



A non-destructive method for evaluating camel meat during freeze-thaw cycles using bio-impedance analysis

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ABSTRACT

Camel meat has a high nutrient profile and is susceptible to deterioration when stored, primarily due to temperature fluctuation in the cold chain. In this study, we utilized electrical impedance to monitor the quality of camel meat following repeated freeze-thaw cycles (two, four and six). Meat properties monitored were colour, pH, and electrical conductivity. Conductivity and pH of camel meat increased, and all colour indices (L^*), (a^*), and (b^*) also underwent significant changes when the meat was subjected to freeze-thaw cycles. The results suggested a reduction in electrical impedance with each freeze-thaw cycle, indicating increased cell membrane permeability and ice crystal-associated structural damage. This study recognizes the potential of electrical impedance to define camel meat quality as a method of further interpreting quality faults associated with freeze-thaw treatment.

1. Introduction

Camel meat, although less common than chicken or beef, is a source of protein. It is distinguished by its mild taste and high nutritional value, including low cholesterol and fat content (Kadim *et al.*, 2022; Baba *et al.*, 2021). Moreover, it contains minerals, essential amino acids, vitamins, biologically active substances, and essential fatty acids such as omega-3 (Mohammed *et al.*, 2020). Camel meat consists of 76–78% water, 19–22% protein, 2.9–3.2% fat, and 1.2% ash (Abdelhadi *et al.*, 2012). It is traditionally used to treat several diseases, for example respiratory diseases, hypertension, cardiovascular diseases, and pneumonia (Si *et al.*, 2022).

In Algeria, where camel meat is very well-regarded for its nutritional composition, this meat is largely produced in the country's southern regions, whereas consumption is dispersed across the country (Djenane *et al.*, 2020). However, like

any other meat, it is highly prone to spoilage during storage and, hence, needs the use of proper preservation methods to ensure its shelf life (Lakehal *et al.*, 2021). Freezing remains one of the most extensive technologies in the meat industry to maintain quality and acts by slowing down microbial growth and minimizing nutrient losses (Daszkiewicz *et al.*, 2018; Medić *et al.*, 2018). On the other hand, during transportation, storage and delivery, camel meat is affected by repeated, fluctuating temperature changes.

Changes in storage temperature have a significant effect on meat's physicochemical properties, which compromise its overall quality (Rahman *et al.*, 2014; Cheng *et al.* 2019; Qi *et al.*, 2012). Monitoring and detecting such changes are, therefore, necessary to maintain product safety and consumer trust. One monitoring means is electrical impedance, now becoming a powerful means for evaluating the quality of biological tissues like meat (Caicedo-Eraso *et al.*, 2020; Zhao *et al.*, 2017). The technique can

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quantify variations in electrical properties resulting from physiological changes in meat during freezing and thawing (Fuentes et al., 2013).

Previous studies have established that electrical impedance is capable of differentiating fresh from thawed beef, chicken, pork, and fish meats (Bai et al., 2018; Wei et al., 2016; Dell'Osa et al., 2021; Chen et al., 2017). There are limited studies on camel meat, however. This study aimed to fill this gap by introducing a new method for detecting camel meat freeze-thaw cycles through bioimpedance measurement. Through the investigation of electrical impedance change, this research aimed to provide the first fundamental data for considering bioimpedance as a tool for camel meat quality monitoring during storage, thus improving camel meat cold chain management.

2. Materials and Methods

Eleven camel (*Camelus dromedarius*) meat samples were obtained from an Algerian municipal slaughterhouse in El Ouadi. Sections of biceps femoris were selected 48 hours post-mortem. Each section was cut into pieces of approximately equal weight, individually vacuum-packed, and stored frozen at -20°C in a freezer (CRF-NT64GF40, Condor, Algeria). The freezing temperature was monitored using an infrared thermometer (TIA 101, China). The meat samples were then subjected to a series of freezing and thawing cycles (two, four and six) at controlled temperatures to mimic the temperature fluctuations of the cold chain. In each cycle, the meat samples were frozen for one week at -20°C and thawed at a refrigerator temperature of 4°C . A group of meat samples was also used as a control group, i.e., they were not subjected to freeze-thawing and were measured directly in the fresh state.

2.1 pH measurement

The pH of each meat sample was measured in a mixture resulting from homogenizing 10 g of meat in 90 mL of distilled water (Zhu et al., 2019). The pH meter (INOLAB) used was previously calibrated before inserting the electrode into the homogenate.

2.2 Electrical conductivity

Electrical conductivity was assessed using a conductivity meter (WTW Lab 540). Briefly, 9 g of each meat sample was homogenized with 90 mL of

distilled water and stirred for 20 min. Electrical conductivity levels were then measured.

2.3 Colour

Before the colorimetric analysis, camel meat samples, approximately 1.5 cm thick were prepared. Images were captured using a computer vision system consisting of a custom-designed enclosure equipped with two adjustable lamps positioned 50 cm above the samples at a 45° angle to achieve consistent illumination. A digital camera (Canon DS126621, China) was fixed vertically at a distance of 30 cm from the sample surface. To reduce external light interference, the interior of the enclosure was covered with light-absorbing black fabric (Lakehal and Lakehal, 2023). Digital analysis of colourimetric parameters, including Lab, HSI, and RGB, was performed using Adobe Photoshop CS3 software.

2.4 Impedance measurement

The electrical impedance measurement was performed using a portable LCR meter (LCR meter BR 2832, China) equipped with a two-needle system, each needle having two Kelvin electrodes. The device utilizes colour-coded cables with gold-plated contacts and reinforced protection. The needles, with dimensions of 10 mm in length, 2.5 mm in width, and 2 mm in height, were placed on the surface of the meat sample to complete the circuit. Measurements were taken at four different frequencies: 10 kHz, 1 kHz, 120 Hz and 100 Hz at four different regions of the meat. For each meat sample, both needles were inserted parallel to the direction of the muscle fibres to a depth of 13 mm, with a 2 cm distance between them. All measurements were conducted at a temperature of $4^{\circ}\text{C} \pm 1^{\circ}\text{C}$ and repeated four times at each frequency, both on fresh meat and after each freeze-thaw cycle.

2.5 Statistical analysis

The data were statistically analysed using analysis of variance (ANOVA), which was done with IBM SPSS Statistics version 26. The means were compared with Tukey's post-hoc test. A difference was regarded significant if the probability was $p < 0.05$.

3. Results and Discussion

3.1 pH

The pH of camel meat remained almost constant after the second freeze-thaw cycle (Table 1). However, it significantly increased to 5.41 ± 0.07 after the fourth cycle, compared to fresh meat (pH 5.16). By the end of the sixth cycle, the pH measured was 5.54 ± 0.04 . This result corroborates the findings of *Qi et al.* (2012), who observed an increase in pH after five freeze-thaw cycles of beef ($p < 0.05$). This increase in pH after a series of cycles, measured in the current study, could be linked to the release of free amino acids and dipeptides resulting from protein hydrolysis (*Hou et al.*, 2020). Additionally, *Ali et al.* (2015) reported a significant reduction in pH after the sixth cycle. In our previous research (*Lakehal et al.* 2023), we concluded that the variation in meat pH relative to its initial value was affected by oxidation rates, microbial growth, and exudate. This phenomenon may result from the loss of minerals and small protein compounds in the form of exudates, leading to an ionic imbalance in the meat (*Baygar and Alparslan*, 2015).

3.2 Electrical conductivity

Table 1, which shows the influence of freeze-thaw cycles on electrical conductivity, demonstrates a progressive increase with each cycle, with values rising from 1426 ± 23 to 1993 ± 22 . It is important to note that there was no significant difference between fresh meat and the second cycles (C2). However, starting from cycle 4 (C4), a notable difference emerges, marked by a sharp increase in conductivity, reaching 1893, then 1993 in cycle 4. Indeed, each cycle causes cell membrane degradation, leading to the release

of intracellular fluids, which increases conductivity (*Leng et al.* 2020). Thus, this increase reflects the deterioration of meat quality. Electrical conductivity is commonly used to assess the freshness of frozen meat, serving as a reliable indicator of product quality (*Leng et al.*, 2024). Electrical conductivity is a useful parameter for assessing the impact of freezing on meat (*Lakehal et al.* 2021).

3.3 Colour

The evolution of the colour parameters is presented according to the number of freeze-thaw cycles (Table 1). From the first thawing cycle, the lightness of the fresh meat was significantly lower than that of the meat that underwent the freeze-thaw process. The increase in the lightness of red meat after freeze-thaw cycles was observed by *Xia et al.* (2009) in a study on pork. This increase was attributed to the greater light reflection caused by an increased amount of free water, a consequence of heightened protein denaturation (*Holman et al.*, 2017; *Seong et al.* 2017), or by an increase in intramuscular fat content (*Pinheiro et al.* 2019).

The redness (a^*) values of the meat revealed a decrease following the first cycle, but a significant difference ($P < 0.05$) was only detected in the last freeze-thaw cycle (C6) compared to the others (Table 1). These results are similar to those observed by *Qi et al.* (2012), who also noted a decreasing trend in redness with an increasing number of freeze-thaw cycles in lamb meat. The colour changes in the meat during the freeze-thaw cycles can be attributed to the reduction of myoglobin in its chemical form (*Shang et al.* 2020). Indeed, the free radicals generated during lipid oxidation can alter the structure of the haeme group and trigger myoglobin oxidation, leading to a loss of meat colour, which manifests as a decrease in redness intensity. (*Xia et al.*, 2009; *Utrera et al.* 2014).

Table 1. Physicochemical properties of camel meat subjected to multiple freeze-thaw cycles

Physico-chemical parameters	C0	C2	C4	C6
pH	5.165 ± 0.01^c	5.2375 ± 0.06^c	5.4175 ± 0.07^b	5.545 ± 0.04^a
Electrical conductivity ($\mu\text{S}/\text{cm}$)	1426 ± 23.3^b	1504.5 ± 35.32^b	1893 ± 45.32^a	1993 ± 21.59^a
L* value (lightness)	31.14 ± 3.21^b	34.28 ± 4.23^a	33.85 ± 3.07^a	34 ± 3.02^a
a^* value (redness)	13 ± 1.73^a	10.28 ± 0.98^a	10.14 ± 1.56^{ab}	9.42 ± 2.07^b
b^* value (yellowness)	8.71 ± 2.98^b	10.42 ± 1.85^{ab}	11.71 ± 1.45^{ab}	14.14 ± 1.52^a

Legend: C0: fresh meat; C2: two freeze-thaw cycles; C4: four freeze-thaw cycles, C6: six freeze-thaw cycles. Data are given as mean values $\pm$ standard deviation. ^{a, b} different letters show a statistically significant difference ($p < 0.05$).

The yellowness (b^*) values of camel meat showed an increase from the first freeze-thaw cycle, reaching their maximum at the sixth cycle (Table 1). This evolution could be attributed to the denaturation of myoglobin, the accumulation of metmyoglobin, and an increase in lipid oxidation (Rahman et al., 2014; Pinheiro et al., 2019). In contrast, Jeong et al. (2011) observed a decrease in the b^* value after two freeze-thaw cycles, where the meat was stored at -65°C for 12 hours, followed by thawing at 4°C for 12 hours.

3.4 Evolution of meat impedance during freeze-thaw cycles

The meat impedance measured in on four different regions of the meat sample and at various frequencies are presented in Figure 1. In the fresh muscle, the impedance measured in region 4 was the highest ($570.9 \pm 1.20 \, \Omega$), while region 3 showed the lowest impedance ($501.1 \pm 0.80 \, \Omega$) among the four

initial measurement locations. These observed variations likely reflect differences in tissue composition or materials measured, particularly regarding the amount of lipids present (Fan et al., 2021; Li et al., 2019). As the excitation frequency increased, the impedance of camel muscle decreased. This was probably due to the high capacitive reactance of the cell membrane at low frequency, where the current flows mainly through the extracellular fluid (Dell’Osa et al., 2021). However, at higher frequencies, the capacitive reactance of the cell membrane decreases, allowing the current to pass through the intracellular fluid as well (Zavadlav et al., 2016).

Impedance values gradually decreased with the repeating of freeze-thaw cycles (Figure 1), suggesting that this procedure enhanced the permeability of cell membranes (Leng et al., 2024). Major structural and chemical changes occur in frozen muscle meat as a result of primary and secondary nucleation and crystal formation during freezing-thawing (Dang et al., 2021). Significant osmotic pressure across the sarcolemma

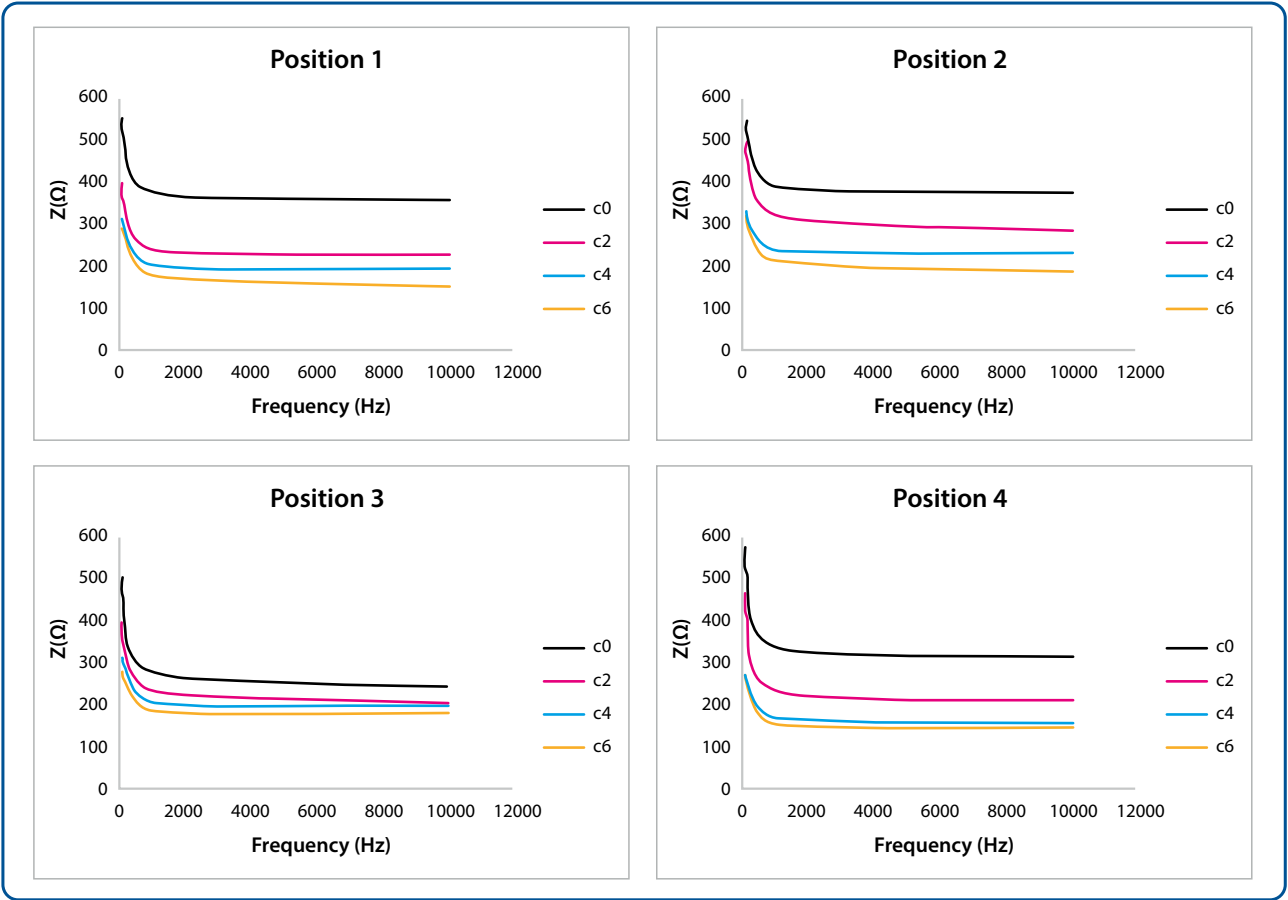


Figure 1. Changes of impedance (Z, Ω) of camel meat at various frequencies and different positions subjected to multiple freeze-thaw cycles.

Legend: C0: fresh meat; C2: two freeze–thaw cycles; C4: four freeze–thaw cycles, C6: six freeze–thaw cycles. Data are given as mean values $\pm$ standard deviation

is created when ice crystals develop, which increases the deformation of muscle microstructures and causes membrane rupture that allows cell contents to leak out (Zhang *et al.*, 2023). Enzymatic activity and oxidation are both accelerated by this process, which can have an impact on several aspects of meat quality.

4. Conclusion

The present study showed that electrical impedance is an effective method of monitoring the quality of camel meat during freeze-thaw processes

. Impedances became lower with an increasing number of freeze-thaw cycles. This was presumed to be a consequence of a breakdown of the cell membrane induced by formation of ice crystals. The findings indicate that electrical impedance is a non-invasive method for detecting certain aspects of quality change in camel meat subjected to multiple freeze-thaw cycles.

Having realized the influence of freezing and thawing cycles on camel meat, electrical impedance spectroscopy could be a valuable tool in monitoring the quality of meat in industrial scale.

Nedestruktivna metoda za procenu kvaliteta mesa kamile tokom ciklusa zamrzavanja i odtapanja korišćenjem analize bioimpedanse

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INFORMACIJE O RADU

Ključne reči:

Električna impedansa

Meso kamile

Kvalitet mesa

Ciklusi zamrzavanja i odmrzavanja

APSTRAKT

Meso kamile karakteriše visok nutritivni kvalitet, ali je podložno degradaciji tokom skladištenja, pre svega usled temperaturnih fluktuacija u hladnom lancu. U ovoj studiji korišćena je električna impedansa za praćenje kvaliteta mesa kamile nakon ponovljenih ciklusa zamrzavanja i odmrzavanja (dva, četiri i šest ciklusa). Praćene su sledeće osobine mesa: boja, pH vrednost i električna provodljivost. Utvrđeno je da se pH vrednost i električna provodljivost mesa kamile povećavaju, dok su svi parametri boje (L*, a*, b*) značajno promenjeni nakon izlaganja ciklusima zamrzavanja i odmrzavanja. Rezultati su ukazali na smanjenje električne impedanse sa svakim dodatnim ciklusom, što sugeriše povećanu propustljivost ćelijskih membrana i strukturna oštećenja izazvana formiranjem kristala leda. Ova studija ukazuje na potencijal primene električne impedanse kao metode za određivanje kvaliteta mesa kamile i bolju interpretaciju oštećenja kvaliteta povezanih sa tretmanima zamrzavanja i odmrzavanja.

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