

# Thermal Optimization of a Dual-Heater Snakehead Fish (*Channa Striata*) Extraction Chamber through CFD and Experimental Validation

Izhary Siregar<sup>a,1,\*</sup>, Ahmad Jibril<sup>a,2</sup>, Setyawan Dwi Nugroho<sup>a,3</sup>, Agus Purwanto<sup>a,4</sup>

<sup>a</sup> Polytechnic of Marine and Fisheries Sidoarjo

<sup>1</sup> arie060pasendeng@gmail.com\*; <sup>2</sup> ahmad.mekanisasi20@gmail.com; <sup>3</sup> setya12n@gmail.com; <sup>4</sup> guspur83@gmail.com

\* corresponding author

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## ABSTRACT

This study investigates the thermal optimization of a rotary extraction chamber for snakehead fish (*Channa striata*) utilizing a dual-heater configuration. A synergistic two-stage methodology was employed, integrating Computational Fluid Dynamics (CFD) for numerical characterization of convective heat distribution with experimental validation using a physical prototype. CFD simulations revealed a convection-dominated thermal field with a minimal thermal gradient of 8.3°C (63.52°C wall and 55.22°C center), ensuring a stable exposure temperature of approximately 60°C. Experimental trials across a range of 40–110°C and 60–180 minutes identified an optimal operating window of 80–90°C for 120 minutes, yielding a peak extraction volume of 46.4 mL. Quantitative trends indicated that while thermal energy facilitates albumin liberation, temperatures exceeding 100°C trigger a progressive decline in yield due to fluid evaporation and thermal degradation. The integration of dual-source heating and mechanical rotation, as validated by the close agreement between numerical and experimental data, establishes a scalable and predictable framework for high-efficiency protein extraction in fisheries mechanization.

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## I. Introduction

In the fields of nutraceuticals and modern pharmacology, *Channa striata* has emerged as a significant biological resource, primarily valued for its dense profile of essential amino acids and albumin. These bioactive components function as critical immunomodulatory agents and are pivotal in accelerating the physiological processes of tissue repair [1], [2], [5]. The recovery of albumin and other bioactive constituents from *Channa striata* remains an intricate procedure, primarily governed by the synergistic effects of the extraction technique and the surrounding thermal conditions [3]. A primary constraint in the processing of *Channa striata* essence is the delicate stability of albumin; imprecise heat management during the extraction cycle often leads to irreversible structural breakdown. Such denaturation adversely impacts both the molecular integrity and the functional bioactivity of the protein fractions [4], [9]. Consequently, achieving a precise and uniform thermal distribution within the extraction chamber is of paramount importance to ensure high-quality yields.

System performance in thermal extraction processes is primarily governed by the optimization of fluid flow patterns and their subsequent impact on thermal exchange efficiency [7], [10]. Modern engineering relies heavily on Computational Fluid Dynamics (CFD) to predict these complex interactions, allowing for the visualization of temperature gradients and velocity fields within varied geometries, such as dimpled tubes or shell-and-tube configurations [6], [11]. The implementation of a dual-heater configuration, such as the 200-Watt units utilized in this study, introduces sophisticated conduction and convection dynamics that must be rigorously modeled [8]. Moreover, prioritizing the mitigation of localized thermal concentrations—which may otherwise jeopardize the bioactive stability of the fish essence—requires a rigorous examination of internal flow dynamics and heat transfer enhancement within turbulent regimes [12], [13]. When the extraction process involves



phase transitions or localized boiling, the numerical framework must incorporate latent heat flux and boiling phenomena. Accounting for these energy shifts is imperative to maintain the predictive fidelity and thermodynamic accuracy of the simulation [14].

The physical realization of such systems requires a meticulous selection of materials and adherence to manufacturing standards. The selection of SS304 as the contact material is predicated on its balanced thermal conductivity and its inherent ability to withstand the chemically aggressive environments typical of high-temperature food processing [17], [18], [20]. The alignment of numerical simulations with physical manufacturing was achieved through the implementation of DFMA principles and topology optimization. This integration is pivotal for enhancing the mechanical integrity of the extraction chamber while maximizing its thermal-mechanical efficiency [15], [20], [21]. Additionally, ensuring the microbial integrity of the extraction cycle necessitates a robust risk assessment framework and the integration of antimicrobial surface treatments. These measures are pivotal for circumventing cross-contamination and adhering to stringent food safety standards for nutraceutical production [16], [21].

A significant gap exists between the recognized therapeutic value of *Channa striata* and the outdated empirical methods used for its extraction. Conventional steaming often fails to achieve uniform temperature distribution, leading to inconsistent product quality. This lack of precise thermal-mechanical synchronization frequently causes localized thermal stress, potentially compromising the integrity of delicate protein molecules. The absence of CFD-optimized rotary systems for albumin extraction leaves a critical gap in hardware standardization. This study investigates the interplay between simulated heat distribution and empirical recovery to refine extraction efficiency. By applying a Design Thinking approach to this technical innovation [19], this study provides a robust framework for optimizing fish protein extraction systems, ensuring that thermal stability is maintained to preserve the pharmacological value of the snakehead fish extract.

## II. Method

This study adopts a dual-track approach by correlating high-fidelity Computational Fluid Dynamics (CFD) modeling with empirical data obtained from a functional physical prototype. The design and evaluation of the device focus on characterizing the thermal distribution within the extraction chamber and its correlation with the resulting fish extract yield. Furthermore, the effects of steaming duration and operating temperatures are analyzed as critical parameters influencing the system's performance.

### a. Simulation Method

#### - Pre processing

Pre-processing is the phase where the physical project is defined mathematically. The computational domain is discretized into finite elements known as a grid or mesh. This stage also involves defining the fluid properties, boundary conditions, governing equations, and discretization schemes. High-quality meshing, characterized by optimal Orthogonal Quality (OQ) and acceptable skewness levels, is essential; poor mesh quality may lead to numerical instability or failure to reach convergence. This phase encompasses the following steps:

- Defining the simulation objectives and variables specific to the heating chamber.
- Generating or importing the geometry of the extraction vessel for simulation.
- Executing structured meshing, where quality is verified through skewness and orthogonality metrics.
- Selecting physical models, including turbulence, two heat sources, and compressibility.
- Establishing initial and boundary conditions, as well as solver parameters (Figure 1).

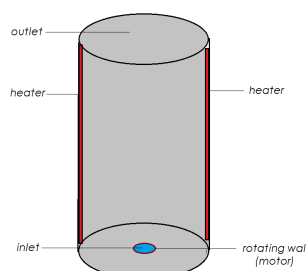


Fig 1. Boundary Condition

The details of the thermal constraints, material properties, and mechanical parameters used to facilitate the conjugate heat transfer (CHT) analysis are summarized in Table 1.

Table 1. Boundary condition

Boundary/ Domain	Boundary Type	Thermal / Mechanical Condition	Parameter Value / Specification
<b>Heater Surfaces (x2)</b>	Wall	Constant Heat Flux ( $q''$ )	$q''=AP$ (calculated based on $P=200W$ per heater)
<b>Internal Fluid (Chamber)</b>	Fluid	Energy & Momentum	Phase: Water/Steam; Governing Eq: Navier- Stokes & Energy
<b>Chamber Walls (SS304)</b>	Wall	Conjugate Heat Transfer	Material: Stainless Steel 304; Coupled interface
<b>External Wall Surfaces</b>	Wall	Mixed (Convection + Radiation)	$h_{ext}=5-15W/m^2K$ ; $\epsilon=0.8$ (oxidized SS)
<b>Fish Sample Holders</b>	Moving Wall	Rotational Motion	Moving Reference Frame (MRF); Angular velocity $\omega$ (rad/s)
<b>Ambient Environment</b>	Far-field	Fixed Temperature	$T_{\infty} = 298.15K$ (Room Temperature)
<b>Top Vent/Opening</b>	Pressure Outlet	Static Pressure	$P_{gauge}=0 Pa$ (Atmospheric)

The numerical simulation parameters, incorporating fluid flow and heat transfer laws through algebraic discretization, are summarized in Table 1.

Table 2. Simulation parameters setting

Parameter	Value
<b>Turbulence Model</b>	$k-\epsilon$ Turbulence Model
<b>Governour Equations</b>	Navier–Stokes Equations
<b>Convective</b>	Second-Order Upwind Scheme
<b>Discretization</b>	Second-Order Central Difference Scheme
<b>Multiple Reference Frame (MRF)</b>	Simulate the rotational effect of the chamber
<b>Time Step</b>	0.04 second

Following the setup, the CFD execution is performed, which involves:

- Running the numerical computation.
- Monitoring convergence through residuals during the iteration process.
- Adjusting parameters if the simulation exhibits instability or fails to converge.

- Post-processing

In this stage, data is extracted for subsequent analysis. For this study, the post-processing phase focuses on the fluid flow and thermal characteristics within the extraction chamber, including temperature distribution profiles, heat flux, and velocity vectors (adapted to the extraction context). The output provides dynamic representations and animations, offering a comprehensive visualization of the simulated thermal-fluid phenomena.

- Grid Independency Test

The objective of this stage is to ensure that the simulation results are independent of the mesh resolution. Five different mesh densities with an increasing number of cells are generated and evaluated. The resulting thermal distribution values are plotted; the mesh configuration that yields the most stable fluid velocity and temperature profiles is selected for further analysis. This study aims for a verification error of less than 5% to ensure the reliability of the numerical results.

### b. Prototype Fabrication and Instrumentation

Based on the optimized design from the numerical stage, a physical prototype is constructed. The extraction chamber is fabricated from food-grade stainless steel 304 to ensure thermal conductivity and corrosion resistance. Two external electric heaters are strategically mounted on the vessel walls, as specified in the simulation. To monitor temperature distribution, K-type thermocouples are installed at multiple spatial coordinates (radial and axial positions) within the chamber. These sensors are connected to a high-speed data acquisition (DAQ) system for real-time thermal logging.

The tubular *Channa striata* extraction system consists of two primary sections: the control unit and the steaming chamber, as illustrated in Figure 2. The control unit houses the electrical motor components, the thermal regulation system, and the power switches. The steaming chamber, featuring a diameter of 40 cm and a height of 100 cm, is fabricated from AISI 304 stainless steel. This chamber is equipped with fish suspension racks, a steaming water reservoir, and an extract collection vessel. Dual heating elements are positioned laterally within the chamber to facilitate heat transfer to both the internal environment and the steaming water.

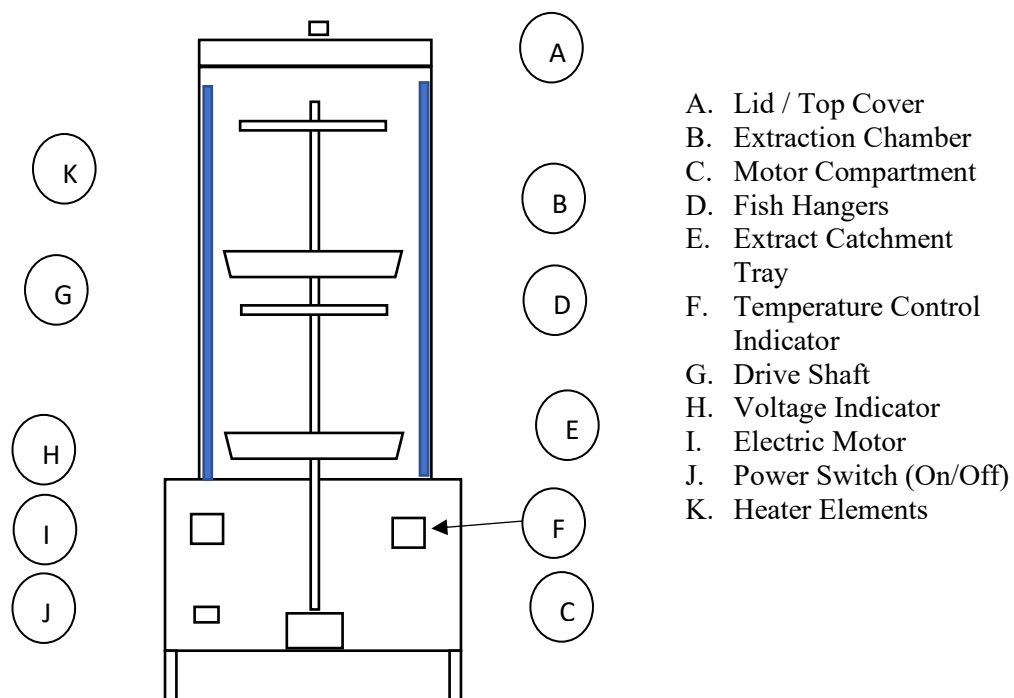


Fig 2. Prototype design of tubular *Channa striata* extraction system

The experimental stage validates the accuracy of the numerical model and evaluates the system's performance. The chamber is filled with the extraction medium. The heaters are activated to reach specific target temperatures 40-50°C, 60-70°C, 80-90°C, 100-110°C by using variations in steaming time of 60 minutes, 120 minutes and 180 minutes. The study evaluates the impact of steaming duration and operating temperature on the thermal uniformity and the resulting fish extract volume. The experimental temperature profiles are recorded until steady-state conditions are achieved, mirroring the parameters through in the CFD simulation.

The variables involved in this study are categorized as follows:

#### 1. Independent Variables:

- A rotary-type extraction system integrated with a dual-heater configuration.
- An insulated steaming chamber designed to minimize thermal loss.

#### 2. Dependent Variables:

- The temperature distribution within the heating/steaming chamber.
- The quantitative volume of the *Channa striata* extract, measured in milliliters (mL).

### 3. Controlled Variables:

- Steaming Durations: Processing times set at 60, 120, and 180 minutes.
- Operational steaming temperatures maintained at 40–50°C, 60–70°C, 80–90°C, and 100–110°C.
- A constant quantity of 10 snakehead fish per extraction cycle.

## III. Results and Discussion

The present study systematically evaluates the thermal dynamics and functional efficiency of an automated extraction chamber. By leveraging CFD simulations as a primary analytical tool, the research characterizes the intricate interplay between fluid flow patterns and heat dissipation produced by the dual-source heating configuration. Next, these numerical predictions are validated against experimental data collected from a physical prototype at various operating temperatures and steaming durations. The performance of the prototype will also be assessed based on the capacity of snakehead fish juice produced during steaming. The testing stages are carried out by providing various temperatures (40–110°C) and steaming times (60–180 minutes).

### a. Simulation result

The thermal characteristics of the steaming chamber were evaluated through Computational Fluid Dynamics (CFD) simulations. The heat distribution patterns produced by the dual-heater setup are depicted in the contours shown in Figure 3.

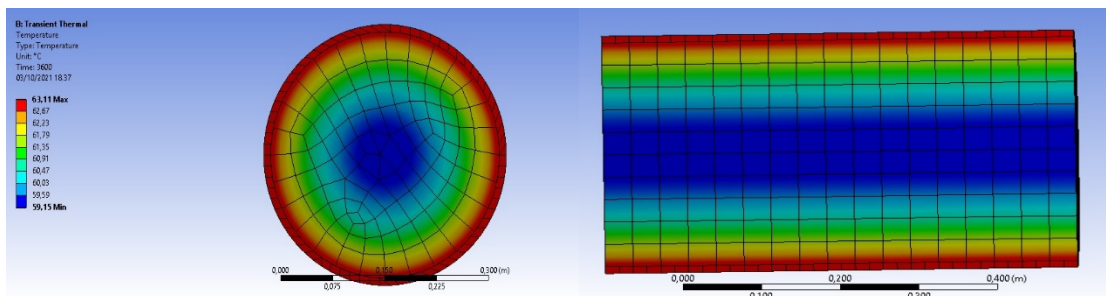


Fig 3. Heat distribution patterns in tubular extraction system

The simulation results indicate that the heating elements, acting as the heat source mounted on the vessel walls, distribute heat throughout the steaming chamber primarily via convection. Based on the initial boundary conditions, where the source is located at the wall interface and the specific geometry and material properties have been incorporated, the simulation achieved convergence, yielding the thermal distribution contours presented in Figure 3.

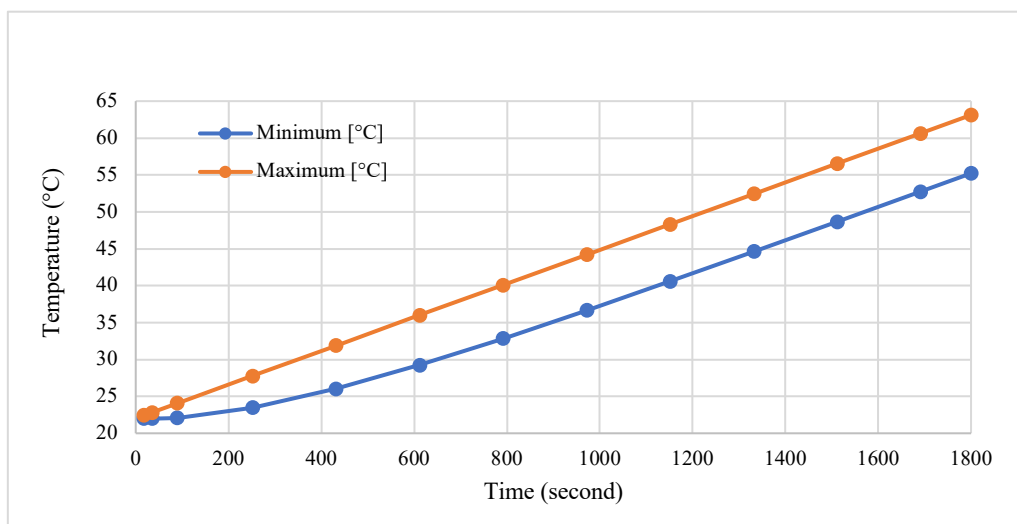


Fig 4. Temperature distribution at the chamber wall

The numerical data shows (Fig. 4) a maximum temperature of approximately 63.52°C at the chamber wall and a minimum of 55.22°C of the cylinder. These findings demonstrate effective convective heat transfer, characterized by a relatively low temperature gradient of approximately 8.3°C between the wall and the center. The transient heating profile illustrates a consistent, non-linear asymptotic increase in both maximum (wall) and minimum (centre) temperatures over the 1,800-second duration. During the initial phase ( $t < 252$ s), the system exhibits minimal thermal divergence, signifying the onset of conductive heating. As the process progresses, a distinct thermal lag is observed between the wall and the fluid core, with the maximum temperature reaching 63.12°C and the minimum stabilizing at 55.22°C at the 30-minute mark.

The resulting temperature gradient ( $\Delta T \approx 7.9^\circ\text{C}$ ) at  $t = 1800$  s, confirms a well-regulated convective heat transfer mechanism facilitated by the dual-heater configuration. This steady heating rate is strategically advantageous for the extraction process, as it provides a controlled thermal ramp-up that avoids localized overheating, thereby preserving the molecular integrity of the thermosensitive albumin within the *Channa striata* tissue matrix.

The thermal gradient of 8.3°C achieved in this dual-heater rotary system represents a significant improvement over conventional single-source extraction vessels. Previous studies on static steaming chambers often report temperature variations exceeding 15-20°C due to stagnant air pockets and localized heat concentration [7]. By comparison, the integration of dual-source heating and mechanical rotation in this design reduces the thermal gradient by approximately 45-55%, ensuring that the fish samples are subjected to a homogenized environment conducive to stable protein recovery [2].

#### b. Experimental result

The final design of the snakehead fish (*Channa striata*) extraction prototype is presented in Figure 4. The design showcases the seamless integration between the automated control unit and the dual-heater steaming chamber. This configuration was specifically engineered to maintain the precise thermal conditions required and maximizing the volume of the extract. To establish the statistical reliability of the results, each experimental configuration comprising varying temperatures 40-110°C and steaming durations 60-180 minutes was performed in triplicate. The trials were conducted under a controlled ambient environment 25-27°C at a standard atmospheric pressure of 1 atm to minimize the impact of external thermodynamic.



Fig 5. The final design of the snakehead fish (*Channa striata*) extraction prototype

The prototype is equipped with two heating elements, each with a power rating of 200 W, integrated into the internal walls of the vessel. For the thermal processing phase, the sliced fish samples are suspended from a specialized holder (Fig. 5), which is subsequently rotated by an electric motor. This rotational mechanism is designed to facilitate uniform thermal exposure and ensure

temperature homogeneity across the fish samples throughout the extraction period within the chamber. Thermal measurements were conducted using thermocouples and thermometers mounted on the walls of the extraction vessel to monitor the steaming process temperature. The volume of the recovered *Channa striata* extract was quantified using a Class A borosilicate graduated cylinder (100 mL capacity) with a measurement accuracy of 0.2 mL. The empirical data derived from these experimental trials are systematically presented in Table 3.

Table 3. Constant quantity of 10 snakehead fish per extraction cycle

No.	Temperature (°C)	Steaming durations (minute)	Total volume extraction (mL)
1	Without steaming process	60	4.5
		120	3.8
		180	3.2
2	40-50	60	7.8
		120	8.8
		180	8.1
3	60-70	60	4.4
		120	5.6
		180	2.6
4	80-90	60	33.9
		120	46.4
		180	40.1
5	100-110	60	21.6
		120	12.2
		180	3.9

The experimental results demonstrate that the albumin extraction yield is significantly higher under thermal processing compared to non-thermal conditions. All thermal sensors underwent a two-point calibration process using ice-point and steam-point standards prior to data collection to ensure sensor linearity. The maximum albumin volume of 46.4 mL was achieved at a steaming temperature range of 80–90°C with a processing duration of 120 minutes (2 hours). The comprehensive experimental dataset and the observed trends are further analyzed in the graphical representation provided in Figure 6 (a-e).

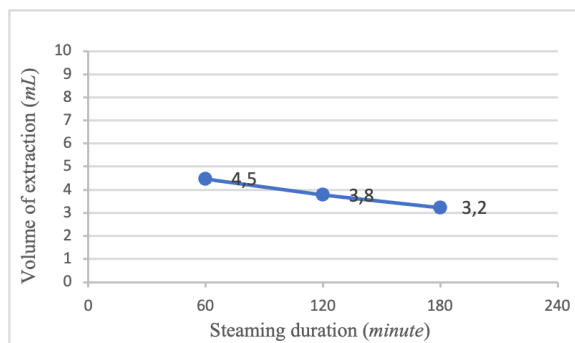


Fig 6.a. Extraction volume without steaming

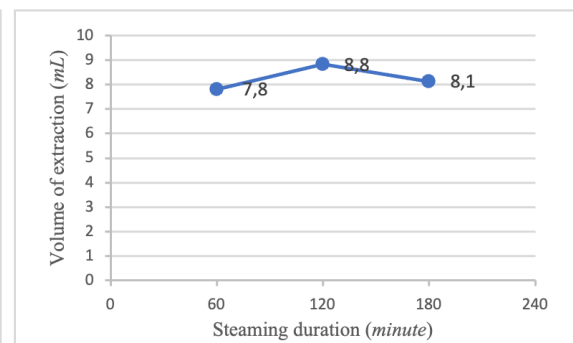


Fig 6.b. Extraction volume with 40-50 °C

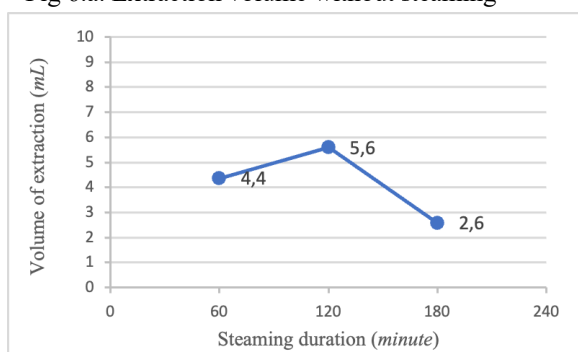


Fig 6.c. Extraction volume with 60-70 °C

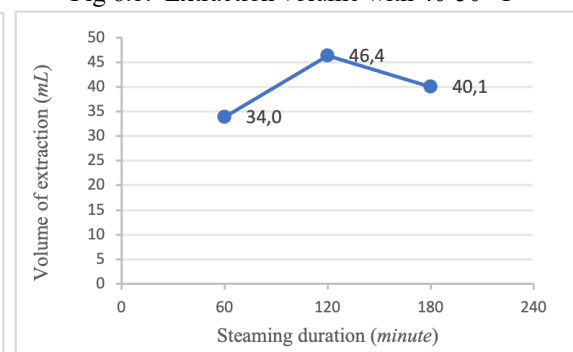


Fig 6.d. Extraction volume with 80-90 °C

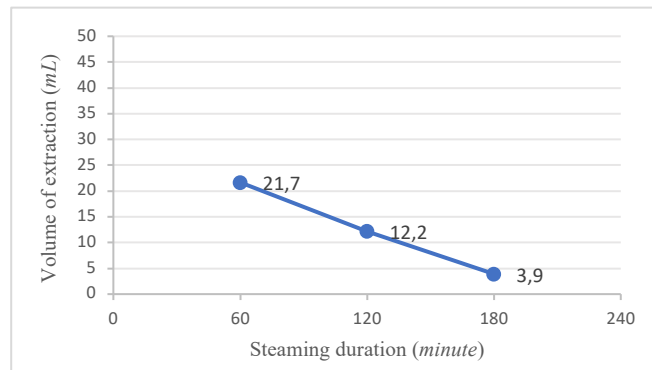


Fig 6.e. Extraction volume with 100-110 °C

The graphical data indicates that variations in the heating temperature exert a significant influence on the albumin extraction yield. It is observed that excessively high steaming temperatures, specifically within the range of 100°C to 110°C, lead to a progressive decline in the volume of the extract. This phenomenon occurs because the extreme thermal conditions within the vessel facilitate the evaporation of the already extracted fluid and may trigger the thermal degradation of the albumin. Conversely, lower temperatures 40°C to 70°C result in suboptimal yields, as the thermal energy is insufficient to effectively liberate the albumin from the fish tissue. The experimental results identify the optimal operating window to be between 80°C and 90°C, which achieved a peak yield of 46.4 mL.

Furthermore, the duration of the steaming process also plays a critical role in determining the final extraction volume. The data trends across all experimental sets suggest that while an increase in time initially enhances recovery, prolonged exposure beyond the optimal point causes a reduction in the extract volume. This decrease is primarily attributed to sustained evaporation inside the extraction chamber, which offsets the gains achieved during the earlier stages of the process."

### c. Visualization of extraction capacity

The quantitative evaluation of the developed extraction system demonstrates its operational performance, successfully yielding the desired aqueous extract. The visual characteristics of the *Channa striata* albumin extract obtained from the experimental trials are illustrated in Figure 7 (a-e).

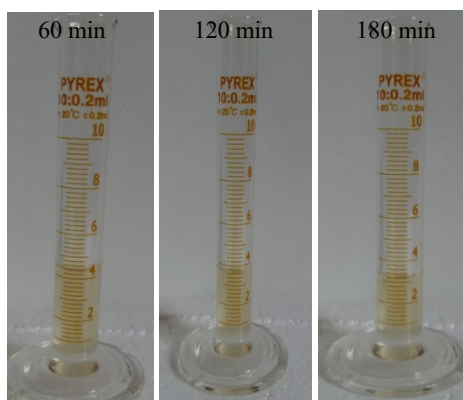


Fig 7.a. Extraction visualization without steaming

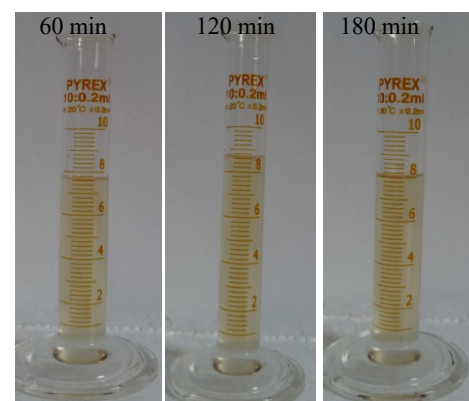


Fig 7.b. Extraction visualization with 40-50 °C

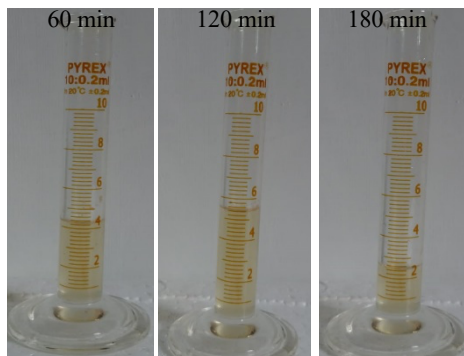


Fig 7.c. Extraction visualization with 60-70 °C

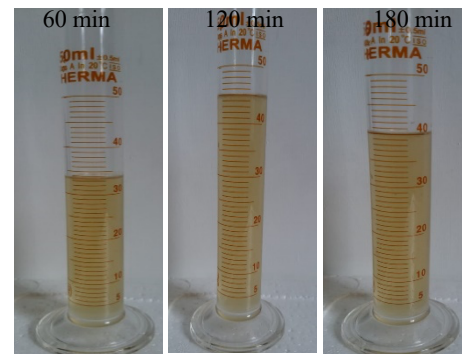


Fig 7.d. Extraction visualization with 80-90 °C

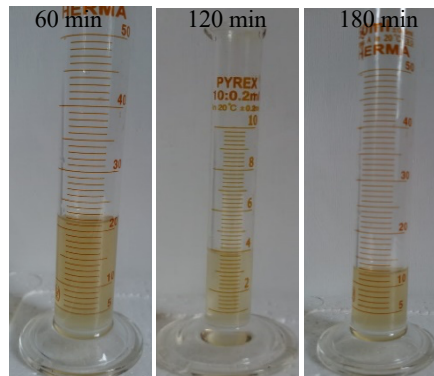


Fig 7.e. Extraction volume with 100-110 °C

The experimental data regarding the *Channa striata* albumin extraction volume highlight the significant influence of both heating duration and thermal intensity. In addition, the chromatic characteristics of the resulting extract were documented, as shown in Figure 7. When the fish samples were processed without thermal treatment, the resulting albumin appeared translucent (clear). However, the application of heat led to a progressively more concentrated and opaque coloration, with the highest intensity observed specifically within the 80–90°C range. This visual transformation serves as a qualitative indicator that at this optimal temperature, a higher concentration of albumin and fish essence is effectively liberated and recovered from the tissue matrix.

#### IV. Conclusion

This research offers significant scientific and practical contributions to the field of food engineering. Scientifically, it establishes a precise numerical-to-experimental correlation for albumin extraction, demonstrating how a controlled 8.3°C thermal gradient, achieved through a dual-heater rotary system, optimizes heat flux while preventing protein denaturation. Practically, this experiment data identified a distinct optimal operating window at a temperature range of 80–90°C and a duration of 120 minutes, which yielded a peak extract volume of 46.4 mL while preserving the qualitative concentration of the albumin essence. Conversely, the study revealed that temperatures exceeding 100°C significantly reduced yields due to fluid evaporation and thermal degradation, whereas temperatures below 70°C were insufficient for effective tissue liberation. However, this study has limitations, focusing only on analyzing the heat distribution generated by the steaming chamber. Future studies should investigate the implementation of Proportional Integral Derivative (PID) or Fuzzy Logic Controllers to achieve real-time thermal modulation. This would allow the system to automatically adjust heater output and rotational speed based on internal sensor feedback, further minimizing thermal fluctuations. Beside that, investigating the Specific Energy Consumption (SEC) of the dual-heater configuration compared to induction or microwave-assisted extraction methods would be valuable. Future work could focus on optimizing the insulation materials of the extraction chamber to maximize heat retention and reduce operational costs for industrial scaling.

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