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IMPACT OF THAWING METHODS ON THE PHYSICOCHEMICAL AND NUTRITIONAL PROPERTIES OF BEEF MEAT

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ABSTRACT

This study aimed to examine the impact of various thawing methods (refrigerator, room temperature, and microwave oven) on the physicochemical and nutritional properties of beef meat (*Longissimus dorsi*). The following analyses were performed: weight loss, water content, ash, fat and protein content, water-holding capacity, colour, texture, water activity (a_w), pH value, and mineral composition. The results indicated that the thawing method significantly affects meat quality ($p<0.05$).

The highest weight loss was recorded in samples thawed in a microwave oven (2.36%), while the lowest was in samples thawed in the refrigerator (0.81%). The highest water content was found in meat thawed in the refrigerator (74.99%), and the lowest was in samples thawed at room temperature (74.42%). The meat thawed at room temperature had the lowest water-holding capacity and the highest fat content. Colour changes were noted in all treatments, showing a decrease in lightness (L^*) as well as in a^* and b^* values, except for microwave-thawed samples. The highest texture firmness was measured in samples thawed in the refrigerator (4.34 kg). Water activity and pH levels increased after thawing in all treatments. Mineral content varied between fresh and thawed samples, with certain minerals showing notable deviations.

It was concluded that the slow defrosting method (at refrigerator temperature) best preserves the nutritional quality of beef meat.

Keywords: thawing methods, beef meat, quality, nutritional properties

INTRODUCTION

Freezing preservation is the most common method of food preservation. It can extend the shelf-life of food at subzero temperatures by removing large amounts of water from the solute phase to inhibit chemical, microbial, physical, and other reactions (Saki et al., 2023). Compared to other preservation methods, freezing is an important means to maintain the nutritional value and organoleptic properties of meat during processing, storage and transportation (Gan et al., 2022). Understanding the mechanism of ice formation is very important to improve the quality of frozen foods. The method is based on converting water in the form of ice crystals and lowering the temperature, which can stop all chemical, biochemical, and microbiological processes (Lovrić et al., 2003). The transition water to ice, simultaneously increase in the concentration of dissolved substances, and affects the reduction of water activity in food (Delgado & Sun, 2007), by reducing the activity of water below 0.7 when the metabolic activity of most microorganisms is significantly decreased or completely stopped (Nesvadba, 2008).

The formation of ice during the freezing process leads to both physical and chemical changes in the product (Li et al., 2018). The intensity of these changes is largely influenced by the freezing rate, storage conditions, and the thawing method (Muela et al., 2012; Zequan et al., 2019). When freezing occurs slowly, fewer crystallization centers are formed, mainly in the intercellular spaces. The extended time required for ice crystal formation allows more water to be drawn from muscle fibers, resulting in larger crystals. Rapid freezing results in a greater number of crystallization centers forming both between and within muscle cells, the shorter freezing time limits water migration, and producing smaller crystals. Ultra-rapid freezing of meat generates a high number of very small ice crystals, primarily located inside the muscle fibers (Vuković, 2012; Živković & Stajić, 2016).

Before use, most frozen foods need to be thawed after being frozen and stored in that state. Thawing is the reverse process of freezing (Nesvadba, 2008). There are various methods for thawing frozen meat, and the most common traditional techniques include thawing in a refrigerator, in cold water, at room temperature, or using a microwave oven. In addition to these, modern thawing methods have been developed, such as high-pressure thawing, acoustic thawing, thawing by electro-heating (Akhtar et al., 2013), ultrasonic thawing and infrared thawing (Gan et al., 2022). During the thawing process, meat is often accompanied by protein degradation, fat oxidation, color deterioration and reduced water holding capacity due to the melting of ice crystals (Gan et al., 2022). Therefore, in order to improve the quality of thawed meat, it is important to adopt appropriate thawing methods (Alonso et al., 2016).

This paper aims to examine the influence of different thawing procedures (at room temperature, in the microwave oven, and in the refrigerator at 4°C) on the physico-chemical properties of beef meat.

MATERIAL AND METHODS OF WORK

Analyses were performed on a sample of fresh beef meat (*Longissimus dorsi*) obtained from the market. The pieces were cut into 2.0 cm thick slices, packed in polyethylene bags and, after marking, froze at a temperature of -20ºC. After freezing the samples were stored at -20 °C for 24 h, until the analysis. Before the analysis, the samples were thawed in one of the following ways: 2 hours at 20°C (at room temperature), thawing in a microwave oven (2450 MHz, 700 W) to the temperature of 4°C in the center of the piece of meat, and 10 hours at 4°C (in a refrigerator). All analyses were performed on fresh (unfrozen) samples, as well as on samples after freezing and after certain defrosting treatments of the samples thawing using different methods.

The freezing/thawing weight loss was determined by measuring the weight of fresh meat samples before freezing and after thawing. The moisture content was determined by drying (BAS ISO 1442:2007), ash by incineration at 550°C (BAS ISO 936:2007), fat by extraction (BAS ISO 1443:2007), and protein by Kjeldahl method (BAS ISO 937:2007). The compression method (Grau & Hamm, 1953) was used to measure the water-binding capacity of beef meat, using the digital planimeter (Placom KP-92N, Koizumi, JAPAN). Water activity (a_w) was measured by direct readings in Aw Meter (Novasina LabMaster-AW 1119971). The pH value was measured by inserting a pH meter (Hanna instruments, HI 2211) into aqueous meat extract. Instrumental colour measurement was performed using a spectrophotometer CM-2600d (Konica Minolta Sensing Inc., Japan), colour parameters, expressed as CIE L^*, a^* and b^* values, were determined as respective indicators of lightness, redness, and yellowness. Texture was determined using a Texture Analyzer TA.XT plus (Stable Micro Systems) with Warner-Blatzler knife cutting blade which measures the shear force needed to cut the sample (1×1 cm). The meat samples were prepared according to Mandić et al. (2013).

Sample preparation for mineral analysis was carried out by digestion with a mixture of acids, and an Optical Emission Spectrophotometer (ICP OES Optima 8000, Perkin Elmer) was used to determine the mineral content (Savanović, 2021).

All analyses were performed with three repetitions, and instrumental colour and texture measurement with 10 repetitions.

Statistical processing of the obtained results was performed using the Microsoft Excel 2013 software package and the IBM SPSS Statistics 22.0 computer program for Windows (Armonk, NY, United States). The results obtained in this paper are presented as mean values ± standard deviation (SD). The significance of differences between arithmetic means was determined by analyzing the variance with one independent variable (One way ANOVA) and multiple interval tests (Tukey Post-hoc test) and expressed with 95% probability ($p<0.05$).

RESULTS AND DISCUSSION

Weight loss and chemical composition of beef meat are presented in Table 1. As can be seen from the results, the thawing method has a statistically significant influence ($p<0.05$) on the weight loss and chemical composition of beef meat. Weight loss is an important change that occurs during freezing and thawing of products. The analysis showed that significant weight loss was observed in the meat thawed in the microwave (2.36%). This result differs significantly from the results obtained for meat thawed at room temperature (1.32%) and refrigerator temperature (0.81%). The formation of ice during freezing leads to physical and chemical changes in the product. The main physical effects include mechanical damage, changes in muscle fibers and cell membranes, water migration, ice recrystallization, and moisture loss during thawing (Sučić et al., 2010; Savanović et al., 2017; Park & Kim, 2024). The amount of water released during thawing depends on the characteristics of the meat (pH value, presence of fatty tissue), the speed and method of freezing, storage conditions and duration, and the thawing technique (Vuković, 2012). Rapid freezing is characterized by the formation of a large number of small crystals, and the amount of water during thawing is minimal. The larger the crystals formed during freezing lead to greater the damage to the cell, and the greater the loss of tissue fluids during the thawing of the meat. The primary cause of such changes is the formation of large ice crystals, which mechanically damage tissues, and these damages are irreversible (Savanović, 2021).

Table 1. Weight loss and chemical composition of beef meat.

		Weight loss (%)	Water (%)	Protein (%)	Fat (%)	Ash (%)
	fresh meat		75.79^{a}±0.09	21.95^{a}±0.06	0.21^{a}±0.01	1.19^{a}±0.03
Thawing method	room temperature	1.32^{a}±0.02	74.42^{b}±0.09	22.11^{b}±0.06	0.38^{b}±0.01	1.25^{b}±0.01
	microwave oven	2.36^{b}±0.04	74.43^{b}±0.03	23.34^{c}±0.03	0.36^{b}±0.00	1.31^{c}±0.01
	refrigerator	0.81^{c}±0.02	74.99^{c}±0.06	22.14^{b}±0.03	0.25^{c}±0.02	1.21^{ab}±0.02

$^{a-c}$ Mean values with a different letter in the same column are statistically significantly different from 95% probability ($p<0.05$)

The water content in fresh beef ranges from 60% to 75%, depending on the part of the meat. The water content is greatly influenced by fat content, with their levels in meat being inversely related (meat with less fat has higher water content) (Savanović, 2021). Fresh samples of analyzed beef meat had an average water content of 75.79% before freezing. After thawing, the highest water content was in those thawed in the refrigerator (74.99%), followed by the samples thawed in the microwave oven (74.43%), and the lowest water content was found in the samples thawed at room temperature (74.42%). Analyzing Brazilian frozen beef imported into Algeria, Ziani et al. (2018) report similar values of water content (average 75.25%).

During thawing, some water is released from the food as it transitions from a solid to a liquid state. This fluid loss occurs due to ice crystal formation during freezing and the muscle tissue's reduced ability to reabsorb the fluid when thawed (Delgado & Sun, 2007; Sučić et al., 2010; Savanović et al., 2019). The quality of thawed food is influenced not only by the freezing speed and storage conditions but also by the thawing rate. Slow thawing, particularly in meat, allows water to reattach to proteins, reducing fluid loss. Additionally, when thawing occurs slowly at lower ambient temperatures, microbial activity is somewhat suppressed. As a result, slow thawing tends to have a less negative effect on food quality (Vereš, 2004).

By analyzing the protein content, it was determined that the fresh beef samples, before freezing, had an average protein content of 21.95%. After thawing, due to the loss of some water, the protein content increased slightly in samples thawed in a microwave oven (23.34%), while it decreased in samples thawed in a refrigerator (22.14%) and at room temperature (22.11%). Similar values were obtained by Ziani et al. (2018).

During freezing and storage, changes occur in proteins (denaturation and oxidation, modification of the amino acid chain), cause a decrease in the functional properties of proteins and affect the meat quality after thawing (Savanović & Grujić, 2017, Çalışkan Koç et al., 2025). Sabow et al. (2020) state that the crude protein content in frozen meat is expected to be lower than in fresh meat because denaturation and loss in gelatin caused by extended frozen storage also due to proteolysis.

Fat content in fresh beef meat was 0.21%, and after thawing ranged from 0.25-0.38% (thawing in refrigerator and at room temperature, respectively). Çalışkan Koç et al. (2025) consider that the higher fat content in meat has been linked to lower electrical conductivity, leading to longer thawing time. It has been suggested that different factors may affect fat content in beef cattle meat such as breed, rearing system and nutritional supply, weight at slaughter, gender and for the same animal according to the piece recovered (Ziani et al., 2018; Sabow et al., 2020).

Ash content in analyzed samples ranged from 1.21-1.31% in beef meat thawed in a refrigerator and in microwave, respectively, and in fresh meat 1.19%. The present results were similar with literature data (Ziani et al., 2018; Ngom et al., 2022). The amount of minerals in meat depends, above all, on the age and type of animal, feeding, and breeding method (Savanović, 2021).

Table 2 show results for water-holding capacity (WHC), water activity and pH value of examined beef meat. The thawing methods had a statistically significant influence ($p<0.05$) on WHC of beef meat after thawing.

Table 2. Influence of thawing methods on water-holding capacity (WHC), a_w and pH value of beef meat.

		WHC (cm^2)	**a_w**	**pH**
	fresh meat	$1.31^{a}\pm0.03$	$0.881^{a}\pm0.001$	$5.77^{a}\pm0.03$
Thawing method	room temperature	$2.16^{b}\pm0.01$	$0.883^{a}\pm0.001$	$5.88^{b}\pm0.06$
	microwave oven	$2.10^{c}\pm0.02$	$0.883^{a}\pm0.001$	$5.81^{ab}\pm0.01$
	refrigerator	$1.59^{d}\pm0.03$	$0.895^{b}\pm0.001$	$6.03^{c}\pm0.02$

[a-d] Mean values with a different letter in the same column are statistically significantly different from 95% probability ($p<0.05$)

In fresh meat WHC values was 1.31 cm^2, and after thawing ranged from 1.59-2.16 cm^2 (refrigerator and room temperature, respectively). Szmańko et al. (2021) reported that WHC value of fresh meat was higher than that of frozen meat. The meat thawed using slower thawing methods had a greater water-holding capacity and released less fluid during compression than meat thawed faster. The major water-holding carrier in muscles is myofibrillar proteins, due to their specific chemical structure (Rede & Petrović, 1997), and is an indirect measure of protein denaturation (Savanović & Grujić, 2017).

Values for a_w were 0.881 in fresh beef meat, 0.883 in samples thawed at room temperature and in microwave and 0.895 in the sample thawed in refrigerator. The melting of ice in the extracellular spaces causing an increase in water activity (Akhtar et al., 2013).

The pH value of fresh beef sample was 5.77, whereas those of beef samples thawed at room temperature, using a microwave oven, and in a refrigerator increased significantly to 5.88, 5.81, and 6.03, respectively ($p<0.05$). Ike et al. (2018) report pH value for beef from 5.1-6.2. Park and Kim (2024) attribute the rise in pH to amino acid leakage during prolonged thawing, noting that extended thawing damages muscle cells and leads to drip, which contributes to the increase. Variations in pH are likely due to glycogen breakdown into lactic acid and proteolysis, which increases free alkaline groups, and/or variations in muscle protein water-holding capacity, influencing the color, appearance, and shelf life of the meat samples (Wali et al., 2025).

Instrumentally measured color and texture parameters of fresh and thawed beef meat are presented in Table 3. The obtained results showed that thawing procedures had statistically significant effect ($p<0.05$) on the colour and texture of beef meat. The *L** value on the surface of the fresh meat sample was 43.53, and for thawed samples values were slightly lower, ranged from 42.12-43.31. There was an increase in the share of red (*a** value) and yellow colour (*b** value) in sample thawed in microwave compared to those measured on fresh meat. The color of meat depends on the concentration and state of myoglobin (Mb) and hemoglobin (Hb). The change in meat colour is a result of changes in the chemical state of myoglobin and the postmortem processes (changes in the muscles) (Savanović, 2021). Park and Kim (2024) consider that *L** values of beef samples significantly decreased when they were thawed in a refrigerator, in cold water, and at room temperature. Freezing and thawing affect on *a** value of meat samples due to myoglobin oxidation, increasing the temperature tended to increase myoglobin oxidation and discoloration in beef (Park & Kim, 2024).

Table 3. Instrumentally measured color and texture parameters of fresh and thawed beef meat.

		L^*	a^*	b^*	Texture (kg)
	fresh meat	$43.93^{a}\pm0.79$	$12.06^{ab}\pm0.79$	$10.49^{ab}\pm0.57$	$3.22^{a}\pm0.31$
Thawing method	room temperature	$42.94^{ab}\pm0.53$	$11.97^{a}\pm0.87$	$10.26^{ab}\pm0.89$	$4.01^{b}\pm0.81$
	microwave oven	$43.31^{a}\pm0.59$	$13.52^{b}\pm0.90$	$11.75^{a}\pm0.77$	$4.08^{b}\pm0.84$
	refrigerator	$42.12^{b}\pm0.64$	$11.74^{a}\pm0.78$	$9.76^{b}\pm0.57$	$4.34^{c}\pm0.90$

$^{a-b}$ Mean values with a different letter in the same column are statistically significantly different from 95% probability ($p<0.05$)

The texture of thawed meat was harder than fresh meat sample, due to structural changes in the tissues. Fresh meat was the softest (3.22 kg), and the thawed meat had bigger hardness (4.01-4.34). Savanović (2021) considers that the increase in meat hardness after freezing occurs as a result of various physico-chemical changes in proteins and strengthening of the protein matrix. Results present by Park and Kim (2024) show that the beef sample thawed using a microwave oven had the maximum hardness, gumminess, and chewiness compared with those thawed using other methods. The increase in shear force within the muscle could result from differences in connective tissue content, sarcomere length, and muscle fiber size along its entire length (Stafford et al., 2024).

Table 4 shows the mean values of macroelements content in fresh and thawed samples of beef meat. Based on the obtained results, it was determined that there was statistically significantly difference ($p<0.05$) for some minerals (Na, P). The most dominant minerals in beef meat were phosphorus and potassium, ranged from 2715.07-2795.83 mg/kg, and 1391.86-1798.76 mg/kg, respectively.

Table 4. Content of macroelements (mg/kg) of fresh and thawed beef meat.

		P	K	Mg	Na
	fresh meat	$2795.42^{a}\pm10.44$	$1572.94^{a}\pm35.25$	$293.47^{a}\pm0.60$	$164.50^{a}\pm5.65$
Thawing method	room temperature	$2719.61^{b}\pm32.43$	$1735.12^{a}\pm21.42$	$291.41^{a}\pm10.11$	$745.44^{b}\pm4.54$
	microwave oven	$2795.83^{a}\pm15.44$	$1391.86^{a}\pm8.68$	$293.43^{a}\pm16.85$	$334.02^{ac}\pm6.97$
	refrigerator	$2715.07^{b}\pm36.61$	$1798.76^{a}\pm48.59$	$292.26^{a}\pm2.61$	$632.44^{bc}\pm8.18$

$^{a-c}$ Mean values with a different letter in the same column are statistically significantly different from 95% probability ($p<0.05$)

The amount of Na and K from the collected fresh meat samples was analyzed by Wali et al. (2025) with ICP-OES were Na-508.81 mg/kg, and K-2994.13 mg/kg. The same authors state that age, breed, nutrition, birthplace, and other environmental factors can all have an impact on the mineral content of meat. Campo et al. (2024) report that Pyrenean beef is an excellent source of potassium, phosphorus, and zinc, and low in sodium. The same authors state highest values for K and P (352-404 mg/100g and 163-188mg/100g, respectively), and similar values Mg and Na (21-27 mg/100g, 40-66 mg/100g, respectively).

Based on the results shown in Table 5, the content of microelements in the fresh and thawed meat samples ranged as follows (mg/kg): zinc 164.40-215.96, calcium 51.21-70.56, iron 17.08-24.50, manganese 0.04-0.15 and copper 0.62-0.80. Some of analyzed minerals were below the detection limit (Se-2µg/L, Al, As, Hg-1µg/L). The significant differences ($p<0.05$) were observed in the concentration of Fe, Mn, and Cu. Sabow et al. (2020) report that Fe and Zn exhibited the highest concentrations in the two types of meat analyzed, compared to the other essential elements. The same authors state that muscles of cattle are the tissues where Zn is most likely to accumulate. Similar content of Ca and Fe report (Campo et al., 2024).

Table 5. Content of microelements (mg/kg) of fresh and thawed beef meat.

		Zn	Ca	Fe	Mn	Cu
	fresh meat	$164.40^{a}\pm1.24$	$55.21^{a}\pm2.09$	$19.20^{a}\pm0.29$	$0.13^{ab}\pm0.01$	$0.80^{a}\pm0.08$
Thawing method	room temperature	$177.27^{ab}\pm0.31$	$58.61^{a}\pm3.02$	$18.37^{a}\pm0.11$	$0.09^{ac}\pm0.01$	$0.62^{b}\pm0.03$
	microwave oven	$215.96^{c}\pm8.03$	$70.56^{a}\pm6.94$	$17.08^{a}\pm0.08$	$0.04^{c}\pm0.04$	$0.70^{ab}\pm0.09$
	refrigerator	$193.97^{b}\pm2.70$	$51.21^{a}\pm3.12$	$24.50^{b}\pm2.88$	$0.15^{b}\pm0.01$	$0.72^{ab}\pm0.02$

$^{a-c}$ Mean values with a different letter in the same column are statistically significantly different from 95% probability ($p<0.05$)

Concentrations of toxic metals (Hg and As) in fresh and thawed beef meat were below the limit of detection, and maximum limits of toxic metals permissible in red meat for EU countries for mercury is 1.0 mg/kg and for arsenic 0.3 mg/kg (Nkosi et al., 2021).

CONCLUSIONS

Freezing meat causes certain major or minor irreversible physical and chemical changes in food. While freezing enhances the meat's sustainability and extends its shelf life, it also leads to alterations due to the formation of ice crystals. Additionally, the method of thawing can significantly influence the quality of thawed meat.

By analyzing the data obtained in this study, the thawing method significantly affects the physical and chemical properties of beef meat. Microwave thawing caused the highest weight loss, while refrigerator thawing preserved moisture best and resulted in the least damage. Besides changes in the basic chemical composition, different thawing procedures also impact the colour, texture, pH value, and water activity of thawed beef. Mineral content also varied with thawing method.

The method used for thawing plays a crucial role in determining meat quality. Based on the results, it can be concluded that slow thawing of beef (at refrigerator temperature) allows helps retain water and protein quality, reduces fluid loss, and maintains better pH and water activity levels. If food is thawed slowly, the ambient temperature remains low, which can inhibit microorganism growth.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

LITERATURE

Akhtar, S., Khan, M. I., & Faiz, F. (2013). Effect of thawing on frozen meat quality: A comprehensive review. *Pakistan Journal of Food Sciences*, *23*(4), 198–211.

Alonso, V., Muela, E., Tenas, J., Calanche, J. B., Roncalés, P., & Beltrán, J. A. (2016). Changes in physicochemical properties and fatty acid composition of pork following long-term frozen storage. *European Food Research and Technology*, *242*(12), 2119–2127. https://doi.org/10.1007/s00217-016-2708-y

Çalışkan Koç, G., Özkan Karabacak, A., Süfer, Ö., Adal, S., Çelebi, Y., Delikanlı Kıyak, B., & Öztekin, S. (2025). Thawing frozen foods: A comparative review of traditional and innovative methods. *Comprehensive Reviews in Food Science and Food Safety*, *24*(2), e70136. https://doi.org/10.1111/1541-4337.70136

Campo, M. M., Romero, J. V., Guerrero, A., Bouzaida, M. D., Resconi, V. C., Tesniere, G., Santolaria, P., & Olleta, J. L. (2024). Nutrient composition of beef from the pyrenees. *Journal of Food Composition and Analysis*, *133*, 106452. https://doi.org/10.1016/j.jfca.2024.106452

Delgado, A. E., & Sun, D.-W. (2007). Influence of surface water activity on freezing/thawing times and weight loss prediction. *Journal of Food Engineering*, *83*(1), 23–30. https://doi.org/10.1016/j.jfoodeng.2006.10.010

Gan, S., Zhang, M., Mujumdar, A. S., & Jiang, Q. (2022). Effects of different thawing methods on quality of unfrozen meats. *International Journal of Refrigeration*, *134*, 168–175. https://doi.org/10.1016/j.ijrefrig.2021.11.030

Grau, R., & Hamm, R. (1953). Eine einfache Methode zur Bestimmung der Wasserbindung im Muskel. *Naturwissenschaften*, *40*(1), 29–30. https://doi.org/10.1007/BF00595734

Ike, C., Ebiringa, P., Ike, P., Nwogu, P., & Akwari, P. (2018). Effect of Boiling Time On The Proximate Composition And Microbiological Quality Of Various Parts Of Cattle Meat Sold In Owerri, Imo State, Nigeria. *International Journal of Engineering & Technology Sciences*, *5*, 2348–7968.

Li, D., Zhu, Z., & Sun, D.-W. (2018). Effects of freezing on cell structure of fresh cellular food materials: A review. *Trends in Food Science & Technology*, *75*, 46–55. https://doi.org/10.1016/j.tifs.2018.02.019

Lovrić, T., Tripalo, B., Hribar, J., & Pozderović, A. (2003). *Procesi u prehrambenoj industriji s osnovama prehrambenog inženjerstva*. Hinus.

Mandić, S., Vučić, G., & Stojković, S. (2013). *Kontrola kvaliteta mesa i proizvoda od mesa*. Tehnološki fakultet, Univerzitet u Banjoj Luci. https://pub.unibl.org/s/cir/item/49966

Muela, E., Sañudo, C., Campo, M. M., Medel, I., & Beltrán, J. A. (2012). Effect of freezing method and frozen storage duration on lamb sensory quality. *Meat Science*, *90*(1), 209–215. https://doi.org/10.1016/j.meatsci.2011.07.003

Nesvadba, P. (2008). Thermal properties and ice crystal development in frozen foods. In: Evans J. (ed). Frozen Food Science and Technology. Blackwell Publishing Ltd.

Ngom, R. V., Ndzana, V. de P., Bohounbele, D., Houli, V., Oumara, B., & Pagnah, A. Z. (2022). Nutritional Quality of Meat from Cattle Breed in Livestock Production Area of Cameroon. *Open Journal of Animal Sciences*, *12*(3), Article 3. https://doi.org/10.4236/ojas.2022.123035

Nkosi, D., Bekker, J., & Hoffman, L. (2021). Toxic Metals in Wild Ungulates and Domestic Meat Animals Slaughtered for Food Purposes: A Systemic Review. *Foods*, *10*(11), 2853. https://doi.org/10.3390/foods10112853

Park, M. H., & Kim, M. (2024). Effects of Thawing Conditions on the Physicochemical and Microbiological Quality of Thawed Beef. *Preventive Nutrition and Food Science*, *29*(1), 80–86. https://doi.org/10.3746/pnf.2024.29.1.80

Rede, R., & Petrović, L. (1997). *Tehnologija mesa i nauka o mesu.* Novi Sad: Tehnološki fakultet. Univerzitet u Novom Sadu. https://www.tehnologijahrane.com/knjiga/tehnologija-mesa-i-nauka-o-mesu

Sabow, A. B., Qadir, S. W., Majed, Z. J., & Mahmwd, A. A. (2020). Chemical Compositions and Heavy Metal Contents of Local Fresh and Imported Frozen Beef Cattle Meat Available in

Savanović, D., et al. (2025). Impact of thawing methods on the physicochemical and nutritional properties of beef meat. *STED Conference 14*(2), 239-246.

Ranya Markets. *Asian Journal of Dairy and Food Research*. *39*(4), 328. https://arccjournals.com/journal/asian-journal-of-dairy-and-food-research/DR-194

Saki, N., Ghaffari, M., & Nikoo, M. (2023). Effect of active ice nucleation bacteria on freezing and the properties of surimi during frozen storage. *LWT*, *176*, 114548. https://doi.org/10.1016/j.lwt.2023.114548

Savanović, D. (2021). *Konzervisanje mesa smrzavanjem*. Banja Luka: Tehnološki fakultet, Univerzitet u Banjoj Luci. https://pub.unibl.org/s/lat/item/48666

Savanović, D., & Grujić, R. (2017). Protein changes during the freezing and storage of meat and meat products. *Veterinarski Žurnal Republike Srpske, 17*(1), 105–118.

Savanović, D., Grujić, R., Mandić, S., & Savanović, J. (2017). Uticaj smrzavanja na kvalitet prehrambenih proizvoda (Effect of freezing on food products quality). *Proceedings V International Congress "Engineering, Environment and Materials in Processing Industry",* Jahorina, Republic of Srpska, Bosnia and Hercegovina, 565–582.

Savanović, D., Radoslav, G., & Savanović, J. (2019). The influence of the freezing rate on the physico-chemical properties of pork meat (M. *Longissimus dorsi*). *Acta Periodica Technologica*, *50*, 228–235. https://doi.org/10.2298/APT1950228S

Stafford, C., Taylor, M., Spurling, R., Crump, Z., Alberto, A., Alruzzi, M., Ali, L., Okamoto, L., Bird, T., Page, C., Thornton, K., Dai, X., & Matarneh, S. (2024). The influence of different freezing and thawing conditions on the quality of beef rib primals. *LWT*, *209*, 116771. https://doi.org/10.1016/j.lwt.2024.116771

Sučić, R., Cvrtila, Ž., Njari, B., & Kozačinski, L. (2010). Senzorne, kemijske i mikrobiološke promjene u smrznutom mesu peradi. *MESO: Prvi hrvatski časopis o mesu*, *XII*(6), 342–351.

Szmańko, T., Lesiów, T., & Górecka, J. (2021). The water-holding capacity of meat: A reference analytical method. *Food Chemistry*, *357*, 129727. https://doi.org/10.1016/j.foodchem.2021.129727

Vereš, M. (2004). *Principi konzervisanja namirnica*. Poljoprivredni fakultet Univerziteta u Beogradu. https://www.tehnologijahrane.com/knjiga/principi-konzervisanja-namirnica

Vuković, I. (2012). *Osnove tehnologije mesa.* Veterinarska komora Srbije. https://www.tehnologijahrane.com/knjiga/osnove-tehnologije-mesa-2

Wali, M. A., Lemma, Y. S., Mekonon, F. S., Yizengaw, M. B., Adera, K. M., Sekhar, M. R., & Botsa, S. M. (2025). Nutritional and chemical characterization of cow, camel, and goat meat from Kebridehar, Ethiopia: A comparative analysis and statistical approaches. *RSC Advances*, *15*(10), 7617–7629. https://doi.org/10.1039/d4ra07096h

Zequan, X., Zirong, W., Jiankun, L., Xin, M., Hopkins, D. L., Holman, B. W. B., & Bekhit, A. E.-D. A. (2019). The effect of freezing time on the quality of normal and pale, soft and exudative (PSE)-like pork. *Meat Science*, *152*, 1–7. https://doi.org/10.1016/j.meatsci.2019.02.003

Ziani, K., Fatima, I., & Khaled, M. B. (2018). Physicochemical Quality Assessment of Brazilian Frozen Beef Imported into Algeria. *The North African Journal of Food and Nutrition Research*, *02*(03), 67–71. https://doi.org/10.5281/zenodo.1340685

Živković, D., & Stajić, S. (2016). *Tehnologija mesa 1.* Beograd: Poljoprivredni fakultet Univerziteta u Beogradu.