



Comparative Study of Thermal Effects on Protein-Enriched Cassava Starch with Snakehead Fish and Mackerel Proteins

Agus Supriadi ^{a,*}, Siti Hanggita Rachmawati ^a, Sherly Ridhowati ^a, Gama Dian Nugroho ^a, Daniel Saputra ^b

^a Department of Fisheries Product Technology, Sriwijaya University, Palembang, Indonesia

^b Department of Agricultural Engineering, Sriwijaya University, Palembang, Indonesia

Abstract. *Cassava-starch composites enriched with fish proteins offer a means to tailor texture and moisture management during thermal processing. We evaluated ten formulations (P1–P10) with varying proportions of snakehead fish and mackerel proteins and measured expansion, water absorption, color (ΔE^*), and density. Expansion peaked at low protein ratios and subsequently declined: mackerel P2 reached $4.38 \pm 0.96\%$, snakehead P1 reached $4.08 \pm 1.40\%$, and both decreasing to 0.8% at P10. Water absorption also decreased with increasing protein, from $14.04 \pm 0.93\%$ (mackerel P1) and $11.67 \pm 1.36\%$ (snakehead P1) to $5.54 \pm 2.16\%$ and $4.10 \pm 0.41\%$ at P10, respectively. The water-absorption-expansion relationship was non-linear and best described by second-order polynomials (Snakehead: $y = 0.0764x^2 - 0.8101x + 2.9686$; $R^2 = 0.978$ and Mackerel: $y = 0.0975x^2 - 1.4896x + 6.1685$; $R^2 = 0.960$), indicating diminishing expansion gains at higher absorption. Apparent (saturated) density increased during soaking and plateaued at ~ 150 min; lower-protein formulations exhibited higher saturated density due to greater water uptake. Collectively, these results show that choosing the protein type and ratio enables targeted control of expansion, hydration, and density—mackerel favoring higher expansion at lower absorption, and snakehead providing a more gradual, controllable response—offering practical levers for designing fish-protein–starch products with desired textures.*

Keywords: *Cassava starch composites; Mackerel protein; Physical properties; Snakehead protein.*

Type of the Paper: Regular Article.



1. Introduction

Protein enrichment of cassava-starch composites to tailor texture, expansion, water retention, and gelatinization behavior has received considerable attention in the food industry [1]. Cassava-starch composites can incorporate different protein sources to broaden functionality. Fish proteins, for instance, have unique biochemical properties that affect composite behavior during thermal processing. Snakehead and mackerel proteins are promising edible protein sources for improving the chemical, physical (mechanical), and thermal properties of cassava-based composites.

Understanding protein–starch interactions under thermal conditions is crucial. These interactions—including covalent and noncovalent (e.g., electrostatic) forces—impact composite

performance, with the structural integrity and utility of the materials depend on the synergistic behavior of protein and starch [2]. Such knowledge is vital for developing optimal protein-enriched formulations for industrial thermal processing [3].

A key challenge in producing protein-rich cassava-starch composites is predicting how different protein sources alter physical properties after heating. Wijaya et al. [1] reported differences in emulsifying capacity and fat content between snakehead and mackerel proteins, which could differentially affect water absorption, expansion, and density after heat treatment. Such compositional variability complicates prediction of blend performance, and relatively few studies directly compare candidate blends in the same matrix [4].

To address these gaps, the present work examined the effects of varying ratios of snakehead fish and mackerel proteins on the physical attributes of cassava-starch composites during thermal processing. This systematic approach aims to reveal ratios that optimize expansion, water absorption, and density, key attributes for food and packaging applications [1].

Protein-polysaccharide ratios are influenced by temperature, pH, and ionic strength. Snakehead protein, known for its emulsifying ability, is expected to form strong covalent bonds with starch, potentially enhancing expansion and water retention during thermal processing [5]. In contrast, the higher fat content commonly observed in mackerel protein may increase hydrophobicity and alter wetting behavior (contact angle), thereby modulating composite structure and texture [6]. These interactions are central to tailoring composite properties for specific applications.

Despite prior study on protein-starch binding, most studies focus on single protein sources such as soy or gelatin [7], and the thermal interactions of fish proteins with starch remains underexplored. The combined effects of snakehead and mackerel protein is insufficiently explored, particularly under thermal processing. Accordingly, this study examined cassava-starch scaffolds modified with these fish proteins to inform potential industrial applications.

This study aims to determine how different ratios of snakehead and mackerel proteins influenced the physical properties of cassava-starch composites during thermal processing, focusing on expansion, water absorption, hardness, color, and density. The findings are intended to guide the development of protein-enriched starch composites for food processing applications based on the evaluated parameters [2].

2. Materials and Methods

2.1. Material

The key components were cassava starch (tapioca), ground *snakehead* protein, and ground *mackerel* protein, used to prepare protein-enriched cassava-starch composites. Cassava starch

served as the polysaccharide matrix, while fish proteins were incorporated to modulate thermal and physical properties of the composites.

2.2. Sample preparation

Sample preparation followed [8] with minor adaptations. Whole *snakehead* and *mackerel* (1.2–1.5 kg) were filleted, minced, and used as protein sources. For each formulation (Table 1), the required mass of ground fish and cassava starch were weighed to achieve the specified protein–starch ratio. The ground fish was homogenized and mixed with water (50% of the cassava starch) and salt (2% of the minced fish), then combined with cassava starch. The dough was hand-kneaded and formed into cylinders (~2 cm diameter, ~7 cm length). Samples were boiled at 100 °C for 15 minutes (timing started at a rolling boil), drained on a sieve, blotted, and cooled to room temperature prior to measurement.

Table 1. Protein-Cassava Starch Composition Ratios

Composition	Fish Protein or Minced (%)	Cassava Starch (%)
P1	0	100
P2	10	90
P3	20	80
P4	30	70
P5	40	60
P6	50	50
P7	60	40
P8	70	30
P9	80	20
P10	90	10

2.3. Experimental Setup

The physical properties (density, color, water absorption, and expansion) were evaluated on three independent samples per formulation (n = 3), unless stated otherwise.

- Apparent density (g cm^{-3}) was determined by water displacement following Madiouli et al. [9]. Each sample's mass (after blotting) and displaced water volume were recorded, and density was calculated as $\rho = m/V$. Measurements were taken at $t = 0, 30, 60, 90, 120$, and 150 minutes during soaking; the final (“saturated”) density was defined as the first time point at which the mass change was < 0.02 g.
- Color was measured with a colorimeter (CS-100) for L^* , a^* , b^* after calibration to a white standard. Total color difference was calculated as: $\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$, where Δ denotes the difference between the boiled sample and the baseline.
- Water absorption. Following Van de Vondel et al. [11], water absorption (%) was calculated as =

$K_a = \frac{b_1 - b_2}{b_2} \times 100\%$, where K_a : Water Absorption , b_1 : Weight after soaking and b_2 : Weight before soaking

- Expansion (%) was calculated as $Exp = \frac{V_{after} - V_{before}}{V_{before}} \times 100$, where volumes were measured by displacement before and after boiling [10].

2.4. Statistical Analysis

Statistical Analysis Each condition (density, colour, water absorption, and expansion) was tested in triplicate ($n = 3$). Data are reported as mean $\pm$ SD. Trends across formulations were analyzed using regression models; specifically, the water-absorption versus expansion relationships were fitted with second-order polynomial and logarithmic models, with equations and R^2 values reported Madiouli et al. [9].

3. Results and Discussion

3.1. The Impact of Protein Ratio on Expansion of Cassava Starch Composites

Fig. 1 showed expansion trends for composites containing *snakehead* and *mackerel* protein. Both proteins exhibited measurable leavening at low-protein formulations (P1–P4), with peak expansion occurring at the early ratios (≤ 4 –5%) and declining as protein increased (P5–P10), reaching $\sim 0.8\%$ at P10.

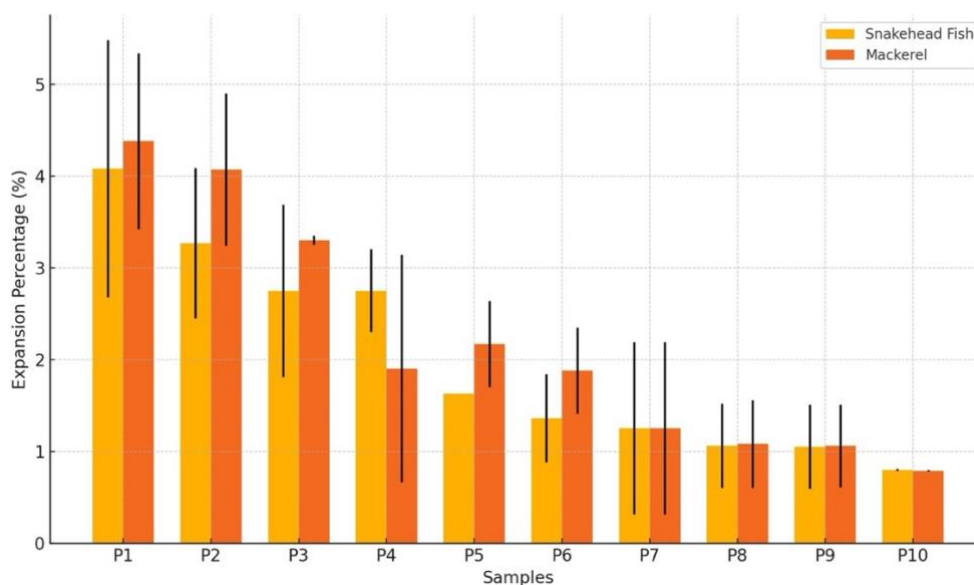


Fig. 1. Expansion (%) of cassava-starch composites with *snakehead fish* protein and *mackerel* protein.

The reduction in expansion with increasing protein aligns with protein–starch interactions that limit bubble growth at higher protein levels by forming more compact networks [11].

At early ratios, snakehead protein's emulsifying capacity may support bubble stabilization and transiently enhance expansion [5]. In contrast, mackerel protein peaks earlier (P2) and declines more rapidly beyond P4, consistent with its lower solubility and emulsifying capacity [12].

As protein content increased (P5–P10), protein–starch interactions intensified, yielding thicker, less porous networks that limited expansion. Previous studies similarly reported that higher protein levels inhibit air-cell development [4], consistent with our observations for both snakehead and mackerel composites.

These findings underscore the importance of optimizing protein ratios when expansion is critical. Snakehead protein may be suitable for products requiring higher volume (e.g., expanded snacks) at lower protein ratios, whereas decreasing expansion at higher protein suggested the existence of application-specific optima.

3.2. Water Absorption and Its Relation to Fish Protein–Carbohydrate Composition

Water absorption capacity varied with protein type and content in cassava-starch composites, as presented in Fig. 2. Mackerel protein composites consistently absorbed more water than snakehead protein composites. For instance, in P1, water absorption was $14.04\% \pm 0.93\%$ for mackerel and $11.67\% \pm 1.36\%$ for snakehead, respectively. Increasing the protein ratio also led to a continuous decrease in water absorption, with the lowest values recorded at P10 (Snakehead: $4.10\% \pm 0.41\%$, Mackerel: $5.54\% \pm 2.16\%$).

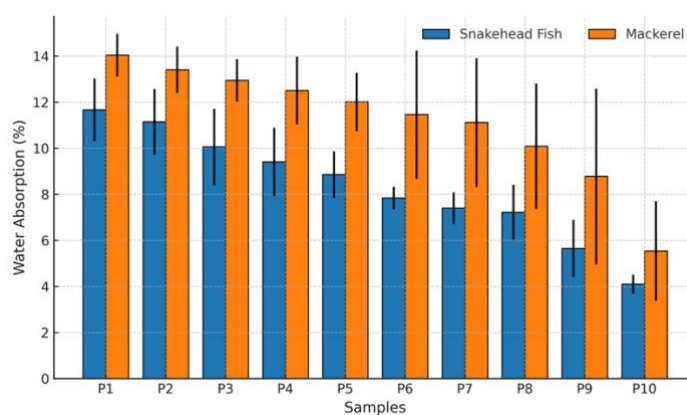


Fig. 2. Water Absorption (%) of fish protein-carbohydrate composite

Water absorption was generally higher in Mackerel protein composites, particularly in formulations P1 to P4, due to higher lipid content. Fish proteins are polar and hydrophilic, and the presence of polar amino acids facilitates water retention inside the composite matrix [13]. Additionally, adequate fat content promotes moisture distribution, absorption, and binding ability, contributing to higher water retention in these composites [14]. However, water absorption decreases with increasing protein content, as denser composites absorb less moisture.

In terms of water absorption, snakehead protein composites exhibited higher performance

than Mackerel. This discrepancy may be due to the comparatively low fat content in snakehead protein, which limits hydrophilic interactions with the starch matrix. Furthermore, the higher protein content in both snakehead and mackerel samples promotes protein-starch interactions, reducing porosity and water absorption ability [15].

Our results align with previous research on fish protein-starch systems, demonstrating the water affinity of proteins due to hydration [7]. However, increasing protein content generally reduces this capacity, indicating the formation of denser networks within the composite. Fluctuations were observed in the mackerel samples (P9 and P10), such as the pegged water absorption, suggesting that higher protein levels can lead to more variable water absorption, possibly due to protein variance or moisture control during the processing [16]. These findings have practical implications for food science and technology, particularly in understanding and controlling the water absorption properties of fish protein-starch systems.

3.3. Relationship water absorption and expansion for Snakehead fish and Mackerel composite.

The relationship between water absorption and expansion in both snakehead and mackerel composites shows a clear positive correlation, as illustrated in Fig. 3. This association was non-linear for both proteins and best described by a second-order polynomial rather than a linear model. The fitted equations were: snakehead, $y = 0.0764x^2 - 0.8101x + 2.9686$; $R^2 = 0.978$ and mackerel, $y = 0.0975x^2 - 1.4896x + 6.1685$; $R^2 = 0.960$. The higher R^2 values indicated a substantially better goodness-of-fit than a logarithmic or linear approximation.

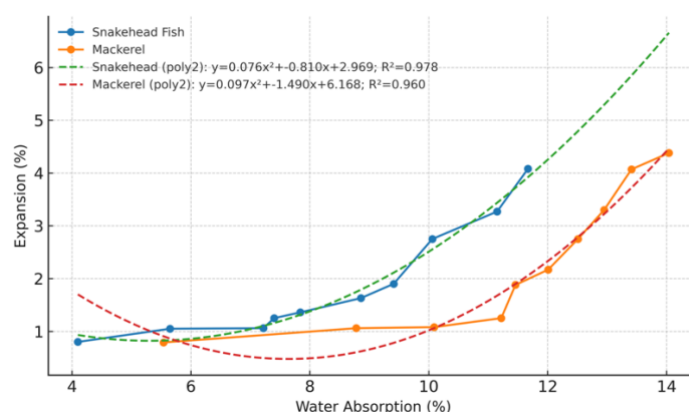


Fig. 3. Relationship between water absorption and expansion for Snakehead fish and Mackerel composites

Across the measured range, expansion increased with water absorption for both systems, exhibiting positive curvature (convexity), which indicates that the sensitivity of expansion to additional water increases at higher water-absorption levels. At any given water-absorption value, the mackerel curve lies above the snakehead curve, showing higher predicted expansion for mackerel composites throughout the domain.

At lower water-absorption levels, mackerel composites attained higher expansion than snakehead composites, consistent with a matrix that more readily entraps air at modest moisture contents, possibly influenced by protein structure and lipid-mediated effects favoring air-cell formation [17]. In contrast, snakehead composites required greater water uptake to achieve comparable expansion, aligning with reports that lean fish proteins form tighter protein–starch networks that need more moisture to expand effectively [18]. As water absorption increases, the curvature of both polynomial fits indicates that expansion gains taper rather than increase linearly. This behavior suggests that excessive water eventually reduces expansion efficiency by over-plasticizing the matrix and limiting gas-cell stability—consistent with prior observations in related systems [19].

Practically, adopting the quadratic models allows more accurate prediction and control of texture: for a desired expansion level, the protein type can be selected and the formulation can be adjusted toward the corresponding water-absorption range indicated by the fitted curves. This non-linear relationship also indicates that changes in water absorption at higher level have a greater effect on expansion than equal changes at the lower levels, which is important for process control and quality-by-design in protein-enriched starch products.

3.4. Density of Snakehead Fish Protein-Carbohydrate Composites

Apparent (saturated) density increased over time and stabilized by ~150 min (Fig. 4). Saturated treatment means were in the physically plausible range ($1.03\text{--}1.18\text{ g cm}^{-3}$), with individual measurements spanning $0.91\text{--}1.65\text{ g cm}^{-3}$ across formulations.

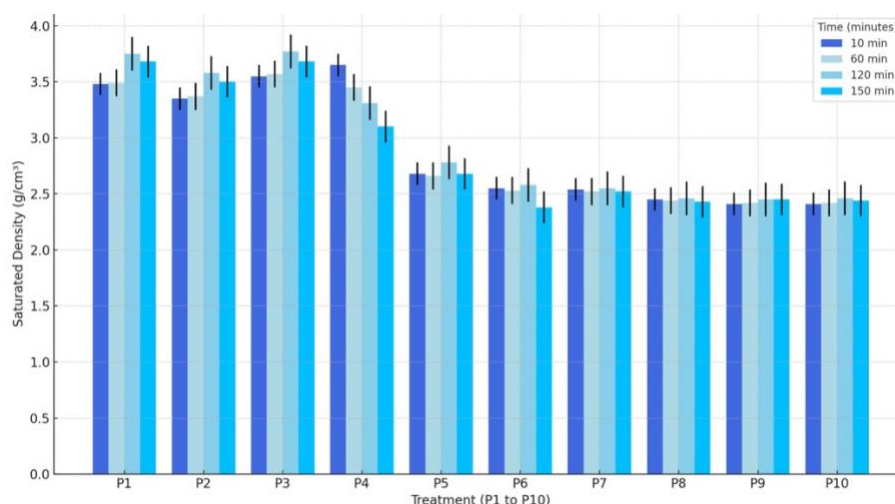


Fig. 4. Apparent (saturated) density (g cm^{-3}) at multiple time intervals

Higher protein ratios tended to yield denser, less porous matrices, while lower ratios allowed greater water uptake. The rise over the first ~120 minutes indicated ongoing imbibition into the protein–starch network, consistent with previous observations for protein-enriched starch systems [20], where similar water absorption behaviour was reported for protein-enriched starch

composites. After 150 minutes, the density plateaued, indicating that the composite had reached maximum water-holding capacity. At this point, the matrix had absorbed as much water as possible without further structural change. The higher saturated densities in samples P1 to P4, which contained lower protein ratios, suggest a more open and porous structure, facilitating water penetration and retention. These composites likely formed a looser matrix, resulting in higher water absorption and, thus, greater density.

At higher protein (P5–P10), composites presented denser structures and lower water uptake, consistent with reports that protein enrichment can restrict hydration and increase firmness in starch matrices [21].

Between-sample variability (e.g., P3, P5, P6) likely reflected differences in protein–starch interactions, with stronger interactions producing denser composites with lower water-holding capacity [12]. Practically, higher saturated densities are suitable for moist or tender products (e.g., fish cakes, patties), whereas lower densities favor drier, crisper formats.

The standard deviations for these samples suggest that variations in protein network structure affected water absorption, leading to differences in the final composite density. These findings have practical implications for formulating food products where texture and moisture retention are critical.

On the other hand, composites with lower saturated densities, such as those in P5 to P10, are more suitable for products requiring a firmer texture and lower moisture content, such as fish snacks or crackers. In conclusion, the density data highlight the importance of optimizing protein–starch ratios to achieve desired structural properties in snakehead protein-enriched composites. By controlling protein content, manufacturers can tailor the density and moisture retention of the final product to suit specific industrial requirements, whether for a moist, tender texture or a firmer, drier structure.

3.5. *Density of Mackerel protein/carbohydrate composites*

Mackerel-based composites showed a similar time course: density increased through ~120–150 minutes and then plateaued (Fig. 5). Saturated densities of mackerel protein/cassava starch composites were comparable to the results observed in snakehead protein composites, with densities gradually increasing during 45–150 minutes and remaining constant thereafter (Fig. 5). Treatment means ranged from ~1.04–1.12 g cm⁻³, with individual measurements spanning 0.91–1.68 g cm⁻³. Slightly higher averages than snakehead composites suggest differences in network structure attributable to mackerel protein.

The increase in density reflects a similar water absorption process across samples. However, the slightly higher values for mackerel composites indicate differences in the protein–starch network formed.

The steady increase in density during the initial 120 to 150 minutes aligns with previous studies on protein-starch systems, where water absorption gradually increases density as water penetrates the composite matrix [20]. After 150 minutes, density plateaued, indicating saturation and that no further water absorption occurred. This stabilization suggests that the mackerel protein-composite matrix had reached its maximum water-holding capacity. Higher saturated densities in early samples (P1 to P4) imply a more porous structure, allowing excellent water retention, consistent with findings that lower protein concentrations produce less rigid matrices, enabling better water penetration [21]. In contrast, denser structure in higher protein samples (P5 to P10) limited water-holding capacity, resulting in lower saturated densities.

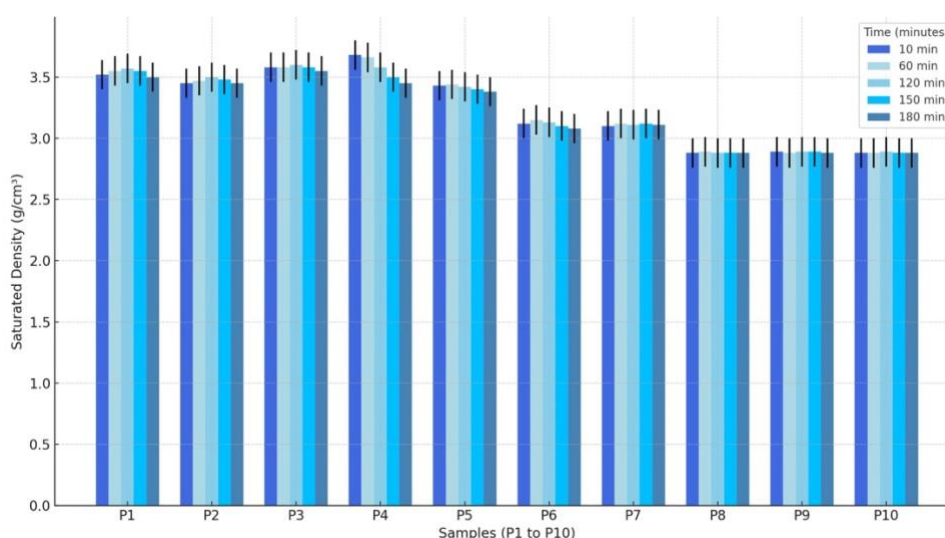


Fig. 5. Apparent (saturated) density (g cm^{-3}) at multiple time intervals

Mackerel protein composites exhibited higher average density than snakehead protein composites, likely due to the structural characteristics of mackerel protein. Its higher fat content may contribute to a denser protein-starch network by limiting water absorption compared to the leaner snakehead protein. This trend aligns with studies showing that proteins with higher fat content form tighter, less porous structures, reducing water penetration [22].

A slight decrease in density beyond 150 minutes, particularly in P1 and P3, suggests that oversaturation or structural weakening occurred. Prolonged immersion can damage the composite matrix in protein-carbohydrate systems, reducing composite density [23], and ultimately compromising the integrity of the composite.

These results are crucial for controlling moisture and product texture in food products. Composites with higher saturated densities (P1–P4) are preferable for products requiring moisture retention, such as fish cakes and pempek. In contrast, later samples (P5 to P10), which exhibit lower and more consistent saturated densities, are better suited for products requiring firmer or drier textures, such as fish snacks or crackers, where a stable structure is critical for product

preservation.

In summary, the results for mackerel protein composites suggest that protein–starch ratios must be carefully controlled to achieve targeted water-holding capacity and structural properties. Product applications can be guided by saturated density, allowing manufacturers to adjust protein content to control texture and moisture retention for specific products.

3.6. Comparative Analysis of Saturated Density

Comparison of snakehead and mackerel composites (Fig. 4, Fig. 5) revealed differences in hydration and structure: densities for both increased over time and plateaued around ~150 minutes, but the distribution patterns differed by protein type.

Saturated-density ranges for snakehead composites were approximately 0.91–1.65 g cm⁻³ (individual values; treatment means 1.03–1.18), while mackerel ranged from 0.91–1.68 g cm⁻³ (means 1.04–1.12). Higher densities at lower protein levels reflected greater water uptake in less rigid matrices, while higher protein content produced tighter networks and consequently lower saturated densities. Protein-specific differences likely stemmed from compositional characteristics, including lipid content. This indicates that the mackerel protein matrix forms a harder, more rigid structure than the snakehead protein matrix, potentially due to its greater fat content in the former and the distinct spatial arrangement of its proteins.

Higher densities at low protein levels in mackerel composites align with greater water uptake in less rigid matrices, whereas snakehead's emulsifying behavior favored different network formation at early ratios [22]. This indicates that the higher-fat content in mackerel meat can result in a denser matrix, restricting water absorption. In contrast, snakehead protein, with its lower fat content and superior emulsifying properties, forms a looser structure that permits greater water absorption, particularly during the initial experiment phase.

Another critical difference between the two composites is the point at which density reaches saturation. Saturation occurred earlier (around 120 minutes) in mackerel composites, suggesting that mackerel protein composites achieve maximum water-holding capacity faster than snakehead protein composites. This earlier stabilization in mackerel samples indicates that the protein-starch interactions in mackerel limit water absorption more efficiently, possibly due to stronger hydrophobic interactions within the matrix [24]. In contrast, snakehead composites continued to absorb water until approximately 150 minutes, reflecting the more hydrophilic nature of snakehead proteins, which allows for extended water uptake.

The modestly greater variability observed in snakehead composites, specifically in samples P3 and P5, suggests more pronounced inconsistency in water-absorption behavior. In comparison, mackerel composites were more homogenous, exhibiting a more stable water absorption behavior. This variability likely reflects differences in protein structures and its interactions with starch. The

higher emulsifying ability of snakehead protein may have caused variations in the protein-starch network, resulting in variable water holding capacity between samples [4,25]. Meanwhile, the denser and more stable structure of mackerel composites produced less variation in water retention, suggesting that mackerel protein develops a more uniform network that reduces batch-to-batch differences in water-holding capacity.

Differences in saturated density between the two protein types have practical implications for product development. With more water absorption and higher initial density, snakehead protein composites may be particularly fit for products requiring moist and tender texture, such as fish cakes, patties, and other wet or semi-dry formulations. Their stronger tensile integrity and ability to retain more water offer advantages in applications where moisture retention is critical. Conversely, mackerel protein composites appear more appropriate for products that require a firm and dry texture such as fish snacks, crackers, and similar applications that prioritize structure and shelf stability over moisture retention.

This comparative analysis highlights the significance of protein choice when developing starch-protein composites. The differing water absorption and density characteristics of snakehead and mackerel proteins allow meaningful customization of food products to meet specific textural and moisture-retention requirements. Adjusting the protein source and proportion can efficiently alter the physical properties of the final product.

3.7. *Effects on Color of Fish Protein-Cassava Starch Composites*

Total color change (ΔE^*) increased with protein ratio for both systems (Fig. 6), with larger shifts at higher ratios (P6–P10). Snakehead composites showed a more pronounced rise after P6, reaching approximately ~ 8.0 at P10, while mackerel composites exhibited a more gradual rise, peaking at around ~ 7.5 at P10).

This color change may be attributed to protein denaturation and the Maillard reaction during increasing thermal processing. As the protein denatures and interacts with reducing sugars, it reacts with sugars in the cassava starch matrix to form browning compounds from Maillard reactions, such as melanoidins, which contribute to sample darkening [26]. The sharp increase in ΔE for the Snakehead protein composites after P6 indicates a more reactive protein-starch combination than in mackerel composites. The higher emulsifying capacity of snakehead protein may account for the more pronounced Maillard reaction and the larger color changes observed in the later composites [27].

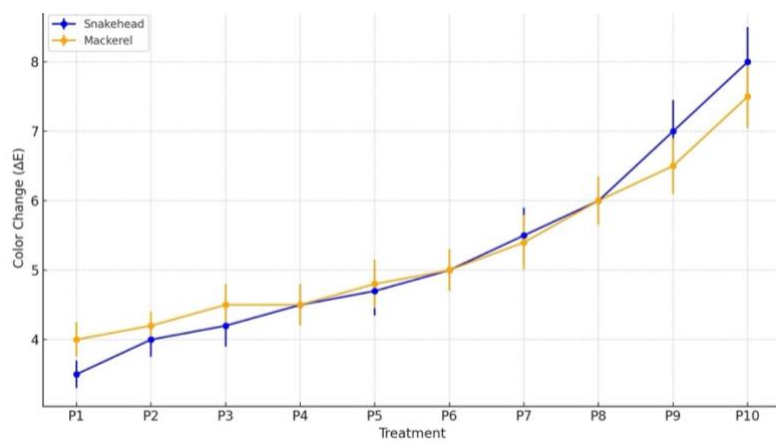


Fig. 6. The total colour change (ΔE^*) of Snakehead and Mackerel protein/carbohydrate composites

Mackerel protein composites demonstrate a slower and more consistent color change. This may be attributed to the higher fat content in mackerel, as fats can reduce the Maillard browning rate by interfering with and inhibiting protein-sugar interactions. Moreover, lipid oxidation in mackerel protein composites may lead to an alternative browning process that produces less extreme color change than in snakehead proteins [28]. The higher fat content may also protect against rapid protein denaturation, enabling browning effects to develop more stable.

The color change in the later samples was highly variable, suggesting that as the protein ratio increases, the likelihood of light browning effects also increases unpredictably over time. This greater variability may stem from uncoordinated moisture distribution, unequal protein thermal stability, and fluctuations in protein-sugar interactions, all of which can contribute to inconsistent browning in protein-enriched composites [29]. The error bars for all measurements indicate that increasing protein levels correspond to increased light browning, which occurs most consistently in samples with the highest protein addition (P8 to P10).

The variability in color change between snakehead and mackerel composites is an essential attribute for product appearance, a relevant quality consideration in the food sector. Darker color changes make snakehead composites better suited for products requiring a deep, roasted appearance (e.g., grilled or baked fish-based items), while lighter and more consistent may coloration of mackerel composites may be preferable for products needing a fresher or natural look (e.g., lightly processed or frozen fish items).

From a food processing perspective, higher protein ratios lead to more variable color changes, indicating that greater control in thermal processing conditions is required. For example, small changes in temperature, moisture content, or processing time may also affect color changes. Thus, to improve color uniformity, foams with higher protein ratios may require stabilizers, moisture-optimized formulations, and refined processing temperatures [30].

The color modifications observed in snakehead and mackerel protein composites show that protein type and the ratio are significant factors influencing the visual characteristics of protein-enriched starch composites. Manufacturers can manage the color profile of these products according to consumer perceptions and application requirements by adjusting protein levels and manufacturing conditions.

4. Conclusions

The findings of this study demonstrate that the type and proportion of protein critically influence the thermal–physical properties of cassava starch composites. Expansion was greatest at low protein ratios (mackerel P2 = $4.38 \pm 0.96\%$, snakehead P1 = $4.08 \pm 1.40\%$) but declined sharply to $\approx 0.8\%$ at P10 in both systems, indicating that higher protein loading consistently suppressed expansion. Water absorption also decreased with increasing protein content, with mackerel composites consistently absorbing more than snakehead at comparable ratios (e.g., P1: $14.04 \pm 0.93\%$ vs $11.67 \pm 1.36\%$; P10: $5.54 \pm 2.16\%$ vs $4.10 \pm 0.41\%$). The relationship between expansion and water absorption followed a non-linear trend, best described by second-order polynomials (snakehead: $R^2 = 0.978$; mackerel: $R^2 = 0.960$), reflecting diminishing expansion gains at higher absorption levels. Apparent density increased with soaking time and stabilized at ~ 150 minutes, with lower-protein composites showing higher saturated densities due to greater hydration, while higher protein levels produced denser but less hydrated matrices. Finally, color difference (ΔE^*) rose with protein ratio in both systems, becoming most pronounced at higher ratios (P6–P10), with snakehead showing a stronger shift.

For products targeting lighter, more voluminous textures, lower protein ratios with mackerel protein are advantageous. For firmer or more structurally stable textures, snakehead protein at moderate–higher ratios provides a more gradual and controllable expansion response, along with lower saturated density. Overall, selecting the protein source and adjusting the ratio offer practical means to tailor hydration, expansion, density, and visual attributes of fish-protein–starch products. Future work should extend validation across broader thermal profiles (time/temperature), quantify microstructure and rheology, incorporate dry-basis formulation control (total solids), and evaluate sensory and processing robustness to support industrial application.

Abbreviations

ΔE^*	Total color difference (color change parameter in CIE color space)
L^*	Lightness (CIE Lab color coordinate)
a^*	Red–green coordinate (CIE Lab color coordinate)
b^*	Yellow–blue coordinate (CIE Lab color coordinate)
R^2	Coefficient of determination (goodness-of-fit statistic in regression analysis)
SD	Standard Deviation
ρ	Density (g cm^{-3})

Data availability statement

Supplementary data to this article can be found online at Supriadi, Agus (2024). Data Penelitian Thermal Influence on the Physical Properties of Protein-Enriched Cassava Starch Composites: A Comparative Study of Snakehead Fish and Mackerel Protein Ratios. figshare. Journal contribution. <https://doi.org/10.6084/m9.figshare.27128877.v1>

CRedit authorship contribution statement

Agus Supriadi: conceptualization, methodology, writing-original draft. **Siti Hanggita Rachmawati:** Data curation, formal analysis, review, editing, resource. **Sherly Ridhowati:** writing review and editing. **Gama Dian Nugroho:** editing and data visualization. **Daniel Saputra:** conceptualization, supervision, writing review, editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to acknowledge the financial support from Sriwijaya University (Competitive Grand, 2024)

References

- [1] Wijaya W, Patel AR, Setiowati AD, Van Der Meeren P. Functional colloids from proteins and polysaccharides for food applications Trends in Food Science & Technology Functional colloids from proteins and polysaccharides for food applications. Trends Food Sci Technol 2017;68:56–69. <https://doi.org/10.1016/j.tifs.2017.08.003>.
- [2] Babak V, Dickinson E, Miller R. Food Colloids. Fundamental of Formulation 2001;13:91. https://www.researchgate.net/publication/230370087_Food_Colloids-Fundamentals_of_Formulation_Edited_by_E_Dickinson_and_R_Miller_Royal_Society_of_Chemistry_Cambridge_2000_pp_424_price_7950_ISBN_0_85404_850_2
- [3] Wijaya W, Patel AR, Setiowati AD, Van der Meeren P. Trends in Food Science & Technology Functional colloids from proteins and polysaccharides for food applications. Trends Food Sci Technol 2017;68:56–69. <https://doi.org/10.1016/j.tifs.2017.08.003>.
- [4] Dickinson E. Microgels - An alternative colloidal ingredient for stabilization of food emulsions. Trends Food Sci Technol 2015;43:178–88. <https://doi.org/10.1016/j.tifs.2015.02.006>.
- [5] Pires C, Ramos C, Teixeira B, Batista I, Nunes ML, Marques A. Hake proteins edible films incorporated with essential oils: Physical, mechanical, antioxidant and antibacterial properties. Food Hydrocoll 2013;30:224–31. <https://doi.org/10.1016/j.foodhyd.2012.05.019>.
- [6] Gutiérrez TJ, Tapia MS, Pérez E, Famá L. Structural and mechanical properties of edible films made from native and modified cush-cush yam and cassava starch. Food Hydrocoll 2015;45:211–7. <https://doi.org/10.1016/j.foodhyd.2014.11.017>.
- [7] Hernández-Fernández N, Adriano-Anaya L, Salvador-Figueroa M, Betancur-Ancona D, Vázquez-Ovando A. Impact of organic fertilization on physicochemical and functional properties of cassava starch. Starch/Staerke 2015;68:549–57. <https://doi.org/10.1002/star.201500257>.

- [8] Fajri M, Dasir D. Studi Tenggang Waktu Penggunaan Daging Ikan Gabus Pada Pembuatan Pempek Lenjer. *Edible* 2017;6:20–6. <https://jurnal.um-palembang.ac.id/edible/article/view/628>
- [9] Madiouli J, Sghaier J, Lecomte D, Sammouda H. Determination of porosity change from shrinkage curves during drying of food material. *Food and Bioproducts Processing* 2012;90:43–51. <https://doi.org/10.1016/j.fbp.2010.12.002>.
- [10] Haryanti AM, Darmanti S, Izzati M. Kapasitas Penyerapan dan Penyimpanan Air pada Berbagai Ukuran Potongan Rumput Laut *Gracilaria verrucosa* sebagai Bahan Dasar Pupuk Organik. *BIOMA* 2008;10:1-6. http://eprints.undip.ac.id/1982/1/Bioma_Anik_Juni_08.pdf
- [11] Van de Vondel J, Lambrecht MA, Housmans JAJ, Rousseau F, Schymkowitz J, Delcour JA. Impact of hydrothermal treatment on denaturation and aggregation of water-extractable quinoa (*Chenopodium quinoa* Willd.) protein. *Food Hydrocoll* 2021;115. <https://doi.org/10.1016/j.foodhyd.2021.106611>.
- [12] Jyothi AN, Pillai SS, Aravind M, Salim SA, Kuzhivilayil SJ. Cassava starch-graft-poly(acrylonitrile)-coated urea fertilizer with sustained release and water retention properties. *Advances in Polymer Technology* 2018;37:2687–94. <https://doi.org/10.1002/adv.21943>.
- [13] Ogundele GF, Adebayo TK, Adeyanju AA, Bamidele OP. Nutritional composition and in vitro starch digestibility of Banku flour processed from cassava (*Manihot esculenta* Crantz) root and quality protein maize grains. *Int J Food Sci Technol* 2022;57:6548-56. <https://doi.org/10.1111/ijfs.15996>.
- [14] Awoyale W, Oyedele H, Adenitan AA, Adesokan M, Alamu EO, Maziya-Dixon B. Correlation of the quality attributes of fufu flour and the sensory and instrumental texture profiles of the cooked dough produced from different cassava varieties. *Int J Food Prop* 2022;25:326–43. <https://doi.org/10.1080/10942912.2022.2026955>.
- [15] Toraya-Avilés R, Segura-Campos M, Chel-Guerrero L, Betancur-Ancona D. Effects of pyroconversion and enzymatic hydrolysis on indigestible starch content and physicochemical properties of cassava (*Manihot esculenta*) starch. *Starch - Stärke* 2016;69:1600267. <https://doi.org/10.1002/star.201600267>.
- [16] Bertram HC, Kristensen M, Andersen HJ. MEAT Functionality of myofibrillar proteins as affected by pH , ionic strength and heat treatment – a low-field NMR study. *Meat Science* 2004;68:249–56. <https://doi.org/10.1016/j.meatsci.2004.03.004>.
- [17] Martínez MM, Manuel G. Rheological and microstructural evolution of the most common gluten-free flours and starches during bread fermentation and baking. *Journal of Food Engineering* 2017;197:78–86. <https://doi.org/10.1016/j.jfoodeng.2016.11.008>.
- [18] Cropotova J, Mozuraityte R, Standal IB, Aftret KC, Rustad T. The effect of sous-vide cooking parameters, chilled storage and antioxidants on quality characteristics of Atlantic mackerel (*Scomber scombrus*) in relation to structural changes in proteins. *Food Technol Biotechnol* 2019;57:191–9. <https://doi.org/10.17113/ftb.57.02.19.6032>.
- [19] Smaniotto F, Zafeiri I, Prosapio V, Spyropoulos F. Understanding the encapsulation and release of small molecular weight model actives from alginate fluid gels. *Food Structure* 2021;27. <https://doi.org/10.1016/j.foostr.2021.100179>.
- [20] Ortiz MER, Martín-Martínez ES, Padilla LPM. Rheological and Thermal Properties of Extruded Mixtures of Rice Starch and Isolated Soy Protein. *Starch - Stärke* 2008;60:577–87. <https://doi.org/10.1002/star.200800212>.
- [21] Lyu Z, Sala G, Scholten E. Water distribution in maize starch-pea protein gels as determined by a novel confocal laser scanning microscopy image analysis method and its effect on structural and mechanical properties of composite gels. *Food Hydrocoll* 2022;133. <https://doi.org/10.1016/j.foodhyd.2022.107942>.
- [22] Villanueva M, Ronda F, Moschakis T, Lazaridou A, Biliaderis CG. Impact of acidification and protein fortification on thermal properties of rice, potato and tapioca starches and

- rheological behaviour of their gels. *Food Hydrocoll* 2018;79:20–9. <https://doi.org/10.1016/j.foodhyd.2017.12.022>.
- [23] Jian W, Wu H, Wu L, Wu Y, Jia L, Pang J, Sun YM. Effect of molecular characteristics of Konjac glucomannan on gelling and rheological properties of Tilapia myofibrillar protein. *Carbohydr Polym* 2016;150:21–31. <https://doi.org/10.1016/j.carbpol.2016.05.001>.
- [24] Romani VP, Machado AV, Olsen BD, Martins VG. Effects of pH modification in proteins from fish (Whitemouth croaker) and their application in food packaging films. *Food Hydrocoll* 2018;74:307–14. <https://doi.org/10.1016/j.foodhyd.2017.08.021>.
- [25] Sánchez-Becerril M, Marangoni AG, Perea-Flores MJ, Cayetano-Castro N, Martínez-Gutiérrez H, Andraca-Adame JA, Pérez-Martínez JD. Characterization of the micro and nanostructure of the candelilla wax organogels crystal networks. *Food Structure* 2018;16:1–7. <https://doi.org/10.1016/j.foostr.2018.02.001>.
- [26] Zhang Z, Arrighi V, Campbell L, Lonchamp J, Euston SR. Properties of partially denatured whey protein products: Viscoelastic properties. *Food Hydrocoll* 2018;80:298–308. <https://doi.org/10.1016/j.foodhyd.2017.12.039>.
- [27] Torres O, Tena NM, Murray B, Sarkar A. Novel starch based emulsion gels and emulsion microgel particles: Design, structure and rheology. *Carbohydr Polym* 2017;178:86–94. <https://doi.org/10.1016/j.carbpol.2017.09.027>.
- [28] Olivares ML, Costabel LM, Zorrilla SE, de Vicente J. Calcium-induced skim milk gels: Effect of milk powder concentration and pH on tribo-rheological characteristics and gel physico-chemical properties. *Food Hydrocoll* 2022;124. <https://doi.org/10.1016/j.foodhyd.2021.107335>.
- [29] González LC, Loubes MA, Tolaba MP. Incidence of milling energy on dry-milling attributes of rice starch modified by planetary ball milling. *Food Hydrocoll* 2018;82:155–63. <https://doi.org/10.1016/j.foodhyd.2018.03.051>.
- [30] Yu W, Gilbert RG, Fox GP. Malt protein inhibition of β -amylase alters starch molecular structure during barley mashing. *Food Hydrocoll* 2020;100. <https://doi.org/10.1016/j.foodhyd.2019.105423>.