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Impact of freezing and thawing on the quality and textural properties of minced pork at different particle sizes

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Abstract
Minced pork is a versatile, widely consumed product that is often frozen to extend its shelf life in the supply chain. However, the freezing-thawing process induces physicochemical changes that can significantly affect meat quality. While mincing produces particles of different sizes, it remains unclear how these variations affect the product's resilience to frozen-thawed damage. This study investigated the effect of freezing and thawing on the physicochemical properties of minced pork of varying sizes. Fresh pork shoulder samples were divided into two equal batches, with each batch minced into three sizes (4 mm, 6 mm, and 11 mm). Each sample unit was pooled by size and replicated 15 times. The first batch was stored at −18 °C until frozen, then thawed in a chiller at 4 °C. The second batch was analysed in its fresh form. Both fresh and freeze-thawed samples were evaluated for various physicochemical properties, including colour, texture, drip loss, cooking loss, and pH. The study found that mince size (4, 6, 11 mm) significantly ($p < 0.05$) influences meat quality in both fresh and frozen-thawed samples. Freeze-thawed pork showed significantly higher values for drip loss, cooking loss, pH, and cohesiveness than fresh samples. Results indicated that smaller mince sizes freeze faster, forming smaller, more uniform ice crystals. In contrast, larger mince sizes freeze more slowly, leading to larger crystals that can cause texture degradation upon thawing. Additionally, the study revealed an interaction between mince size and meat condition: colour attributes (lightness and yellowness) increased as mince size decreased, whereas quality traits (pH, gumminess, chewiness, and resilience) increased with larger mince sizes. Mince size significantly affects the quality parameters of minced pork, with smaller sizes maintaining better quality after freezing and thawing. To minimize quality loss, processors should prefer 4 mm and 6 mm minces for frozen pork.

Keywords Minced pork, Freezing-thawing, Colour, Texture, Minced size

1 Introduction

Meat is a staple food worldwide, and its consumption is increasing globally due to its composition in the provision of essential protein, amino acids (lysine, leucine, isoleucine, valine, methionine, phenylalanine, threonine, tryptophan, and histidine), minerals (Iron, Zine, Selenium. and Potassium), and vitamins (Rich in B and fat-soluble vitamins D and A), which are the essential for human growth and development [1]. Fresh pork constitutes about 20% protein, 75% water (depending on the cut), and 5% fats, minerals, and vitamins [2]. Minced Pork is a meat product that is commonly used to prepare versatile forms of dishes. The estimated human consumption of pork is approximately 12.43 kg per capita globally [3]. Freezing is one of the most effective methods for preserving pork, given its high water content, which helps maintain quality during long-term storage [4]. However, the subsequent thawing process often leads to noticeable deterioration in quality due to the formation of crystals that damage tissues [5], significantly affecting meat quality parameters, such as colour, texture, water-holding capacity, and pH [6–8].

The quality of minced meat is influenced by factors such as freshness, appearance, tenderness, and taste, which are crucial for consumer acceptability [9]. Meat quality attributes such as colour, tenderness, juiciness, and flavour depend on factors such as age, breed of the animal, body condition at slaughter, sex, and the plane of nutrition [10, 11]. Freshness plays a vital role in assessing the quality of minced meat [12], which is often more difficult to evaluate virtually than whole cuts due to its tendency to disintegrate [13]. The quality of minced meat (colour, tenderness, juiciness, and flavour) directly impacts consumer decisions. The freezing and thawing process leads to protein denaturation and damage to muscle structure, resulting in low water retention and deteriorating water quality [14]. Additionally, the formation of ice crystals during freezing can increase intercellular solute concentration, hastening meat spoilage (physical and chemical spoilage rather than microbial spoilage) [15]. Physical spoilage occurs when ice crystals form, physically damaging the meat's structure and leading to water loss. This causes the meat to become dry, tough, and less juicy. Chemical spoilage results in an increase in intercellular solute concentration due to protein denaturation and lipid oxidation, which occur during the freezing-thawing process.

Existing studies have explored the effects of freezing on whole meat in other species, such as buffalo and duck, in products like burgers and sausages [16–18], but have overlooked the impact of freezing on pork, particularly across different sizes. This gap in the literature makes it essential to investigate how freezing and thawing affect minced pork of varying sizes and their effects on key quality parameters, including colour, texture, water-holding capacity, and pH. It is hypothesised that smaller minced sizes may experience greater quality deterioration due to a higher surface area exposed to freezing conditions, leading to increased ice crystal damage. In industrial meat production, minced pork is commonly processed to particle sizes of 6, 8, and 12 mm, with 8 mm grind size being the most prevalent. This study investigates the impact of particle size (4, 6, and 11 mm) on minced pork quality, using particle sizes above and below the industrial standard of 8 mm. The study identifies the optimal particle size to minimise quality loss during freezing, thereby improving product quality for consumers.

2 Materials and methods

2.1 Sample collection and preparation

A total of 5 kg of shoulder meat was collected from five different porkers (6 months ± 2 weeks old) from Tip Top Meat (TTM) Sdn. Bhd., a commercial pig abattoir located at Jalan Rawang, Pekan, 45,600 Bestari Jaya, Selangor, Malaysia. The samples were stored in plastic bags, placed in a container with ice, and transported (distance covered: 73.1 km; time duration: 2 h) to the Meat Science Laboratory, Department of Animal Science, Faculty of Agriculture, Universiti Putra Malaysia, 43,400 Serdang, Selangor, Malaysia, for analysis. The meat samples were prepared by trimming off all visible fat, skin, and unwanted tissues with a sharp knife. Then, a mechanical meat mincer was used to mince the meat into three different sizes: 4 mm, 6 mm, and 11 mm, using different blade orifices. The minced meat was divided into two equal parts; the first part was used in its fresh form, while the second part was freeze-thaw meat, where the samples were placed into a well-labelled polyethene bag, stored in a − 18 °C freezer for two days until it was completely frozen, and then transferred to a chiller at 4 °C overnight to freeze-thaw (thawed).

2.2 Experimental design

The minced samples (fresh and freeze-thawed meats) were separately pooled by minced size and randomly allocated to three groups. Each unit was thoroughly mixed and replicated three times according to particle size. Each subgroup was replicated fifteen times using a Completely Randomised Design (CRD). The experimental design is presented in Fig. 1.

2.3 Meat colour analysis

The colour coordinates (*L**, *a**, and *b**) of the pork samples were measured using the Colour Flex EZ (SAA 103611 Calia Technology SDN BHD, Malaysia) as described by [19]. The *L** value indicates lightness on a scale of 0 (all light absorbed) to 100 (all light reflected), *a** indicates red (+ ve) to green colour (-ve), and *b** indicates yellow (+ ve) to blue colour (-ve). The instrument was calibrated with a black-and-white tile as a reference before the experiment. The fresh and freeze-thawed minced samples were allowed to bloom for 30 min before colour measurement [20]. The fresh samples were evaluated immediately in their fresh state without storage, while the frozen-thaw samples underwent thawing before colour evaluation. The samples were placed individually on a cube, and readings were taken in triplicate for each sample.

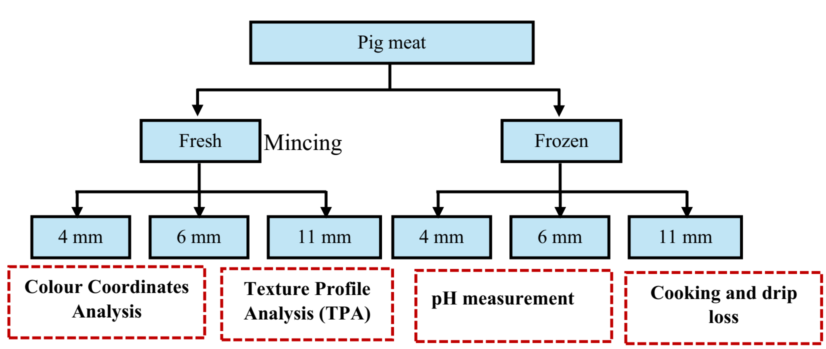

Fig. 1 Flowchart of the experimental design

2.4 Textural profile analysis (TPA)

The TPA of the meat samples was measured using a TA-HD Plus Texture Analyser (Stable Micro Systems, Surrey, UK). The meat samples were compressed to 80% of their original height using a cylindrical probe of 8–10 cm in diameter at a compression load of 25 kg, with a crosshead speed of 50 cm/min, through a puncture (compression) test [21]. The minced samples were gently positioned under the probe, where the machine applied a controlled force by compressing the sample twice to measure its resistance or deformation. The first compression determines the sample's initial resistance to deformation, often referred to as hardness [22]. After the first compression, the relaxation phase allows the sample to relax and recover (elastic behaviour). The second compression measured springiness, the ability of minced meat to return to its original form after deformation [23].

2.5 Determination of drip loss and cooking loss

Drip loss was determined using the centrifuging method published by [24]. A centrifuge machine, Eppendorf AG 22,331 Hamburg, with serial no: 5428BQ316778, made in Germany, was used according to the procedure published by [25]. With slight modification, a piece of tissue paper was placed in the centrifuge tube, followed by the minced sample. The sample was spun at 20,000 rpm for 15 min at 4 °C, then removed and reweighed. The percentage drip loss was determined using the formula.

$$\text{Drip loss } (\%) = (\text{initial weight} - \text{final weight})/\text{initial weight } \times 100$$

Cooking loss determination was conducted as described by Honikel [26]. A water bath (Memmert GmbH + Co. KG, D-91126 Schwabach, Germany, Type WTB 50) was used in the study. The minced samples were placed in a polyethylene bag and submerged in a water bath set to 78 °C. The samples were then cooked for an additional 15 min. After cooking, the samples within the bags were allowed to cool under running tap water for 5 min before being weighed again. Cooking loss was used as an indication of water-holding capacity. The following formula was used to calculate the percentage cooking loss:

$$\text{Cooking loss } (\%) = (\text{initial weight} - \text{final weight})/\text{initial weight} \times 100$$

The initial weight of the minced meat sample before cooking in the water bath (g) and the final weight of the minced meat sample after cooking in the water bath (g) were used for the computation.

2.6 Measurement of pH value

The pH of the minced meat sample was determined using a portable pH meter (Mettler Toledo, AG 8603, Switzerland). The pH meter electrode was calibrated with a standard solution, a certified potassium hydrogen phthalate buffer solution of pH 4.0, and then with a phosphate buffer of pH 7.0 before use. A 0.5 g minced meat sample was placed into a clean, dry kitchen mortar and pestle for crushing. The crushed samples were transferred to a tube, and 10 mL of ice-cold double-distilled water containing 5 mM sodium iodoacetate (Sigma-Aldrich Merck) was added to prevent further glycolysis. The mixture was homogenized using a homogenizer machine (Wiggin Hauser® D-500, Germany) for 20 s. A handheld glass electrode attached to the pH meter was used to measure the pH of the resultant homogenates as described by Hayat et al. [27]. The initial pH was measured 3 h post-mortem, while the final pH (ultimate) was measured 24 h after the meat was stored at 4 °C.

2.7 Statistical analysis

The data collected were subjected to a 2-way analysis of variance (ANOVA) to analyse the effects of different minced sizes (independent variables) on meat quality parameters (dependent variables) using SAS (Statistical Analysis System) (SAS Institute Inc., Cary, NC, USA, 2011 version 9.3). Where significant differences at the 95% level exist between the means, the means were separated using the Least Significant Difference (LSD).

3 Results and discussion

3.1 Meat colour

The *L** (lightness), *a** (redness), and *b** (yellowness) values of fresh and freeze-thaw pork of different minced sizes are presented in Table 1. The value for lightness indicated that, numerically, the minced pork was lighter in the freeze-thaw state (42.11 ± 0.834) than in the fresh state (41.59 ± 0.406); however, no significant differences ($p > 0.05$) were observed among the samples. Significant differences ($p < 0.05$) were observed in *a** and *b** between the fresh and freeze-thaw, where the latter recorded a high value of 14.30 ± 0.410 for *a** and 18.26 ± 0.324 for *b**, to 10.31 ± 0.141 and 14.93 ± 0.262 for a* and b*, respectively, in the fresh sample. The higher reflectance in freeze-thaw meat can be attributed to muscle protein denaturation, which increases the free water content of the flesh. This change in lightness was further explained by Holman et al. [28] as a result of the freeze-thaw effect on the minced meat. Additionally, Wang et al. [29] reported that the increase in *L** was due to the accumulation of a large amount of moisture on the surface of the minced sample. Significant differences ($p < 0.05$) were observed among different mince sizes, with 4 mm minced size recorded the higher values in *L** and *b** (44.48 ± 0.647) and *b** (17.90 ± 0.364). In comparison, 6 mm and 11 mm sizes recorded the same values *a** (40.99 ± 0.630, 40.09 ± 0.737), *b** (16.33 ± 0.634, 15.57 ± 0.430) respectively, however, no significant difference ($p > 0.05$) was observed in *a** in all the minced sizes. Zhang et al. [30] suggested that the significantly higher lightness and yellowness in 4 mm particles could be due to disruption of the muscle structure during thawing, causing some free water to flow to the muscle surface. Furthermore, Zhao et al. [31] explained that the lack of significant differences in *L** values across meat conditions could be attributed to factors such as water content, muscle fibre type, and myoglobin concentration, which primarily influence L*. These factors were more pronounced when the pork meat was minced.

Table 1 Effect of minced size on the colour of frozen-thawed pig shoulder minced meat

Treatment	L*	a*	b*
Condition (CD)			
Fresh	41.59 ± 0.406	10.31 ± 0.141^{b}	14.93 ± 0.262^{b}
Freeze-thaw	42.11 ± 0.834	14.30 ± 0.410^{a}	18.26 ± 0.324^{a}
LSD	1.43	0.89	0.59
Size (SZ)			
4 mm	44.48 ± 0.647^{a}	12.36 ± 0.522	17.90 ± 0.364^{a}
6 mm	40.99 ± 0.630^{b}	12.70 ± 0.496	16.33 ± 0.634^{b}
11 mm	40.09 ± 0.737^{b}	11.87 ± 0.772	15.57 ± 0.430^{b}
LSD	2.13	1.32	0.67
Interaction (CD x SZ)	NS	NS	*

a, b, c indicate means with different superscripts within the same column and row are significantly different ($p < 0.05$). * Significant difference ($p < 0.05$). NS = not significantly different ($p > 0.05$). ±= Standard Error Mean. LSD= Least Significant Difference. CD= Condition, SZ=size. L* = lightness, a* = redness, b* = yellowness

The redness (a^*) value in the thawed minced meat is significantly higher; however, no significant differences ($p > 0.05$), irrespective of minced size, were recorded, which might be due to the oxidation process of oxymyoglobin that occurred during the freeze-thawing process, which led to the reduction in the metmyoglobin [32]. Additionally, the process resulted in pigment breakdown and the formation of metmyoglobin, leading to significantly higher a* and b* colour in the freeze-thaw minced meat compared to fresh meat. The finding suggests that the freeze-thaw process accelerates myoglobin oxidation. The findings of the present study agree with the previous study by Sales et al. [33], which reported lower values for a^* and b^* in fresh minced pork as compared with the freeze-thawed meat, and that the L^* value was slightly increased as the meat passed through the freeze-thaw process. The result reported by [34] differs from the findings of this study, which showed a decrease in L*, a*, and b* values of minced pork after freezing and thawing.

3.2 Drip loss, cooking loss, and pH

Water-holding capacity is another essential parameter in evaluating meat quality and is inversely proportional to drip loss [35]. The results on the effect of different minced sizes of fresh and freeze-thaw minced pork on drip loss, cooking loss, and pH are presented in Table 2. The results showed a significant difference ($p < 0.05$) exists in the values of drip loss, cooking loss, and pH. There was high drip loss (18.37 ± 0.113) and cooking loss (25.88 ± 0.239) in the freeze-thaw minced meat compared to the fresh minced meat, 17.55 ± 0.194 and 24.70 ± 0.494, respectively; this might be attributed to the formation of ice crystals during freezing, which may lead to the destruction of muscle fibre and result in water loss [36]. Furthermore, the breakdown of muscle protein during cooking could be the reason for high cooking loss, as the protein does not bind effectively to water molecules. The increase in drip loss was attributed to myofibrillar degradation, which rendered the protein unable to bind water molecules [37]. At the same time, the cooking loss reflects the degree of damage to cells and tissue membranes after the freeze-thaw process [38]. This results in more nutrient loss, vitamins (water-soluble vitamins), and minerals [39]. The pH results also indicated a lower pH of 6.42 in the fresh sample compared to the freeze-thaw. Typically, fresh pork has a slightly acidic pH. This slight increase is attributed to the freeze-thaw effects, which disintegrate muscle fibres, leading

Table 2 Effects of minced sizes on the drip loss, cooking loss, and pH of fresh and freeze-thaw minced pork

Treatment	Drip loss (%)	Cooking loss (%)	pH	pH_{24}
Condition (CD)				
Fresh	17.55 ± 0.194^b	24.70 ± 0.494^b	6.42 ± 0.023^b	6.74 ± 0.031
Freeze-thaw	18.37 ± 0.113^a	25.88 ± 0.239^a	6.49 ± 0.034^a	6.74 ± 0.023
LSD	0.29	0.39	0.06	0.00
Size (SZ)				
4 mm	17.00 ± 0.201^c	22.08 ± 0.159^c	6.46 ± 0.045^{ba}	6.89 ± 0.033^a
6 mm	17.96 ± 0.183^b	25.13 ± 0.259^b	6.52 ± 0.014^a	6.68 ± 0.033^b
11 mm	18.90 ± 0.144^a	28.66 ± 0.389^a	6.39 ± 0.020^b	6.67 ± 0.022^c
LSD	0.43	0.57	0.09	0.00
Interaction (CD x SZ)	*	*	*	NS

a, b, c, means with different superscripts within the same column and row indicate significant differences ($p < 0.05$) exist within and across minced sizes and meat conditions. * Significantly different. NS = not significantly different ($p > 0.05$). LSD = Least Significant Difference. pH = determined at the fresh form, pH_{24} = determined after stored for 24 h at 4 °C to the release of intracellular buffers, such as peptides and phosphate, which have strong buffer capacity, into the sarcoplasm, thereby neutralising H + and increasing pH [40].

The results also revealed a significant difference ($p < 0.05$) among the different minced sizes in terms of drip and cooking loss, as well as pH. The findings indicate that increased water losses are associated with increased minced size. This finding aligns with the results of Muela et al. [41], who reported an increase in cooking loss, suggesting that this may result from the melting of ice crystals during the freeze-thaw process, which disrupts muscle structure. The pH value is commonly used as a significant indicator of meat quality. A decrease in pH value in meat depends on the quantity of glycogen in the muscle at the time of slaughter. Higher glycogen content led to a higher rate of anaerobic glycolysis, resulting in faster lactic acid production and, consequently, a higher post-mortem pH.

The effect of minced size on pH and post-mortem pH of fresh and freeze-thaw minced pork meat is presented in Table 2. The result indicates a significant difference ($p < 0.05$) in the pH of the fresh and freeze-thaw, while no significant difference ($p > 0.05$) was observed in the post-mortem of the fresh and freeze-thaw minced meat. However, the pH values of the two conditions are within the normal range (near neutral). Ideally, the ultimate pH should be lower than the initial pH due to post-mortem glycolysis, which breaks down glycogen into lactic acid, causing a rapid drop in pH. The slightly higher ultimate pH value recorded in this study might be due to pre-slaughter handling of the animal (stress). Additionally, the pH changes observed in the present study are consistent with [42], who explained that the rise in pH could be attributed to the degradation of proteins and amino acids. Furthermore, the increase in pH could be attributed to the activity of autolytic enzymes and proteolytic microorganisms, which lead to the formation of amines and ammonia [43]. However, the results of this study differ from those of Cheng et al. [44], who reported no significant difference ($p > 0.05$) in pH between fresh and freeze-thaw minced meat.

3.3 Texture profile analysis (TPA)

The TPA is an important indicator of meat quality, closely linked to the sample's water content. The effect of fresh and freeze-thaw minced pork of different minced sizes on the textural profile analysis (TPA) is presented in Table 3. The results showed significant differences ($p < 0.05$) in hardness, cohesiveness, and chewiness between fresh and freeze-thaw samples, whereas no significant differences ($p > 0.05$) were observed in adhesiveness, springiness, gumminess, and resilience. The higher hardness value in fresh meat (514.67 ± 20.803) compared to freeze-thaw meat (351.56 ± 14.334) could be attributed to differences in muscle composition and water content. Fresh meat has a high water content and a firm muscle structure, resulting in a higher perceived hardness than freeze-thawed minced pork. Freeze-thawed meat may be less firm due to the freezing and thawing process [45]. The findings of the present study are consistent with those of Xia et al. [46], who reported declines in hardness and chewiness in freeze-thawed minced pork compared with fresh meat. The result for cohesiveness is similar to that reported by Zhu et al. [47], who explained that this may be due to disruption of protein structure and cell membranes resulting from ice crystal formation during freezing, leading to water loss and reduced cohesiveness. Additionally, Qi et al. [48] reported that decreases in hardness and chewiness in freeze-thaw meat are due to protein and

Table 3 Effect of minced sizes on textural profile analysis (TPA) of fresh and freeze-thaw mince shoulder meat of the pig

Treatment	Hardness	Adhesiveness	Springiness	Cohesiveness	Gumminess	Chewiness	Resilience
Condition							
Fresh	514.67 ± 20.803^{a}	-10.69 ± 1.61	0.43 ± 0.018	0.39 ± 0.013^{b}	430.24 ± 22.529	253.29 ± 14.381^{a}	0.16 ± 0.011
Freeze-thaw	351.56 ± 14.334^{b}	-8.43 ± 0.737	0.47 ± 0.008	0.49 ± 0.007^{a}	410.33 ± 20.794	217.09 ± 13.944^{b}	0.150.005
LSD	59.55	3.54	0.04	0.02	33.36	35.01	0.02
Size							
4 mm	400.29 ± 13.509	-7.18 ± 1.093	0.45 ± 0.023	0.41 ± 0.020	370.29 ± 18.643^{b}	187.33 ± 13.744^{b}	0.12 ± 0.010^{b}
6 mm	432.93 ± 20.957	-9.78 ± 1.229	0.46 ± 0.014	0.45 ± 0.016	374.51 ± 22.646^{b}	229.76 ± 11.939^{b}	0.16 ± 0.005^{ba}
11 mm	466.12 ± 43.460	-11.71 ± 2.026	0.46 ± 0.013	0.44 ± 0.016	516.06 ± 22.438^{a}	288.48 ± 18.531^{a}	0.18 ± 0.011^{a}
LSD	88.79	5.29	0.07	0.03	49.73	52.20	0.03
Interaction (CD x SZ)	NS	NS	NS	NS	NS	*	NS

a, b, c indicate means with different superscripts within the same column and row differ significantly ($p < 0.05$). *Significant difference ($p < 0.05$). NS = not significantly different ($p > 0.05$). ±=Standard Error Mean. *CD* Condition, *SZ* size lipid oxidation. Furthermore [49], explained why the chewiness value should not be high in fresh meat compared to freeze-thaw meat, which contradicts his findings, where he stated that the freezing-thawing process altered meat structure, resulting in more compacted meat and a higher chewiness value in freeze-thaw pork minced meat compared to fresh.

The different mince sizes have a significant effect ($p < 0.05$) on gumminess, chewiness, and resilience, with values increasing as mince size increases. Larger minced sizes (11 mm) have non-disrupted and intact muscle structure compared to smaller minced sizes (4 mm), resulting in higher values for gumminess, chewiness, and resilience in the larger minced size (11 mm). This finding is consistent with the results of Zhou et al. [50].

3.4 Interactions between meat-minced size and meat conditions

According to Fig. 2, there is an interaction between meat conditions (fresh and freeze-thaw and different minced sizes (4 mm, 6 mm, and 11 mm) with regard to the colour (L* a* b*) of minced pork. The values are higher in freeze-thaw meat across all minced sizes than in fresh meat of the same sizes, except for L* and a* in the 11 mm sizes, which are higher in fresh meat. This suggests that as the meat is minced, more surface area is exposed to light, and during the freezing-thawing process, more water is lost, thereby increasing the colour indices.

According to Fig. 3, the results revealed that minced size affects fresh and freeze-thaw minced meat; however, this effect is more pronounced in freeze-thaw minced beef, except for cooking loss (11 mm), which shows no significant difference ($p > 0.05$) across the meat conditions. The trends indicated that as mince size increases, drip and cooking losses also increase. This could be attributed to the disruption of protein structure that occurs during meat mincing. This interaction is similar to the result obtained by Witte et al. [51].

Figure 4 presents the relationship between different minced sizes under various conditions. The results revealed a significant interaction between minced size and the conditions (fresh and freeze-thaw) for minced pork. The pH value is higher in freeze-thaw minced pork than in fresh minced pork, and it decreases as mince size increases (11 mm < 6 mm < 4 mm). According to [52], mincing meat disrupted the structure, increased

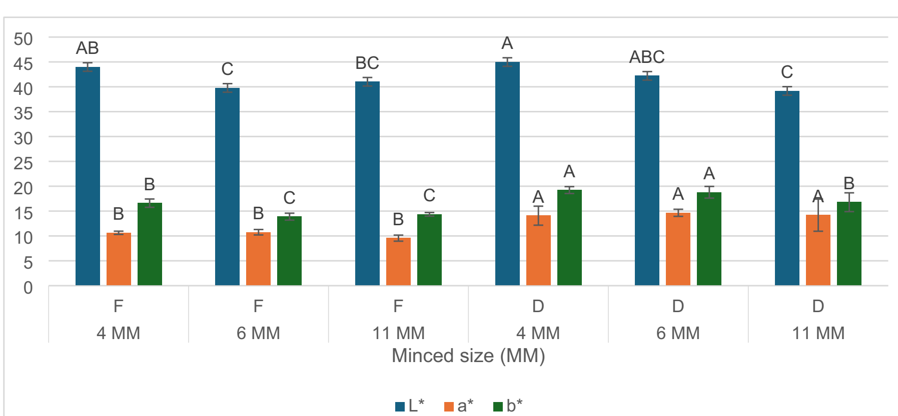

Fig. 2 L*, a*, and b* values for the different minced sizes of fresh and freeze-thaw minced pork. F = Fresh meat. D = Freeze-thaw meat. A, B, C, and D show significant differences. Error bars indicate the standard deviation

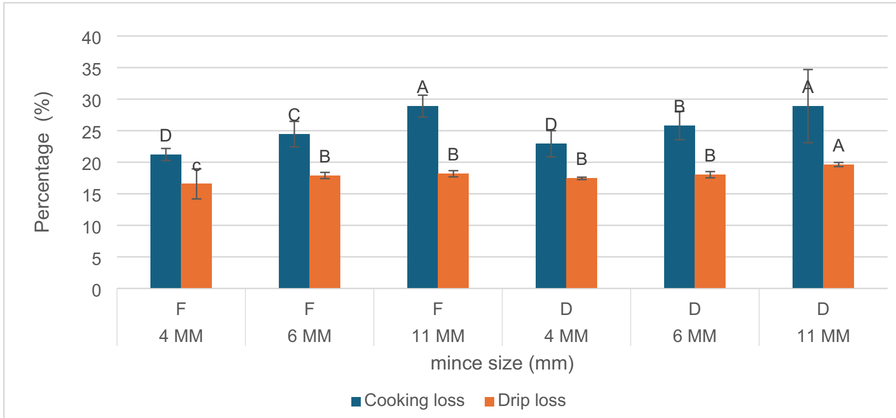

Fig. 3 Cooking loss and Drip loss values for the different minced sizes of fresh and freeze-thaw minced pork. F = Fresh meat. D = Freeze-thaw meat. A, B, C, and D show significant differences exist. Error bars indicate the standard deviation

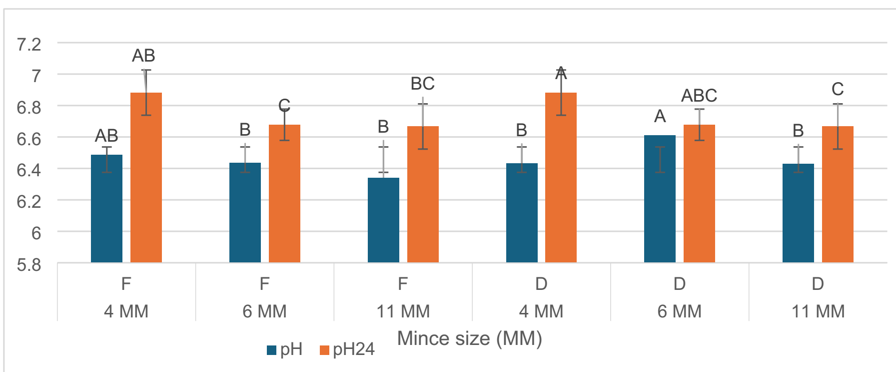

Fig. 4 pH values for the different minced sizes of fresh and freeze-thaw minced pork. F = Fresh meat. D = Freeze-thaw meat. A, B, C, and D show significant differences exist. Error bars indicate the standard deviation

surface area (4 mm), and accelerated glycolysis and lactic acid production, thereby lowering pH. The finding agrees with the results obtained by Zhu et al. [53].

Figure 5 presents the interaction between different minced sizes and meat conditions on the hardness and gumminess of minced pork. The results showed that the hardness and gumminess of minced pork increase with increasing mince size, and this applies to both fresh and freeze-thaw meat, except for the hardness at 11 mm in freeze-thaw meat. The increase is more pronounced in fresh minced meat; this might be due to the smaller size of the meat, which disrupts muscle fibres more, leading to a softer texture, whereas larger minced sizes have more undisturbed muscle fibres, resulting in tougher minced meat [54]. The findings of the study are consistent with those of Devaraj et al. [11], who reported that freezing-thawing causes protein denaturation and structural alterations, leading to a decrease in pork hardness and gumminess.

According to Fig. 6, the results revealed that chewiness increases as the minced size decreases, in the following order: 11 mm > 6 mm > 4 mm. This indicates that the larger the minced size, the less disruption of muscle fibres, leading to greater chewiness.

According to Fig. 7, the results revealed that mince size affects the fresh minced meat, while there is no interaction with the freeze-thaw sample of different sizes.

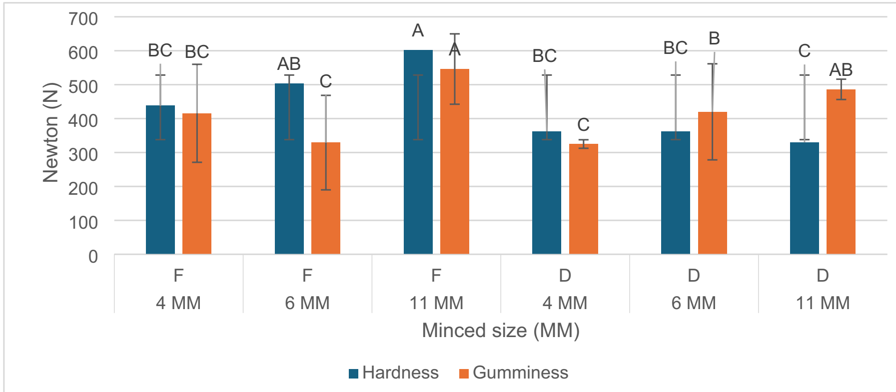

Fig. 5 Hardness and gumminess values for different minced sizes of fresh and freeze-thaw minced pork. F = Fresh meat. D = Freeze-thaw meat. A, B, C, D show significant differences exist. Error bars indicate the standard deviation

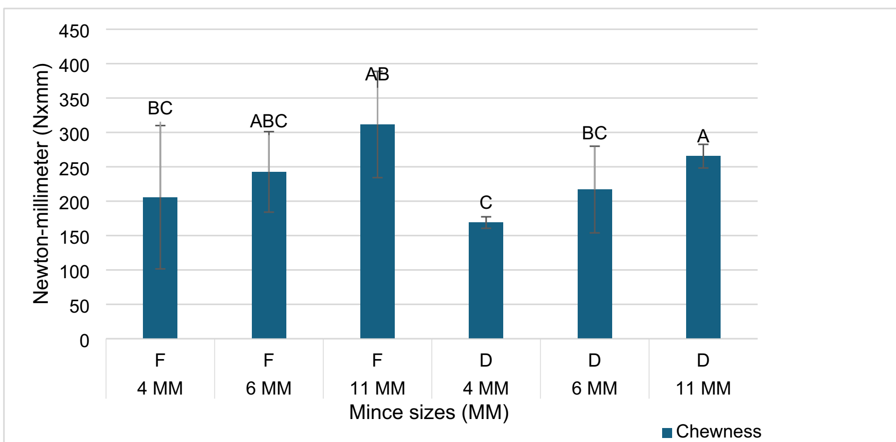

Fig. 6 Chewiness values of different minced sizes of fresh and freeze-thaw pork shoulder minced meat. F = Fresh meat. D = Freeze-thaw meat. A, B, C, and D show significant differences exist. Error bars indicate the standard deviation

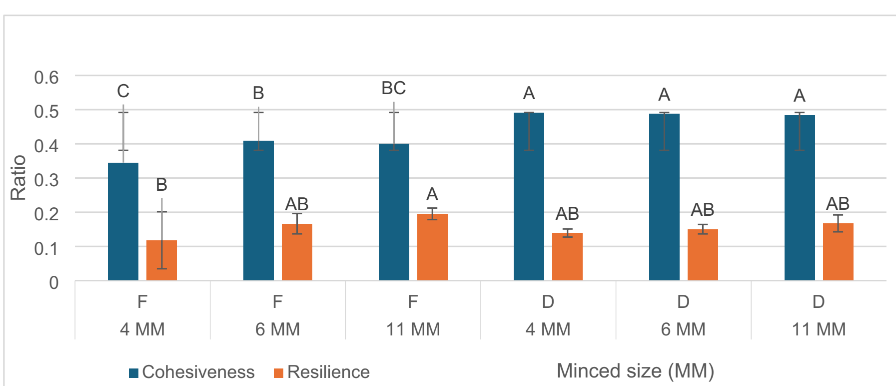

Fig. 7 Cohesiveness and resilience values for different minced sizes of fresh and freeze-thaw pork shoulder minced meat. F = Fresh meat. D = Freeze-thaw meat. A, B, C, and D show significant differences exist. Error bars indicate the standard deviation

4 Conclusion

The minced size of pork significantly affects meat quality parameters, including colour, drip loss, cooking loss, pH, and TPA, in both fresh and freeze-thaw meat. The freezing-thawing process had a pronounced impact on the quality characteristics of pork, including a*, b* drip loss, cooking loss, pH, hardness, cohesiveness, and chewiness, with smaller sizes (4 mm and 6 mm) indicating better quality after freezing-thawing. The 4 mm minced meat exhibited higher water content and improved textural properties compared with the 11 mm minced meat. Therefore, to minimize quality loss, it is recommended that processors use 4- and 6-mm mince for frozen pork. Future research should focus on antioxidant treatments or faster freezing methods to mitigate quality loss in mince pork.

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Author contributions
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Data availability
The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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