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Heat Penetration and Quality Characteristics of Ready-To-Eat Thermally Processed Mangalorean-Style Squid Rings in Masala in Retort Pouch

Devika Gundubilli[a], Manjanaik Bojayanaik[a*], Madonna Thomson Thachil[a] Gouthamy Puthanangadi Dasan[a], Sachin Dnyanoba Chavan[a], Vyankatesh Tekade[a], Tameshwar[a], Maga Raju Siravati[a], Srinu Nayak Banavath[a], Veena Shetty Alandur[b], Chitradurga Obaiah Mohan[c]

[a]*Department of Fish Processing Technology, Karnataka Veterinary, Animal and Fisheries Sciences University, College of Fisheries, Mangaluru - 575 002, India*

[b]*Department of Microbiology, NITTE (Deemed to be University), K. S. Hegde Medical Academy (KSHEMA), Deralakatte, Mangaluru - 575 018, India*

[c]*Fish Processing Division, ICAR-Central Institute of Fisheries Technology, Kochi, Kerala - 682 029, India*

Abstract

The present work aimed to optimize the thermal processing of Mangalorean-style squid rings in masala in a retort pouch and evaluate its sensory and textural changes during storage. The recipe was developed based on the authentic culinary style prevalent in Mangaluru, Karnataka, India, followed by sensory evaluation. Mangalorean-style squid rings in masala (270 ± 10 g) were packed in retort pouches, steam exhausted, heat sealed, and thermally processed at selected F_0 values (10 and 12 min) and stored for 90 days. Thermal processing caused a slight increase in TVBN and TBARS values compared to raw squid but no significant differences were observed between the two F_0 treatments. The sensory characteristics and texture profile of the products remained comparable between treatments after 90 days of storage. The cook values at F_0 10 and 12 minutes were 81.54 and 94.05 min, respectively, indicating greater thermal impact at higher processing intensity. Thermal processing at F_0 10 minutes resulted in a 19.46% reduction in total process time compared to F_0 12 minutes, demonstrating improved heating efficiency. Accordingly, an F_0 value of 10 min was identified as the optimal processing condition for the preparation of ready-to-eat 'Mangalorean-style' squid rings in masala using retort pouch technology.

Keywords: Thermal processing, retort pouch, squid, texture profile, sensory, TPT, F_0

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*Email: manjanaikb@rediffmail.com

Introduction

Molluscan shellfish resources occupy a prominent place among exploited marine fishery resources worldwide owing to their abundance, nutritional quality and unique taste and texture. The major species involved in the global molluscan shellfish trade include squid, cuttlefish, octopus, scallops, etc., of which squid attracts particular attention due to its high nutritional value and significant contribution to global fisheries. Squid is a rich source of high-quality protein, vitamins, minerals, and essential fatty acids. Squid species belonging mainly to the families Loliginidae and Ommastrephidae contributed approximately 9% of the global marine capture production in 2020, while squid, along with cuttlefish and octopus, accounted for around 7% of the global fish trade by value (Food and Agriculture Organization [FAO], 2022). The key regions in the global squid trade include the United States of America, the European Union, China, Japan, Korea, India and Southeast Asia. In India, squid landings accounted for 105,818 tonnes (Central Marine Fisheries Research Institute [CMFRI], 2023) and exports were primarily in frozen form, contributing USD 454.61 million for 83,846 tonnes during 2022–2023 (Marine Products Export Development Agency [MPEDA], 2023). Although squid is predominantly

traded in fresh and frozen forms, the demand for value-added and ready-to-eat (RTE) squid products is steadily increasing.

There are several emerging technologies for food processing, such as high-pressure processing, ultrasound treatment and ohmic heating. However, thermal processing using retort remains the most widely accepted method for producing shelf-stable, safe and convenient RTE seafood products (Awuah, Ramaswamy, & Economides, 2007; Ganachari, Bojayanaik, Chavan, & Fernandes, 2025a). Retort processing involves the application of high temperature to food sealed in hermetic containers, ensuring destruction of spoilage and pathogenic microorganisms and enabling long-term storage at ambient temperature. Traditional canning methods, however, are associated with higher material and processing costs. In this context, retort pouches have emerged as an efficient alternative due to their advantages such as lower cost, reduced weight, improved heat transfer and better energy efficiency (Murphy, Marks, & Davidson, 2002; Juliano, Koutchma, Sui, Barbosa-Cánovas, & Sadler, 2010).

Most retort pouches are constructed using a three- or four-layer laminate structure consisting of polyester (outer layer), nylon (intermediate layer), aluminium foil (barrier layer) and polypropylene (inner sealing layer). The melting point of polypropylene (~138 °C) is higher than the standard sterilization temperature (121.1 °C), ensuring structural integrity during processing (Majumdar, Roy, & Saha, 2017). Retort pouch processing offers significant advantages, including reduction in processing time, improved product texture and better retention of sensory quality. Processing in pouches has been reported to reduce process time by approximately 35% compared to conventional cans while maintaining equivalent lethality (Mohan, Ravishankar, Bindu, Geethalakshmi, & Gopal, 2006). Steam air and water immersion over-pressure retort systems are commonly used, with steam air systems often exhibiting shorter come-up time and total process duration (Adepoju, Omitoyin, Mohan, & Zynudheen, 2017).

Ready-to-eat Indian ethnic seafood products have considerable global potential due to their unique flavour, cultural appeal and nutritional benefits. Several studies have reported the development of thermally processed seafood products, including freshwater prawn curry (Majumdar et al., 2017), mackerel curry (Dinakaran, Mohan, Panda, Ravishankar, & Gopal, 2017), cobia products (Shakila, Raj, & Felix, 2015), squid products (Dileep, Sudhakara, & Basavakumar, 2012) and shrimp-based products (Mohan et al., 2006). More recent studies have also focused on optimizing F_0 values in retort pouch seafood products, such as Pangasius chunks (Tekade et al., 2024), GIFT tilapia (Vaghabhai et al., 2023), cobia fish curry (Tameshwar et al., 2024), shrimp curry products (Ganachari et al., 2025a) and pacu fish masala (Chavan et al., 2025), highlighting the importance of balancing microbial safety with sensory and nutritional quality.

Mangaluru, a major port city on the South-West coast of India, is well known for its distinctive spicy seafood cuisine, which is widely appreciated both nationally and internationally. Despite the popularity of Mangalorean-style seafood dishes, scientific studies on their thermal processing and shelf-stable product development are limited. The present study aims to optimize the thermal processing of 'Mangalorean-style squid rings in masala' in retort pouches and evaluate the physicochemical, sensory and textural changes during storage. Since squid is highly sensitive to heat treatment, improper or prolonged cooking can lead to undesirable toughening and rubbery texture; therefore, optimization of thermal processing conditions is critical to maintain product quality.

Although several studies have reported thermal processing of squid and other seafood products, most are limited to generic curry formulations, lower F_0 values and do not address process optimization in terms of energy efficiency and higher lethality levels. Furthermore, limited information is available on region-specific formulations, such as authentic Mangalorean-style squid products and their behaviour during retort processing and storage. Therefore, the present study focuses on optimizing thermal processing conditions by evaluating heat penetration characteristics, product quality and process efficiency to develop a shelf-stable, ready-to-eat, authentic Mangalorean-style squid product.

Materials and Methods

The fresh squid (*Loligo duvauceli*) (total length varying from 15 to 25 cm) was procured from the fish landing centre, Mangaluru, India, packed in polyethylene bags with ice and transported to the laboratory in an insulated ice box. The raw material was washed, weighed, and dressed. The dressing

yield was calculated. The Indian spices for preparing authentic Mangalorean-style masala powder were purchased from the local market (Table 2), followed by sun-drying, light frying and powdering after cooling. A laminated flexible retort pouch (150 × 200 mm) (12 μm polyester/ 9 μm nylon/ aluminium foil/ 70 μm cast polypropylene) was used for packing the Mangalorean-style squid rings in masala and for further thermal processing. The pilot scale horizontal over-pressure retort unit (M/ s. Lakshmi Engineering Pvt Ltd., Chennai, India) was used for thermal processing of Mangalorean-style squid rings in masala.

The recipe for Mangalorean-style squid rings in masala was developed based on the culinary recipe practiced in Mangaluru, India. The preparation of squid rings in masala is schematically represented in Fig. 2. The squid tubes were cleaned, dressed and cut into rings of uniform thickness (approximately 0.8–1 cm) to ensure uniform heat penetration, as described in standardized squid processing methods (Gopinath, Anthony, Nagarajarao, Jaganath, & Krishnaswamy, 2007). The squid rings were blanched in 8% brine solution at 80 °C for 6 minutes instead of prolonged boiling, followed by draining and holding under hygienic conditions to prevent overcooking and texture toughening.

The Mangalorean-style squid rings in masala were prepared using the ingredients given in Table 1. At first, finely chopped onion was fried in refined vegetable oil at 90–100 °C until a light brown colour developed under controlled heating conditions. This was followed by the addition of chopped green chilli, garlic, ginger, tomato and curry leaves and the mixture was cooked for 5–7 minutes until a uniform paste-like consistency and characteristic colour were obtained. The masala powder was prepared separately by lightly roasting individual spices (coriander, cumin, mustard, fenugreek, caraway, clove, cardamom, black pepper, cinnamon, star anise, turmeric, fennel and poppy seeds) at 60–70 °C until flavour development, followed by grinding into a fine homogeneous powder to ensure uniform mixing (Table 2). The masala powder and paste mixture was cooked under controlled heating conditions (80–90 °C) with continuous stirring. Heating was continued until the characteristic aroma developed. This was followed by the addition of blanched squid rings to the mixture and the contents were mixed thoroughly to ensure uniform coating of masala over the squid rings.

Approximately 270 ± 10 g of squid rings in masala was added to each retort pouch. A uniform headspace was maintained to facilitate proper heat transfer and sealing integrity, following standard retort processing practices. An adequate number of retort pouches were fixed with the packing glands (model GKJ 13009C052 made from 50 mm stainless steel tubes) and inserted with a thermocouple. The tip of the thermocouple was positioned near the geometric centre, corresponding to the expected slowest heating region of the pouch. Adequate care was taken to prevent the masala from contaminating the sealing area. The residual air was removed by steam exhausting, and the pouches were sealed immediately by a vertical band sealer (GEMP PACK, Ayanavaram, India) to achieve hermetic sealing. The filled and sealed pouches were loaded into the over-pressure retort and heat processed to the required F_0 values.

The thermal process was designed to achieve commercial sterility against *Clostridium botulinum* spores using a reference temperature of 121.1 °C and a z-value of 10 °C, which are standard specifications for *C. botulinum* (Stumbo, 1973). Preliminary trials were conducted to determine the appropriate range of thermal processing conditions for Mangalorean-style squid rings in masala packed in retort pouches (Fig. 1). The product was processed at F_0 values ranging from 7 to 14 min at 121.1 °C to assess the effects on degree of cooking, texture and sensory acceptability. Samples processed at lower F_0 values (7 min) were found to be undercooked, exhibiting inadequate texture development and poor sensory scores, whereas those processed at higher F_0 values (14 min) showed signs of overprocessing, including excessive softening and loss of desirable textural characteristics. Based on these preliminary observations, F_0 values of 10 and 12 minutes were identified as the most suitable for final product development. The filled and sealed retort pouches containing squid rings in masala were thermally processed to target F_0 values of 10 and 12 min.

The Eval Flex Four-Channel Thermal Validation and Sterilisation Monitoring System (Cat. 21401004, Ellab A/S, Trollesmindealle 25, DK-3400 Hilleroed, Denmark) was used in the study. The heat penetration data were monitored with the help of a four-channel thermocouple probe system, two of which recorded the product temperature and the other two retort temperature. The probes used for the experiments were copper/ cupronickel thermocouples

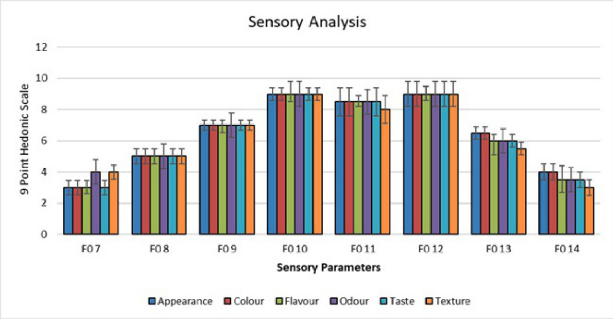

Fig. 1. Sensory analysis for optimization of Total Lethality (F_0) of Mangalorean-style squid rings in masala processed at F_0 7, 8, 9, 10, 11, 12, 13 and 14 min

(Ellab SSATS) of stainless-steel electrode with a length of 4 cm and a diameter of 1.2 mm, with the accuracy of <0.2 °C. During thermal processing, the product temperature, lethality and cook value were recorded every 30 seconds.

Total process time (TPT) was calculated according to the method of Stumbo (1973) by summing Ball's process time (B) and 58% of the come-up time (CUT), as expressed by the relation TPT = B + 0.58 × CUT, which accounts for the lethality contribution during the heating phase. The lethality value (F_0) was computed as the equivalent time (in minutes) at 121.1 °C required to achieve a specified level of microbial inactivation, using a reference temperature (Tref) of 121.1 °C and a z-value of 10 °C, following standard thermal processing principles (Stumbo, 1973). The cook value (CV), which represents the extent of thermal degradation of heat-sensitive nutrients (e.g., thiamine), was calculated using a reference temperature of 100 °C and a z-value of 33 °C, as described by Ranganna (2000). The thermal processing system was programmed with Tref = 121.1 °C and z = 10 °C for F_0 determination and Tref = 100 °C and z = 33 °C for cook value estimation, ensuring accurate evaluation of both microbial safety and quality changes during processing. Post-processing, the pouches were cooled, dried, labelled and stored at room temperature for 90 days and analysed for different parameters.

The proximate composition (moisture, ash, crude protein and crude fat) of raw squid and thermally processed Mangalorean-style squid rings in masala were analysed by the method of Association of Official Analytical Chemists [AOAC] (2010). Trimethylamine nitrogen (TMA-N), total volatile base nitrogen (TVBN) and peroxide value (PV) were determined by the AOAC (2010) method. The thiobarbituric acid reactive substances (TBARS) value was estimated using the method of Raghavan and Hultin (2005). The raw squid samples were analysed for total plate count (TPC) by the spread plate technique, whereas the thermally processed products were evaluated for total plate count and commercial sterility. The average number of colonies was expressed as CFU (colony-forming units) per gram of sample (American Public Health Association [APHA], 2017).

To test the commercial sterility, the representative retort pouches containing Mangalorean-style squid rings in masala were incubated at temperatures of 37 °C and 55 °C for 15 days and 5 days, respectively, to determine the presence of surviving mesophilic and thermophilic microorganisms. After the required incubation period, approximately 1 to 2 g of the sample was drawn with sterilized forceps and inoculated into the sterilized thioglycolate broth in test tubes. The top of the broth was covered with sterilized liquid paraffin to create an anaerobic condition. These tubes were then incubated at 37 °C for 2 days and at 55 °C for 4 days, respectively (IS 2168:1971) and checked for the presence of turbidity, which is indicative of microbial growth.

Sensory evaluation of the thermally processed Mangalorean-style squid rings in masala was carried out by a panel of 30 trained panellists. The panellists were familiar with seafood products and were briefed on the evaluation criteria before assessment. Samples were evaluated for appearance, colour, flavour, odour, taste, texture and overall acceptability using a 9-point hedonic scale (Meilgaard, Civille, & Carr, 1999). Thermally processed pouches containing squid rings in masala were randomly selected and evaluated on 0^{th} and 90^{th} day of storage. It was then heated in boiling water for 10 minutes. The contents of the pouches were emptied into coded white enamel plates and were served warm to the panellists in separate booths. The panellists were asked to assign a score between 1 and 9 to each coded sample for sensory parameters. A sensory score of 5 was taken as the limit of acceptability (1= dislike extremely; 2= dislike very much; 3= dislike moderately; 4= dislike slightly; 5= neither like nor dislike; 6= like slightly; 7= like moderately; 8= like very much; 9= like extremely).

Texture profile analysis (TPA) of the raw squid and thermally processed Mangalorean-style squid rings

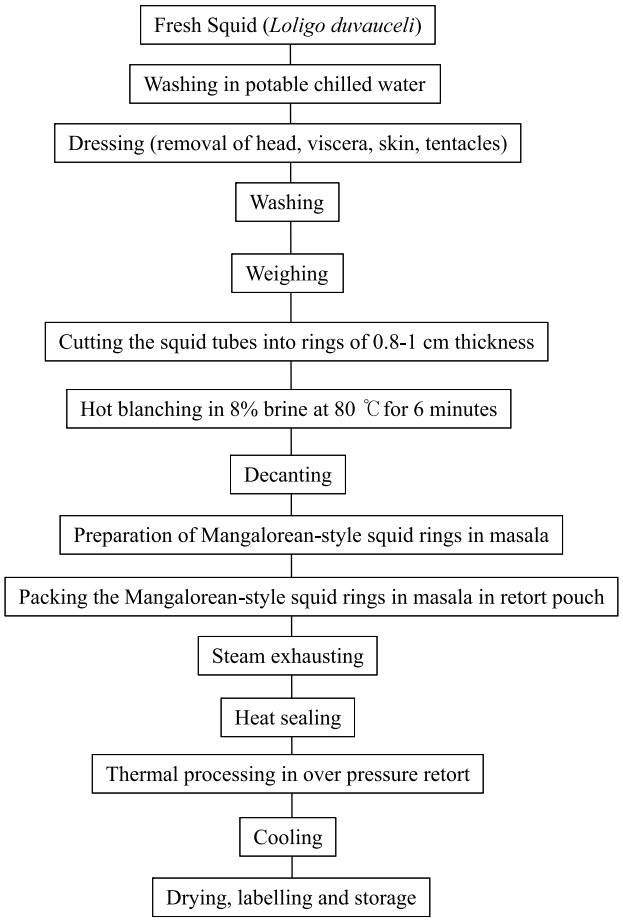

Fig. 2. Schematic chart for the preparation of Mangalorean-style squid rings in masala in a retort pouch

in masala was done based on the compression of samples using a TA-TX2 texture analyser (Stable Micro System Ltd, Surrey, UK) fitted with a cylindrical probe of 75 mm diameter and a load cell of 50 N. The randomly selected samples were drawn on 0^{th} and 90^{th} day of the storage. The texture measurement consisted of two consecutive compressions of test samples at 40% compression at a cross-head speed of 12 mm per minute (Mohan et al., 2006). Force by time data from each test was used to calculate the mean values for the texture profile parameters as described by Bourne (1980).

The statistical package, SPSS (version 20; SPSS Inc., Chicago, IL, USA), was used for data analysis. All experimental analyses were carried out in triplicate (n=3), and the results are presented as mean ± standard deviation. Data were subjected to one-way ANOVA followed by Duncan's Multiple Range Test ($p \leq 0.05$). Sensory evaluation was conducted using a panel of 30 trained members, and the scores were recorded using a standard hedonic scale.

Results and Discussion

An initial trial of thermal processing of the Mangalorean-style squid ring in masala in a retort pouch was done at F_0 values ranging from 7 to 14 minutes at a temperature of 121.1 °C, since the typical range of F_0 values for fish and meat products is from 5 to 20 minutes, as documented by Bratt (1995). Sensory analysis revealed that the product was under-cooked at F_0 7 and over-cooked at F_0 14 (Fig. 1). Thus, F_0 10 and 12 minutes were selected for further study. Heat penetration characteristics of thermally processed Mangalorean-style squid rings in masala are presented in Table 3, with heating and cooling profiles shown in Figs. 3 and 4. The heating curves exhibited a rapid temperature rise during the come-up phase followed by a gradual approach to the target temperature, indicating efficient heat transfer and uniform heat distribution within the product matrix. The short come-up time (3 min) indicates efficient heat transfer, which contributes to reduced overall process duration. The absence of a pronounced lag phase and the smooth heating profile further suggest effective heat penetration up to the cold point, ensuring adequate thermal processing. The similar J_h and J_c values across both F_0 levels suggest consistent heating and cooling behaviour, indicating that increasing lethality did not significantly alter heat transfer mechanism. The comparable slopes of heating and cooling curves for both treatments confirm that heat transfer was primarily governed by product composition and pouch characteristics rather than processing severity.

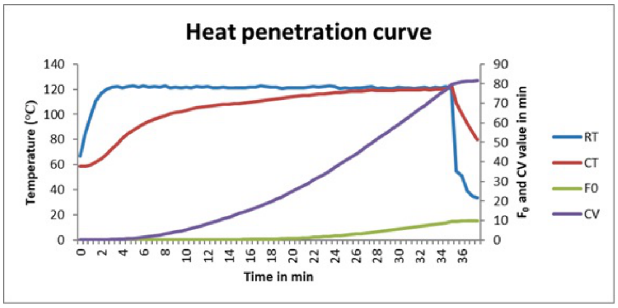

Fig. 3. Heat penetration curve for thermally processed Mangalorean-style squid rings in masala at F_0 10 minutes

RT= Retort temperature, CT= Core temperature, CV= Cook value

Table 1. Ingredients used for the preparation of Mangalorean-style squid rings in masala

Ingredients	Quantity
Oil	100 mL
Onion	300 g
Green Chilli	35 g
Tomato	200 g
Curry leaves	5 g
Ginger	25 g
Garlic	25 g
Masala powder	30 g
Red chilli powder	25 g
Salt	20 g
Squid rings	1000 g

Table 2. Composition of masala powder (ingredients) used for the preparation of Mangalorean-style squid rings in masala

Ingredients	Quantity per kg of masala powder
Coriander	500 g
Cumin	125 g
Mustard	50 g
Fenugreek	50 g
Caraway	50 g
Clove	25 g
Cardamom	25 g
Black pepper	125 g
Cinnamon	50 g
Star anise	50 g
Turmeric	50 g
Fennel	50 g
Poppy	100 g

The total process time was 27.54 min and 32.90 min for F_0 values of 10 and 12 min, respectively. A 19.46% reduction in process time was observed in the product processed at F_0 10 compared to F_0 12 min. The cook value also increased from 81.54 to 94.05 min, indicating greater thermal impact on product quality at higher lethality levels. Extended exposure at higher F_0 values results in increased thermal load, which may adversely affect texture and nutritional quality without significant improvement in microbial safety. This demonstrates the typical trade-off between achieving microbial safety and preserving quality attributes. Compared to previous studies, the present work achieved lower process times (27.54 & 32.90 min for F_0 10 and 12 min, respectively) despite higher F_0 values. Gopinath et al. (2007) reported 37 min for F_0 8, while Dileep et al. (2012) reported 55.36 min for F_0 7.45. Recent studies on shrimp and fish retort products also reported comparable or higher process times at lower F_0 levels (Chavan et al., 2025; Ganachari et al., 2025b). The relatively shorter process time observed in the present study can be attributed to improved heat transfer efficiency associated with retort pouch geometry (higher surface area-to-volume ratio) and the semi-liquid nature of the masala.

The average yield of squid rings from whole squid was 43.57%, reflecting typical processing losses associated with dressing and ring preparation in cephalopods. The proximate composition of raw squid meat (Table 4) indicated high moisture (86.72 ± 0.56%) and low lipid content (1.50 ± 0.02%), confirming its classification as a lean seafood, which is consistent with earlier reports on *L. duvauceli* (Raman & Mathew, 2015). However, the relatively higher moisture and lower protein content observed in the present study compared to literature values may be attributed to differences in season, size and post-harvest handling conditions. Following thermal processing, a significant reduction in moisture content was observed, accompanied by a proportional increase in crude protein, fat and ash contents. Rather than merely indicating compositional change, this reflects concentration effects due to moisture loss and structural modification of muscle proteins during heating. Similar trends have been reported in retort-processed green mussel, tuna and other seafood products, where thermal treatment led to moisture reduction and apparent nutrient enrichment (Biji et al., 2015; Mohan, Remya, Murthy, Ravishankar, & Kumar, 2015; Chavan et al., 2025). The reduction in moisture is primarily associated with heat-induced denaturation of myofibrillar proteins, leading to decreased water-holding capacity and expulsion of bound water, as previously described (Trinidad, Francisco, Ana, & Navarro, 1994; Bell, Farkas, Hale, & Lanier, 2001). In squid muscle, which contains relatively high collagen and connective tissue, thermal processing further contributes to structural shrinkage and fluid loss, thereby intensifying this effect. Recent studies on

Table 3. Heat penetration characteristics of thermally processed Mangalorean-style squid rings in masala at F_0 10 and F_0 12 min in a retort pouch

Parameters	F_0 10 minutes	F_0 12 minutes
$J_{h,}$ lag factor of heating	0.97	0.98
$J_{c,}$ lag factor of cooling	0.99	1.02
$F_{h,}$ slope of heating curve (minute)	15.5	19.5
U, time for sterilization at retort temperature (minute)	9.90	11.42
F_h/U	1.57	1.71
G, final temperature deficit (°C)	1.30	1.51
B, Ball's process time (minute)	25.80	31.16
Come up time (minute)	3	3
Total process time (minute)	27.54	32.90
Cook value (minute)	81.54	94.05

retort-processed seafood products have also demonstrated that product composition and heating intensity significantly influence moisture retention and textural properties (Mallick, Gopal, Ravishankar, & Vijayan, 2006; Ganachari et al., 2025a).

The total plate count (TPC) of raw squid was 2 × 10^5 CFU/g, while no evidence of microbial growth was observed in the processed product. TMA-N and TVBN contents in raw squid were 9.70 ± 0.20 mg% and 21.93 ± 0.81 mg%, respectively and were within acceptable limits. The TBARS value of raw squid meat was 0.65 ± 0.30 mg MDA/kg (Table 4). These results collectively indicate good initial freshness and low pre-processing oxidative load, which are prerequisites for stable retort products (Mohan et al., 2015; Barbosa, Trigo, Fett, & Aubourg, 2018; Dasan et al., 2021; Chavan et al., 2025). Thermal processing increased TMA-N levels to 11.76 ± 0.25 mg% (F_0 10) and 10.03 ± 0.25 mg% (F_0 12), while TVBN increased to 28.50 ± 0.50 and 29.30 ± 0.26 mg%, respectively. This increase can be primarily attributed to thermal degradation of trimethylamine oxide (TMA-O) rather than microbial spoilage, as commercial sterility is achieved during retort processing (Gill, Thompson, Gould, & Sherwood, 1987; Connell, 1995). Similar increases in volatile bases due to heat-induced chemical reactions have been reported in canned green mussel (Biji et al., 2015), canned yellowfin tuna (Mohan et al., 2015) and shrimp curry (Dasan et al., 2021). Although TMA-N showed significant variation between F_0 treatments, TVBN did not differ significantly, indicating that increasing lethality beyond F_0 10 min does not substantially influence total volatile base formation. This observation is consistent with recent retort studies on fish and shrimp masala products, where higher F_0 values resulted in minimal changes in TVBN but increased thermal load (Chavan et al., 2025; Ganachari et al., 2025b).

Despite the increase, TMA-N and TVBN values remained within the acceptable limits (TMA-N: 10–15 mg%; TVBN: 35–40 mg%), confirming that the product retained acceptable quality and shelf stability. This aligns with findings in retort-processed Pangasius and Cobia products, where biochemical indices increased during processing and storage but remained within safe limits, indicating stable shelf life (Tameshwar et al., 2024; Tekade et al., 2024).

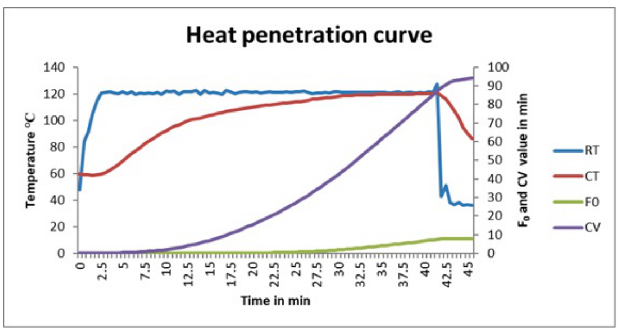

Fig. 4. Heat penetration curve for thermally processed Mangalorean-style squid rings in masala processed at F_0 12 minutes

Where RT= Retort temperature, CT= Core temperature, CV= Cook value

Table 4. Changes in biochemical quality parameters of raw and thermally processed Mangalorean-style squid rings in masala at F_0 10- and 12-min during storage

Biochemical parameters	Raw squid	Squid rings in masala (Day 0)	
		F_0 10 minutes	F_0 12 minutes
Moisture (%)	86.72 ± 0.56^c	72.32 ± 0.91^a	74.04 ± 1.92^b
Ash (%)	1.19 ± 0.35^a	3.25 ± 0.90^b	2.97 ± 0.05^b
Crude Fat (%)	1.50 ± 0.02^a	3.98 ± 0.02^b	3.63 ± 1.05^b
Crude Protein (%)	13.12 ± 0.44^a	20.78 ± 1.09^c	18.59 ±1.09^b
TMA-N (mg-N %)	9.70 ± 0.20^a	11.76 ± 0.25^b	10.03 ± 0.25^a
TVBN (mg-N %)	21.93 ± 0.81^a	28.50 ± 0.50^b	29.30 ± 0.26^b
PV (Milli equivalents of O_2 per kg sample)	ND	ND	ND
TBARS (mg malonaldehyde/ kg)	0.65 ± 0.30^a	1.03 ± 0.03^b	1.20 ± 0.17^c

Where TMA-N = Trimethylamine, TVBN = Total volatile base nitrogen, TBARS = Thiobarbituric acid reactive substances and PV = Peroxide value. The values are expressed as mean ± standard deviation (n=3) and different superscripts in the same rows indicate significant differences ($p < 0.05$) among the different treatments.

Table 5. Sensory score of Mangalorean-style squid rings in masala processed at F_0 10 and 12 minutes during 90 days of storage

Sensory characteristics	'Squid rings in masala' in a retort pouch			
	Day 0		Day 90	
	F_0 10 minutes	F_0 12 minutes	F_0 10 minutes	F_0 12 minutes
Appearance	8.77 ± 0.44^a	8.44 ± 0.88^a	8.70 ± 0.48^a	8.60 ± 0.52^a
Colour	8.60 ± 0.70^a	8.30 ± 0.95^a	8.60 ± 0.52^a	8.20 ± 0.63^a
Odour	8.40 ± 0.52^b	7.70 ± 0.82^a	8.20 ± 0.79^{ab}	8.05 ± 0.50^{ab}
Taste	8.40 ± 0.52^b	7.50 ± 0.97^a	8.50 ± 0.71^b	8.45 ± 0.50^b
Texture	8.60 ± 0.70^a	8.60 ± 0.70^a	8.50 ± 0.50^a	8.55 ± 0.50^a
Overall acceptability	8.54 ± 0.41^b	7.96 ± 0.84^a	8.50 ± 0.38^b	8.45 ± 0.24^b

Where values are expressed as mean ± standard deviation (n=30) and the different superscripts in the same row indicate significant differences ($p < 0.05$) among different treatments during storage

Peroxide value (PV) (Milli equivalents of O_2 per kg sample) was not detected in both raw and processed samples, indicating minimal primary lipid oxidation and effective oxygen barrier properties of the retort pouch system. However, TBARS increased significantly to 1.03 ± 0.03 (F_0 10) and 1.20 ± 0.17 mg MDA/ kg (F_0 12). This increase reflects secondary lipid oxidation due to thermal disruption of muscle structure and release of pro-oxidants during heating (Min & Ahn, 2005; Bindu, Ravishankar, & Gopal, 2007). Similar increases in TBARS have been consistently reported in retort-processed seafood, where lipid oxidation progresses during processing and storage but remains within acceptable sensory limits (Mohan et al., 2015; Dasan et al., 2021; Tekade et al., 2024; Chavan et al., 2025; Ganachari et al., 2025a). The slightly higher TBARS value at F_0 12 compared to F_0 10 further confirms that increased thermal severity accelerates oxidative reactions (Chavan et al., 2025; Ganachari et al., 2025b).

Thermally processed Mangalorean-style squid rings in masala in retort pouches at both F_0 values were found to be commercially sterile. The thioglycolate broth tubes inoculated with the samples processed did not develop any turbidity after 2 days of incubation at 37 °C and 4 days at 55 °C. This confirmed the adequacy of thermal processing for

Table 6. Texture profile analysis of thermally processed Mangalorean-style squid rings in masala at F_0 10 and F_0 12 min during 90 days of storage

Texture profile characteristics	Raw squid	Squid rings in masala in a retort pouch			
		Day 0		Day 90	
		F_0 10 minutes	F_0 12 minutes	F_0 10 minutes	F_0 12 minutes
Hardness (N)	0.053 ± 0.02^{c}	0.046 ± 0.02^{a}	0.045 ± 0.02^{a}	0.048 ± 0.02^{ab}	0.050 ± 0.01^{ab}
Gumminess (N)	0.029 ± 0.00^{e}	0.022 ± 0.00^{b}	0.021 ± 0.00^{a}	0.025 ± 0.00^{c}	0.027 ± 0.01^{d}
Cohesiveness	0.558 ± 0.07^{b}	0.493 ± 0.02^{a}	0.466 ± 0.02^{a}	0.53 ± 0.22^{ab}	0.546 ± 0.17^{b}
Springiness (mm)	2.628 ± 0.80^{b}	1.035 ± 0.58^{a}	1.180 ± 0.51^{a}	1.170 ± 0.02^{a}	1.130 ± 0.06^{a}
Chewiness (N)	0.078 ± 0.04^{c}	0.030 ± 0.01^{b}	0.024 ± 0.01^{a}	0.029 ± 0.01^{b}	0.031 ± 0.00^{b}

Where values are expressed as mean ± standard deviation (n=3), and the different superscripts in the same row indicate significant differences ($p < 0.05$) among different treatments during storage

achieving commercial sterility. The attainment of commercial sterility in the present study is consistent with previous reports on retort-processed seafood products, where properly optimized F_0 values effectively ensure the destruction of spoilage and pathogenic microorganisms without post-incubation growth (Mohan et al., 2006; Dasan et al., 2021; Ganachari et al., 2025b).

The 9-point hedonic scale proposed by Meilgaard et al. (1999) was used to determine consumer preference. The hedonic scores of sensory parameters analysed are presented in Table 5. The appearance, colour and texture did not show any significant difference between the two treatments (F_0 10 and 12 minutes) throughout the storage, indicating the sensory stability of the products for three-month storage. Samples processed at F_0 10 min showed significantly higher scores for odour, taste and overall acceptability at the beginning of storage, but as the storage progressed to the 90th day, this difference became insignificant. This may be attributed to the gradual mixing and uptake of spices and flavours in masala by squid rings as time progresses. The observed sensory stability of scores during storage is in agreement with previous studies on retort-processed seafood, where gradual flavour equilibration and spice diffusion lead to comparable acceptability over time despite initial differences between processing conditions (Mohan et al., 2006; Sreelakshmi, Manjusha, Nagalakshmi, Chouksey, & Venkateshwarlu, 2015; Dasan et al., 2021).

The texture profile of raw squid and thermally processed squid rings in masala packed in a retort pouch at two F_0 values is given in Table 6. The TPA parameters viz., hardness (maximum force achieved at the first bite), gumminess, cohesiveness, springiness (degree to which the food product returns to its original height after being compressed), and chewiness exhibited a significant decrease after thermal processing. The declining trend of hardness and chewiness with increasing F_0 was attributed to the thermal softening of muscle structure due to high temperature during thermal processing. Excessive softening at higher F_0 may lead to a less desirable, mushy texture, whereas moderate F_0 levels preserved firmness and enhanced consumer acceptability. This trend was consistent with sensory scores, highlighting the importance of selecting an optimal F_0 to balance product safety and textural quality. During heat processing, thermal denaturation and solubilization of connective tissue proteins lead to the dissociation of muscle proteins and further softening of meat (Bindu, Ravishankar, Dinesh, Mallick, & Gopal, 2011). A similar trend of decrease in hardness after thermal processing was observed by Biji et al. (2015) in green mussel in TFS cans, Bindu et al. (2007) in black clam in retort pouch, and Gopinath et al. (2007) in squid masala in TFS cans. The hardness and springiness of products processed at both F_0 values did not change significantly during storage.

Thermal processing of authentic Mangalorean-style squid rings in masala in a retort pouch caused a slight increase in TVBN and TBARS compared to raw squid, but within the acceptable range. However, no significant differences were observed between products processed at an F_0 of 10 and 12 minutes, and sensory and textural attributes remained comparable after 90 days of storage. The

cook values at F_0 10 and 12 min were 81.54 and 94.05 min, respectively, indicating greater thermal impact at the higher processing intensity while maintaining acceptable product quality in both treatments. Processing at F_0 10 minutes reduced total process time by 19.46%, demonstrating improved energy efficiency without compromising product safety or quality. Therefore, thermal processing at F_0 10 min was identified as the optimal condition for producing shelf-stable ready-to-eat Mangalorean-style squid rings in masala in retort pouches with acceptable sensory and textural quality.

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