International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; 9(8): 482-491
www.biochemjournal.com
Received: 16-06-2025
Accepted: 18-07-2025

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Effect of thermal processing on quality and shelf life of black tiger shrimp (*Penaeus monodon)* curry in retort pouches during ambient storage

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DOI: https://www.doi.org/10.33545/26174693.2025.v9.i8g.5224

Abstract
This study evaluates the effect of thermal processing on the quality and shelf life of Black Tiger shrimp (*Penaeus monodon*) curry packed in flexible retort pouches. Shrimp curry was processed at two lethality values (F_0 8 and F_0 9 minutes) using an overpressure retort and stored at ambient conditions for 180 days. Heat penetration characteristics, commercial sterility, biochemical parameters (TVB-N, TMA-N, FFA, PV, TBA-RS, pH, and indole), texture, colour, and sensory attributes were comprehensively assessed. Both F_0 values achieved commercial sterility and ensured microbial safety, with F_0 8 exhibiting slightly better retention of texture, colour, and flavour. Thermal processing at F_0 8 and F_0 9 minutes resulted in cook values of 87.23 and 86.44 min, respectively. Biochemical parameters increased gradually over storage but remained within acceptable limits. Textural properties such as hardness and chewiness declined over time, more prominently in F_0 9-treated samples. Sensory scores decreased during storage, but products remained acceptable, with F_0 8 maintaining superior overall acceptability. Colour analysis showed darkening and increased redness/yellowness due to thermal effects and pigment intensification. The study confirms that F_0 8 processing optimally balances microbial safety with desirable organoleptic quality, promoting ready-to-eat shrimp curry as a stable, nutritious, and convenient seafood product.

Keywords: Thermal processing, seafood, F_0 value, biochemical analysis, texture profile analysis, sensory evaluation

Introduction
Ready-to-eat (RTE) seafood products are gaining popularity globally due to changing consumer lifestyles, demand for convenience and improved processing technologies. Among these, thermal processing of retort pouch packed food has proven highly effective in preserving seafood products without compromising safety or quality. The retort pouches, with its multilayer laminate and flexible structure, allows rapid heat penetration, making it ideal for thermally processed high-value species like *Penaeus monodon* (Murphy *et al*., 2002) [1]. Black tiger shrimp (*P. monodon*) is known for its taste, good texture and nutritional benefits. Several culinary recipes are being practiced in India to prepare thermally processed shrimp products. Spices and aromatic compounds can improve flavour of the product but can also change thickness, color, and heat flow during sterilization (Manju *et al*., 2007; Sreenivasan *et al*., 2010) [2, 3].
The objective of thermal processing is to achieve commercial sterility while retaining nutritional and sensory quality. Key parameters such as the F_0 value and cook value must be optimized. Teixeira *et al*. (1969) [4] emphasized the importance of evaluating these indicators in retorted products for heat penetration studies. In shrimp curry products, where both conduction and convection mechanism occur, understanding heat transfer kinetics is crucial for accurate thermal processing (Ghosh, 2012) [5]. Retort pouch processing offers advantages over traditional canning, including reduced cooking time, better retention of nutrients and organoleptic properties, and lower environmental impact due to lightweight packaging. However, improper process design can result in overprocessing, leading to undesirable changes in texture, especially in delicate proteins, which compromises food safety (Ghavidel & Davoodi, 2011) [6].

Sensory evaluation plays a critical role in assessing consumer acceptability. Spice-rich matrices undergo significant alterations in aroma and appearance upon sterilization, requiring refined process optimization to maintain sensory integrity (Manju *et al*., 2007) [2]. Packaging integrity, seal quality, and barrier properties of retort pouches also influence shelf stability and safety. Laminated structures combining polyester, nylon, aluminium foil, and polypropylene provide excellent protection against oxygen and moisture ingress while withstanding high sterilization temperatures (Murphy *et al*., 2002) [1]. The synergy between packaging technology and thermal processing conditions is important for successful RTE product development.

The current study investigates the thermal characteristics, microbial safety, biochemical parameters, and physical characteristics of *P. monodon* shrimp in spiced curry packed in retort pouches. It aims to evaluate heat penetration behaviour, sterilization effectiveness through F_0 value assessments, and resultant sensory attributes. By identifying optimal processing parameters, the research contributes to the growing demand for value-added seafood products tailored to modern convenience and quality standards. The findings expected to support innovation in the Indian seafood industry and promote sustainable processing practices.

Materials and Methods

Materials

Fresh black tiger shrimp (*Penaeus monodon*) with an average length of 21.1 cm and a count of 16-20 per kilogram were procured from the landing center at Mangalore, Karnataka, India. Samples were transported under iced conditions (ice-to-shrimp ratio 1:1) to the processing laboratory. Laminated four-ply flexible retort pouches were used for packaging, composed of 12 µm polyester (outer layer), 9 µm aluminum foil, 15 µm nylon (middle layer), and 70 µm polypropylene (inner cast). Pouches measured 150 × 200 mm and held 300 g of product (Floeter India Retort Pouches Pvt Ltd, Haryana, India). A pilot-scale horizontal overpressure retort (Lakshmi Engineering Works, Chennai, India) comprising a retort vessel, boiler, air compressor and PLC-based control system was employed for thermal processing. All chemicals and glassware used were of analytical (AR) grade.

Preparation of Shrimp in Curry Medium

Black Tiger shrimp were cleaned by washing in chilled potable water (1-2°C), then peeled, beheaded, and deveined. The cleaned shrimp were blanched by immersing them in a 6% salt solution at 100 ± 2°C for 10 minutes and set aside for use in the curry. The curry was prepared using a standard recipe (Table 1). The wet paste was made using onion, tomato, garlic, ginger, green chilli, curry leaves and turmeric. The lightly fried spices, byadagi chilli, black pepper, poppy seeds, cinnamon, coriander, cumin, turmeric, and salt were ground into a fine mixture to prepare dry masala powder. Cooking began with frying chopped onion, green chili, curry leaves, garlic, ginger, turmeric, and shallots in a small amount of refined sunflower oil until lightly browned. The wet paste was then added and cooked until the mixture changed colour, followed by the addition of the dry masala paste, tamarind paste, and coconut milk. The curry was simmered gently to remove raw flavour, then adjusted with salt and water to reach the desired flavour and consistency. Finally, the blanched shrimp were added to the curry, and the mixture was simmered over low heat until it reached a gentle boil, ensuring the shrimp absorbed the rich flavors of the masala.

Table 1: Recipe for Preparation of Shrimp in curry medium

Ingredients	Quantity (g)	Ingredients	Quantity (g)
Dressed Shrimp	1000	Cinnamon	20
Onion (Big)	250	Poppy seeds	20
Tomato	250	Curry and coriander leaves	15
Green chilli	100	Tamarind	50
Crushed ginger and garlic	50	Shallots- small onion	150
Byadagi red chilli	100	Round chilli (dry boriya red chilli)	50
Coriander seed	100	Oil	100
Turmeric powder	10	Water	1.5 L
Black pepper	20	Salt	To taste
Cumin	20		

Filling and Sealing

Approximately 250 ± 5 g of hot shrimp curry was filled into retort pouches. Selected pouches were fitted with stainless-steel packing glands (Model GKJ 13009C052) and thermocouple tips were inserted into shrimp at the slowest heating point. Sealing surfaces were cleaned using sterile tissue. Pouches were steam-exhausted, hermetically sealed and loaded into the retort for thermal processing to attain desired F_0 values.

Thermal processing of Black tiger shrimp in curry medium

Shrimp curry pouches were thermally processed to achieve target lethality (F_0 values of 8 and 9 minutes), followed by cooling and air drying prior to storage and subsequent analysis. Thermal validation was conducted using the Ellab E-val Flex Four Channel System (Cat. 21401004; Ellab A/S, Trollesmindealle 25, DK-3400 Hilleroed, Denmark), which recorded real-time core and retort temperatures, F_0 values, and cook values (CV) at 60-second intervals. Measurements were captured using Ellab SSATS copper/cupronickel thermocouples with stainless-steel electrodes (4 cm length, 1.2 mm diameter, accuracy < 0.2°C). F_0 calculations were performed with system settings of T = 121.1°C and Z = 10°C, while cook value constants (for thiamine degradation) were applied at T = 100°C and Z = 33°C. Processing time was determined using Ball's mathematical model as per the protocol established by Stumbo (1973) [7].

Proximate, Biochemical, and Microbiological Analyses

Moisture, ash, protein, and fat contents of raw and processed black tiger shrimp were determined using AOAC (2010) [8] methods. The values were expressed as % (wet weight basis). Biochemical parameters like TVB-N, TMA-N, PV, FFA, TBA-RS, Indole were performed for raw as well as processed shrimp. TVB-N and TMA-N were determined by Conway's micro diffusion method (Conway, 1962) [9]. TBA value was determined using the method of Raghavan and Hultin (2005) [10]. Peroxide value was determined using the method of Kirk and Sawyer (1991) [11]. Free fatty acid (FFA) value was determined using the method of Dyer and Morten (1956) [12]. pH was determined using the pH meter. Indole is determined by modified colorimetric method described by

Cheuk *et al*., (1981) [13]. The total plate count (TPC) was estimated for raw shrimp by the spread plate technique. (ICMSF, 1986) [14].

Commercial sterility test

To evaluate commercial sterility, shrimp curry pouches processed at two different F_0 values were incubated under conditions designed to detect mesophilic and thermophilic bacterial survivors. Samples were held at 37°C for 15 days and at 55°C for at least 5 days. Following incubation, the pouches were aseptically opened, and 1-2 g of sample was transferred using sterilized forceps into sterile test tubes containing fluid thioglycolate broth. To establish anaerobic conditions, sterilized liquid paraffin was layered over the broth surface. The tubes were then incubated at 37°C for 48 hours and at 55°C for 4 days. The assessment protocol adhered to the guidelines specified in IS:2168 1971 [15].

Texture Profile Analysis

Textural characteristics of raw and thermally processed Black Tiger shrimp at varying thermal lethality (F_0) values were evaluated using a texture analyzer (TA-XT Plus, Stable Micro Systems, UK). A cylindrical probe (75 mm diameter) equipped with a 50 N load cell was employed to perform a double compression test. Samples were compressed twice to 40% of their original height at a crosshead speed of 12 mm/min, following the standard method described by Bourne (1978) [16] and further adapted by Mohan *et al*. (2006) [17].

Colour Analysis

Colour measurements of all samples were carried out using a colourimeter (ColorFlex EZ, HunterLab, Reston, VA, USA) equipped with an 8° diffuse geometry and a D65/10° standard illuminant. The instrument was calibrated prior to analysis using standard black and white reference tiles provided by the manufacturer. Colour was recorded in the CIELAB colour space, providing L* (lightness), a* (red-green), and **b*** (yellow-blue) values.

Sensory Evaluation

The organoleptic quality of processed product in curry medium was assessed using a 9-point hedonic scale (Meilgaard *et al*., 1999) [18] by a trained panel comprising 25 members, including researchers, scientists, and postgraduate students. Processed retort pouches were conditioned and stored under ambient conditions for 180 days. Post-storage, samples were randomly selected for sensory analysis. Prior to evaluation, pouches were reheated in boiling water for 10 minutes. The contents were then served warm on coded, white enamel plates to ensure unbiased assessment. Attributes assessed included appearance, color, flavor, chewiness, succulence, toughness, and overall acceptability.

Statistical Analysis: A minimum of triplicate samples was analysed for all the analyses. For sensory analysis, mean values from 25 are presented. The results were expressed as mean ± standard deviation. Duncan multiple range test was performed to find out the difference in mean ($p<0.05$). The SPSS 26.00 statistical package was used for the analysis of the experimental results**.**

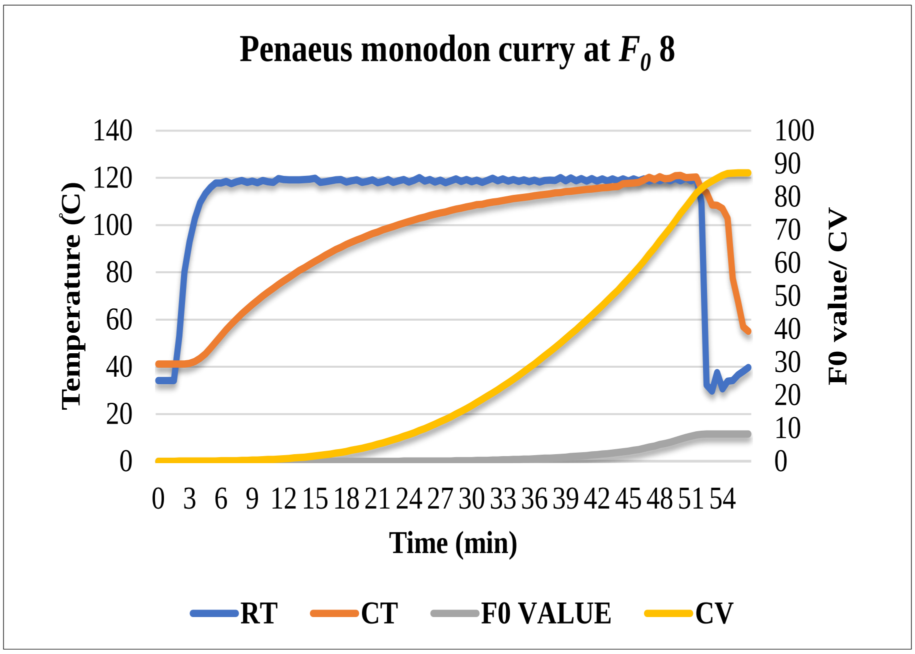
Results and Discussion

Thermal processing

Shrimp curry packed in retortable pouches was processed at two lethality values, F_0 8 and F_0 9 minutes. Heat penetration characteristics were calculated (Table 2) using data gathered from the Ellab system. The come-up times were 6.5 minutes (F_0 8) and 4.5 minutes (F_0 9), indicating that the retort chamber reached sterilization temperature quickly under both conditions (Figure 1). Minimal variation in heating lag (Jh) and cooling lag (Jc) factors between treatments suggested stable heat transfer dynamics throughout processing. The heating curve slope (f_h) was 22 minutes for F_0 8 and 20.5 minutes for F_0 9. Total process times to achieve sterilization were 30.54 minutes and 30.04 minutes, respectively. Cook values (CV), which represent the cumulative thermal impact on product quality, were 87.23 minutes for F_0 8 and 86.44 minutes for F_0 9. A slight reduction in total processing time and CV was observed at the higher F_0 value, likely due to faster heat penetration and optimized sterilization kinetics. These results aligned with the recommended F_0 range of 5-20 minutes for seafood products (Frott & Lewis, 1994) [19]. Comparable findings were reported by Mohan *et al*. (2006) [17], who documented a CV of 86.14 minutes and a total process time of 33.79 minutes for shrimp kuruma at F_0 8 min. Majumdar *et al*. (2017) [20] observed significantly longer process durations and higher cook values in freshwater prawn curry, with CV reaching 107.93 and 117.55 minutes for F_0 8 and F_0 9, respectively. Sreenath *et al*. (2007) [21] reported a cook value of 95.4 minutes in shrimp curry processed in tin-free steel cans. More recently, Puthanangadi *et al*. (2021) [22] documented process times of 37.11 and 39.88 minutes and CV of 84.07 and 92.41 minutes for masala-packed shrimp processed at F_0 8 and F_0 9 min.

Table 2: Heat penetration characteristics of shrimp curry in reportable pouches at two different F_0 values

Parameters	F_0 8	F_0 9
Come-up-time (min)	6.5	4.5
Heating lag factor (J_h)	1.01	0.97
Cooling lag factor (J_c)	1.00	1.01
fh slope of heating curve (min)	22	20.5
U	8.47	9.85
fh/U	2.59	2.08
g (⁰C)	4.839	4.28
Cook value (min)	87.23	86.44
Balls process time (min)	26.77	27.03
Total process time (min)	30.54	30.04



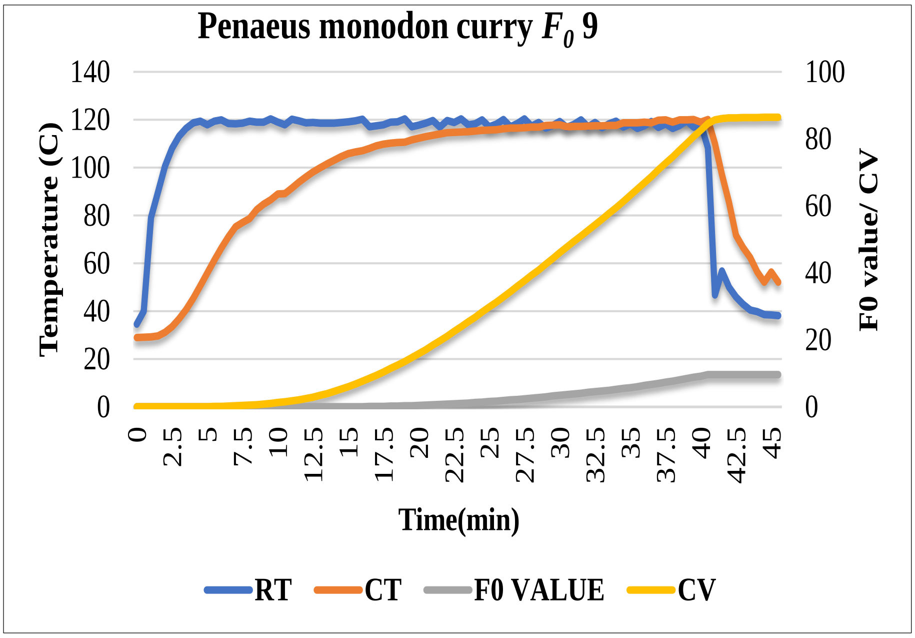


Fig 1: Heat penetration rate of shrimp in curry medium processed at F_0 8 and 9 min.

Proximate composition of raw black tiger shrimp

The proximate composition of raw and processed shrimp curry is presented in **Table 3**. In this study, the average moisture content of *P. monodon* was 79.36 %, crude protein content was 17.15 %, crude fat content was 1.23 %, and ash content was 1.05 %. This indicates that the shrimp used in the study is a lean variety with a good quantity of protein. Similar results were reported for black tiger shrimp, with 80.47% moisture, 17.1% protein, 1.23% fat, and 0.95% ash, as reported by Sriket *et al.* (2007) [23]. Akintola *et al.* (2013)[24] and Marichamy *et al*. (2011) [25] reported that the moisture and protein contents of fresh *P. monodon* were 75.18% and 20.34%, respectively.

Table 3: Proximate composition of raw shrimp *(P monodon*) and thermally processed Shrimp Curry at F_0 8 and F_0 9 min.

Sl. No.	Proximate composition	Raw material *(P monodon)*	Fish curry	
			***F₀* 8**	***F₀* 9**
1	Moisture (%)	79.36 ± 0.69	80.65 ± 0.57	80.20 ± 0.42
2	Crude protein (%)	17.15± 0.46	15.84 ± 0.25	16.19 ± 0.17
3	Total lipid (%)	1.23± 0.35	3.49 ± 0.50	3.51± 0.49
4	Ash content (%)	1.05± 0.04	2.86 ± 0.16	2.44 ± 0.53

*Values are presented as mean ± standard deviation of triplicates sample (*n* = 3).

Biochemical Analysis: The biochemical quality of shrimp curry was evaluated for 180 days at room temperature. Samples processed at F_0 8 and F_0 9 minutes showed consistent increases across all indicators, although values remained within acceptable limits. Raw shrimp had a TVB-N value of 5.64 mg N/100 g. After thermal processing, values rose to 8.06 mg N/100 g for F_0 8 and 8.64 mg N/100 g for F_0 9. By day 180, levels reached 15.16 mg N/100 g and 15.98 mg N/100 g, respectively. The increase was due to the breakdown of proteins and TMAO during heating and storage. These results agreed with earlier reports on retorted shrimp and salmon (Mohan *et al*., 2006; Rodriguez *et al*., 2009; Biji *et al*., 2015) [17, 26, 27]. All samples stayed below the spoilage threshold of 20 mg N/100 g.

TMA-N content of raw shrimp was 2.84 mg N/100 g in raw shrimp. Retorted samples had slightly higher values of 3.06 mg N/100 g (F_0 8) and 3.88 mg N/100 g (F_0 9). After 180 days, TMA-N reached 7.68 mg N/100 g and 8.02 mg N/100 g. The increase resulted from thermal degradation of TMAO into TMA. Similar trends were observed in sardine, mussel and Pangasius products (Uriarte-Montoya *et al*., 2010; Puthanangadi *et al*., 2021, Tekade *et al*., 2024) [28, 22, 29]. The values remained well below rejection limits. Initial PV in raw shrimp was 1.86 mEq O_2/kg. Retorted samples had values of 1.12 mEq O_2/kg (F_0 8) and 1.58 mEq O_2/kg (F_0 9). After storage, PV increased steadily to 9.39 mEq O_2/kg and 9.57 mEq O_2/kg. This was attributed to oxidative changes in lipids caused by heat and oxygen exposure. Earlier studies reported that PV levels between 10-20 mEq O_2/kg mark the onset of rancidity in fish products (Connell, 1995; Ahn & Min, 2005) [30, 31].

TBA-RS values were 0.30 mg malonaldehyde/kg in raw samples. Retorted products had values of 0.52 mg/kg (F_0 8) and 0.58 mg/kg (F_0 9). By day 180, the values reached 1.21 mg/kg and 1.47 mg/kg. The increase reflected secondary oxidation of lipids due to prolonged storage. Previous research confirmed similar TBA-RS trends in heat-treated mussels (Biji *et al*., 2015 [27]. Raw shrimp contained 0.18% FFA. Retorted samples started at 0.21% (F_0 8) and 0.29% (F_0 9). FFA levels rose to 1.11% and 1.23% by day 180. The increase was caused by thermal hydrolysis of triglycerides. Thermal processing is known to accelerate lipid degradation in fish (Aubourg *et al*., 1990; Medina *et al*., 1995)[32, 33]. FFA values remained within acceptable limits.

Raw shrimp had a pH of 6.31. Retorting reduced the pH to 5.43 (F_0 8) and 5.46 (F_0 9). During storage, pH gradually rose to 6.15 and 6.21, respectively. The increase was due to protein breakdown and amine release. Indole in raw shrimp was 13.46 µg/100 g. Retorted samples showed values of 13.69 µg/100 g (F_0 8) and 13.93 µg/100 g (F_0 9). By day 180, indole increased to 17.97 µg/100 g and 18.03 µg/100 g. This slight rise was consistent with slow tryptophan degradation. Values remained well below the FDA limit of 25 µg/100 g (Okada *et al*., 1994) [34].

Table 4: Changes in biochemical parameters of thermally processed Black tiger shrimp (*Penaeus monodon*) in curry medium with different F_0 value during storage at ambient temperature.

Parameters	DOS	Raw *shrimp*	F_0 8 Curry	F_0 9 Curry	*p* Value
TVBN (mg N/100g)	0	5.64 ±0.36	8.06 ± 0.18^{a}	8.64 ±0.34^{a}	0.061
	30		9.11 ± 0.12^{b}	9.76 ±0.27^{b}	0.018
	60		10.15 ± 0.43^{c}	11.04 ±0.67^{c}	0.127
	90		11.73 ± 0.37^{d}	12.15 ±0.38^{d}	0.248
	120		12.88 ± 0.13^{e}	13.73 ±0.30^{e}	0.011
	150		13.96 ± 0.33^{f}	15.04 ±0.84^{f}	0.076
	180		15.16 ± 0.38^{g}	15.98 ±0.47^{g}	0.107
	p Value		<0.001	<0.001	
TMAN (mg N/100g)	0	2.84 ±0.16	3.06 ±0.19^{a}	3.88±0.62^{a}	0.093
	30		3.95 ±0.14^{b}	4.35±0.39^{a}	0.175
	60		4.79 ±0.38^{c}	5.17±0.41^{b}	0.309
	90		5.14 ±0.44^{c}	6.01±0.47^{c}	0.079
	120		6.23 ±0.33^{d}	6.87± 0.31^{d}	0.072
	150		6.93 ±0.27^{e}	7.78± 0.21^{e}	0.012
	180		7.68 ± 0.51^{f}	8.02 ± 0.0.19^{e}	0.330
	p Value		<0.001	<0.001	
PV (mEq of O2/kg)	0	1.86 ± 0.08	1.12 ± 0.05^{a}	1.58 ± 0.55^{a}	0.225
	30		2.09± 0.12^{b}	3.12 ± 0.29^{b}	0.005
	60		3.23 ± 0.37^{c}	4.14 ± 0.37^{c}	0.039
	90		5.37 ± 0.15^{d}	6.43 ± 0.57^{d}	0.036
	120		7.14± 0.19^{e}	8.01 ± 0.51^{e}	0.049
	150		8.29± 0.52^{f}	8.68 ± 0.51^{e}	0.631
	180		9.39± 0.43^{g}	9.57 ± 0.42^{f}	0.411
	p Value		< 0.001	<0.001	
TBA-RS (mg malonaldehyde/kg)	0	0.30 ± 0.02	0.52 ± 0.17^{a}	0.58 ± 0.10^{a}	0.596
	30		0.62 ± 0.10^{ab}	0.68 ± 0.02^{a}	0.389
	60		0.71 ± 0.10^{ab}	0.77 ± 0.04^{ab}	0.391
	90		0.77 ± 0.10^{ab}	0.81 ± 0.07^{ab}	0.771
	120		0.85 ± 0.06^{b}	0.91 ± 0.21^{ab}	0.633
	150		0.93 ± 0.19^{bc}	1.12 ± 0.25^{b}	0.424
	180		1.21 ± 0.32^{d}	1.47 ± 0.39^{c}	0.364
	p Value		<0.001	<0.001	
FFA (% oleic acid)	0	0.18 ± 0.01	0.21 ± 0.02^{a}	0.29 ± 0.01^{a}	0.002
	30		0.36± 0.01^{b}	0.41 ±0.01^{b}	0.006
	60		0.54 ± 0.02^{c}	0.56 ±0.05^{c}	0.469
	90		0.66± 0.06^{d}	0.69 ±0.02^{d}	0.391
	120		0.83 ± 0.04^{e}	0.91 ±0.02^{e}	0.040

	150		0.95 ± 0.02^{f}	1.04 ± 0.08^{f}	0.285
	180		1.11 ± 0.10^{g}	1.23 ± 0.13^{g}	0.125
	p Value		<0.001	<0.001	
pH	0	6.31 ± 0.45	5.43±0.21^{a}	5.46±0.54^{a}	0.733
	30		5.58±0.15^{ab}	5.62±0.37^{ab}	0.710
	60		5.63±0.44^{abc}	5.76±0.27^{ab}	0.521
	90		5.73±0.13^{bcd}	5.82±0.10^{ab}	0.353
	120		5.93±0.19^{bcd}	5.89±0.16^{ab}	0.792
	150		6.03±0.14^{cd}	5.98±0.05^{ab}	0.825
	180		6.15±0.16^{d}	6.21±0.41^{b}	0.629
	p Value		<0.001	<0.001	
Indole (µg/100 gm)	0	13.46 ± 0.50	13.69 ±0.31^{a}	13.93 ± 0.35^{a}	0.417
	30		14.55 ±0.50^{ab}	14.69 ± 0.36^{b}	0.721
	60		15.08 ±0.29^{bc}	15.24 ± 0.40^{b}	0.624
	90		15.92 ±0.37^{c}	16.13 ±0.14^{c}	0.404
	120		17.03 ±0.87^{d}	17.19 ±0.46^{d}	0.792
	150		17.45 ±0.75^{d}	17.56 ±0.57^{de}	0.506
	180		17.97 ±0.11^{d}	18.03 ±0.12^{e}	0.850
	p Value		<0.001	<0.001	

*Values are expressed as mean ± standard deviation Different superscripts in same rows indicate significant differences ($p < 0.05$) (n=3)

Commercial sterility test: The commercial sterility of thermally processed shrimp curry packed in flexible retort pouches was tested. No signs of turbidity or microbial growth were observed in thioglycolate broth following incubation at 37 °C for 48 hours and at 55 °C for 4 days. Both the products processed at F_0 8 and F_0 9 min remained sterile throughout the 180-day ambient storage period. This result confirmed that the total lethality imparted during retort processing was sufficient to inactivate vegetative cells and heat-resistant spores, including *Clostridium botulinum*, the primary safety concern in low-acid seafood products. These findings are consistent with earlier studies on tilapia fish curry (Taral *et al*., 2023) [35] and cobia chunks curry (Tameshwar *et al*., 2024) [36], prawn curry (Majumdar *et al*., 2017) [20], and shrimp curry in tin-free steel cans (Sreenath *et al*., 2007) [21]. The application of validated retort conditions and effective heat penetration ensured microbial safety for extended shelf life.

Colour Analysis

The colour parameters of shrimp curry underwent noticeable changes during 180 days of ambient storage (Figure 2). Samples processed at F_0 8 and F_0 9 minutes showed a progressive decline in lightness (L*), with values dropping from 49 to 40.16 and from 48.96 to 39.81, respectively. This reduction in L* indicated darkening of the product with time and thermal intensity. Simultaneously, both redness (a*) and yellowness (b*) increased significantly ($p < 0.05$), suggesting enhanced pigment intensity and browning reactions. The increase in a* and b* values was attributed to heat-induced denaturation of carotenoid proteins and muscle proteins (Tekade *et al*., 2024) [29]. This alteration exposed and intensified carotenoid pigments, particularly astaxanthin, which imparted reddish-orange hues to the muscle tissue (Okada *et al*., 1994)[34]. These findings were in line with earlier studies showing similar trends in retorted shrimp and prawn products. For instance, Sreenath *et al*. (2007)[21] reported L*, a*, and b* values of 16.85, 8.16, and 15.97 for shrimp curry processed at F_0 7, and 16.47, 8.20, and 15.90 for F_0 8. Likewise, Majumdar *et al*. (2017) [20] observed decreasing L* values of 54.00, 49.36, and 46.42 as F_0 increased from 6 to 9 in freshwater prawn curry. These results confirmed that prolonged heat exposure affected colour intensity. The darkening and pigment concentration were more evident at higher F_0 values, but no major visual difference was noted between F_0 8 and 9, indicating that both treatments induced comparable colour transitions.

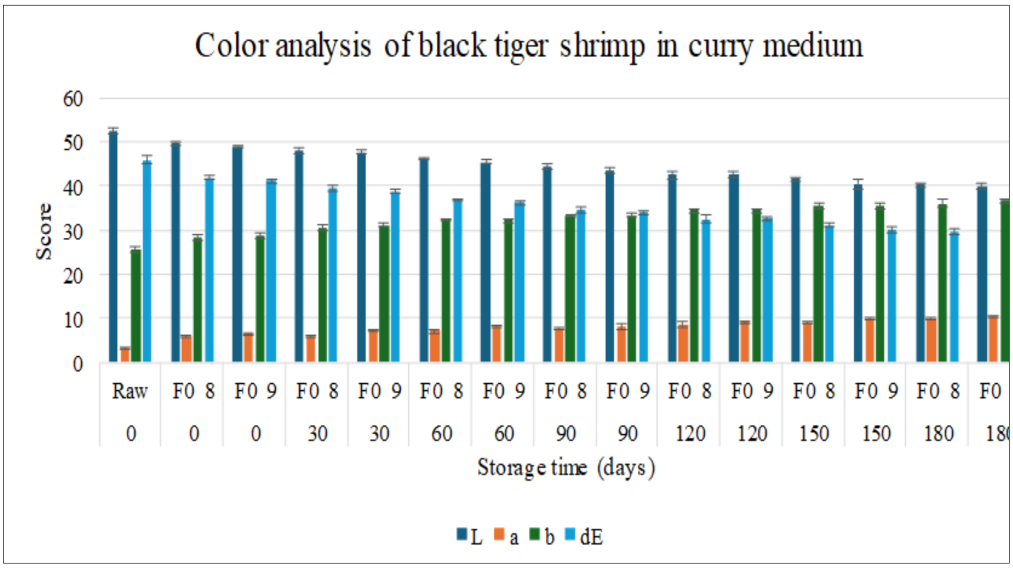


Fig 2: Colour parameters of raw and thermally processed shrimp curry processed at F_0 8 and 9

Instrumental Texture profile analysis

Texture Profile Analysis (TPA) was used to assess mechanical changes in shrimp curry after thermal processing and storage (Figure 3). Raw shrimp showed hardness (3.14 Kgf), springiness (0.69 mm), cohesiveness (0.55), gumminess (1.73 Kgf), and chewiness (1.20 Kgf·mm). These values increased after retorting due to protein denaturation and structural tightening (Mohan *et al*., 2006) [17]. After 180 days of ambient storage, samples processed at F_0 8 showed reduced hardness (1.98 Kgf), springiness (0.51 mm), and chewiness (0.47 Kgf·mm). This decline was attributed to heat-induced muscle weakening and moisture loss. Samples at F_0 8 retained better texture than F_0 9, suggesting that higher F_0 caused more softening and breakdown of myofibrillar structures (Sreenath *et al*., 2007; Mallick *et al*., 2010) [21, 37]. Springiness and gumminess both declined with increasing F_0 values, consistent with earlier studies on prawn curry and heat-treated fish products (Majumdar *et al*., 2017) [20]. Cohesiveness remained relatively stable but trended slightly lower during storage. Overall, extended heating reduced structural integrity and impacted bite quality. The changes were similar to those reported for retorted shrimp and surimi-based products (Ali *et al*., 2005; Shah *et al*., 2017, Lingaraju *et al*., 2025) [38, 39, 40]. These findings confirmed that thermal intensity strongly influenced textural properties. Milder processing at F_0 8 preserved firmness and elasticity better, contributing to improved sensory characteristics over time

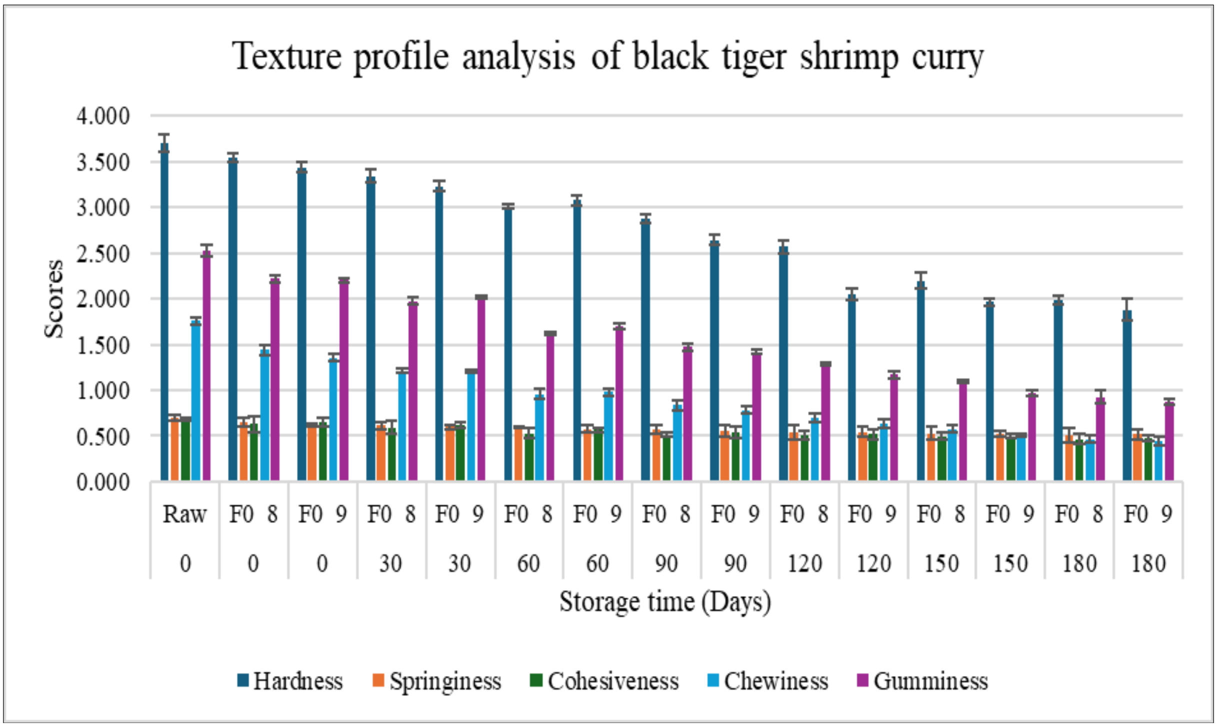


Fig 3: Instrumental texture Profile analysis for raw and thermally processed shrimp curry processed at F_0 8 and 9 min.

Sensory Evaluation

Sensory attributes of shrimp curry were assessed by a trained panel over 180 days of storage. Samples processed at F_0 8 and F_0 9 minutes were evaluated for appearance, colour, flavour, firmness, succulence, toughness, and overall acceptability (Table 5). At day 0, both treatments received high scores across all attributes. Appearance ranged from 8.70 to 8.80, colour from 8.70 to 8.90, and overall acceptability was above 8.80. The scores declined gradually over the storage period. By day 180, samples processed at F_0 8 retained higher ratings than those at F_0 9. Final scores for overall acceptability were 8.30 (F_0 8) and 8.20 (F_0 9), while colour dropped to 8.10 and 7.90, respectively. The decrease in sensory quality was more evident in the F_0 9 sample. The reduction in scores over time was attributed to pigment oxidation, texture softening, and accumulation of lipid oxidation products. The milder F_0 8 treatment preserved firmness, flavour, and colour better than the higher F_0 value. No significant differences were observed in toughness across the storage period, indicating that both treatments maintained acceptable texture integrity. These findings confirmed that shrimp curry processed at F_0 8 minutes offered superior sensory retention during storage. Similar trends were reported by Majumdar *et al*. (2017) [20] and Sreenath *et al*. (2007) [21], who noted better consumer acceptance in mildly retorted prawn and shrimp curry products. The results emphasized the importance of optimizing thermal load to balance safety and sensory quality in ready-to-eat seafood.

Table 5: changes in Sensory evaluation of raw and thermally processed black tiger shrimp Curry processed at F_0 8 and F_0 9.

Parameters	DOS	Raw shrimp	F_0 8 Curry	F_0 9 Curry	*p* Value
Appearance	0	8.80±0.42	8.70±0.48^{a}	8.70±0.48^{a}	0.933
	30		8.60±0.52^{ab}	8.50±0.71^{ab}	0.722
	60		8.40±0.52^{ab}	8.30±0.67^{abc}	0.714
	90		8.30±0.67^{ab}	8.20±0.63^{abc}	0.714
	120		8.20±0.63^{ab}	8.10±0.57^{abc}	0.714
	150		8.10±0.99^{ab}	8.00±0.47^{bc}	0.777
	180		7.90±0.99^{b}	7.80±0.79^{c}	0.806
	p Value		<0.001	<0.001	
Colour	0	8.70±0.48	8.80±0.42^{a}	8.70±0.48^{a}	0.628
	30		8.70±0.48^{ab}	8.60±0.70^{ab}	0.714
	60		8.60±0.52^{abc}	8.50±0.71^{abc}	0.722
	90		8.50±0.53^{abc}	8.40±0.70^{abc}	0.714
	120		8.40±0.52^{abc}	8.30±0.67^{abc}	0.433
	150		8.20±0.42^{bc}	8.00±0.74^{bc}	0.552
	180		8.10±0.74^{a}	7.90± 0.74^{c}	
	p Value		<0.001	<0.001	
Flavour	0	8.80±0.42	8.90±0.32^{a}	8.90±0.31^{a}	0.912
	30		8.90±0.32^{a}	8.80±0.42^{a}	0.556
	60		8.80±0.42^{ab}	8.60±0.51^{ab}	0.355
	90		8.70±0.48^{ab}	8.50±0.52^{abc}	0.388
	120		8.60±0.70^{ab}	8.30±0.48^{bc}	0.279
	150		8.50±0.53^{ab}	8.20±0.42^{bc}	0.177
	180		8.30±0.67^{b}	8.10±0.56^{c}	0.482
	p Value		<0.001	<0.001	
Firmness	0	8.80±0.42	8.90±0.32^{a}	8.80±0.42^{a}	0.556
	30		8.80±0.42^{ab}	8.60±0.52^{ab}	0.355
	60		8.70±0.48^{ab}	8.50±0.53^{ab}	0.388
	90		8.60±0.52^{ab}	8.40±0.70^{ab}	0.476
	120		8.50±0.71^{ab}	8.30±0.67^{ab}	0.526
	150		8.40±0.52^{ab}	8.20±0.79^{ab}	0.511
	180		8.30±0.48^{b}	8.10±0.74^{b}	0.482
	p Value		<0.001	<0.001	
Succulence	0	8.9±0.32	8.90±0.32^{a}	8.80±0.42^{a}	0.556
	30		8.80±0.42^{ab}	8.70±0.48^{ab}	0.628
	60		8.70±0.48^{ab}	8.60±0.52^{ab}	0.660
	90		8.60±0.70^{ab}	8.50±0.53^{ab}	0.722
	120		8.50±0.71^{ab}	8.40±0.52^{ab}	0.722
	150		8.40±0.52^{ab}	8.30±0.67^{ab}	0.714
	180		8.30±67^{b}	8.20±0.42^{b}	0.696
	p Value		<0.001	<0.001	
Toughness	0	8.80±0.42	8.70±0.48^{a}	8.70±0.48^{a}	0.918
	30		8.60±0.52^{a}	8.60±0.52^{a}	0.963
	60		8.50±0.53^{a}	8.50±0.53^{a}	0.945
	90		8.40±0.70^{a}	8.40±0.70^{a}	0.951
	120		8.30±0.67^{a}	8.20±0.79^{a}	0.764
	150		8.30±0.48^{a}	8.20±0.79^{a}	0.736
	180		8.20±0.79^{a}	8.10±0.74^{a}	0.773
	p Value		<0.001	<0.001	
Overall acceptability	0	8.90±0.32	8.90±0.32^{a}	8.80±0.42^{a}	0.556
	30		8.80±0.42^{ab}	8.70±0.48^{a}	0.628
	60		8.70±0.48^{ab}	8.60±0.52^{a}	0.660
	90		8.60±0.53^{ab}	8.50±0.71^{a}	0.722
	120		8.50±0.67^{ab}	8.40±0.70^{a}	0.754
	150		8.40±0.74^{ab}	8.30±0.48^{a}	0.714
	180		8.30±0.88^{b}	8.20±0.79^{a}	0.736
	p Value		<0.001	<0.001	

* Values are expressed as mean ± standard deviation Different superscripts in same rows indicate significant differences (p<0.05) (n=3)

Conclusion

The study successfully developed ready to eat thermally processed shrimp curry packed in flexible retort pouches. The product was thermally processed at two different lethality (F_0 value of 8 and 9 min) using commercial pilot scale over pressure retort. The study clearly proved the reduction in moisture content post thermal processing and increase of crude protein, crude fat and ash content of the samples after thermal processing and all biochemical constituents such as TVB-N, TMA-N, TBARS, FFA, PV values were increasing but were within the acceptable limit. pH was observed very marginal variation throughout the storage period which indicated that product maintained its microbial quality during storage life. The products processed at F_0 value of 8 and 9 min were commercially sterile and have good sensorial acceptance. These findings confirmed that shrimp curry processed at F_0 8 minutes offered superior sensory retention during storage.

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