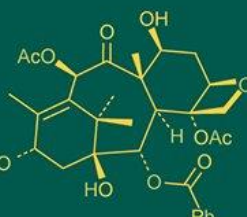


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Optimization of physical properties and storage characteristics of crab-incorporated noodles using response surface methodology

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Abstract

The present study focused on the development of a nutritionally enriched and shelf-stable crab-incorporated noodle product through systematic formulation optimization and storage evaluation. Raw material analysis confirmed that *Charybdis cruciata* is a rich source of high-quality protein with favorable biochemical, microbiological, and sensory characteristics, making it suitable for value-added product development. Although the yield of crab meat powder was relatively low (4.33%), it provided a concentrated and stable nutrient source. Response Surface Methodology (RSM) was effectively employed to optimize the formulation, identifying 20% crab meat powder and 80% wheat flour as the optimal combination. This formulation significantly enhanced protein content (up to 20.05%) while maintaining good sensory acceptability (score of 8.4) and high model reliability (R^2 up to 0.9983). Storage studies over 180 days under ambient conditions revealed that packaging systems significantly influenced product quality. Gradual changes were observed in physicochemical, microbiological, and sensory attributes; however, oxygen scavenger packaging demonstrated superior performance by effectively controlling lipid oxidation, protein degradation (TMA-N, TVBN), and microbial growth, while preserving texture, cooking quality, and overall acceptability. Vacuum packaging showed moderate effectiveness, whereas LDPE packaging exhibited the fastest deterioration. Overall, the study demonstrates that crab-incorporated noodles can be successfully developed as a protein-enriched, acceptable, and shelf-stable food product. The optimized formulation with 20% crab meat powder combined with oxygen scavenger packaging effectively extends shelf life beyond 180 days under ambient storage conditions.

Keywords: Crab meat powder; *Charybdis Cruciata*; value-added product; protein enrichment; response surface methodology (RSM); noodle formulation; shelf life; packaging systems.

Introduction

The increasing global population and rising food security concerns have created an urgent need for safe, affordable, and nutritionally rich protein sources, particularly in developing and low-income countries where access to high-quality dietary protein remains limited. Conventional terrestrial protein resources alone are insufficient to satisfy growing nutritional demands, leading to increasing attention toward sustainable aquatic food resources. Seafood and other aquatic organisms are recognized worldwide for their superior nutritional quality due to the presence of highly digestible proteins, balanced amino acid profiles, omega-3 fatty acids, vitamins, and essential minerals that are often lacking in cereal-based diets. Among aquatic foods, crustaceans such as shrimp, lobster, and crabs are highly valued because of their nutritional richness, sensory appeal, and increasing market demand. Seafood contributes significantly to global nutrition by supplying nearly 15% of the total animal protein consumed worldwide while also supporting the livelihoods and economies of millions of people involved in fisheries and aquaculture sectors. India has experienced remarkable growth in seafood exports in recent years, highlighting the increasing importance of value-added seafood products with improved quality, shelf stability, and market potential. International trade patterns further indicate a growing consumer preference for processed and ready-to-cook seafood products, particularly crab-based products, creating substantial opportunities for the development of innovative functional foods.

Crabs are among the most commercially important crustaceans and are highly appreciated for their delicate flavour, firm texture, low fat content, and high nutritional value.

Crab meat is an excellent source of high-quality protein, essential amino acids, minerals such as calcium, zinc, iron, and phosphorus, as well as bioactive compounds and long-chain omega-3 fatty acids that contribute to human health. The striped swimming crab, *Charybdis cruciata*, possesses considerable nutritional and commercial potential due to its rich composition of digestible proteins, unsaturated fatty acids, and essential micronutrients. However, its utilization remains limited because of rapid perishability, consumer preference issues, and inadequate processing techniques. The high moisture content and nutrient-rich nature of crab meat create favorable conditions for microbial growth and quality deterioration, making preservation a major challenge during storage and distribution. Consequently, advanced preservation and processing methods are required to improve shelf life, maintain product quality, and enhance consumer acceptability. Drying is considered one of the most effective preservation techniques as it reduces moisture content, inhibits microbial activity, enhances storage stability, and facilitates transportation and utilization. Conversion of crab meat into powder form offers additional advantages by enabling its incorporation into various food products as a protein-rich functional ingredient. Among different convenience foods, noodles are highly suitable for nutritional fortification because of their affordability, versatility, long-standing consumer acceptance, and ease of preparation. Wheat flour-based noodles are particularly popular because of their desirable functional and textural properties. In recent years, incorporation of marine protein ingredients into noodles has gained increasing attention as a strategy for developing nutrient-enriched functional foods; however, excessive incorporation may negatively influence sensory quality, texture, colour, and storage stability, thereby necessitating optimization of formulation and processing parameters. Response Surface Methodology (RSM) is widely used in food product development to optimize ingredient combinations and processing conditions efficiently while minimizing experimental trials. Therefore, the present study focuses on the development and optimization of crab meat powder incorporated noodles using refined wheat flour and crab meat powder derived from *Charybdis cruciata*, with emphasis on improving nutritional quality, sensory acceptability, microbial safety, and shelf stability under ambient storage conditions through appropriate formulation and packaging optimization.

2. Materials and methods

2.1 Raw materials and chemicals

Fresh striped swimming crabs, *Charybdis cruciata*, were procured from the Veraval fish market and transported to the Department of Fish Processing Technology, College of Fisheries Science, Kamdhenu University, Veraval, in insulated Styrofoam boxes maintained at 0–2 °C to preserve freshness. The crabs were washed with chilled potable water to remove impurities, and their length and body weight were recorded before frozen storage for further experimentation. All chemicals and reagents used in the study were of analytical grade and procured from Fisher Scientific and SRL Pvt. Ltd., while microbiological media were obtained from Hi-Media Laboratories. Borosil glassware was used for analytical procedures following standard laboratory protocols.

2.2 Methodology

In the present study, crab meat powder was prepared from fresh striped swimming crab, *Charybdis cruciata*, following a standardized processing procedure under hygienic laboratory conditions. The prepared crab meat powder was utilized for the development of protein-enriched crab noodles through two sequential experiments. In Experiment No. 1, different formulations of crab noodles were prepared by varying the proportions of crab meat powder and refined wheat flour using Response Surface Methodology (RSM) to optimize the product formulation. The experimental combinations consisted of crab meat powder levels ranging from 10–30% and wheat flour levels ranging from 70–90%, including formulations such as 10:90, 15:85, 20:80, 25:75, and 30:70 ratios of crab meat powder to flour. The ingredients were thoroughly mixed to obtain a uniform dough, followed by sheeting, extrusion, steaming, drying, and packaging to produce shelf-stable noodles. The prepared noodles were evaluated for proximate composition, physical characteristics, biochemical quality, microbiological safety, and sensory acceptability to determine the optimum formulation with desirable nutritional and quality attributes. Based on the optimization results obtained through RSM, the best-performing noodle formulation was selected for Experiment No. 2 to study the effect of different packaging materials on storage stability under ambient conditions using a Completely Randomized Design (CRD). The optimized crab noodles were packaged in three different packaging systems, namely low-density polyethylene (LDPE) packaging as control (T₀), vacuum packaging (T₁), and oxygen scavenging packaging (T₂). The packaged products were stored at ambient temperature and periodically analyzed to evaluate the influence of packaging conditions on quality retention and shelf life. During the storage period, comprehensive analyses including proximate composition, physical properties, biochemical changes, microbiological quality, and sensory evaluation were carried out to assess the stability and consumer acceptability of the developed crab noodles. The overall methodology was designed to optimize formulation and packaging conditions for the development of nutritionally enriched, shelf-stable crab-based noodles with improved quality and storage characteristics.

2.3 Nutritional evaluation of raw material and noodles

2.3.1 Physical Analysis

Fresh striped swimming crabs, *Charybdis cruciata*, were evaluated for basic physical characteristics prior to processing. The average body length and weight of the crabs were recorded as 10.75 ± 0.50 cm and 200.00 ± 0.70 g, respectively, using a measuring tape and electronic weighing balance. Yield assessment was conducted during different stages of processing, including steaming, meat extraction, drying, and powder preparation, to determine material recovery and process efficiency. Yield percentage was calculated using the formula:

$$\text{Yield (\%)} = \frac{\text{Weight at each processing stage}}{\text{Initial raw material weight}} \times 100$$

From 20 kg of raw crab, the final crab meat powder yield obtained was 0.87 kg (4.33%), indicating progressive reduction in material during processing.

2.3.1.1 Texture profile Analysis

Texture profile analysis (TPA) of the developed crab noodles was performed using a Brookfield CMAPC1 Texture Analyzer to evaluate their textural properties. Prior to analysis, noodle samples were equilibrated to room temperature and subjected to compression testing using a 50 kg load cell fitted with a cylindrical compression probe. The analysis was conducted under fixed operating conditions with a target distance of 5 mm, trigger force of 50 g, and pre-test, test, and post-test speeds maintained at 5.0 mm/s. The parameters including hardness, cohesiveness, springiness, and chewiness were recorded to assess the texture quality and structural characteristics of the crab-incorporated noodles.

2.3.1.2 Water Absorption Capacity (WAC)

Water absorption capacity of crab noodle powder was determined according to the method described by Sosulski (1962) using a centrifuge. Approximately 1 g of sample was weighed into a centrifuge tube and 10 ml of distilled water was added. The mixture was thoroughly mixed and allowed to stand at room temperature for 30 minutes with intermittent shaking. The suspension was then centrifuged at 3000 rpm for 15 minutes. The supernatant was carefully decanted and the sediment was weighed. Water absorption capacity was expressed as grams of water absorbed per gram of sample.

$$\text{WAC (g/g)} = \frac{(\text{Weight of hydrated sample} - \text{Initial sample weight})}{\text{Initial sample weight}}$$

2.3.1.3 Bulk Density

Bulk density of the crab noodle powder was determined according to the standard method described by Anon (1998). A known quantity of the sample was gently filled into a graduated measuring cylinder without compacting and the volume occupied by the sample was recorded. The bulk density was calculated as the ratio of the mass of the sample to the volume occupied.

$$\text{Bulk Density (g/ml)} = \frac{\text{Weight of sample}}{\text{Volume of sample}}$$

2.3.1.4 Cooking Loss

Cooking loss of crab noodles was determined following the method described by Li and Chang (1981). A known weight of noodles (approximately 10 g) was cooked in boiling water for a specified time. After cooking, the noodles were drained and the cooking water was collected and evaporated to dryness in a hot air oven. The residue obtained represented the solids lost during cooking. Cooking loss was expressed as the percentage of dry matter lost during cooking.

$$\text{Cooking Loss (\%)} = \frac{\text{Weight of residue after evaporation}}{\text{Initial weight of noodles}} \times 100$$

2.3.2. Proximate Analysis

Proximate composition of raw materials and dried noodles were estimated as per AOAC (2012) method. Total nitrogen content of raw materials as well as noodles was estimated by micro-kjeldahl method, and the crude protein content was determined on the basis of total nitrogen content by multiplying with the factor 6.25. The total carbohydrate

content was calculated by the difference between total weight of the food components (fat, moisture, ash and protein content) and the total weight of the sample.

2.3.3 Biochemical analysis

Biochemical quality evaluation of the developed crab noodles included determination of Trimethylamine Nitrogen (TMA-N), Total Volatile Base Nitrogen (TVB-N), pH, and Peroxide Value (PV) using standard analytical procedures. TMA-N and TVB-N were estimated by the Conway micro-diffusion method using trichloroacetic acid (TCA) extract to evaluate spoilage-related volatile nitrogen compounds, and the values were expressed as mg/100 g sample.

$$\text{TMA-N/TVB-N (mg/100 g)} = \frac{(V_g - V_h) \times 0.14 \times \text{Volume of extract}}{\text{Volume of sample taken} \times \text{Weight of sample}} \times 100$$

The pH of the samples was measured electrometrically using a calibrated digital pH meter after homogenization with distilled water. Peroxide Value (PV), indicating primary lipid oxidation, was determined by the iodometric titration method using chloroform lipid extract and expressed as

$$\text{Peroxide Value (meq/kg)} = \frac{1000 \times (V - X) \times \text{Volume of extract}}{W \times \text{Aliquot volume}}$$

These biochemical parameters were analyzed to assess freshness, lipid stability, and overall storage quality of the crab-incorporated noodles.

2.3.4 Total Plate Count (TPC)

Total Plate Count (TPC) was determined using Plate Count Agar following AOAC (2012) standard procedures. After incubation at 37 ± 1 °C for 48 h, microbial load was expressed as CFU/g.

$$\text{TPC (CFU/g)} = \text{Average number of colonies} \times \text{Dilution factor}$$

2.3.5 Sensory Characteristics

Sensory evaluation of crab noodles was conducted using a 9-point Hedonic scale with five trained panellists assessing appearance, colour, texture, flavour, odour, and overall acceptability, where scores above 6 indicated acceptable product quality.

2.3.6. Statistical analysis

The experiment was conducted according to simplex lattice mixture design. A part of this Response Surface Methodology will be used to study the interaction consequence of variables on crab noodles production using Design-Expert® version v25.0 (Stat-Ease Inc., USA) to determine the significant effects and to find out the best treatment combination. ANOVA (Analysis of Variance) Statistical technique was used to find out the significant difference in samples between the treatments as per the Standard Statistical Methods. It was carried out based on the experimental data using IBM BASIC windows release 1.13.

3. Results and discussion

3.1 Nutritional evaluation of raw material

The present study utilized fresh striped swimming crab, *Charybdis cruciata*, as the raw material for the preparation of crab meat powder and subsequent development of crab-based noodles. After procurement, the crabs were

thoroughly cleaned and processed through steaming, meat extraction, drying, and grinding to obtain crab meat powder, which was further incorporated into noodle formulations at different proportions along with wheat flour according to the experimental design. In Experiment-1, Response Surface Methodology (RSM) was employed to optimize the formulation of crab noodles, while Experiment-2 evaluated the storage stability of the optimized product under different packaging materials at ambient temperature. The quality characteristics of the raw material were analyzed prior to product development to determine its suitability for processing and nutritional enrichment. The physical characteristics of the fresh crabs indicated uniformity in size and weight, with an average body length of 10.75 ± 0.50 cm and body weight of 200.00 ± 5.70 g, which supported consistency during processing operations. The proximate composition analysis revealed that fresh crab meat contained high moisture ($74.08 \pm 0.38\%$) and protein content ($19.27 \pm 0.14\%$), along with low fat ($1.22 \pm 0.05\%$), ash ($4.13 \pm 0.13\%$), and carbohydrate ($1.33 \pm 0.04\%$) levels, indicating its nutritional suitability as a protein-rich ingredient for functional food development (Gillman, 2001). The biochemical quality parameters of fresh crab were within acceptable freshness limits, with pH, TMA-N, TVB-N, and peroxide value recorded as 8.20 ± 0.05 , 3.18 ± 0.03 mg/100 g, 14.64 ± 0.5 mg/100 g, and 2.42 ± 0.04 meq/kg fat, respectively, confirming the freshness and good quality of the raw material. Similarly, microbiological evaluation showed a low total plate count of 3.05 ± 0.82 log CFU/g, indicating hygienic handling and safe microbial quality of the crab samples (FSSAI, 2017). Sensory analysis further demonstrated high consumer acceptability, with appearance, colour, odour, texture, and overall acceptability scores ranging from 8.4 to 8.6 on the 9-point hedonic scale, reflecting the freshness and desirable sensory characteristics of the crab meat (Anupama *et al.* 2020). Colour analysis of

the fresh crab showed L^* , a^* , and b^* values of 54.32 ± 0.11 , -10.98 ± 0.16 , and 6.12 ± 0.07 , respectively, indicating characteristic colour properties of the raw material. Yield assessment during processing demonstrated progressive reduction in material recovery from the initial 20 kg raw crab, resulting in final crab meat powder yield of 0.87 kg (4.33%), while steamed whole crab, extracted meat, and dried meat yields were recorded as 44.67%, 18.67%, and 4.67%, respectively (Table 4.2). In addition, wheat flour used for noodle preparation exhibited $11.36 \pm 0.25\%$ protein, $1.52 \pm 0.03\%$ fat, $12.09 \pm 0.39\%$ moisture, $1.83 \pm 0.05\%$ ash, and $73.2 \pm 0.41\%$ carbohydrate content, supporting its suitability as the primary base ingredient for noodle formulation. Overall, the results confirmed that the selected raw materials possessed desirable nutritional, biochemical, microbiological, and sensory quality characteristics suitable for the development of nutritionally enriched crab-based noodles.

3.2. Optimization of crab-incorporated noodles

Response Surface Methodology (RSM) based on Simplex lattice Mixture Design (SLMD) was employed to optimize the formulation of crab-incorporated noodles by evaluating the combined effect of crab meat powder (10–30%) and wheat flour (70–90%) on product quality characteristics. Fifteen experimental runs, including centre point replications, were conducted to study the influence of formulation variables on proximate composition, microbiological quality, and sensory attributes of the developed noodles. Experimental data were analyzed using Design-Expert® Software, and quadratic regression models were found to best describe the responses. ANOVA results indicated significant model effects ($p < 0.05$), while high R^2 values confirmed the adequacy and predictive ability of the developed optimization models.

Table 1: Simplex Lattice Mixture Design (SLMD) with results for product responses

RUN	STD	Factor 1	Factor 2	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
		A Meat (%)	B Flour (%)	Crude protein (%)	Crude fat (%)	Moisture (%)	Ash (%)	Microbio-logical Analysis (TPC)	Sensory Analysis
1	5	15	85	17.50	1.14	8.50	4.70	3.20	7.8
2	2	10	90	14.92	0.97	8.20	3.50	3.10	7.4
3	13	10	90	15.30	0.96	8.30	3.60	3.00	7.6
4	15	30	70	22.50	2.19	9.80	6.80	3.80	7
5	1	30	70	22.40	2.11	9.50	6.60	3.90	7.2
6	7	10	90	15.40	0.98	8.10	3.50	3.20	7.4
7	8	20	80	19.90	1.40	9.00	5.50	3.40	8.4
8	12	30	70	22.60	2.30	9.90	6.60	4.00	6.8
9	6	30	70	22.30	2.16	9.60	6.50	3.70	7.0
10	11	20	80	20.10	1.50	9.20	5.60	3.30	8.6
11	9	30	70	22.70	2.22	9.70	6.70	3.80	7.0
12	4	25	75	21.73	1.80	9.40	6.09	3.60	7.8
13	10	10	90	14.81	0.95	8.40	3.60	3.10	7.4
14	14	20	80	20.00	1.40	9.10	5.50	3.40	8.4
15	3	20	80	20.20	1.50	9.00	5.60	3.50	8.4

The contour plot for crude protein (Figure 1.A) showed that increasing crab meat powder significantly enhanced the protein content of noodles, with the optimum formulation observed at 20% crab meat powder and 80% wheat flour. Protein values ranged from 14.92–22.6%, with a predicted optimum value of 20.05%. Similar enhancement in protein content of seafood-fortified noodles was also reported by Kamalakanth *et al.*, who observed increased protein levels

with higher fish mince incorporation, confirming the suitability of crab meat powder for protein enrichment.

The contour plot for crude fat (Figure 1.B) indicated a slight increase in fat content with increasing crab meat powder incorporation due to the presence of natural seafood lipids. The optimized formulation (20:80) showed a predicted fat value of 1.46%, while experimental values ranged between 0.95–2.3%, thereby maintaining the noodles as a healthy

low-fat product. Similar marginal increases in fat content were reported by Yerlikaya *et al.* during seafood powder incorporation in noodles.

Moisture contour analysis (Figure 1.C) demonstrated a slight increase in moisture content with higher crab meat powder levels because of the water-binding capacity of seafood proteins and chitin. The optimized formulation recorded a predicted moisture value of 9.06%, while observed values ranged from 8.1–9.9%, remaining within the desirable range for dried noodles. Similar moisture trends were observed by Kamalakanth *et al.* in seafood-fortified noodle products.

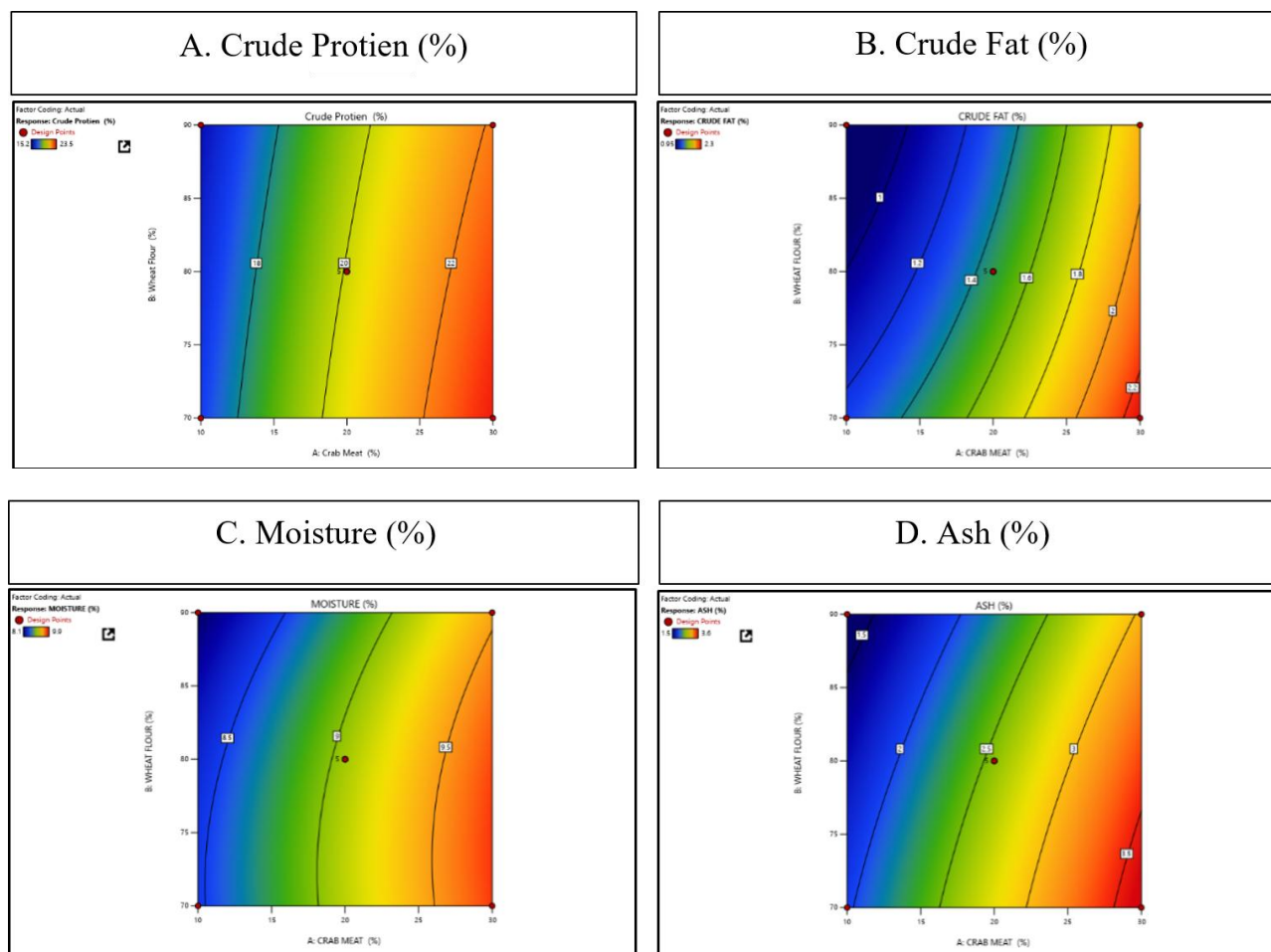
The ash content contour plot (Figure 1.D) revealed that mineral content increased with rising crab meat powder incorporation due to the naturally higher mineral composition of crab meat. Ash values ranged from 3.50–6.80%, with a predicted optimum value of 5.56% at the optimized formulation. Similar improvements in ash and mineral content were also reported by Viji *et al.* during incorporation of seafood protein powder into noodles.

The Total Plate Count contour plot (Figure 1.E) showed a slight increase in microbial load with increasing crab meat powder levels, possibly due to natural seafood microflora.

However, the optimized formulation maintained acceptable microbiological quality with a predicted TPC value of 3.42 log CFU/g and observed values between 3.0–4.0 log CFU/g. Comparable microbiological stability in seafood-enriched noodles was similarly reported by Viji *et al.*

The sensory contour plot (Figure 1.F) indicated that moderate incorporation of crab meat powder improved sensory acceptability, whereas excessive incorporation negatively affected flavour, colour, odour, and texture. The optimized formulation achieved a sensory score of 8.4, corresponding to the “like very much” category on the hedonic scale. Similar sensory behaviour was reported by Parvathy *et al.*, where moderate seafood incorporation improved acceptability while higher levels reduced sensory quality.

Numerical optimization using Design-Expert® Software identified the optimum formulation as 20% crab meat powder and 80% wheat flour. The optimized noodles exhibited desirable nutritional, microbiological, and sensory quality characteristics, while validation experiments closely matched the predicted values, confirming the adequacy and predictive capability of the developed regression models.



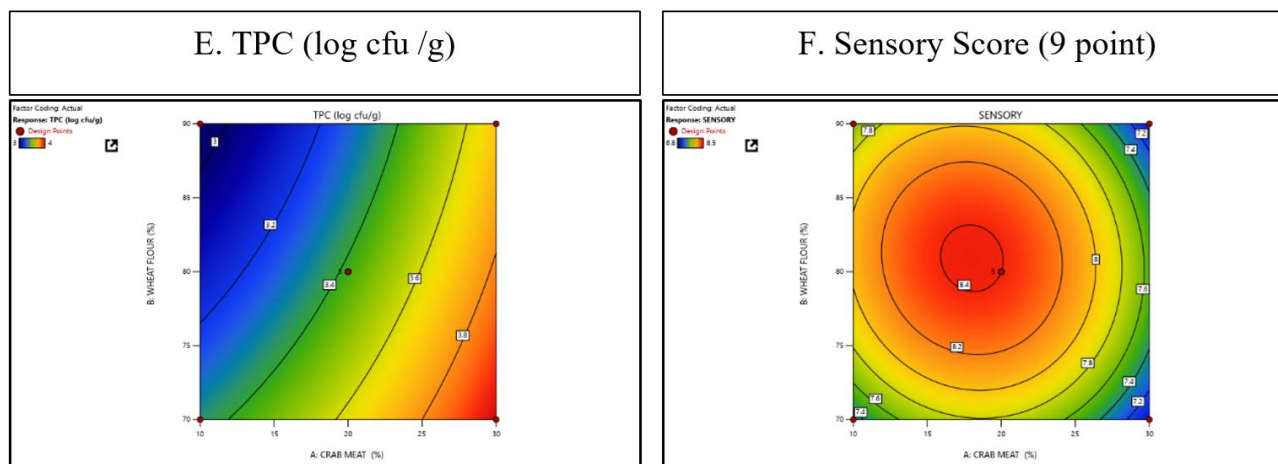


Fig 1 (A-F): Contour plot showing the effect of crab meat powder (%) and wheat flour (%) on the moisture content of crab incorporated noodles.

3.3 Storage studies of the optimized crab-incorporated noodles

Optimized crab noodles (20% crab meat powder + 80% wheat flour) were stored under ambient conditions using LDPE (T_1), vacuum (T_2), and oxygen scavenger packaging (T_3) to evaluate physicochemical, microbial, and sensory stability.

3.3.1 Texture profile analysis

Texture Profile Analysis of cooked crab noodles was performed monthly using a TA.XT Plus Texture Analyzer (Stable Micro Systems, UK) to evaluate hardness, chewiness, springiness, and gumminess during ambient storage under LDPE, vacuum, and oxygen scavenger packaging.

Texture Profile Analysis revealed significant changes in the textural quality of cooked crab-incorporated noodles during 180 days of ambient storage under different packaging conditions. Hardness gradually decreased from 12.26–12.28 N at day 0 to 9.05 N (T_1), 9.20 N (T_2), and 10.31 N (T_3), indicating progressive weakening of the noodle matrix due to moisture absorption, oxidative deterioration, and weakening of protein–starch interactions. Similar reductions in hardness during storage of seafood-fortified noodles were also reported by Parvathy *et al.*. Chewiness declined from 7.63 N.mm to 3.50 N.mm during storage because of moisture migration, lipid oxidation, and degradation of the starch–protein network, which agrees with the observations of Lekjing *et al.* and Xiao *et al.* in fortified noodle products. Springiness also showed a continuous reduction from 0.93 mm to 0.67 mm owing to deterioration of the viscoelastic gluten–starch matrix, oxidative degradation of protein disulfide bonds, and structural relaxation during prolonged storage, while similar elasticity-related behaviour in protein-enriched noodles was observed by Sudha *et al.*. In contrast, gumminess increased progressively from 1.15 N to 2.61 N due to starch retrogradation, enhanced moisture uptake, and strengthening of protein–starch interactions, leading to a denser and more cohesive noodle structure. Comparable increases in gumminess during storage were reported by Shaviklo *et al.* and Ikbali *et al.*, who associated these changes with improved water-binding capacity and progressive densification of the protein–starch matrix. Among all treatments, oxygen scavenger packaging (T_3) consistently retained superior textural quality by maintaining comparatively higher hardness, chewiness, and

springiness with lower gumminess, indicating better protection against oxygen-induced quality deterioration and moisture ingress compared to vacuum packaging (T_2) and LDPE packaging (T_1). Statistical analysis further demonstrated significant effects ($p < 0.05$) of storage period and packaging treatments on most texture parameters, confirming the strong influence of packaging systems on noodle texture stability during storage.

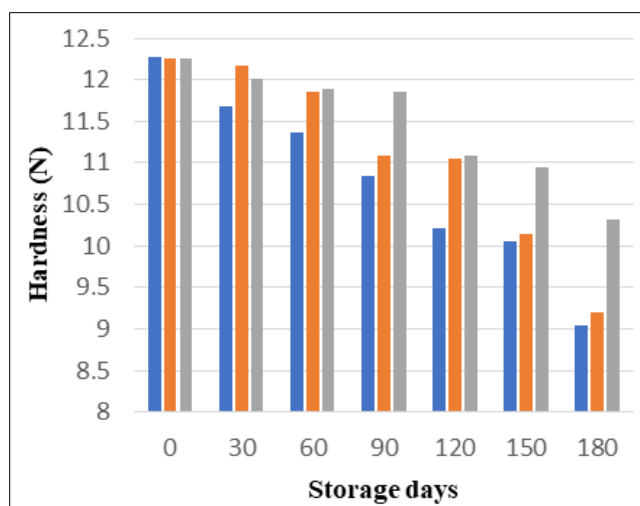


Fig 2: Variations in the Hardness (N)

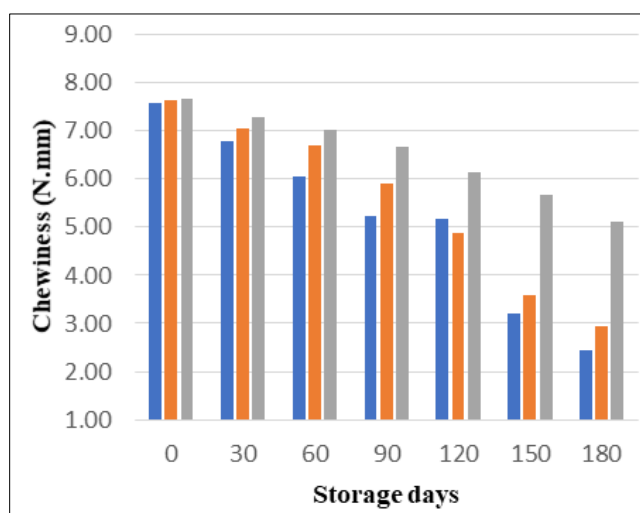


Fig 3: Variations in the Chewiness (N.mm)

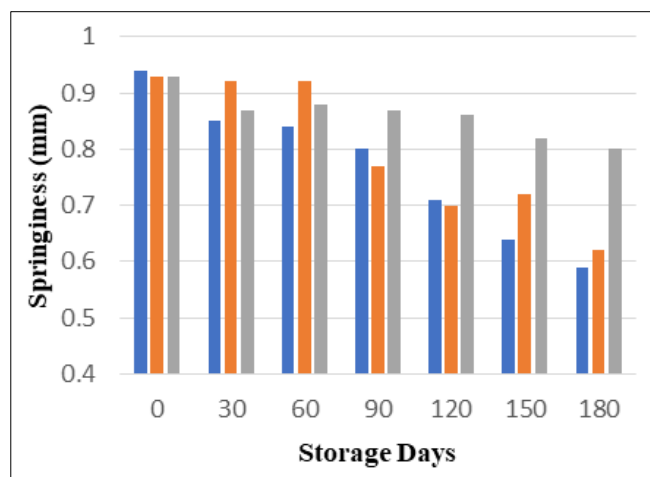


Fig 4: Variations in the Springiness (mm)

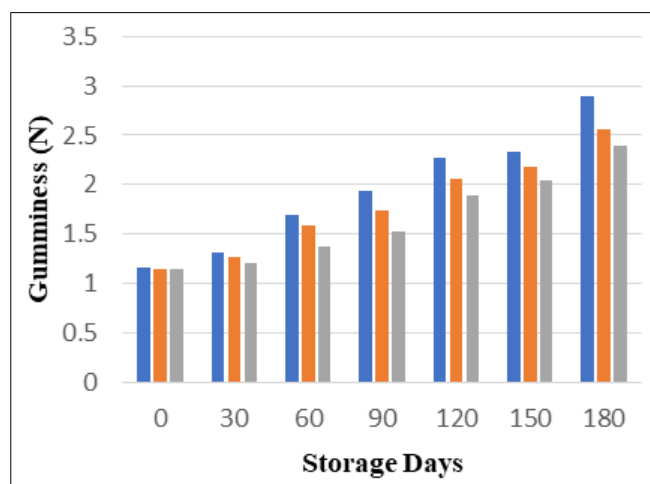


Fig 5: Variations in the Gumminess (N)

3.3.2 Water Absorption Capacity (WAC)

Water Absorption Capacity (WAC) of cooked crab-incorporated noodles gradually decreased during 180 days of ambient storage, declining from 295.78% at day 0 to 249.00% at the end of storage due to reduced water-holding ability of the protein–starch matrix, starch retrogradation, and oxidative deterioration of proteins and lipids. Among packaging treatments, oxygen scavenger packaging (T_3) retained the highest mean WAC (281.05%), followed by vacuum packaging (T_2), while LDPE packaging (T_1) recorded the lowest value, indicating greater oxidative and moisture-related deterioration. Statistical analysis revealed significant effects ($p < 0.05$) of storage period, packaging treatment, and their interaction on WAC. Similar reductions in hydration and water absorption properties during storage of seafood-fortified noodles were reported by Hossain *et al.* and Wang *et al.*, where low-oxygen packaging better preserved water-holding stability and overall cooking quality during prolonged storage.

3.3.3. Bulk Density (BD)

Bulk density of cooked crab-incorporated noodles gradually decreased during 180 days of ambient storage, declining from 0.35 g/cc at day 0 to 0.26 g/cc at the end of storage due to moisture absorption, slight swelling, and reduced compactness of the noodle structure. Among packaging

treatments, oxygen scavenger packaging (T_3) maintained the highest mean bulk density (0.32 g/cc), followed by vacuum packaging (T_2), while LDPE packaging (T_1) recorded the lowest value (0.29 g/cc). Statistical analysis revealed that storage period significantly affected ($p < 0.05$) bulk density, whereas packaging treatments and their interaction were non-significant. Similar decreasing trends in bulk density during storage of seafood-fortified noodles were reported by Yerlikaya *et al.* and Lekjing *et al.*, who also observed that storage duration had a greater influence on bulk density than packaging conditions.

3.3.4. Cooking Loss (CL)

Cooking loss of crab-incorporated noodles increased progressively during 180 days of ambient storage, rising from 5.08% at day 0 to 9.05% at the end of storage, indicating gradual deterioration in cooking quality and structural integrity of the noodles. Among packaging treatments, LDPE packaging (T_1) recorded the highest mean cooking loss (7.39%), followed by vacuum packaging (T_2) at 6.76%, whereas oxygen scavenger packaging (T_3) maintained the lowest mean value (5.93%), demonstrating superior preservation of noodle structure during storage. A sharper increase in cooking loss was particularly observed in LDPE packaging after 90 days of storage. Statistical analysis revealed that storage period, packaging treatment, and their interaction significantly affected ($p < 0.05$) cooking loss, while the low coefficient of variation (3.58%) indicated good experimental precision. The increase in cooking loss during prolonged storage may be attributed to moisture migration, oxidative deterioration, weakening of the protein–starch matrix, and starch retrogradation, which collectively reduced the structural stability of noodles and increased solid leaching during cooking. Similar increases in cooking loss during ambient storage of seafood-based noodle products were reported by Gillman *et al.*, who observed progressive structural breakdown and increased solid loss in crab meat incorporated pasta during extended storage. The present findings confirmed that low-oxygen packaging systems, particularly oxygen scavenger packaging, effectively minimized cooking loss and better preserved the cooking quality of crab-incorporated noodles during ambient storage.

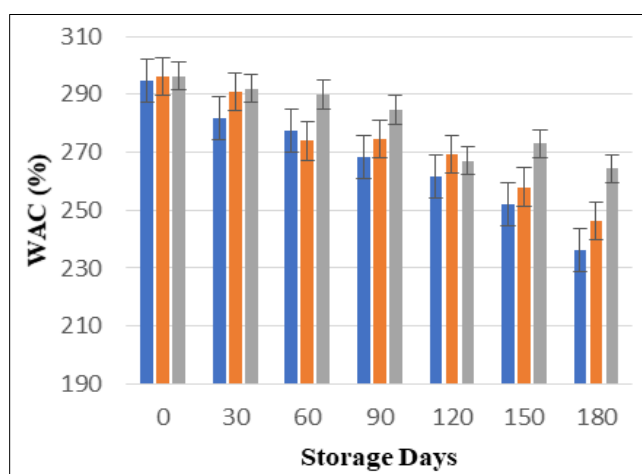


Fig 6: Water Absorption Capacity (WAC)

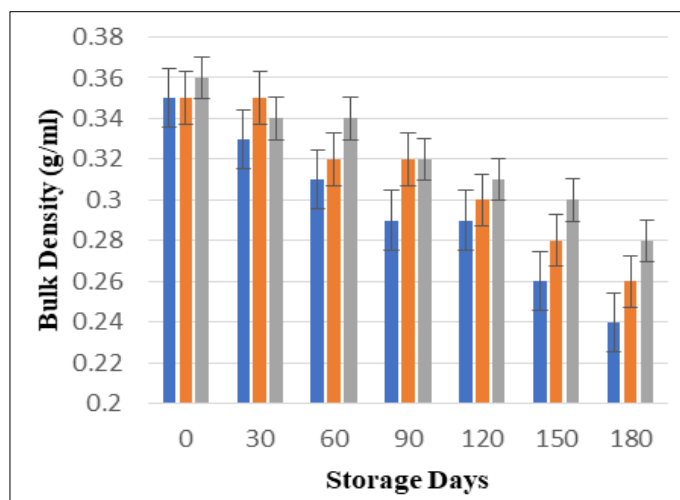


Fig 7: Bulk Density (BD)

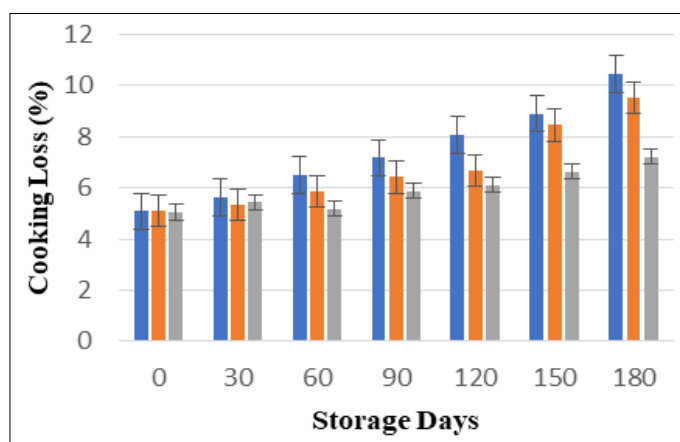


Fig 8: Cooking Loss (CL)

3.3.5 Evaluation of Sensory Characteristics

Sensory evaluation of cooked crab-incorporated noodles revealed a progressive decline in appearance, colour, odour, and overall acceptability during 180 days of ambient storage under different packaging conditions. Appearance scores decreased from 8.73 to 3.87, while colour scores declined from 8.39 to 3.67 due to melanosis, oxidative browning, moisture-induced surface changes, and oxygen exposure during prolonged storage. Similarly, odour scores reduced from 8.73 to 4.00 owing to oxidative deterioration, moisture absorption, and development of undesirable seafood odours. Overall acceptability also decreased significantly from 8.67 to 4.17 as a result of combined deterioration in sensory attributes including appearance, flavour, texture, colour, and odour. Among the packaging treatments, oxygen scavenger packaging (T_3) consistently retained superior sensory quality, maintaining the highest appearance (7.31), colour (7.20), odour (7.10), and overall acceptability (7.20) scores, followed by vacuum packaging (T_2), whereas LDPE packaging (T_1) exhibited the greatest sensory deterioration, particularly after 90 days of storage. Statistical analysis indicated significant effects ($p < 0.05$) of storage period, packaging treatment, and their interaction on all sensory parameters, confirming the strong influence of oxygen exposure on sensory stability. The improved sensory retention observed in oxygen scavenger and vacuum packaging was mainly attributed to reduced oxidative spoilage, delayed melanosis, minimized moisture-related deterioration, and better preservation of volatile flavour

compounds. Similar reductions in sensory quality during storage of seafood-based noodle products were reported by Anupama *et al.*, who observed rapid deterioration in conventional plastic packaging, while Lekjing *et al.* and Huang *et al.* also reported gradual sensory deterioration during prolonged ambient storage. The present findings confirmed that low-oxygen packaging systems effectively preserved sensory quality and extended the shelf stability of crab-incorporated noodles under ambient conditions.

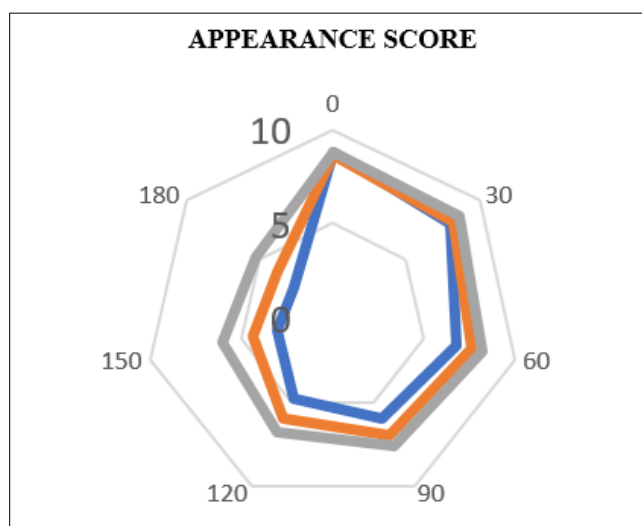


Fig 9: Appearance score

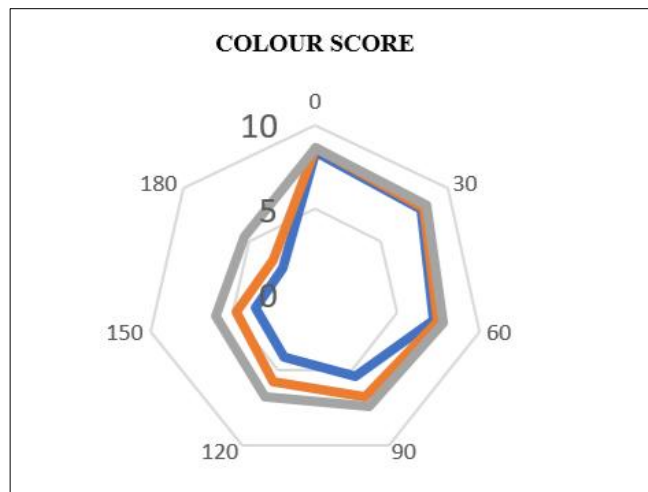


Fig 10: Colour score

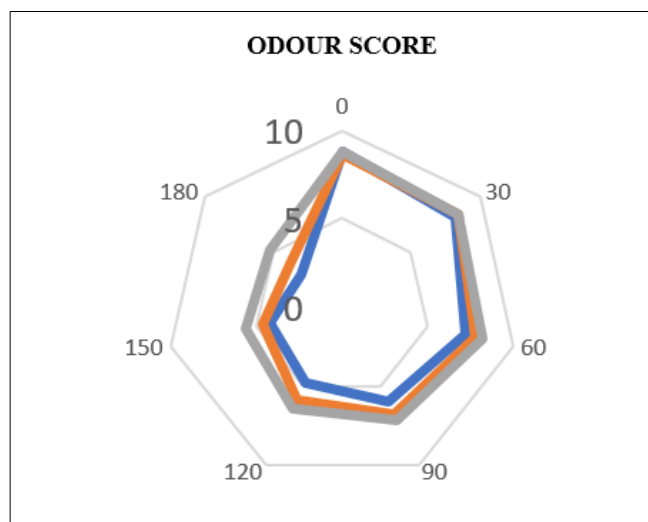


Fig 11: Odour score

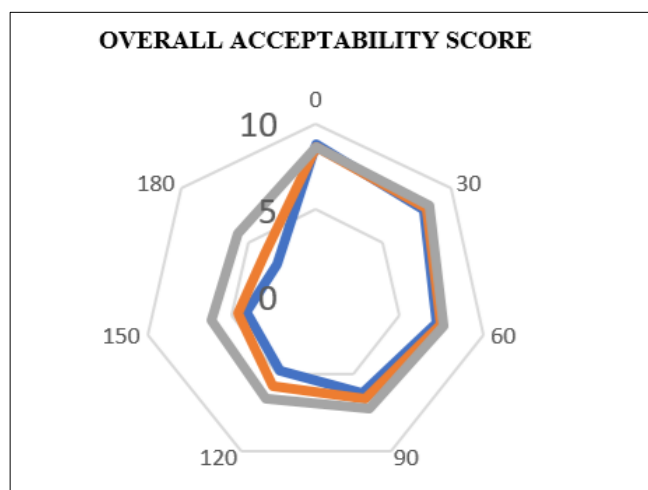


Fig 12: Overall acceptability

3.3.6 Total Plate Count (log cfu/g)

Total Plate Count (TPC) of cooked crab-incorporated noodles increased progressively during 180 days of ambient storage, rising from 2.40 log CFU/g at day 0 to 5.75 log CFU/g at the end of storage due to increased moisture availability and oxygen exposure, which promoted microbial growth during prolonged storage. Among packaging treatments, LDPE packaging recorded the highest

microbial load (4.83 log CFU/g), followed by vacuum packaging (3.35 log CFU/g), whereas oxygen scavenger packaging maintained the lowest TPC (2.50 log CFU/g), indicating superior microbiological stability. A rapid increase in microbial count was particularly observed in LDPE packaging after 60 days of storage. Statistical analysis revealed significant effects of storage period, packaging treatment, and their interaction on TPC values. The lower microbial load observed in oxygen scavenger and vacuum packaging was attributed to restricted oxygen availability and delayed microbial proliferation. Similar increases in microbial load during storage of seafood-based noodles and pasta products were reported by Anupama *et al.* and Gillman and Skonberg, who also observed improved shelf stability under low-oxygen packaging conditions.

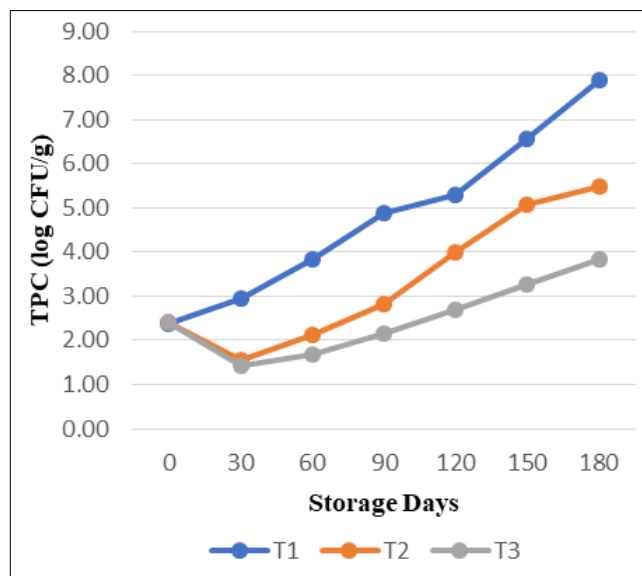


Fig 13: Microbiological Evaluation

4. Conclusion

The present study successfully demonstrated the development of a nutritionally enriched, shelf-stable crab-incorporated noodle product through systematic optimization and storage evaluation. The raw material characterization confirmed that *Charybdis cruciata* is a high-quality protein source with desirable biochemical, microbiological, and sensory attributes, suitable for value addition. The conversion of crab meat into powder, despite low yield (4.33%), resulted in a nutritionally concentrated and stable ingredient. The application of Response Surface Methodology effectively optimized the formulation, establishing 20% crab meat powder and 80% wheat flour as the ideal combination, achieving enhanced protein content (up to 20.05%), acceptable sensory quality (8.4), and strong model reliability (R^2 up to 0.9983). This highlights the efficiency of RSM in balancing nutritional improvement with consumer acceptability. Storage studies clearly established that packaging had a major influence on quality retention under ambient conditions. During 180 days of storage, gradual deterioration occurred in texture, functional, biochemical, microbiological, and sensory properties; however, the extent of change depended on packaging type. Oxygen scavenger packaging (T_2) performed best by minimizing increases in TMA-N, TVB-N, peroxide value, and microbial load, while better preserving texture, cooking quality, proximate composition,

and sensory scores. In contrast, vacuum packaging (T₁) showed moderate stability, and LDPE packaging (T₀) deteriorated fastest. Overall, the study proved that crab-incorporated noodles can be successfully developed as a protein-enriched, acceptable, and shelf-stable product, with 20% crab meat powder as the optimum incorporation level and oxygen scavenger packaging as the most effective system, extending shelf life beyond 180 days under ambient storage.

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