that rheological optimization is fundamental in developing stable, printable fish protein gels. Extrusion-based 3D printing provides a promising platform for transforming marine proteins into innovative, consumer-oriented food products, supporting sustainable protein utilization and advanced food engineering applications.

References

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