Antenna lobster meat: biochemical changes and a simple and inexpensive tenderizing procedure

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In lobster fisheries along the Brazilian coast, lobster cephalothorax is discarded overboard. The cephalothorax corresponds to 2/3 of the crustacean in weight, and its meat yields 26.6% of the total weight of the *Panulirus argus* lobster. This means that thousands of tons of meat are wasted in fishing. However, some fishing companies have taken the initiative to use the meat extracted from the cephalothorax, including the meat from the antennas, which corresponds to a yield of 5% in relation to the weight of the cephalothorax. The problem with using antennae meat lies in the fact that when cooked, after being stored frozen, it becomes different, "strange," tough, and therefore loses its commercial acceptance. This study aims to monitor some of these biochemical changes in the raw material and develop a simple, practical, and inexpensive methodology to promote its softening. Biochemical test results showed variations in pH, from 6.63 to 7.73, salt-soluble proteins, from 23.47 to 10.52 mg/g, and formaldehyde, from zero (freshly killed lobster) to 0.0595 mg/g. Sensorial tests showed that treatment III, consisted of a pre-softening with the commercial softener whose composition includes the enzyme papain, was the most efficient.

KEYWORDS: *PANULIRUS ARGUS;* CEPHALOTHORAX UTILIZATION; TEXTURE IMPROVEMENT; PAPAIN; SEAFOOD PROCESSING.

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1. INTRODUCTION

Lobster fishing in Brazil was first initiated in 1955, and it has since grown in significance due to its high commercial value in the international market and the abundance of lobster populations along the Brazilian continental shelf, which extends from Amapá (04°26' N, 51°32' W) to Espírito Santo (21°17' S, 40°56' W) (Cruz et al., 2021). Historically, these crustaceans were used merely as bait in artisanal fisheries targeting more valuable species, such as triggerfish, yellowtail snapper, and red snapper. Currently, however, lobster fishing represents a complex industrial sector, involving numerous companies, hundreds of vessels, thousands of fishermen, and a substantial number of people indirectly engaged in related activities. The economic relevance of this industry as a source of foreign exchange for Brazil lies in its versatile production chain, which markets products such as frozen tails, whole cooked lobsters, and live lobsters (Fonteles-Filho, 1994; Cruz et al., 2013).

As a consequence of intensified exploitation and growing international demand that has not necessarily reduced prices despite increased supply, lobster populations have been subjected to overfishing, leading to a gradual decline in both population size and average body weight. Nevertheless, this scenario can be mitigated by the adoption of effective regulatory policies and by enhancing the processing efficiency, which involves the comprehensive and rational utilization of all lobster components.

In the Brazilian lobster industry, the cephalothorax, which could be a potential source of raw material, is often discarded due to limited storage capacity on fishing vessels and low perceived economic value. This results in the loss of exploitable by-products, such as meat from the antenna, hepatopancreas, and female gonads, as well as the potential to produce flour or paste, or even to commercialize these fractions separately (Venugopal, 2021).

On average, the cephalothorax of live lobsters accounts for approximately one-third of the total weight, resulting in a residue estimated to be 65% of the whole animal (Rebouças et al., 2023; Nguyen et al., 2017). The use of this by-product could significantly increase profitability within the lobster industry. Studies have shown that cooked meat extracted from the cephalothorax corresponds to 26.5% of its natural weight, while meat obtained from the antennules, antennae, and mouthparts represents 5.7%, from the pereiopods (paws) 7.2%, and from the rostrum, sternum, and gill region 13.6% (Costa, 1969).

The primary challenge in utilizing the cephalothorax lies in the need to fish in increasingly distant grounds, which prolongs travel time and sea days, thus delaying on-board processing and compromising raw material quality. Even under freezing conditions, crustacean tissues undergo biochemical degradation, making the meat fibrous and less palatable.

To overcome this limitation, we aimed to investigate the biochemical alterations in lobster antennae meat stored under freezing conditions for a specific period, and to develop a simple and efficient tenderization method capable of improving its sensory and processing characteristics.

2. MATERIAL AND METHODS

Live spiny lobsters (*Panulirus argus*, Latreille, 1804), with an average body weight of approximately 190 g and a total length of 170 mm, were obtained from local artisanal fishermen in Fortaleza, Ceará, Brazil. Upon arrival at the Marine Science Institute (Labomar) of the Federal University of Ceará, the lobsters had their antenna meat removed and were then kept in a freezer at a constant temperature of −15°C for 30 days. During this period, physicochemical analyses, including pH, salt-soluble protein content and formaldehyde concentration, were carried out on these samples at regular intervals (0, 2, 5, 10, 20, and 30 days), and all measurements were performed in triplicate.

The pH of the samples was determined by preparing an extract composed of 10 g of minced antenna meat that was homogenized with 100 mL of distilled water, following the method previously described by Ogawa (1975). The pH was then measured using a Micronal® pHmeter, model B474 (Celm®, Barueri, Brazil).

Salt-soluble protein content was estimated following the method described by Umemoto (1966). In brief, 5 grams of antenna meat were mixed with 95 mL of refrigerated 0.6 M potassium chloride (KCl) and homogenized in a mortar under a temperature of −5°C, while preventing foaming formation. After centrifugation at 7,000 × g for 30 min, the protein content in the supernatant was determined by measuring optical density at 545 nm using a Varian double-beam spectrophotometer (model 635, Varian Tech., Melbourne, Australia).

Formaldehyde concentration was determined using the Nash method as described by Woyewoda et al. (1986). Initially, samples were homogenized with 6% perchloric acid ($HClO_4$) at a 1:2 (w/v) ratio, and the resulting extracts were then neutralized with 30% KOH until reaching pH 7. A diluted aliquot of these extracts was mixed with Nash reagent, and after heating and cooling, the absorbance was measured using the same VARIAN spectrophotometer at 415 nm.

After the 30-day storage period, all antenna meat was subjected to the following softening treatments:

Treatment I (Thermal processing only)

Treatment I consisted of cooking the antenna muscle pieces under controlled temperature and pressure conditions, without enzyme pretreatment. Two thermal regimes were applied:

- Treatment Ia: cooking at 80 °C for 10 min under constant nominal pressure (~80 kPa);
- Treatment Ib: cooking at 100 °C for 10 min under constant nominal pressure (~80 kPa).

After reaching the target temperature, samples were maintained under these conditions for the full 10-min cooking period and were then removed from the heating system.

Treatment II (Papain pretreatment + cooking at atmospheric pressure)

For Treatment II, pre-tenderization was performed by applying papain from a commercial meat tenderizer (Maggi®) at a final concentration of 30 mg of tenderizer per gram of muscle (3%, w/w). To ensure uniform application, the tenderizer was diluted in distilled water to obtain a 3% (w/v) solution, and the muscle pieces were immersed for 15 min at room temperature, a standard exposure time for papain activity.

Immediately after pretreatment, samples were cooked at 100 °C for 10 min under atmospheric pressure.

Treatment III (Papain pretreatment + cooking under pressure)

Treatment III followed the same papain pretreatment protocol described for Treatment II. Papain from a commercial meat tenderizer (Maggi®) was applied at a final concentration of 30 mg of tenderizer per gram of muscle (3%, w/w). The tenderizer was diluted in distilled water to prepare a 3% (w/v) solution, and the muscle pieces were immersed in this solution for 15 min at room temperature to ensure uniform enzyme activity.

Immediately after pretreatment, samples were cooked at 100 °C for 10 min under constant nominal pressure (~80 kPa).

For comparison, cooking at 100°C under atmospheric pressure was designated as the control treatment.

To evaluate the sensory attributes of the treated antenna meat, a qualitative sensory analysis was conducted following the methodology described by the Australian Department of Agriculture (1974). Attributes such as odour, colour, flavour, and texture were assessed by

three trained panelists (pilot-scale, non-consumer panel) with prior sensory experience. Approximately 50 g of sample were presented per panelist under controlled conditions with standardized serving temperature. Panelists rated each attribute on a 3-point hedonic scale (1 = liked, 2 = neutral, 3 = disliked). Training for panelists included definition of attributes, reference standards, familiarization with the sample and handling procedures, practice sessions to align the 3-point scale, and assessment of intra- and inter-panelist consistency.

Statistical analyses, including means, standard deviations (SDs), and correlation coefficients, were computed using StatGraphics® software (Manugistics Inc., Rockville, MD, USA). Duncan's New Multiple Range Test (DNMRT) was performed to determine the significant differences between samples at the 5% probability level.

3. RESULTS AND DISCUSSION

An increase in pH values of lobster antenna meat stored at −15 ºC, from 6.53 ± 0.02 to 7.26 ± 0.04, was observed, indicating that storage duration had a significant effect on pH ($P \leq 0.05$) (Figure 1A). Similar findings have been reported in previous studies on lobster stored under both refrigerated and frozen conditions (Ogawa et al., 1975; Bibiana et al., 2015; Gonçalves et al., 2015). These authors also suggest that cold storage may slightly increase pH, likely due to continued activity of residual tissue enzymes and microorganisms, which promote the formation of basic nitrogen compounds (Tavares et al., 2021; Gonçalves et al., 2015). Shortly after the crustacean dies, pH begins to affect physical characteristics of crustacean muscle, including colour stability, bacterial growth, and consequently endogenous protease activity (Liang et al., 2025).

Regarding protein solubility, a progressive reduction in salt-soluble protein was observed throughout frozen storage. Protein concentrations decreased from 23.47 ± 1.25 mg/mL to 14.52 ± 0.99 mg/mL after 20 days, representing a 38.13 % reduction in solubility (Figure 1B). These findings align with reports that frozen storage promotes muscle protein denaturation, thereby reducing their extractability (Tavares et al., 2021).

Similarly, a significant reduction in salt-soluble protein content in frozen raw lobsters was also observed with increasing storage time, accompanied by increased meat toughness after cooking (Abdelnaby et al., 2024; Ogawa et al., 1987).

The loss of salt-soluble protein, mainly myofibrillar proteins, provides evidence that protein denaturation is induced by freezing and subsequent storage (Tappi et al., 2020; Umemoto, 1966). Because myofibrillar proteins play a key role in muscle contraction and stiffening, their degradation explains the observed textural changes. These findings are consistent with previous studies by Ogawa et al. (1975) and Sun et al. (2023), which also demonstrated a reduction in salt-soluble protein content with increasing storage time.

Freezing denaturation is influenced by storage time and temperature, muscle pH, and concentration of formaldehyde (FA) formed within the tissue sample (Ghribi et al., 2023; Wenna et al., 2021). FA increased progressively during frozen storage, from 0 mg/g in freshly caught lobsters to 0.0595 ± 0.0016 mg/g after storage at −15 °C (Figure 1C). Even small amount of formaldehyde can cause protein cross-linking, leading to increased toughness and a rubbery texture (Mehta et al., 2023; Laly et al., 2018), which was observed in the present study by comparing the results of formaldehyde formation and sensorial tests.

When fish or crustacean meat is subjected to freezing and stored for prolonged periods, post-cooking toughness typically develops. According to Lee & Park (2016), formaldehyde formation is the primary factor responsible for reduced protein extractability and textural degradation in marine species possessing the TMAO/TMAOase system. Although there are other factors involved in this process of physical deterioration, the mechanisms remain only partially elucidated. Moreover, even low concentrations of FA can significantly reduce protein

solubility (Tayri-Wilk et al., 2020). For several fish species, an increase in dimethylamine (DMA) and FA with longer storage time has also been reported (Jinadasa et al., 2022), while muscle stiffness increases concomitantly with a decline in soluble protein content (Nakazawa & Okazaki, 2020).

Figure 1D shows a quadratic model that fits the data accurately ($R^2 = 0.97$), indicating that formaldehyde content explains most of the variation in salt-soluble protein. The negative linear coefficient (−0.3784x) reflects a decrease in protein at low formaldehyde concentrations, while the small positive quadratic term suggests a slight plateau at higher concentrations, approximately from 0.030 to 0.060 mg/g. This is supported by an inverse correlation between formaldehyde accumulation and protein solubility ($r = 0.97$, $\alpha = 0.05$). During frozen storage, the decrease in salt-extracted protein corresponded to increased post-cooking hardness. This aligns with previous reports showing that protein denaturation and formaldehyde formation act synergistically (Woyewoda et al., 1986). While our results describe the relationship between formaldehyde accumulation and protein solubility, earlier studies have shown that the primary biochemical source of formaldehyde accumulation appears to be the activity of TMAOase (trimethylamine oxide aldolase) (Jinadasa et al., 2022).

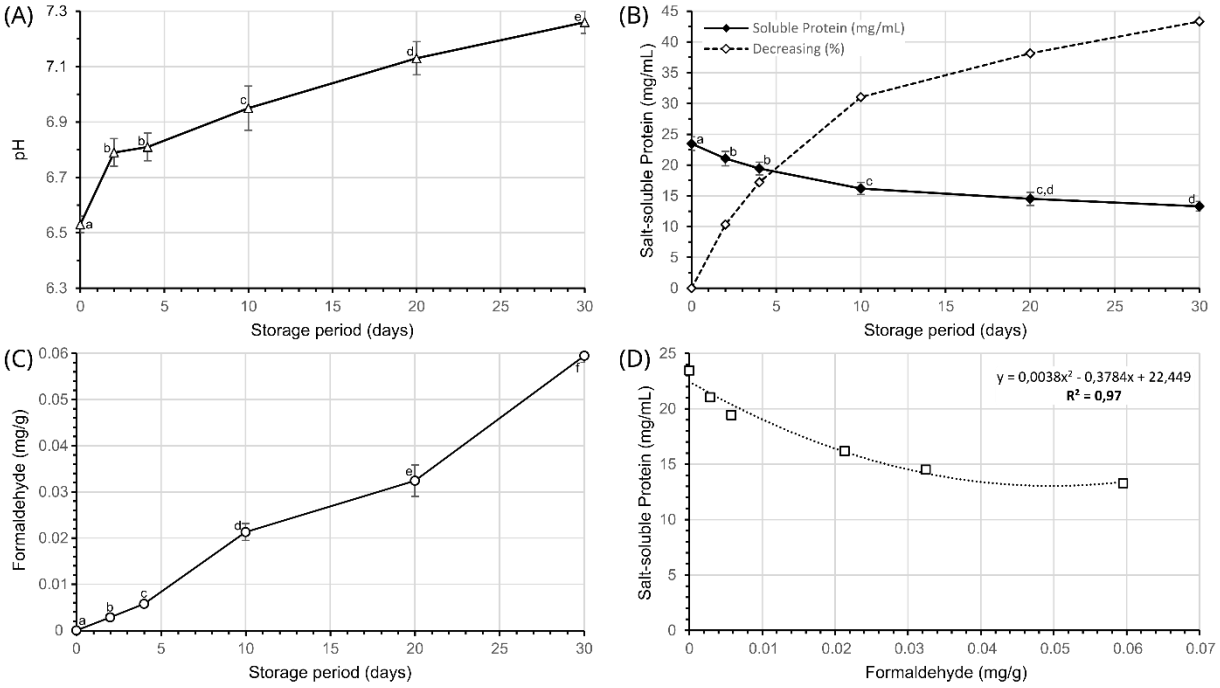

Figure 1. Biochemical variation of lobster meat muscle during frozen storage. (A) pH variation over storage time (days); (B) Salt-soluble protein content; (C) Formaldehyde content; (D) Salt-soluble protein and formaldehyde relationship in lobster meat muscle during frozen storage.

Regarding sensorial attributes, only Treatments II and III, which included papain pre-tenderization, produced satisfactory tenderness in the lobster antenna meat (Figure 2). However, a slight variation in flavour was observed between these treatments, as also illustrated in Figure 2.

These results were obtained through a small trained panel (n = 3), whose reduced size is justified by the panelists' specific expertise and prior training in crustacean sensory evaluation. Each sample was assessed in replicated sessions, and the letters (a–c) shown in Figure 2 were assigned based on the statistical test applied to the replicated scores, following standard procedures for multiple comparison of means. Although minor differences in flavour were observed between Treatments II and III, the overall trends remained consistent across

evaluations, supporting the reliability of the sensory assessment within the methodological constraints of the study.

Treatment III emerged as the most effective quality-preserving treatment, achieving the highest scores for Texture and Flavour, demonstrating its superiority in inhibiting the degradation processes that negatively impact consumer acceptance.

Treatment II also performed exceptionally well, sharing the high Flavour score with Treatment III, although it was slightly surpassed in Texture. Both Treatments II and III represent statistically significant improvements over the Control group, which showed the worst overall performance. The Control group was strongly penalized in Texture, implying a strong rejection of the product due to a critical quality failure. This result is corroborated by the physicochemical data, including a 43 % decrease in salt-soluble protein and a corresponding increase in pH, both indicators of protein denaturation and overall quality loss.

Meat tenderization takes place in connective tissues, and the use of plant-derived enzymes can be used to reduce the toughness that they may present. One of the most used of these proteolytic enzymes is papain, which degrades several tissue proteins, including collagen and elastin (Warriss, 2000; Purchas, 2022), as denatured proteins become better substrates for enzymatic action.

The attributes of Odour and Colour exhibited homogeneous scores across all treatments. Consequently, statistical analysis indicated no significant differences among treatments for these parameters. This suggests that the applied interventions were either ineffective or insufficient to inhibit the chemical reactions responsible for discoloration (browning) or the formation of undesirable volatile compounds associated with odour degradation.

Treatments Ia and Ib, despite differing in cooking temperature (80 °C × 100 °C), yielded similar sensory results and exhibited minimal tenderizing effects. The resulting texture was tough to hard, with a rubbery consistency, indicating inefficient softening under these conditions. Therefore, pressure-based thermal treatments alone are not recommended for tenderizing lobster antenna meat.

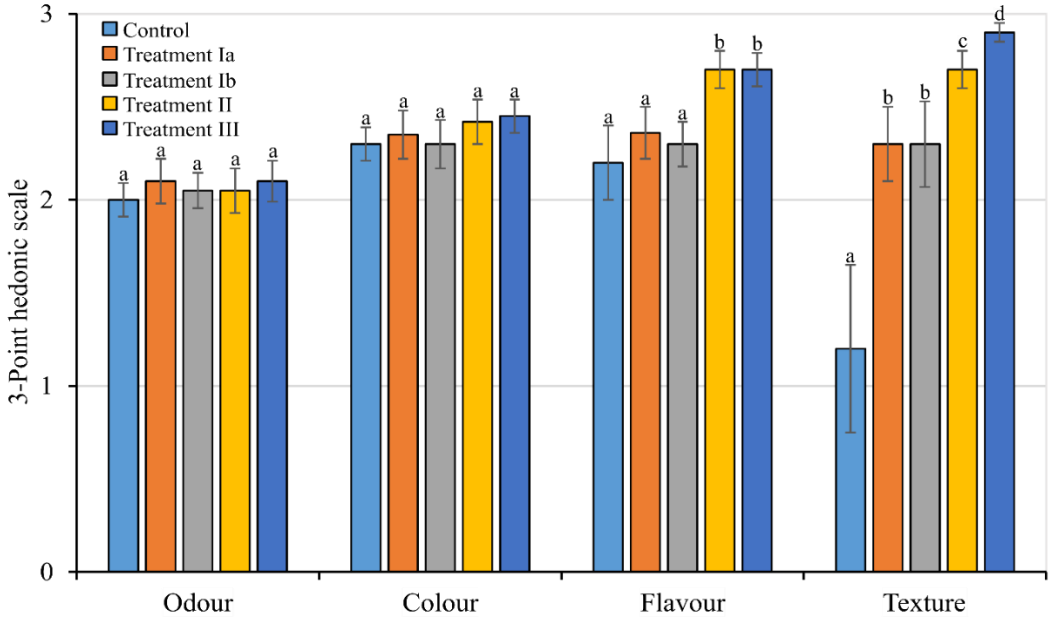

Figure 2. Sensory profile of the meat obtained from the antennae of *Panulirus argus* lobsters. The meat was frozen and subsequently underwent a series of treatments outlined in the Materials and Methods section. Mean liking (3-point hedonic scale, 1 = disliked to 3 = liked) of sensory attributes. Different letters, shown as a–c, within attribute indicate statistically significant differences ($P < 0.05$).

4. CONCLUSIONS

Physicochemical analyses confirmed that formaldehyde concentration increases significantly during the frozen storage of *Panulirus argus* antenna meat, coupled with a marked reduction in salt-soluble protein extractability and a slight elevation in pH over time. The quadratic model ($R^2 = 0.97$) demonstrates that formaldehyde levels account for most of the variation in salt-extracted, reinforcing the biochemical relationship between FA accumulation and protein denaturation. Sensory evaluation indicated that only the papain-treated samples (Treatments II and III) achieved satisfactory tenderization, supporting the potential of enzyme-assisted softening as an effective and low-cost strategy to improve the texture and flavour of lobster antenna meat. Nonetheless, sensory analysis should be interpreted with caution, given the reduced number of sensory panelists and the absence of instrumental texture analyses. Future investigations should optimize papain concentration, incorporate instrumental texture analyses to validate sensory patterns, and further investigate pressure and temperature variations to deepen the understanding of tenderization mechanisms in crustacean tissues.

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Figure Captions

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