



Design-Driven Optimisation of Brine Blanching for Quality Improvement in Freeze-Dried Shrimp Bites

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Abstract

This study optimised brine blanching conditions to produce freeze-dried shrimp bites from *Parapenaeopsis stylifera* using a multilevel factorial design. The effects of brine concentration (1%, 2%, 3% w/v) and blanching duration (1, 3, 5, and 7 min) at 90 °C were assessed on physicochemical, sensory, and structural quality attributes, including blanching loss, sensory acceptability, rehydration ratio, water activity, colour parameters, salt content, astaxanthin content, and texture properties. Both processing variables significantly affected most measured quality attributes, although the magnitude and significance of the main and interaction effects varied across responses. Short-time, low-salt treatments (1–3 min, 1–2% brine) yielded the highest sensory acceptability and rehydration capacity, while effectively preserving colour and texture. Multi-response optimisation identified 3 minutes of blanching at 2% brine concentration as optimal, achieving a composite desirability of 0.511. In contrast, extended treatments (5–7 min, 3% brine) enhanced preservation traits by lowering water activity and improving astaxanthin content, but reduced sensory appeal and rehydration performance. Colour analysis showed that minimal processing better maintained lightness, whereas longer treatments intensified red–yellow pigmentation due to controlled carotenoid release. Texture firmness increased progressively with processing intensity, likely due to enhanced formation of the protein gel network. Overall, the study shows how brine concentration and blanching time can be adjusted to achieve a suitable balance among the

physicochemical, textural, rehydration, and sensory properties of freeze-dried shrimp bites.

Keywords: Brine blanching, freeze-drying, shrimp processing, process optimisation, quality attributes, *Parapenaeopsis stylifera*

Introduction

Parapenaeopsis stylifera, locally known as Kiddi shrimp, is a small-sized penaeid species widely distributed in the Indian Ocean and valued for its nutritional and economic importance (Gopan et al., 2020). Its accessibility in shallow coastal waters makes it a vital resource for both commercial and subsistence fisheries, playing a crucial role in regional food security, especially in coastal diets. The species is nutritionally dense, containing 20–25% protein, low fat levels, and rich profiles of essential amino acids, omega-3 fatty acids, and carotenoids (Strati, Sinanoglou, Kora, Miniadis Meimaroglou, & Oreopoulou, 2012; Mohsin, Mu, Memon, Kalhor, & Shah, 2017; Safaie, 2017). Although the species is widely consumed fresh and in processed forms, its potential for value-added products remains largely unexplored. This creates opportunities for developing dehydration and other preservation methods that can improve shelf life and expand its market potential (Mohsin et al., 2022).

The rising demand for value-added seafood products is driven by consumer preferences for convenient, shelf-stable, and high-protein options that align with increasingly fast-paced modern lifestyles (Liew et al., 2021). Freeze-drying, a preservation method that removes moisture under low temperature and pressure, effectively retains flavour, texture, and nutrients while producing shelf-stable products with extended market reach (Galal Khallaf, Abdelbaset-Donya, Hamza, & Mohammed-Geba, 2021; Nwankwo et al., 2023). This is particularly

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well-suited for shrimp processing due to their favourable sensory and nutritional profiles, contributing to cardiovascular health through essential amino acids and omega-3 fatty acids (Chakraborty, 2025).

However, maintaining product quality during processing presents significant challenges. Blanching has emerged as an essential pre-processing step that involves brief exposure to hot water, steam, or microwave to inactivate enzymes like polyphenol oxidase (PPO), which cause undesirable changes such as browning and off-flavours (Tran et al., 2022). Beyond enzymatic inactivation, blanching preserves texture through protein denaturation, enhances drying efficiency by improving mass transfer, and extends shelf-life by reducing microbial counts and lipid oxidation (Rahman & Perera, 2007; Cyprian et al., 2015; Srivastava & Sit, 2025). Brine blanching, which involves immersing seafood in saline solutions, offers distinct advantages over plain water blanching. The osmotic effect of salt enhances protein solubilisation, improves texture by increasing firmness and moisture retention, and reduces lipid oxidation while lowering microbial load (Cyprian et al., 2015; Rabiepour, Zahmatkesh, & Babakhani, 2024). Higher salt concentrations enhance water-holding capacity (WHC) and improve taste through increased moisture retention (Tan, Tan, & Easa, 2020), while extended blanching times promote enzyme inactivation and prevent flavour and colour degradation (Cruz, Godinho, Aslan, Koçak, & Vieira, 2016). The combined effects of salt concentration and blanching duration are crucial for preserving quality attributes, though excessive treatment may lead to overcooking and textural damage.

Understanding the effects of brine blanching on water activity (a_w) and rehydration capacity is particularly important in freeze-dried seafood processing. Higher salt concentrations typically reduce water activity, improving shelf stability, while optimised blanching conditions enhance rehydration capacity through microstructural changes that improve moisture retention and sensory quality (Delfiya, Mohapatra, Kotwaliwale, & Mishra, 2017; Mu, Gao, Lv, & Zhao, 2024). Although blanching is a well-established step in seafood processing, most studies have focused on specific aspects such as enzyme inactivation, colour stability, and microbial reduction, while largely neglecting critical quality attributes such as instrumental texture and quanti-

tative salt content, factors that strongly influence consumer acceptance and product rehydration performance. Furthermore, previous studies may not have adequately examined interactions among processing variables. In brine blanching, salt concentration and blanching time can jointly affect mass transfer and heat-induced changes. Therefore, their individual and combined effects should be evaluated to optimise the process effectively. This oversight limits the accuracy of modelling and the effectiveness of process optimisation. The application of optimised brine blanching to freeze-dried seafood, particularly in emerging ready-to-eat product formats, also remains underexplored.

Accordingly, this study aimed to optimise brine blanching conditions, specifically salt concentration and blanching time, using a multilevel full factorial design to assess their combined effects on the physicochemical, sensory, and structural quality attributes of freeze-dried shrimp bites (*P. styliifera*).

Materials and Methods

A 3×4 full factorial experimental design was employed using Minitab 21.4.1 to investigate the effects of two processing factors: brine concentration (1%, 2%, and 3% w/v) and blanching duration (1, 3, 5, and 7 min) (Fig. 1). The blanching temperature was kept constant at 90 °C, acknowledging its critical role. Subsequently, all samples were freeze-dried and compared using appropriate quality parameters, viz., blanching loss, sensory evaluation, rehydration ratio, water activity, colour, salt content, astaxanthin, and texture parameters referred to as the response variables. The 3×4 full factorial design comprised 12 treatment combinations, with three independent processing replicates for each, resulting in a total of 36 independent experimental units.

Fresh specimens of *P. styliifera*, with an average weight of 8.15 ± 2.08 g, were purchased from the Thoppumpady Fish Landing Centre, Kochi, Kerala, India. Post-procurement, samples were transported in insulated containers with crushed ice at a 1:1 (w/w) ice-to-shrimp ratio under chilled conditions (2 ± 2 °C) to minimise metabolic and microbial activity. Upon arrival at the laboratory, shrimp were immediately rinsed with chilled potable water (4 ± 1 °C) to remove surface contaminants, then drained on sterilised stainless-steel mesh trays at ambient conditions (~ 22 °C) under aseptic handling to preserve sample integrity.

The shrimps were manually beheaded, peeled, and washed with chilled potable water before being divided into 12 uniform batches (200 ± 1.12 g each) according to the experimental design (Fig. 1). Blanching was performed at 90°C followed by rapid cooling. The blanched samples were frozen using an air-blast freezer (V15.65, Tecnomac, Italy) at -40°C , then freeze-dried in a laboratory freeze-dryer (FD-80-B, ANM Industries, India) for 14 hours at a condenser temperature of -80°C and a pressure of 0.01 mbar. The freeze-dried shrimp bites were packaged in metallised PET-PE (polyester-polyethylene laminate) pouches, sealed in airtight containers, and stored at ambient temperature ($27 \pm 2^\circ\text{C}$) until analysis.

Blanching loss was determined from the difference between the sample weight before and immediately after blanching. The blanched samples were rapidly cooled, drained under standardised conditions, and weighed. Blanching loss was calculated using the following equation.

$$\text{Weight loss (\%)} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100$$

Water activity (a_w), representing the amount of free water available in a food product for microbial growth and chemical reactions, was measured using a water activity meter (Aqua Lab CX3, Washington, USA). Readings were taken within 1–2 minutes of sample placement, with the initial value recorded as the intermediate reading. The total measurement time varied depending on sample characteristics and temperature differences.

The rehydration ratio refers to the relationship between the amount of dehydrated or dried food and the liquid needed to restore it to its original or desired consistency. The rehydration properties were assessed according to Duan, Jiang, Wang, Yu, and Wang (2011) with minor modifications. The samples were immersed in hot water (maintained at 80°C) for one minute, with a water-to-sample concentration of 20:1 (v/w). After the immersion, the samples were carefully drained and gently dabbed with paper towels to remove excess surface moisture. Following this, the rehydrated samples were weighed. The rehydration ratio was calculated as the ratio of the weight of the rehydrated sample to the weight of the corresponding dry sample.

Rehydration ratio =

$$\frac{\text{Weight of sample after rehydration}}{\text{Weight of corresponding dry sample}} \times 100$$

Colour analysis was performed using the Colour Flex XE Spectro colourimeter (Hunter Associates Laboratory, Reston, USA), with a D-65 illuminant and 10° observer standard according to Xu et al. (2022). The colour was quantified through three parameters: L^* (lightness), a^* (red-green axis), and b^* (yellow-blue axis). The sample was placed halfway into a circular glass cell with a 2.5-inch diameter, positioned in the instrument's groove for measurement.

Salt content was analysed according to Tran et al. (2022) using a titrimetric method involving 0.1 N silver nitrate (AgNO_3) as the titrant and potassium chromate (K_2CrO_4) as the indicator. A 2 mL homogenised sample was transferred into a 100 mL volumetric flask and partially diluted with distilled water. To adjust the pH, five drops of 1% phenolphthalein (PP) were added. If the mixture was colourless, 0.1 N sodium bicarbonate (NaHCO_3) was added dropwise until a faint pink colour developed. In cases where the solution was initially pale pink, it was neutralised using 0.01 N acetic acid until the pink colour disappeared. The volume was then made up to 100 mL with distilled water. Subsequently, five drops of 10% potassium chromate solution were added as an indicator, and the mixture was titrated with 0.1 N AgNO_3 until a persistent brick-red colour signified the endpoint. Salt content was calculated based on the volume of AgNO_3 used during titration.

The astaxanthin content in the sample was determined using a UV-Visible spectrophotometer (UV/VIS-1800, Shimadzu, Japan), and analysed according to Tran et al. (2022). A 7.5 g portion of the sample was finely ground and extracted with 100 mL of acetone to release the astaxanthin. The resulting mixture was filtered using Whatman No. 1 filter paper. A 1 mL aliquot of the filtrate was then mixed with an additional 1 mL of acetone and cooled at 4°C for 20 minutes to stabilise the extract. The absorbance of the prepared solution was measured at 455 nm. The astaxanthin concentration was calculated using the calibration curve with the equation $y = 0.28245x$ ($R^2 = 0.99982$).

Texture analysis of shrimp bites was conducted using a texture analyzer (Lloyd Instruments LRX

plus, Lloyd Instruments Ltd, Hampshire, UK). The test was performed on uniformly cut, rehydrated shrimp bites following Chandra and Shamasundar (2015) with minor modifications. A compression test was executed with the following settings: pre-test speed 1.0 mm/s, test speed 1.0 mm/s, post-test speed 1.0 mm/s, and compression distance of 5 mm. A trigger force of 5 g was applied to initiate measurement. The firmness was recorded as the peak force (N) required to compress the sample. Each analysis was conducted in triplicate, and the average value was reported.

Sensory evaluation was conducted using a panel of 20 panellists familiar with seafood quality attributes. The panellists assessed the rehydrated freeze-dried shrimp bites for colour, aroma, taste, flavour, and overall acceptability using a 9-point hedonic scale, where 9 = "like extremely" and 1 = "dislike extremely". Each sample was coded with a random three-digit number and presented in a randomised order to minimise bias. Panellists were instructed to cleanse their palate with warm water between samples. Mean scores were recorded for each attribute, and the overall sensory score was calculated as the average of all five attribute scores (Parvathy, Bindu, & Joshy, 2017).

All physicochemical and texture experiments were carried out in triplicate, while sensory evaluation was conducted with 20 panellists. For sensory analysis, a linear mixed-effects model was employed, with panellists treated as a random effect to account for inter-individual variability. Results are expressed as mean $\pm$ standard deviation (SD). For each physicochemical and instrumental response, a two-factor factorial ANOVA was performed to evaluate the main effects of blanching duration and brine concentration and their interaction. Treatment factors were considered at three brine concentrations (1%, 2%, and 3%) and four blanching durations (1, 3, 5, and 7 min). Statistical significance was assessed at $\alpha = 0.05$. Where significant factor effects were detected, appropriate post-hoc multiple comparisons were performed to identify differences among factor levels. Multi-response optimisation was performed using the desirability function approach in Minitab (MINITAB 21.4.1), with goals set to maximise favourable attributes and minimise unfavourable ones.

Results and Discussion

The multilevel factorial design effectively captured the complex interactions between brine concentration and blanching duration on freeze-dried shrimp bite quality. Table 1 presents all measured response variables and factors along with their respective experimental runs.

Processing conditions significantly affected weight loss during blanching, with both blanching time and salt concentration showing strong main effects ($p < 0.01$). The model demonstrated good predictive capability ($R^2(\text{adj}) = 0.8257$), though the interaction between factors was not significant ($p = 0.059$).

Salt concentration was the dominant factor influencing blanching loss. A 3% salt solution dramatically increased weight loss compared to lower concentrations, while extending blanching time from 1 to 7 minutes also resulted in substantial increases. The absence of a significant interaction indicates these factors operate independently through distinct mechanisms. The progressive increase in blanching loss reflects sequential cellular degradation. Initial thermal treatment inactivates heat-labile enzymes and causes mild protein denaturation without major structural disruption (Reis, 2016). However, prolonged exposure triggers extensive coagulation of myofibrillar proteins, particularly of myosin heavy chains and actin filaments, expelling moisture from the contracting protein matrix (Rahman & Perera, 2007). Salt concentration modulates these effects osmotically. Low concentrations (1-2%) preserve cellular membrane integrity while enabling controlled enzyme inactivation, promoting selective water removal without compromising structural components (Ashie, Simpson, & Smith, 1996). Conversely, high concentrations (3%) create hypertonic conditions causing rapid cellular dehydration, membrane rupture, and extensive leaching of intracellular materials, including proteins, amino acids, and water-soluble vitamins (García & Ardila, 2009).

Water activity was exceptionally sensitive to processing conditions ($p < 0.001$ for both factors), with the model demonstrating an excellent fit ($R^2(\text{adj}) = 99.41\%$). A borderline interaction effect ($p = 0.053$) suggests subtle interdependencies between factors.

The main effects plot (Fig. 2A) shows a strong, systematic decrease in water activity with increasing

Table 1. Response variables and factors along with their respective experimental run

Treatment	Factors		Responses		Water activity	Rehydration ratio	L*	a*	b*	Salt content (mg/g)	Astaxanthin (mg/g)	Hardness (N)	Springiness (N)	Gumminess (kgf.mm)	Stiffness (N/mm)
	Blanching time	Blanching concentration	Blanching loss (%)	Responses											
1	1	1	18.53 ± 2.79	95.73 ± 0.24	0.318 ± 0.012	8.19 ± 0.08	95.73 ± 0.24	3.09 ± 0.12	7.10 ± 0.11	28.67 ± 0.35	0.0207 ± 0.0003	11.24 ± 1.44	0.50 ± 0.32	1.05 ± 0.23	1.39 ± 0.70
2	1	2	23.17 ± 2.48	95.60 ± 0.40	0.298 ± 0.010	7.63 ± 0.14	95.60 ± 0.40	3.26 ± 0.13	7.38 ± 0.09	36.37 ± 0.34	0.0220 ± 0.0001	20.93 ± 1.66	0.56 ± 0.10	1.85 ± 0.36	2.39 ± 0.40
3	1	3	49.27 ± 1.91	94.47 ± 0.23	0.272 ± 0.014	6.69 ± 0.09	94.47 ± 0.23	3.93 ± 0.13	7.68 ± 0.22	39.13 ± 5.02	0.0230 ± 0.0002	24.25 ± 6.05	0.58 ± 0.21	2.58 ± 0.64	3.01 ± 0.53
4	3	1	22.47 ± 2.34	95.20 ± 0.12	0.292 ± 0.013	7.80 ± 0.14	95.20 ± 0.12	3.22 ± 0.12	7.41 ± 0.12	31.43 ± 0.20	0.0233 ± 0.0003	13.46 ± 0.62	0.61 ± 0.17	3.28 ± 0.56	1.61 ± 0.62
5	3	2	28.43 ± 3.99	95.03 ± 0.38	0.262 ± 0.020	7.15 ± 0.15	95.03 ± 0.38	3.40 ± 0.13	7.68 ± 0.19	39.23 ± 0.32	0.0247 ± 0.0003	22.10 ± 1.52	0.60 ± 0.54	4.10 ± 0.31	2.47 ± 0.15
6	3	3	44.23 ± 2.49	94.30 ± 0.17	0.238 ± 0.031	6.34 ± 0.12	94.30 ± 0.17	4.05 ± 0.13	8.00 ± 0.11	46.60 ± 0.26	0.0260 ± 0.0002	31.61 ± 0.71	0.97 ± 0.77	4.92 ± 0.24	4.00 ± 0.27
7	5	1	37.20 ± 1.88	94.97 ± 0.18	0.272 ± 0.050	7.39 ± 0.10	94.97 ± 0.18	3.30 ± 0.10	7.70 ± 0.13	34.33 ± 0.86	0.0258 ± 0.0003	15.31 ± 0.92	0.33 ± 0.11	5.22 ± 0.17	1.97 ± 0.15
8	5	2	42.40 ± 2.72	95.13 ± 0.18	0.248 ± 0.010	6.66 ± 0.14	95.13 ± 0.18	3.55 ± 0.09	8.01 ± 0.24	42.17 ± 0.23	0.0270 ± 0.0002	26.69 ± 0.24	0.83 ± 0.68	6.07 ± 0.64	3.10 ± 0.44
9	5	3	48.90 ± 2.32	94.53 ± 0.20	0.222 ± 0.011	5.93 ± 0.09	94.53 ± 0.20	4.10 ± 0.11	8.31 ± 0.21	49.23 ± 0.38	0.0287 ± 0.0001	34.85 ± 1.05	0.88 ± 0.56	6.95 ± 0.73	4.04 ± 0.31
10	7	1	34.33 ± 2.58	94.63 ± 0.15	0.252 ± 0.015	6.82 ± 0.08	94.63 ± 0.15	3.39 ± 0.08	7.99 ± 0.14	37.30 ± 0.31	0.0278 ± 0.0002	18.64 ± 1.95	0.66 ± 0.38	7.22 ± 0.24	2.12 ± 0.22
11	7	2	38.97 ± 5.42	94.67 ± 0.09	0.228 ± 0.020	6.19 ± 0.13	94.67 ± 0.09	3.70 ± 0.01	8.30 ± 0.11	45.43 ± 0.95	0.0298 ± 0.0001	29.26 ± 1.82	0.82 ± 0.15	8.02 ± 0.59	3.50 ± 0.12
12	7	3	55.40 ± 2.64	93.57 ± 0.15	0.202 ± 0.030	5.28 ± 0.07	93.57 ± 0.15	4.25 ± 0.13	8.57 ± 0.08	52.47 ± 0.52	0.0310 ± 0.0001	38.80 ± 0.62	1.15 ± 0.63	9.03 ± 0.44	4.36 ± 0.43

*Values represent mean ± SD of three replicates

processing intensity. The interaction plot (Fig. 2B) shows largely parallel lines with minor deviations, consistent with the statistically borderline interaction effect. This indicates that while the individual effects of time and salt concentration are strong and consistent, the effect of salt may be marginally more pronounced at longer blanching times. Both factors systematically reduced water activity, with salt concentration having a marginally stronger effect. Relative to the 3% baseline conditions, 1% salt solutions increased a_w by 0.025 units, while reducing blanching time from 7 to 1 min increased a_w by 0.031 units. The reduction in water activity reflects fundamental changes in protein structure affecting water-binding capacity. Thermal processing disrupts native protein conformation, initially exposing hydrophobic residues and increasing the number of water-binding sites, but subsequently promoting protein aggregation and cross-linking that reduces overall water-holding capacity (Damodaran, 2017). Salt operates through dual mechanisms: high concentrations form extensive ion hydration shells that bind free water molecules, while osmotic pressure promotes cellular dehydration during blanching, removing both free and weakly bound water fractions (Joardder, Mourshed, & Masud, 2019; Rahman, 2020). The achieved water activity levels ($a_w < 0.3$) fall well below the thresholds required for pathogenic bacteria ($a_w > 0.95$) and most spoilage organisms (Barbosa-Cánovas, Fontana, Schmidt, & Labuza, 2008). The measured water activity values below 0.30 indicate low water availability for microbial growth and are therefore consistent with good microbiological stability; however, microbial safety and shelf life were not directly evaluated in the present study.

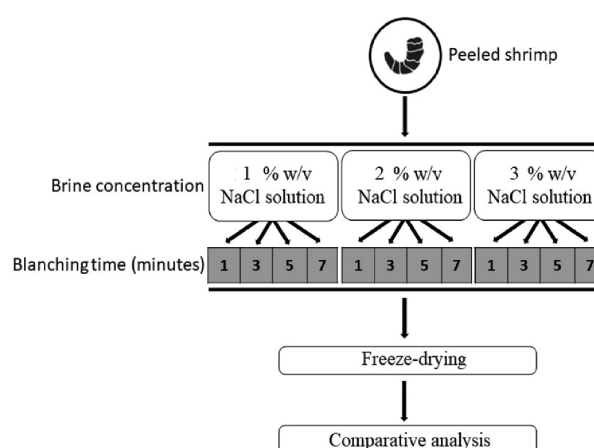
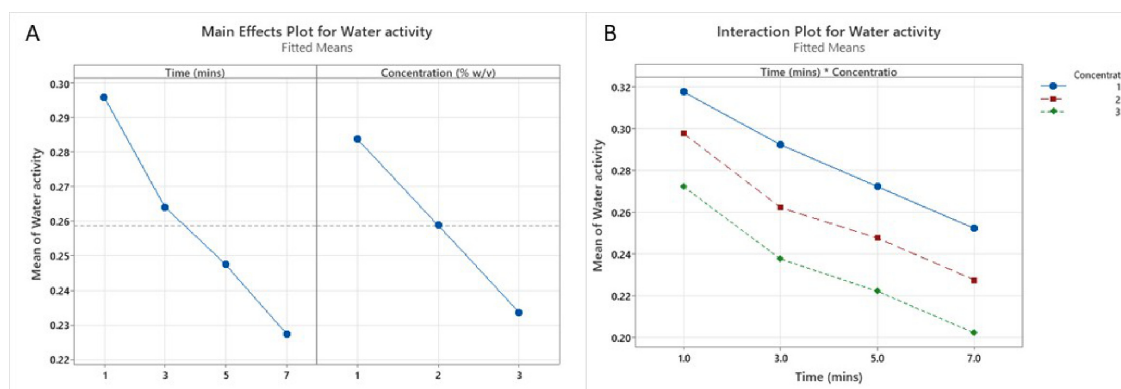


Fig. 1. Experimental Design

The rehydration ratio demonstrated strong dependence on both processing parameters ($p < 0.01$), with the model explaining 94.26% of the variation ($R^2(\text{adj}) = 0.9426$). The interaction effect was negligible ($p = 0.974$), confirming that the factors contributed independently. The main effects plot (Fig. 3A) shows a progressive decrease in rehydration ratio with increasing processing time and concentration, indicating reduced water-absorption capacity under more intense processing conditions. The interaction plot (Fig. 3B) displays nearly parallel trends with slight divergence at higher levels, suggesting that both variables act consistently and independently to reduce rehydration, with only minor interaction effects.

Both factors negatively impacted rehydration capacity, with salt concentration showing slightly stronger effects. Compared to 3% salt solutions, 1% treatments improved rehydration ratios by 0.71 units,

Fig. 2. Main Effect (A) & Interaction Effects (B) Plot for Water activity (a_w)

while reducing blanching time from 7 to 1 min increased ratios by 0.75 units. Superior rehydration under gentle processing conditions reflects the preservation of the native muscle fibre architecture, which is essential for water uptake. Minimal thermal treatment maintains the integrity of the sarcoplasmic reticulum and T-tubule systems, preserving capillary networks necessary for rapid water penetration (Offer & Trinick, 1983). Extended processing causes irreversible structural damage through protein denaturation and cross-linking. Disulfide bond formation between cysteine residues creates dense, impermeable networks that restrict water penetration during rehydration (Tornberg, 2005). Simultaneously, sarcoplasmic protein coagulation fills interfibrillar spaces, reducing porosity essential for efficient water uptake. High salt concentrations exacerbate these effects through osmotic-induced cellular collapse and membrane damage, creating tortuous diffusion pathways that significantly impair rehydration kinetics and final moisture content (Munns, 2002).

Lightness was significantly affected by both processing parameters ($p < 0.01$), though the model explained a moderate portion of the variation ($R^2(\text{adj}) = 0.6482$). No significant interaction was observed ($p = 0.637$).

Minimal processing conditions best preserved product lightness. Reducing blanching time from 7 to 1 min increased L^* values by 0.45 units, while lower salt concentrations (1-2%) maintained superior lightness compared to 3% treatments (improvements of 0.31 and 0.29 units, respectively). Superior lightness values under mild conditions reflect maintenance of the native protein structure responsible for light-scattering properties. The characteristic pale, translucent appearance of high-quality shrimp results from ordered myofibrillar protein arrangement and the absence of light-absorbing pigment-protein complexes (Gao et al., 2016).

Both redness and yellowness showed high sensitivity to processing conditions ($p < 0.01$ for redness, $p < 0.001$ for yellowness), with models explaining

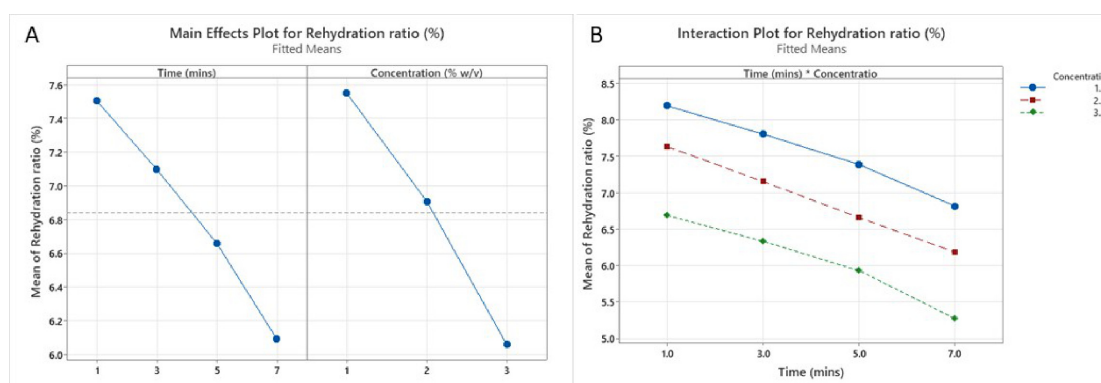


Fig. 3. Main Effect (A) & Interaction Effects (B) Plot for Rehydration Ratio (%)

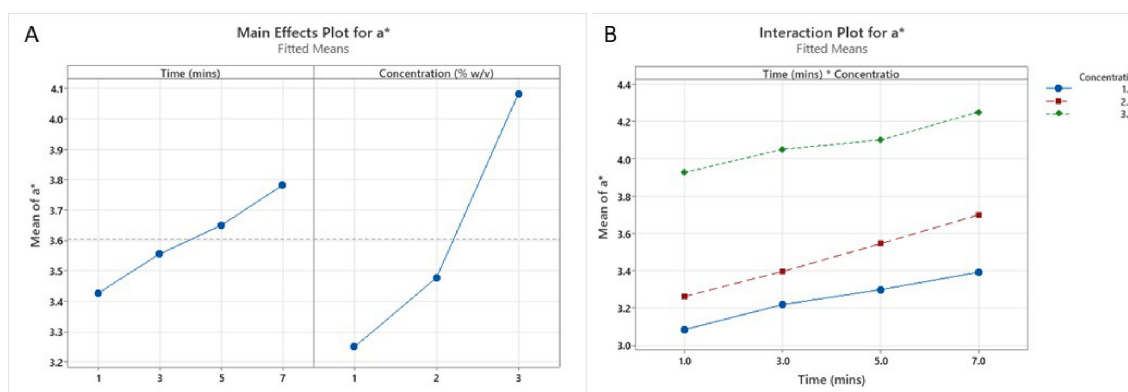


Fig. 4. Main Effect (A) & Interaction Effects (B) Plot for a^*

98.52% and 99.50% of the variation, respectively. Neither parameter showed significant interactions. The main effects plot (Fig. 4A) indicates a noticeable change in a^* values with increasing processing parameters, reflecting alterations in the redness of the product during processing. The interaction plot (Fig. 4B) shows largely parallel lines with small variations, suggesting that the combined influence of the variables on colour development is relatively weak.

Colour intensification occurred with increased processing severity. For redness, 7-minute blanching increased a^* values by 0.36 units compared to 1-minute treatments, while 3% salt solutions enhanced redness by 0.83 units relative to 1% treatments. Yellowness showed an even stronger response, with 7-minute blanching and 3% salt increasing b^* values by 0.90 and 0.59 units, respectively. The progressive increase in redness and yellowness may be associated with increased exposure or extractability of carotenoid pigments during thermal processing (Pattanaik, 2018); however, pigment release and stabilisation were not directly characterised in this study. Salt concentration enhances these effects through multiple mechanisms: promoting protein denaturation to facilitate pigment release, providing ionic environments that stabilise pigments against oxidative degradation, and concentrating pigment compounds through osmotic moisture withdrawal (Pandiselvam et al., 2022).

Salt uptake increased systematically with both processing parameters ($p < 0.05$), with the model explaining 87.11% of the variation. Extended blanching (7 vs. 1 minute) increased salt content by 10.34 mg/g, while higher brine concentrations (3 vs. 1%) increased uptake by 13.93 mg/g. Neither parameter

showed significant interactions. The main effects plot (Fig. 5A) shows a gradual variation in salt content as processing conditions increase, indicating that both time and concentration influence the final salt level in the product matrix. The interaction plot (Fig. 5B) reveals mostly parallel trends with slight deviations, indicating limited interaction between the factors affecting salt retention.

Enhanced salt penetration with extended blanching reflects progressive membrane damage, which increases tissue permeability, facilitating deeper ion diffusion (Thorarinsdottir, Arason, Geirsdottir, Bogason, & Kristbergsson, 2002). The dominant concentration effect follows Fick's laws of diffusion, where steeper gradients dramatically accelerate mass transfer. Remarkably, astaxanthin content increased with processing intensity ($p < 0.001$, $R^2(\text{adj}) = 97.99\%$). Seven-minute blanching increased astaxanthin levels by 0.0076 mg/g compared with 1-minute treatments, while 3% salt solutions increased astaxanthin content by 0.0028 mg/g relative to 1% treatments. Neither parameter showed significant interactions. The main effects plot (Fig. 6A) shows an increasing trend in astaxanthin content with increasing processing intensity, consistent with progressive liberation of protein-bound pigment during extended treatment.

The interaction plot (Fig. 6B) shows moderately parallel lines with small variation, indicating a relatively minor interaction effect between the studied variables.

This finding suggests that controlled thermal processing facilitates the extraction and liberation of bound carotenoids from protein complexes. Native shrimp astaxanthin exists primarily in esterified

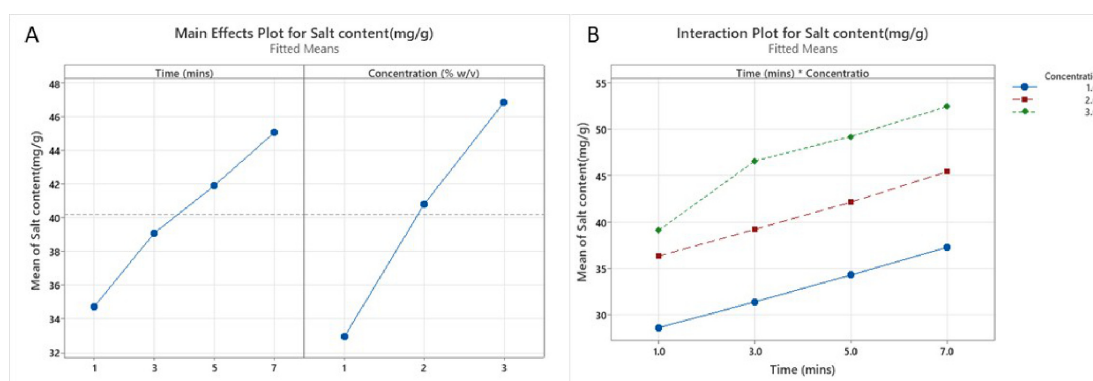


Fig. 5. Main Effect (A) & Interaction Effects (B) Plot for Salt content (mg/g)

forms bound to proteins, making it less accessible for measurement (Subramanian et al., 2015). The observed increase in astaxanthin content with increasing processing intensity may be associated with greater release or extractability of carotenoid pigments from the shrimp matrix following thermal and salt-induced structural changes.

Both hardness and stiffness showed strong responses to processing conditions ($p < 0.001$ and $p < 0.05$, respectively), with models explaining 83.01% and 89.29% of the variation. Extended blanching increased hardness by 10.09 N and stiffness by 1.07 N/mm, while high salt concentrations showed even stronger effects (increases of 17.72 N and 2.08 N/mm, respectively). Neither parameter showed significant interactions. The main effects plot (Fig. 7A) indicates a clear increase in hardness with increasing processing conditions, suggesting the development of a more compact structural network in the product. The interaction plot (Fig. 7B) shows slight divergence among the lines, implying that the combined influence of the factors may contribute to structural strengthening.

The observed increase in hardness and stiffness with increasing processing intensity may be associated with progressive thermal denaturation and aggregation of muscle proteins, resulting in a more compact protein matrix. Thermal processing unfolds native protein structures, exposing reactive groups that form intermolecular bonds, creating three-dimensional networks that enhance mechanical strength (Sun & Holley, 2011). Salt concentration proved dominant in texture development, operating through multiple mechanisms. Ionic strength increases protein solubility and swelling, promoting protein-protein interactions essential for gel formation,

while salt ions mediate cross-linking through electrostatic interactions, creating stronger, more elastic networks (Lanier, Carvajal, & Yongsawatdigul, 2005; Xiang et al., 2025). The greater hardness and stiffness observed at higher brine concentrations may be associated with salt-induced changes in muscle protein hydration, solubility, and aggregation during heating.

Unlike other texture parameters, springiness showed a significant salt concentration effect ($p = 0.004$) but no significant time effect ($p = 0.061$). The model explained 33.76% of the variation, suggesting other unmeasured factors significantly influence this parameter. Neither parameter showed significant interactions. The main effects plot (Fig. 8A) shows variations in springiness across the processing conditions, reflecting modifications in the elastic properties of the product structure. The interaction plot (Fig. 8B) shows nearly parallel lines, indicating a minimal interaction effect between the variables.

High salt concentrations (3%) improved springiness by 0.37 compared to low concentrations (1%), reflecting salt-induced protein modifications that enhance elastic properties. Salt promotes myofibrillar protein solubilisation and swelling, thereby facilitating the formation of more continuous and elastic gel networks capable of better shape recovery after deformation (Lanier et al., 2005).

Gumminess demonstrated exceptional processing sensitivity ($p < 0.001$), with the model explaining 99.89% of the variation, the highest explanatory power among all measured parameters. A borderline interaction effect ($p = 0.078$) suggests potential synergistic effects between processing factors. The main effects plot (Fig. 9A) shows an increase in

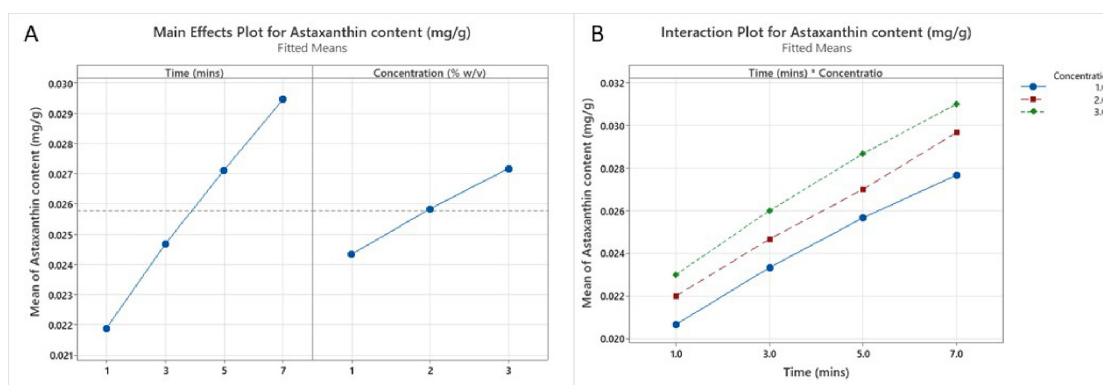


Fig. 6. Main Effect (A) & Interaction Effects (B) Plot for Astaxanthin Content (mg/g)

gumminess with both processing parameters. The interaction plot (Fig. 9B) displays slight deviations from parallel lines, consistent with the borderline interaction effect, suggesting that the effect of salt concentration may be slightly enhanced at longer blanching times. An extended blanching increased gumminess by 6.26 N, while high salt concentrations increased it by 1.68 N.

Chewiness showed more moderate but significant responses ($p = 0.004$ for time, $p < 0.001$ for salt concentration), with 66.79% of the variation explained. The effects were smaller in magnitude (0.09 and 0.17 kgf.mm increases for time and salt, respectively) but followed similar patterns. The dramatic gumminess response reflects the formation of an extensive protein gel network through synergistic heat and salt effects. Gumminess, representing the energy required to disintegrate a semisolid food for swallowing, showed the strongest processing response among all texture parameters, making it an excellent indicator of the degree of protein modification achieved during processing.

Sensory evaluation using a linear mixed-effects model revealed significant effects of both processing parameters on overall acceptability ($p < 0.001$ for both time and salt concentration). Estimation was done with maximum likelihood, and degrees of freedom were adjusted using the Kenward–Roger method, which improves accuracy for small sample sizes. The linear mixed-effects model indicated significant effects of blanching time, brine concentration, and their interaction on overall acceptability ($p < 0.001$). Table 2 presents the sensory evaluation results across all treatment combinations, revealing clear patterns in consumer acceptability. The highest sensory scores were achieved using minimal processing conditions, particularly Treatment 1 (1 min, 1% brine), which scored 8.61 ± 0.21 , indicating “like very much” on the 9-point hedonic scale. The interaction plot (Fig. 10) shows clear deviations from parallel lines, confirming the significant interaction between processing factors. The significant time $\times$ brine concentration interaction indicates that the effect of blanching duration on sensory acceptability

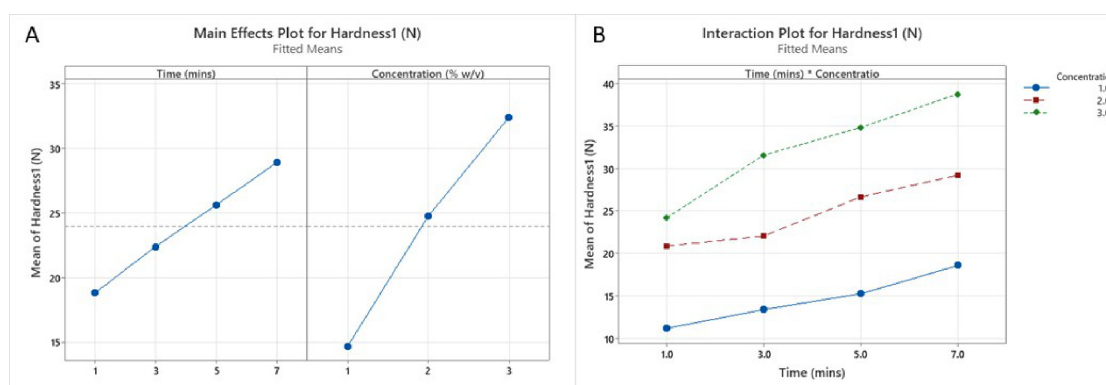


Fig. 7. Main Effect (A) & Interaction Effects (B) Plot for Hardness (N)

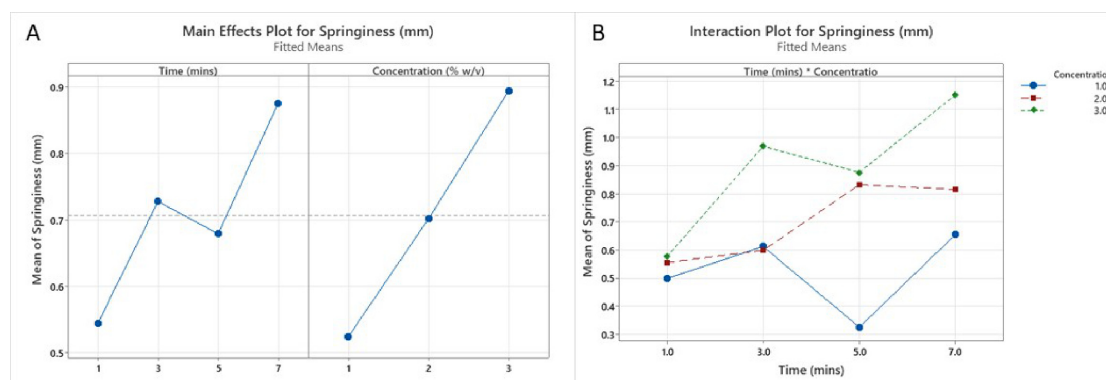


Fig. 8. Main Effect (A) & Interaction Effects (B) Plot for Springiness (mm)

depended on the brine concentration. Therefore, the main effects should be interpreted together with the interaction rather than independently. At a low salt concentration (1%), sensory scores decreased progressively with extended blanching time (from 8.61 at 1 minute to 7.98 at 7 minutes). However, at a moderate salt concentration (2%), the decline was less pronounced, whereas at a high concentration (3%), sensory scores remained relatively stable across different blanching times.

Salt concentration emerged as a dominant factor affecting sensory acceptability. Compared to the 3% baseline, 1% salt solutions improved sensory scores by 0.73 points on average, while 2% solutions increased scores by 0.59 points. The effect of blanching time was complex due to the significant interaction, with shorter processing times (1-3 minutes) generally yielding higher acceptability scores. The variance components analysis revealed that panellist variability accounted for 76.75% of the

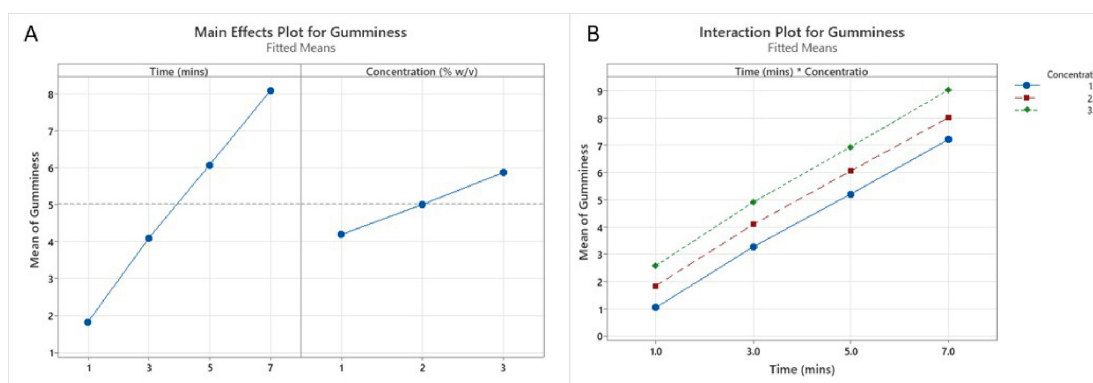


Fig. 9. Main Effect (A) & Interaction Effects (B) Plot for Gumminess

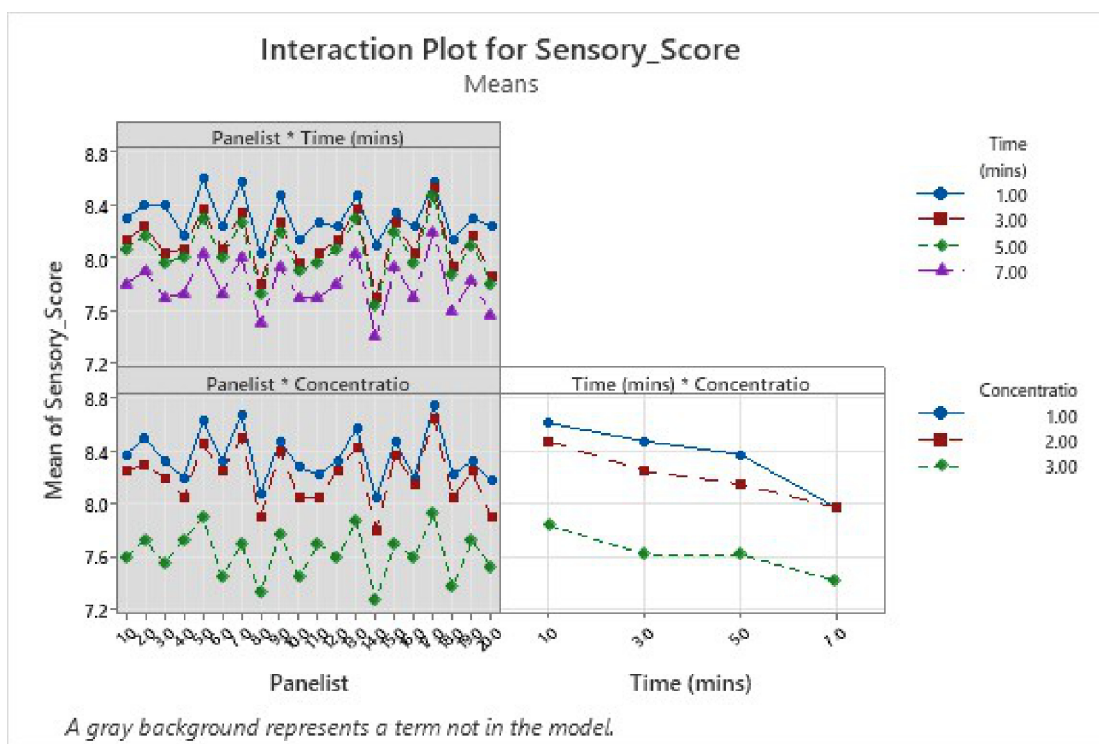


Fig. 10. Interaction Effects Plot for Sensory Score

Table 2. Effect of brine blanching conditions on sensory acceptability of freeze-dried shrimp bites

Treatments	Time (mins)	Concentration (% w/v)	Sensory Score
1	1	1	8.61 $\pm$ 0.21
2	1	2	8.48 $\pm$ 0.21
3	1	3	7.84 $\pm$ 0.20
4	3	1	8.48 $\pm$ 0.20
5	3	2	8.25 $\pm$ 0.24
6	3	3	7.62 $\pm$ 0.21
7	5	1	8.38 $\pm$ 0.21
8	5	2	8.15 $\pm$ 0.24
9	5	3	7.62 $\pm$ 0.21
10	7	1	7.98 $\pm$ 0.21
11	7	2	7.98 $\pm$ 0.20
12	7	3	7.42 $\pm$ 0.21

*Values represent mean $\pm$ SD of sensory scores on a 9-point hedonic scale (n=20 panellists)

total variance, highlighting substantial individual differences in sensory perception. This high degree of variability is common in sensory science, underscoring the importance of using adequate panel sizes and appropriate statistical models, like the mixed-effects model employed here, to account for inter-individual variation.

The multi-response optimisation integrated predictions from both standard least-squares models for the physicochemical and textural responses and the mixed-effects model for the sensory data. To incorporate the sensory predictions into Minitab's Response Optimiser, which is designed for fixed-effects models, the conditional means for each Time $\times$ Concentration combination were calculated from the mixed model output; these values represent the predicted sensory score for each processing condition while accounting for the random variation introduced by the panellists. The resulting matrix of predicted values for all fourteen quality parameters was used as the input for the numerical optimisation, with goals set to maximise sensory score, chewiness, springiness, astaxanthin content, all colour parameters (L^* , a^* , b^*), and rehydration ratio, while simultaneously minimising stiffness, gumminess, hardness, salt content, water activity, and blanching loss.

The numerical desirability analysis identified 3 min of blanching at 2% brine concentration as the most desirable treatment combination among the condi-

tions evaluated, with a composite desirability of 0.511. This value represents a balanced compromise among the competing quality objectives, as the predicted responses under these optimal conditions demonstrate excellent sensory acceptability, balanced texture characteristics, enhanced astaxanthin content with controlled salt uptake, good rehydration capacity combined with shelf-stable water activity, and acceptable processing efficiency. The moderate composite desirability reflects the trade-offs among the different quality attributes. The 3-min blanching treatment at 2% brine provided the most desirable balance among the evaluated sensory, physicochemical, rehydration, and textural properties under the conditions tested. However, microbial and storage studies are required to confirm its suitability for food safety and preservation.

This study demonstrated that brine concentration and blanching duration significantly affect the bite quality of freeze-dried shrimp across all measured physicochemical, sensory, and textural attributes. Gentle treatments (1–3 min, 1–2% brine) generally resulted in higher sensory acceptability and rehydration capacity, whereas more intensive treatments (5–7 min, 3% brine) resulted in lower water activity and higher measured astaxanthin content but reduced sensory acceptability and rehydration performance. Multi-response optimisation identified 3 min of blanching at 2% brine concentration as the most desirable combination (composite

desirability = 0.511). Salt concentration was the dominant factor affecting most quality attributes through osmotic effects on cellular integrity and protein solubilisation, while blanching time had secondary effects through thermal-induced protein modifications. No statistically significant interaction between the two factors was detected for any response except sensory acceptability, indicating that main effects were generally sufficient to interpret the results.

These findings provide a practical basis for selecting brine blanching conditions in freeze-dried shrimp production, allowing processors to adjust parameters toward either sensory appeal or preservation characteristics. The study's factor levels were limited (three salt concentrations, four blanching times), and no untreated control was included in the factorial design, limiting baseline comparison. Before commercial application, the identified treatment combination should be further validated through independent processing trials, microbial evaluation, and storage studies. Future work should expand the range of factors, include untreated controls, incorporate economic and environmental considerations into the optimisation framework, and improve generalisability of the findings.

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References

- Ashie, I. N. A., Simpson, B. K., & Smith, J. P. (1996). Mechanisms for controlling enzymatic reactions in foods. *Critical Reviews in Food Science and Nutrition*, 36(1–2), 1–30. <https://doi.org/10.1080/10408399609527716>
- Barbosa-Cánovas, G. V., Fontana, A., Schmidt, S. J., & Labuza, T. P. (2008). *Water activity in foods: Fundamentals and applications*. Blackwell Publishing & IFT Press. <https://doi.org/10.1002/9780470376454>
- Chakraborty, K. (2025). Recent advances in shrimp nutrition and the nutritional significance of shrimp to human health. In P. Singh, A. Singh, A. Tyagi, & S. Benjakul (Eds.), *Shrimp culture technology: Farming, health management and quality assurance* (pp. 313–339). Springer. <https://doi.org/10.1007/978-981-97-8549-0>
- Chandra, M. V., & Shamasundar, B. A. (2015). Texture profile analysis and functional properties of gelatin from the skin of three species of fresh water fish. *International Journal of Food Properties*, 18(3), 572–584. <https://doi.org/10.1080/10942912.2013.845787>
- Cruz, R. M. S., Godinho, A. I. A., Aslan, D., Koçak, N. F., & Vieira, M. C. (2016). Modeling the kinetics of peroxidase inactivation, colour and texture changes of Portuguese cabbage (*Brassica oleracea* L. var. costata DC) during UV-C light and heat blanching. *International Journal of Food Studies*, 5(2), 180–192. <https://doi.org/10.7455/ijfs/5.2.2016.a6>
- Cyprian, O., Nguyen, M. V., Sveinsdottir, K., Jonsson, A., Thorkelsson, G., & Arason, S. (2015). Influence of lipid content and blanching on capelin (*Mallotus villosus*) drying rate and lipid oxidation under low temperature drying. *Journal of Food Process Engineering*, 39(3), 237–246. <https://doi.org/10.1111/jfpe.12215>
- Damodaran, S. (2017). Amino acids, peptides, and proteins. In S. Damodaran & K. L. Parkin (Eds.), *Fennema's food chemistry* (pp. 235–356). CRC press.
- Delfiya, A., Mohapatra, D., Kotwaliwale, N., & Mishra, A. K. (2018). Effect of microwave blanching and brine solution pretreatment on the quality of carrots dried in solar biomass hybrid dryer. *Journal of Food Processing and Preservation*, 42(2), Article e13510. <https://doi.org/10.1111/jfpp.13510>
- Duan, Z. H., Jiang, L. N., Wang, J. L., Yu, X. Y., & Wang, T. (2011). Drying and quality characteristics of tilapia fish fillets dried with hot air-microwave heating. *Food and Bioprocesses processing*, 89(4), 472–476. <https://doi.org/10.1016/j.fbp.2010.11.005>
- Galal Khallaf, A., Abdelbaset-Donya, A., Hamza, W., & Mohammed-Geba, K. (2021). Molecular tools for assuring human health and environment-friendly frozen shellfish products in the United Arab Emirates markets. *Food Chemistry: Molecular Sciences*, 3, Article 100028. <https://doi.org/10.1016/j.fochms.2021.100028>
- Gao, R., Feng, X., Li, W., Yuan, L., Ge, J., Lu, D., Chen, B., & Yu, G. (2016). Changes in properties of white shrimp (*Litopenaeus vannamei*) protein during thermal denaturation. *Food Science and Biotechnology*, 25(1), 21–26. <https://doi.org/10.1007/s10068-016-0003-0>
- García, M. J., & Ardila, A. M. (2009). Cell volume variation under different concentrations of saline solution (NaCl). *Colombian Journal of Anaesthesiology*, 37(2), 101–109. [https://doi.org/10.1016/S0120-3347\(09\)72002-7](https://doi.org/10.1016/S0120-3347(09)72002-7)
- Gopan, A., Anandan, R., Maiti, M. K., Lalappan, S. L., Devanand, T. N., & Varghese, T. (2020). Nutritional profiling of kiddi shrimp, *Parapenaeopsis stylifera* (H. Milne Edwards, 1837) collected from southwest coast of India. *Journal of Experimental Zoology India*, 23(2), 1943–1949.

- Joardder, M. U. H., Mourshed, M., & Masud, M. H. (2019). *State of bound water: Measurement and significance in food processing*. Springer.
- Lanier, T. C., Carvajal, P. A., & Yongsawatdigul, J. (2005). Surimi gelation chemistry. In J. W. Park (Ed.), *Surimi and surimi seafood* (pp. 435–489). CRC Press.
- Liew, J. Y., Zain, N. S. M., Hashim, D. S., Bakar, T. H. S. T. A., Mahshar, M., & Rosli, F. (2021). An exploration of the key factors affecting consumer buying behaviour of instant food products: A case study of Kota Bharu. *IOP Conference Series Earth and Environmental Science*, 756(1), Article 012014. <https://doi.org/10.1088/1755-1315/756/1/012014>
- Mohsin, M., Hengbin, Y., Luyao, Z., Rui, L., Chong, Q., & Mehak, A. (2022). An application of multiple-criteria decision analysis for risk prioritization and management: A case study of the fisheries sector in Pakistan. *Sustainability*, 14, Article 8831. <https://doi.org/10.3390/su14148831>
- Mohsin, M., Mu, Y., Memon, A. M., Kalhor, M. T., & Shah, S. B. H. (2017). Fishery stock assessment of Kiddi shrimp (*Parapenaeopsis stylifera*) in the northern Arabian Sea coast of Pakistan by using surplus production models. *Chinese Journal of Oceanology and Limnology*, 35(4), 936–946. <https://doi.org/10.1007/s00343-017-6096-3>
- Mu, Y., Gao, W., Lv, S., & Zhao, C. (2024). *Enhancing the quality of Jerusalem artichoke chips: The role of pretreatment optimization in combined vacuum freezing and hot air drying*. Research Square. <https://doi.org/10.21203/rs.3.rs-5036118/v1>
- Munns, R. (2002). Comparative physiology of salt and water stress. *Plant, Cell & Environment*, 25(2), 239–250. <https://doi.org/10.1046/j.0016-8025.2001.00808.x>
- Nwankwo, C. S., Okpomor, E. O., Dibagar, N., Wodecki, M., Zwierz, W., & Figiel, A. (2023). Recent developments in the hybridization of the freeze-drying technique in food dehydration: A review on chemical and sensory qualities. *Foods*, 12(18), Article 3437. <https://doi.org/10.3390/foods12183437>
- Offer, G., & Trinick, J. (1983). On the mechanism of water holding in meat: The swelling and shrinking of myofibrils. *Meat Science*, 8(4), 245–281. [https://doi.org/10.1016/0309-1740\(83\)90013-X](https://doi.org/10.1016/0309-1740(83)90013-X)
- Pandiselvam, R., Tak, Y., Olum, E., Sujayasree, O. J., Tekgöl, Y., Koç, G. C., Kaur, M., Nayi, P., Kothakota, A., & Kumar, M. (2022). Advanced osmotic dehydration techniques combined with emerging drying methods for sustainable food production: Impact on bioactive components, texture, color, and sensory properties of food. *Journal of Texture Studies*, 53(6), 737–762. <https://doi.org/10.1111/jtxs.12643>
- Parvathy, U., Bindu, J., & Joshy, C. G. (2017). Development and optimization of fish-fortified instant noodles using response surface methodology. *International Journal of Food Science and Technology*, 52(3), 608–616. <https://doi.org/10.1111/ijfs.13313>
- Pattanaik, S. S. (2018). Dietary incorporation of caroteino-protein extracted from shrimp shell waste for colour enhancement in Oscar, *Astronotus ocellatus* [AGASSIZ doctoral dissertation]. ICAR-Central Institute of Fisheries Education.
- Rabiepour, A., Zahmatkesh, F., & Babakhani, A. (2024). Preservation techniques to increase the shelf life of seafood products: An overview. *Journal of Food Engineering and Technology*, 13(1), 1–24. <https://doi.org/10.32732/jfet.2024.13.1.1>
- Rahman, M. S. (2020). Osmotic dehydration of foods. In *Handbook of food preservation* (pp. 459–472). CRC Press.
- Rahman, M. S., & Perera, C. O. (2007). Drying and food preservation. In M. S. Rahman (Ed.), *Handbook of food preservation* (pp. 403–432). CRC Press.
- Reis, F. R. (2016). Effect of blanching on food physical, chemical, and sensory quality. In *New perspectives on food blanching* (pp. 7–48). Springer. https://doi.org/10.1007/978-3-319-48665-9_2
- Safaie, M. (2017). Population dynamics of kiddi shrimp, *Parapenaeopsis stylifera* (H. Milne Edwards, 1837) in the north-west of Qeshm Island, Iran. *Tropical Zoology*, 30(1), 13–27. <https://doi.org/10.1080/03946975.2017.1278662>
- Srivastava, P. K., & Sit, N. (2025). A review on fruit and vegetable processing using traditional and novel methods. *Future Postharvest and Food*, 2(1), 4–26. <https://doi.org/10.1002/fpf2.12046>
- Strati, I. F., Sinanoglou, V. J., Kora, L., Miniadis Meimaroglou, S., & Oreopoulou, V. (2012). Carotenoids from foods of plant, animal and marine origin: An efficient HPLC-DAD separation method. *Foods*, 1(1), 52–65. <https://doi.org/10.3390/foods1010052>
- Subramanian, B., Thibault, M. H., Djaoed, Y., Pelletier, C., Touaibia, M., & Tchoukanova, N. (2015). Chromatographic, NMR and vibrational spectroscopic investigations of astaxanthin esters: Application to “Astaxanthin-rich shrimp oil” obtained from processing of Nordic shrimps. *Analyst*, 140, 7423–7433. <https://doi.org/10.1039/C5AN01261A>
- Sun, X. D., & Holley, R. A. (2011). Factors influencing gel formation by myofibrillar proteins in muscle foods. *Comprehensive Reviews in Food Science and Food Safety*, 10(1), 33–51. <https://doi.org/10.1111/j.1541-4337.2010.00137.x>

- Tan, H. L., Tan, T. C., & Easa, A. M. (2020). Effects of sodium chloride or salt substitutes on rheological properties and water-holding capacity of flour and hardness of noodles. *Food Structure*, 26, Article 100154. <https://doi.org/10.1016/j.foostr.2020.100154>
- Thorarinsdottir, K. A., Arason, S., Geirsdottir, M., Bogason, S. G., & Kristbergsson, K. (2002). Changes in myofibrillar proteins during processing of salted cod (*Gadus morhua*) as determined by electrophoresis and differential scanning calorimetry. *Food Chemistry*, 77(3), 377–385. [https://doi.org/10.1016/S0308-8146\(01\)00349-1](https://doi.org/10.1016/S0308-8146(01)00349-1)
- Tornberg, E. (2005). Effects of heat on meat proteins – Implications on structure and quality of meat products. *Meat Science*, 70(3), 493–508. <https://doi.org/10.1016/j.meatsci.2004.11.021>
- Tran, T. Y. N., Nguyen, N. L., Nguyen, T. N. A., Le, D. T., Phan, D. A., Tran, T. T., & Dao, T. P. (2022). Effects of blanching and drying condition on the quality of small shrimp (*Acetes*). *Journal of Food Quality*, 2022(1), Article 3996787. <https://doi.org/10.1155/2022/3996787>
- Xiang, J., Luo, N., Guo, C., Zhang, Y., Chen, X., Wang, X., Yin, X., Wang, X., & Cao, J. (2025). Improvement of myofibrillar protein gel properties after freezing–thawing by magnesium ions and sorbitol: Synergistic effects of ionic bridges and hydrogen bonds. *Food and Bioprocess Technology*, 18, 6621–6633. <https://doi.org/10.1007/s11947-025-03833-6>
- Xu, W., Zhang, F., Wang, J., Ma, Q., Sun, J., Tang, Y., Wang, J., & Wang, W. (2022). Real-time monitoring of the quality changes in shrimp (*Penaeus vannamei*) with hyperspectral imaging technology during hot air drying. *Foods*, 11(20), Article 3179. <https://doi.org/10.3390/foods11203179>