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Full Research Article

HISTOLOGICAL FEATURES, MORPHOMETRIC TRAITS AND MEAT QUALITY OF BROILERS WITH MYOPATHIES IN A LOW-INPUT COMMERCIAL ABATTOIR

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Abstract

Wooden breast, white striping, spaghetti meat and green muscle disease are myopathies that occur on the breast muscles of broilers due to their rapid growth during rearing. These myopathies are characterized by histological changes and negatively affect the quality of broiler meat, thus leading to economic losses. The aim of the study was to determine the histological features of broiler meat with myopathies and the influence of myopathies on morphometric traits and meat quality characteristics of the breast muscles. Data were collected from 80 broiler breast fillets, which underwent macroscopic examination 24 hours post-slaughter, followed by histological analysis of a subset (n = 46). Physicochemical indicators (pH and temperature), meat color, water holding capacity, as well as morphometric traits (weight, width, length and thickness) were determined in all breast muscle samples.Macroscopic examination of breast muscles revealed the presence of myopathies in 50/80 (62.50%) broilers. Wooden breast was identified in 22.50% (n = 18) of broilers, white striping in 13.75% (n = 11),

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spaghetti meat in 16.25% (n = 13), while green muscle disease was detected in 10.00% (n = 8) of the birds. Histological analysis of broiler breast muscles affected by myopathies revealed degeneration and necrosis, hypereosinophilia, loss of cross-striations, sarcoplasmic vacuolization, fiber fragmentation and the presence of inflammatory cells. Broilers with myopathies had significantly lower breast muscle weight compared to individuals without myopathies. The presence of myopathies negatively affected meat quality characteristics, in terms of high ultimate pH, inadequate water holding capacity (lower thawing and cooking loss) and unfavorable meat color (too high or low L^* value). In conclusion, meat from broilers affected by any of the studied myopathies does not fulfill the standards for market placement and is suitable only for processing into lower-quality meat products.

Key Words: broilers, meat quality, morphometric indicators, myopathies, histological features

INTRODUCTION

Poultry meat is widely consumed worldwide, as it is acceptable across different religions and cultures. Investment in this branch of animal production is profitable, as good production results can be achieved in a short period (Mottet & Tempio, 2017). Due to the rapid growth of the world population and the increasing demand for animal-derived food, continuous efforts are being made to improve both production efficiency and food quality (Sammari et al., 2023). The constant need to supply the market with relatively affordable products is supported by good production management, which includes ongoing genetic improvement of productive traits in both light and heavy hybrid lines. Broilers are selected primarily based on production performance, often at the expense of individual welfare and health (Sammari et al., 2023).

In recent years, rapid increases in muscle mass over a short period have led to negative effects on health on broilers (Sammari et al., 2023). Alongside cardiovascular and metabolic disorders resulting from the disproportionate development of the heart, lungs, and musculature, the incidence of various myopathies has become increasingly prevalent (Nikolić et al., 2019; Sammari et al., 2023; Rajčić et al., 2024). Some myopathies affect the pectoralis major muscle, including wooden breast, white striping and spaghetti meat (Sihvo et al., 2014), whereas green muscle disease occurs in the pectoralis minor muscle (Ozmen, 2017; Giampietro-Ganeco et al., 2021). Wooden breast is characterized by firm meat with possible protrusions and frequent petechial hemorrhages on the muscle surface (Sihvo et al., 2014; Rajčić et al., 2024). White striping is associated with increased intramuscular fat deposition (Kuttappan et al., 2013), while spaghetti meat involves the disruption of muscle integrity due to fiber separation (Baldi et al., 2018). Green muscle disease can occur in both fillets, showing color variations from pink, due to hemorrhages, to grayish-green discolorations (Ozmen, 2017; Giampietro-Ganeco et al., 2021).

Although myopathies do not affect broiler carcass safety or pose a risk to consumer health, they negatively influence specific meat quality characteristics (Bošković Cabrol et al., 2023). Affected fillets show altered sensory and technological properties, and depending on the severity, parts or entire carcasses may be discarded or used for lower-quality products (Zanetti et al., 2018).

Although a number of studies have been carried out to evaluate the occurrence of myopathies and their influence on meat quality characteristics, most have been performed in high-input large-scale production systems (Mazzoni et al., 2015; Trocino et al., 2015; Soglia et al., 2016; Baldi et al., 2018; Zanetti et al., 2018; Giampietro-Ganecoet al., 2021; Che et al., 2022; Rajčić et al., 2024), or under controlled experimental conditions (Kuttappan et al., 2012, 2013, 2017; Sihvo et al., 2014; Radaelli et al., 2017; Aguirre et al., 2020), which highlights the need to evaluate conditions in low-input commercial abattoirs. Considering the aforementioned facts, the aim of this study was to determine the histological features of broiler meat with myopathies, and the influence of myopathies on the morphometric traits and meat quality characteristics of the breast muscles.

MATERIALS AND METHODS

Ethical Statement

The study was carried out in full compliance with European legislation governing the protection of chickens kept on farms for meat production (EU Directive, 2007) (No. 2007/43/EC), their welfare during transport (Association of Poultry Producers and Poultry Trade in the EU, 2016) and the relevant welfare requirements at slaughter (EC Council Regulation No. 1099/2009). All broilers were reared on a commercial farm and slaughtered for human consumption under standard commercial conditions. No invasive experimental procedures were performed in vivo; breast meat samples were collected as part of the normal processing workflow. Consequently, the study did not fall within the scope of Directive 2010/63/EU (EU Directive, 2010) on the protection of animals used for scientific purposes and did not require dedicated ethical approval by the local animal welfare and ethical review body.

Experimental Animals, Pre-Slaughter Conditions and Slaughter Procedure

The study was conducted on 80 Cobb 500 male broilers (35 days old) sourced from a single commercial farm and processed at a one low-input commercial slaughter plant (slaughtering capacity of 2,000 broilers/day) in the Belgrade region (Serbia). Broilers were housed under conditions in accordance with the relevant EU Directive (2007/43/EC), on littered floors with continuous access to dry, friable bedding, at a maximum stocking density of 33 kg/m². Birds were fed a commercial diet formulated to meet the National Research Council nutrient recommendations for broilers (NRC, 1994). All broilers underwent the same pre-slaughter treatment (gentle handling), transport (same vehicle and driver; transport duration: ~60 minutes; stocking density:

39 kg/m²) and lairage conditions (lairage duration ~30 minutes; stocking density 39 kg/m²). Slaughter was carried out according to standard industry practices, including electrical stunning, bleeding, scalding, defeathering, evisceration and cooling by water immersion.

Macroscopic examination

To determine the presence of myopathies, breast muscles were examined 24 hours postmortem by visual inspection and palpation for wooden breast, white striping, spaghetti meat and green muscle disease (deep pectoral myopathy). The identification of wooden breast and white striping was performed according to the method described by Kuttapan et al. (2016). White striping was defined by the presence of white striations parallel to the muscle fibers in the pectoralis major muscle, while wooden breast was characterized by a hard consistency affecting part or the entire muscle. Spaghetti meat was identified by applying finger pressure and "pinching" the muscle, which resulted in a loss of structural integrity and the development of a soft, mushy texture (Baldi et al., 2018). Green muscle disease was recognized by discoloration of part or the entire pectoralis minor muscle, ranging from green to grey green (Bilgili & Hess, 2008).

Histological analysis

Breast muscle cuts (n = 46) were collected immediately after macroscopic examination for subsequent histological analysis. The tissue specimens were fixed in 10% neutral buffered formalin (pH = 6.8), processed according to standard histological protocols, and embedded in paraffin. Tissue sections of 5 μm thickness were obtained using a rotary microtome (Cut 5062, Slee, Mainz, Germany), stained with hematoxylin and eosin (HE) and Masson-Goldner trichrome (MG) (Merck Millipore, Darmstadt, Germany), and mounted with DPX medium (Sigma Chemical Co., St. Louis, MO, USA). The prepared histological slides were examined under a light microscope (Olympus CX31, Tokyo, Japan) equipped with a digital camera (Olympus Soft Imaging Solutions, Münster, Germany), and representative microphotographs were acquired.

Morphometric measurements

Breast muscle fillet weight was determined using a digital balance (WPS 600/C, Radwag, Radom, Poland; accuracy ± 0.05 g). Breast muscle fillet length, width and thickness were determined with a digital caliper (accuracy 0.01 mm; Festa, China). The length and width of each fillet were measured along its longest and widest axes, respectively, whereas thickness was determined at the maximal cranial region.

Meat quality measurements

The ultimate pH (pH_{24h}) and temperature (T_{24h}) of the breast cuts (*musculus pectoralis major*) were measured 24 hours post-slaughter using a portable pH meter (Testo 205, Testo AG, Lenzkirch, Germany). Meat color traits (L^*, a^*, b^*) were determined on both the dorsal and ventral surfaces (at six randomly selected points per sample) of breast muscle (*musculus pectoralis major*), using a portable colorimeter (NR110, 3NH Technology Co., Ltd, Shenzhen, China) equipped with a 4 mm aperture, a viewing angle of 2° and a D65 illuminant. The final color traits were calculated as the average of six measurements for L^* (lightness), a^* (redness) and b^* (yellowness). Water-holding capacity of broiler breast cuts (*musculus pectoralis major*) was assessed using three methods (drip loss, thawing loss and cooking loss) as described by Klauke et al. (2013) and Honikel (1998). Broiler meat quality classes were established according to Zhang and Barbut (2005), based on instrumental L^* (lightness) value as follows: (i) pale, soft, and exudative (PSE) meat ($L^* > 53$); (ii) red, firm, and non-exudative (RFN, normal) meat ($46 < L^* < 53$); and (iii) dark, firm and dry (DFD) meat ($L^* < 46$).

Statistical analysis

Statistical analyses were conducted using GraphPad Prism software (version 9.5.1, GraphPad Software, San Diego, CA, USA). Based on the presence of myopathies, breast fillets were categorized into five groups: (i) unaffected fillets –without any sign of myopathies (n = 30); (ii) green muscle disease (n = 8); (iii) spaghetti meat (n = 13); (iv) wooden breast (n = 18); and (v) white striping (n = 11). Descriptive statistics, including the arithmetic mean and standard deviation, were computed for all variables. Group mean differences were analyzed using one-way ANOVA, with Tukey's post hoc test applied for subsequent pairwise comparisons. The Chi-squared test (χ^2) was applied to evaluate differences in the occurrence of broiler meat quality classes among groups. Statistical significance was defined as $P \leq 0.05$, whereas P-values between 0.05 and 0.10 were interpreted as indicative of a trend.

RESULTS

Macroscopic examination and histological analysis of broiler breast for myopathies

Macroscopic examination of breast muscles revealed the presence of myopathies in 50/80 (62.50%) broilers. Wooden breast was identified in 22.50% (n = 18) of the broilers, white striping in 13.75% (n = 11), spaghetti meat in 16.25% (n = 13), while green muscle disease was detected in 10.00% (n = 8) of the broilers (Figure 1).

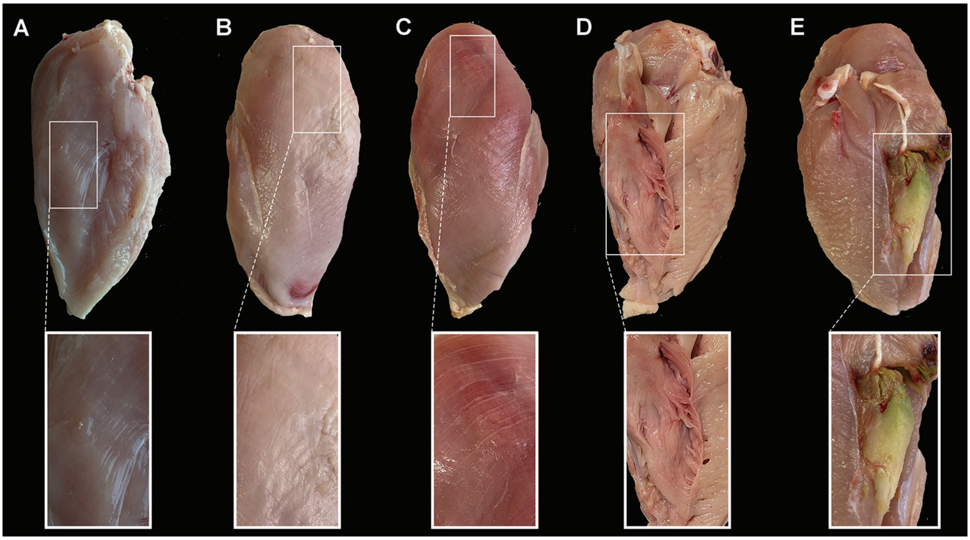

Figure 1. Macroscopic characteristics of broiler meat with and without myopathies: **(A)** Unaffected fillet; **(B)** Wooden breast; **(C)** White striping; **(D)** Spaghetti meat; **(E)** Green muscle disease.

Representative microphotographs of the examined breast muscle sections are presented in Figures 2–6. In sections of breast muscle without macroscopically visible lesions, muscle fibers exhibited a typical polygonal shape with nuclei predominantly located at the periphery of the cells adjacent to the sarcolemma (Figure 2B, D). Cross-striations were clearly discernible, while sarcoplasm was filled with regularly arranged myofibrils, which in cross-sections tended to group into so-called Conheim fields (Figure 2C). A thin layer of connective tissue (endomysium) surrounded individual fibers (Figure 2A–E), with small focal areas occasionally containing adipose tissue (Figure 2C). Rare and scattered inflammatory cells were observed in the connective tissue of some breast muscle sections from broilers that did not have any macroscopically discernable myopathy (Figure 2E, F).

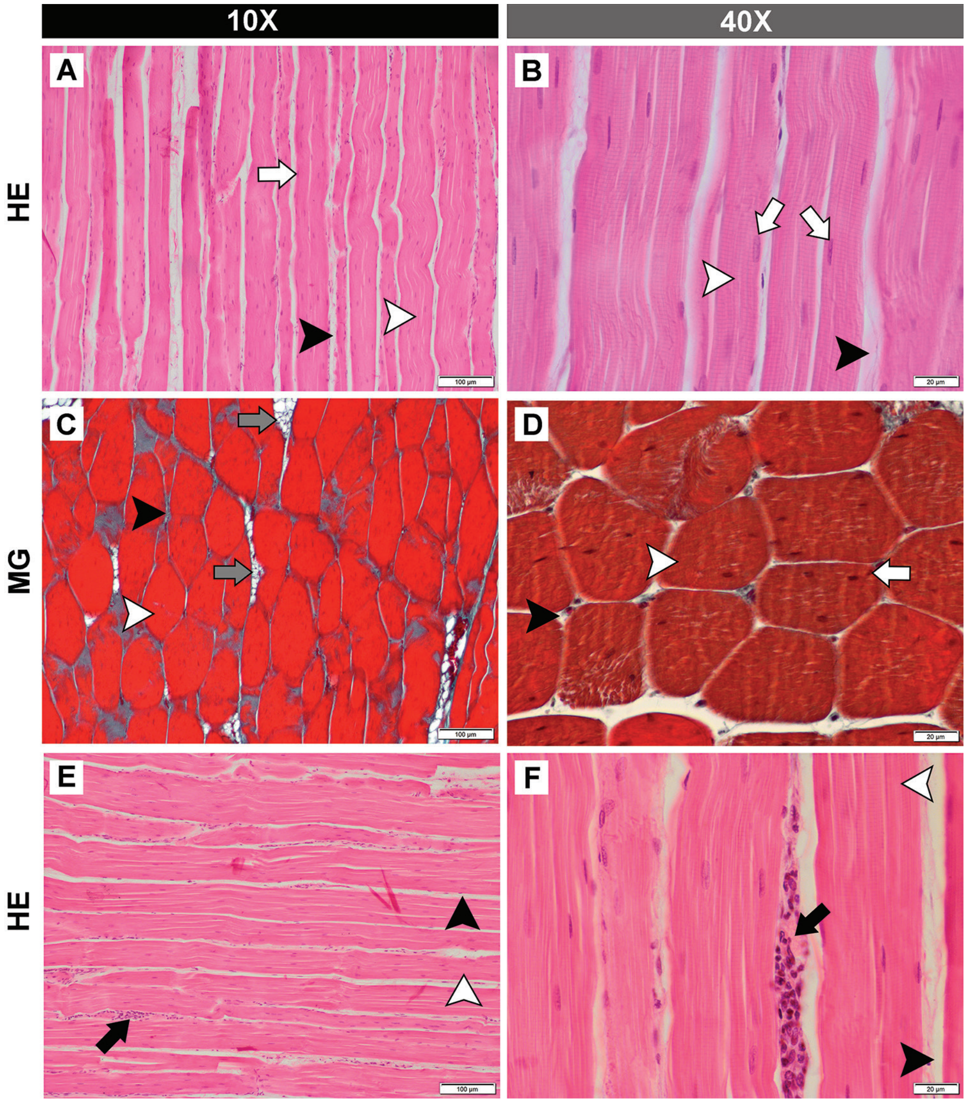

Figure 2. Representative microphotographs of broiler breast muscle sections macroscopically assessed as unaffected by any type of myopathy. Note: **white arrowhead** – muscle fiber; **black arrowhead** – connective tissue (endomysium); **white arrow** – muscle fiber nucleus; **black arrow** – group of inflammatory cells; **gray arrow** – group of adipocytes). Staining with hematoxylin and eosin (HE) (A, B, E, F) and the Masson-Goldner method (MG) (C, D). Images captured using 10× objective (A, C, E) (scale bar: 100 µm) and 40× objective (B, F, F) (scale bar: 20 µm).

Sections of muscle tissue macroscopically classified as wooden breast showed fibers of variable diameter and oval shape (Figure 3D, E). Degenerative and necrotic changes were evident, including hypereosinophilia, loss of cross-striations, sarcoplasmic vacuolization, randomly distributed internal nuclei, fiber fragmentation, and the presence of macrophages and, to a lesser extent, heterophils (Figure 3A–E). Notable accumulation of loose connective tissue (fibrosis) was detected in the perimysium and endomysium (Figure 3A–E), occasionally interspersed with adipocytes (Figure 3C). Inflammatory changes were observed in the connective tissue, characterized by infiltration of lymphocytes, macrophages, heterophils and perivenular accumulation of mononuclear leukocytes (Figure 3A–C).

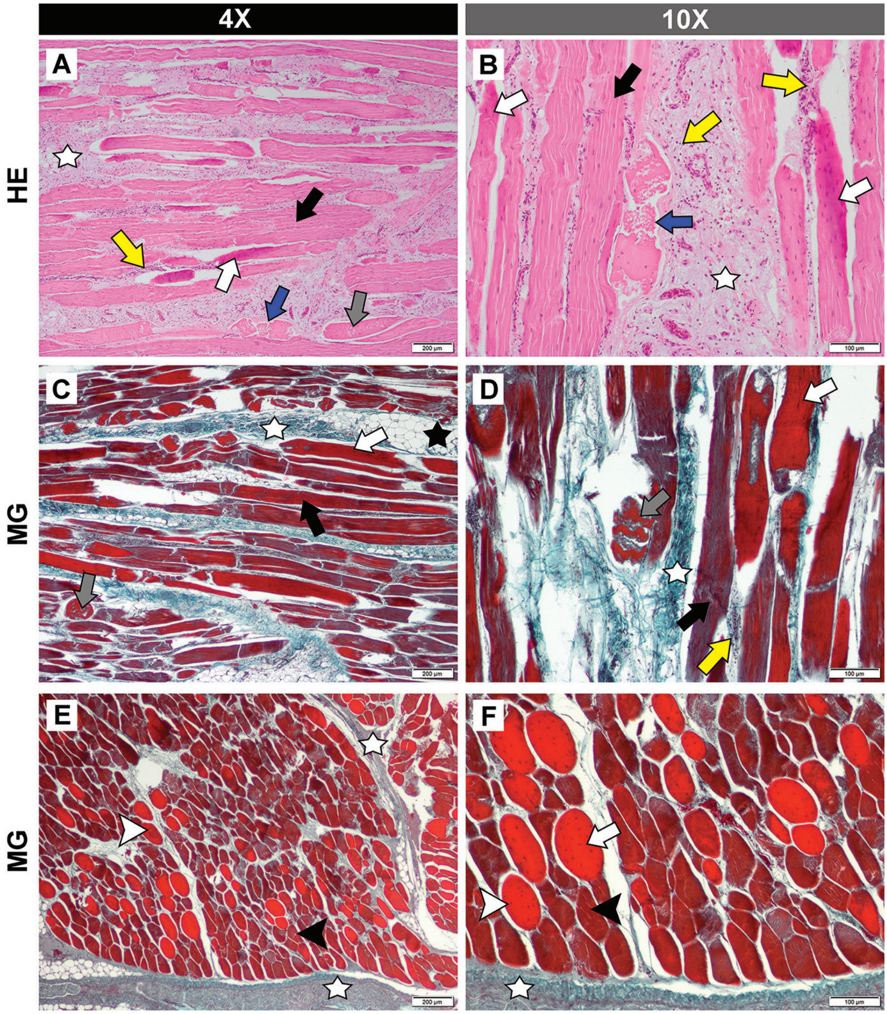

Figure 3. Representative microphotographs of broiler breast muscle sections macroscopically assessed as affected by wooden breast. Note: **white arrowhead** – oval muscle fiber; **black arrowhead** – polygonal muscle fiber; **white arrow** – hypereosinophilic, hyalinized muscle fiber; **black arrow** – loss of cross-striations; **gray arrow** – sarcoplasmic vacuolization; **blue arrow** – muscle fiber fragmentation; **yellow arrow** – infiltration of inflammatory cells; **white asterisk** – fibrotic endomysium and perimysium; **black asterisk** – adipocytes). Staining with hematoxylin and eosin (HE) (A, B) and the Masson-Goldner method (MG) (C, D, E, F). Images captured using 4× objective (A, C, E) (scale bar: 200 μm) and 10× objective (B, D, F) (scale bar: 100 μm).

Histological alterations associated with white striping (Figure 4A–D) and spaghetti meat (Figure 5A–D) were generally similar to those described for wooden breast. However, white striping was distinguished by pronounced adipocyte accumulation (lipidosis) (Figure 4A–D), whereas spaghetti meat was marked by loosening of the endomysial and perimysial connective tissue, facilitating fiber separation (Figure 5A–D). Detailed analysis of longitudinal sections from broilers with spaghetti meat myopathy revealed thin and fragmented fibers surrounded by immature connective tissue, accompanied by extensive infiltration of inflammatory cells (Figure 5A–D).

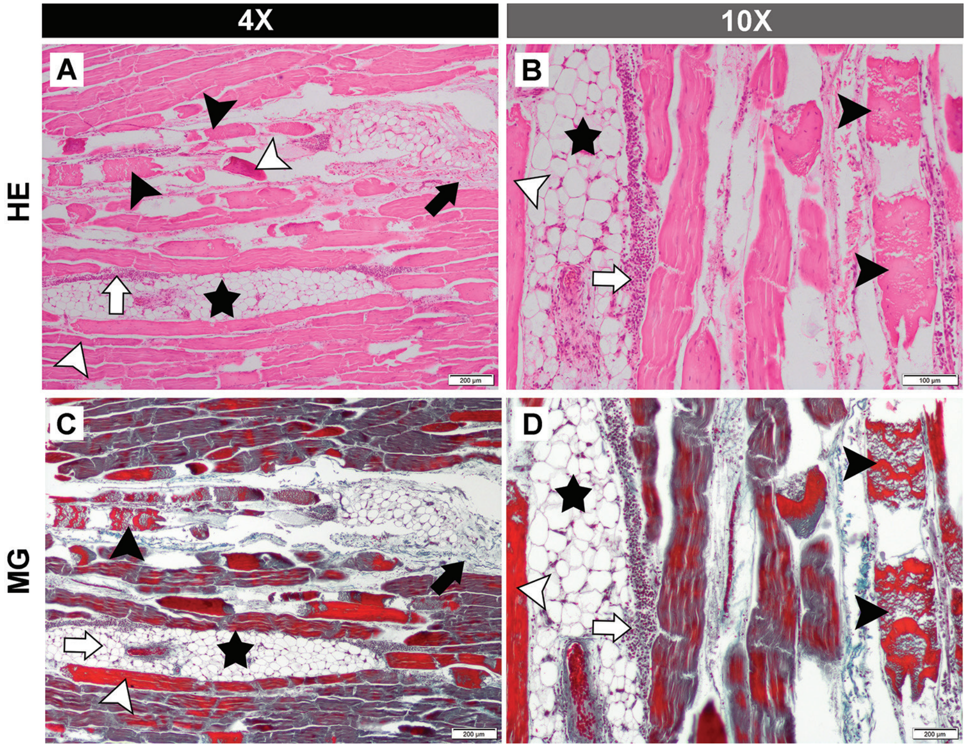

Figure 4. Representative microphotographs of broiler breast muscle sections macroscopically assessed as affected by white striping. Note: **white arrowhead** – hypereosinophilic muscle fiber; **black arrowhead** – degenerated, vacuolated, and necrotic muscle fiber; **white arrow** – infiltration of inflammatory cells; **black arrow** – endomysial fibrosis; **black asterisk** – accumulation of adipose tissue in connective tissue. Staining with hematoxylin and eosin (HE) (A, B) and the Masson-Goldner method (MG) (C, D). Images captured using 4× objective (A, C) (scale bar: 200 μm) and 10× objective (B, D) (scale bar: 100 μm).

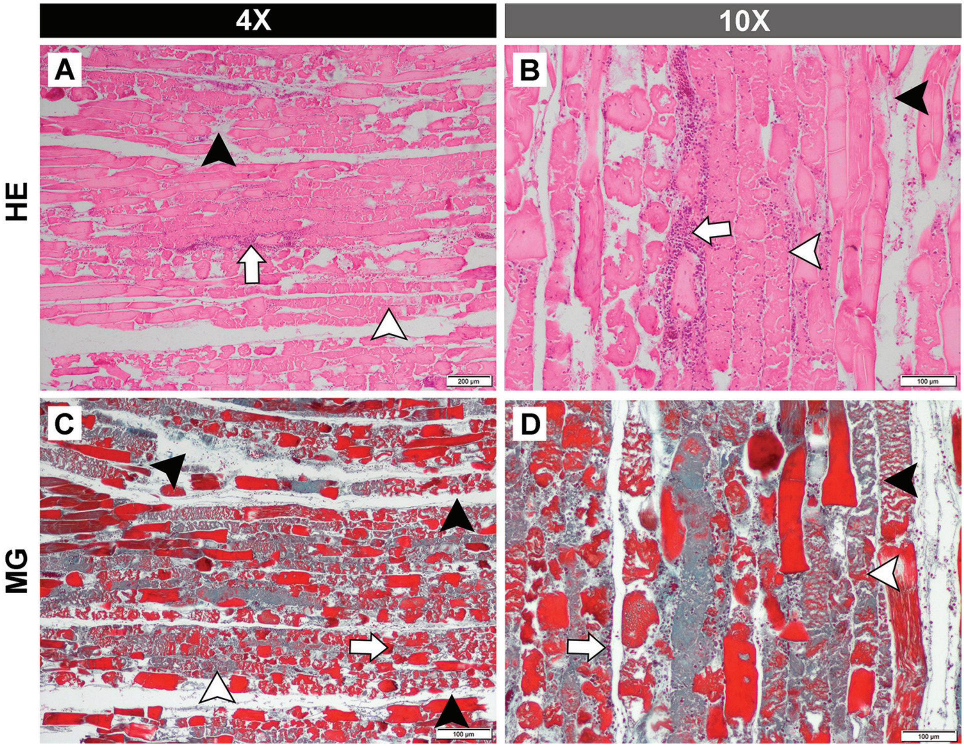

Figure 5. Representative microphotographs of broiler breast muscle sections macroscopically classified as spaghetti meat. Note: **white arrowhead** – thin, fragmented, and degenerated muscle fibers; **black arrowhead** – fine, immature connective tissue surrounding muscle fibers; **white arrow** – infiltration of inflammatory cells. Staining with hematoxylin and eosin (HE) (A, B) and the Masson-Goldner method (MG) (C, D). Images captured using 4× objective (A, C) (scale bar: 200 µm) and 10× objective (B, D) (scale bar: 100 µm).

Microscopic analysis of *musculus pectoralis minor* affected by green muscle disease revealed acute inflammation with infiltration of heterophils and macrophages, edema, hyperemia and hemorrhage in the affected area (Figure 6A–D). Necrosis accompanied by infiltration of mononuclear cells and heterophils was evident in the walls of blood vessels and the surrounding connective tissue (Figure 6E–H). Chronic cases were characterized by large necrotic areas, edematous, hypereosinophilic and necrotic fibers surrounded by hemorrhagic zones with inflammatory cell infiltration (macrophages and lymphocytes). In most cases, wide regions of muscle tissue were replaced by newly formed connective and adipose tissue, while in certain areas, smooth muscle cells in the vessel walls were replaced with connective tissue (Figure 6D–G).

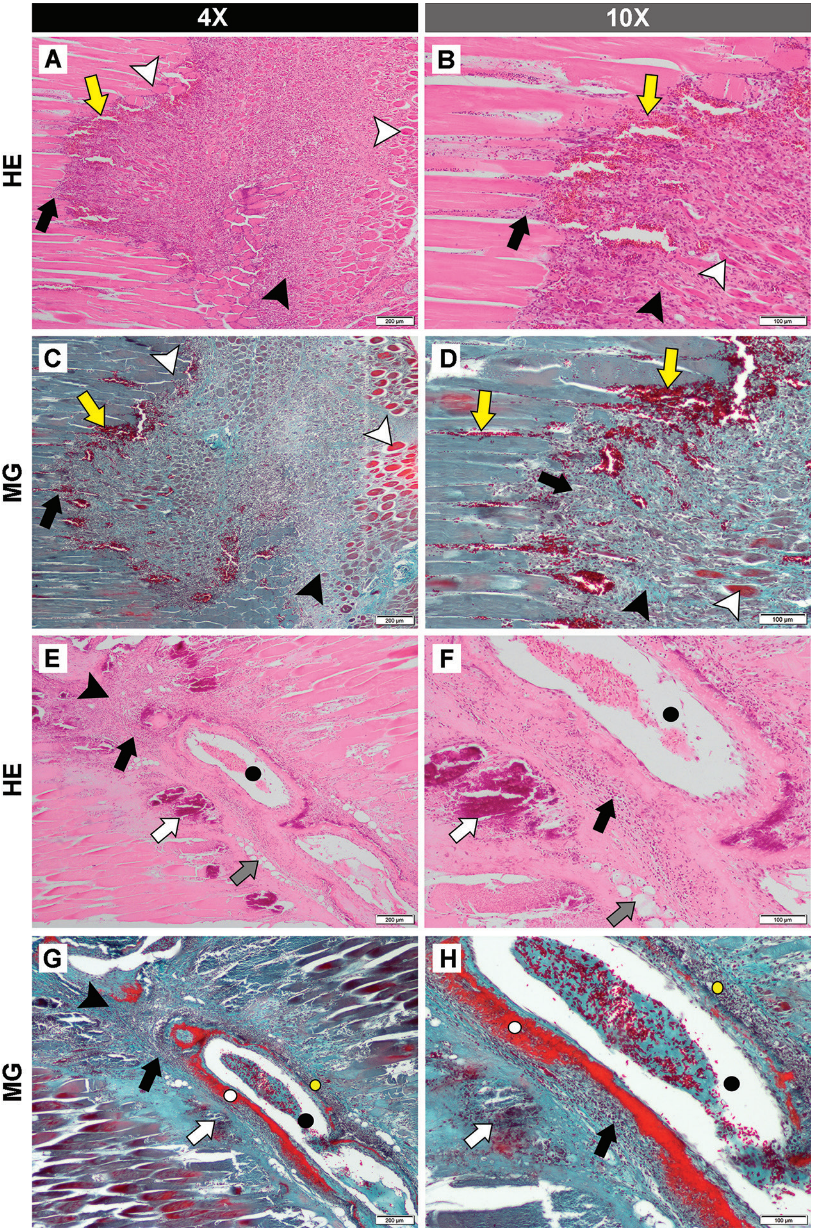

Figure 6. Representative microphotographs of deep broiler breast muscle sections macroscopically diagnosed with green muscle disease. Note: **white arrowhead** – hypereosinophilic and degenerated muscle fibers; **black arrowhead** – accumulation of connective tissue; **white arrow** – necrosis; **black arrow** – infiltration of inflammatory cells; **gray arrow** – adipocyte; **yellow arrow** – hemorrhage; **black dot** – vein lumen; **white dot** – smooth muscle cells in the vein wall; **yellow dot** – connective tissue in the vein wall). Staining with hematoxylin and eosin (HE) (A, B, E, F) and the Masson-Goldner method (MG) (C, D, G, H). Images captured using 4× objective (A, C, E, G) (scale bar: 200 μm) and 10× objective (B, D, F, H) (scale bar: 100 μm).

Effects of broiler breast myopathies on morphometric traits and meat quality characteristics

The effects of broiler breast myopathies on the morphometric traits of fillets are shown in Table 1. The presence of myopathy significantly affected (reduced) the broiler breast muscle weight (*P*=0.001) and length (*P*=0.005). Additionally, broiler breast fillets affected by green muscle disease showed a tendency (*P*=0.059) toward reduced breast muscle width.

The effects of broiler breast myopathies on the meat quality characteristics are depicted in Tables 2 and 3. The presence of broiler breast myopathies significantly affected most of the studied meat quality parameters, including ultimate pH (*P*<0.001), thawing loss (*P*=0.001), cooking loss (*P*<0.001), as well as *L** (*P*<0.001), *a** (*P*<0.001) and *b** (*P*<0.001) values. In addition, the presence of breast myopathies in broilers significantly affected the distribution of meat quality classes. The highest occurrences of DFD meat were observed in broilers with either wooden breast or white striping (*P*=0.002) myopathies. Furthermore, broiler breast fillets affected by green muscle disease showed a tendency (*P*=0.094) toward a higher occurrence of PSE meat. In contrast, unaffected fillets had the highest occurrence of RFN meat (*P*=0.005).

Table 1. Effect of myopathies on the morphometric properties of broiler breast muscle *(musculus pectoralis)* (n = 80).

Myopathy type	Unaffected fillets	Green muscle disease	Spaghetti meat	Woody breast	White striping	*P*-value	Significance
Number of fillets (n = 80)	30	8	13	18	11		
Morphometric properties							
Breast muscle weight (g)	325.60 ± 30.46^a	255.60 ± 16.58^b	269.20 ± 63.12^b	283.00 ± 41.46^b	282.40 ± 57.64^b	0.001	*
Breast muscle length (mm)	176.70 ± 9.14^a	157.40 ± 5.84^b	175.60 ± 10.11^a	177.00 ± 11.75^a	174.20 ± 12.50^a	0.005	*
Breast muscle width (mm)	86.27 ± 7.72	80.18 ± 5.47	88.64 ± 10.16	86.67 ± 9.27	92.79 ± 8.89	0.059	t
Breast muscle thickness (mm)	37.01 ± 6.61	36.99 ± 6.16	35.82 ± 4.66	37.27 ± 6.99	33.45 ± 6.90	0.573	ns

*Statistical significance at the level of $P<0.05$; t: tendency ($0.05 < P < 0.10$); ns: not significant ($P>0.10$)
– Different letters within rows indicate statistical significance at the level $P<0.05$ ($^{a-b}$)

Table 2. Effect of broiler breast myopathies on meat quality (*musculus pectoralis*) characteristics (n = 80).

Myopathy type	Unaffected fillets	Green muscle disease	Spaghetti meat	Woody breast	White striping	*P*-value	Significance
Number of fillets (n = 80)	30	8	13	18	11		
Physicochemical parameters							
pH_{24h}	5.81 ± 0.10^a	6.33 ± 0.10^b	6.20 ± 0.40^b	6.19 ± 0.21^b	6.28 ± 0.44^b	<0.001	*
T_{24h} (°C)	2.83 ± 0.51	2.93 ± 0.14	2.92 ± 0.13	2.93 ± 0.14	3.00 ± 0.10	0.645	ns
Water-holding capacity parameters (%)							
Drip loss	2.81 ± 1.76	2.53 ± 0.83	2.92 ± 3.03	2.73 ± 2.09	2.07 ± 1.11	0.840	ns
Thawing loss	6.61 ± 1.50^a	3.27 ± 1.15^b	5.04 ± 2.43^a	3.23 ± 1.14^b	3.37 ± 1.84^b	0.001	*
Cooking loss	28.18 ± 3.53^a	16.77 ± 7.63^b	28.05 ± 4.68^a	21.27 ± 7.08^c	21.75 ± 6.97^c	<0.001	*
Meat color parameters							
*L** (lightness) value	51.13 ± 1.90^a	55.03 ± 1.67^b	47.56 ± 1.67^c	46.69 ± 4.06^c	46.67 ± 4.27^c	<0.001	*
*a** (redness) value	1.24 ± 0.47^a	0.85 ± 0.55^b	2.75 ± 1.32^c	2.70 ± 1.63^c	2.69 ± 0.99^c	<0.001	*
*b** (yellowness) value	4.46 ± 1.03^a	7.98 ± 4.21^b	4.20 ± 1.05^a	3.40 ± 0.96^c	3.83 ± 0.82^c	<0.001	*

*Statistical significance at the level of $P<0.05$; t: tendency ($0.05 < P < 0.10$); ns: not significant ($P>0.10$)
– Different letters within rows indicate statistical significance at the level $P<0.05$ ($^{a-b}$)

Table 3. Effect of broiler breast myopathies on the frequency of meat quality classes (*musculus pectoralis*) (n = 80).

Myopathy type	Unaffected fillets	Green muscle disease	Spaghetti meat	Wooden breast	White striping	*P*-value	Significance
Number of fillets (n = 80)	30	8	13	18	11		
Meat quality classes (%)							
Pale, soft and exudative meat ($L^* > 53$)	20.00	62.50	15.38	16.67	27.27	0.094	t
Red, firm and non-exudative meat ($46 < L^* < 53$)	80.00^a	37.50^b	69.24^c	38.89^b	27.27^b	0.005	*
Dark, firm and dry meat ($L^* < 46$)	0.00^a	0.00^a	15.38^a	44.44^b	45.46^b	0.002	*

*Statistical significance at the level of $P<0.05$; t: tendency ($0.05 < P < 0.10$); ns: not significant ($P>0.10$)
- Different letters within rows indicate statistical significance at the level $P<0.05$ ($^{a-b}$)

DISCUSSION

The pathogenesis of wooden breast, white striping and spaghetti meat is increasingly linked to early-onset metabolic overload in rapidly growing breast muscle, which leads to insufficient vascularization and localized hypoxia (Abasht et al., 2016; Sihvo, 2019; Bošković et al., 2025). These hypoxic conditions promote excessive generation of reactive oxygen species, triggering oxidative stress, mitochondrial dysfunction and impaired ATP production, as reported in multiple metabolomic and transcriptomic studies (Abasht et al., 2016; Wu et al., 2024; Bošković et al., 2025). The resulting oxidative damage to lipids, proteins and mitochondria accelerates myofiber degeneration, activates inflammatory pathways and promotes the fibro-adipogenic remodeling characteristic of wooden breast and white striping (Bošković et al., 2025; Wang et al., 2025). In the case of spaghetti meat, severe metabolic imbalance and proteolytic activation contribute to reduced fiber cohesion and structural integrity loss (Wu et al., 2024; Choi et al., 2025). In contrast, green muscle disease (deep pectoral myopathy) originates from ischemia due to increased intramuscular pressure within the *musculus pectoralis minor* (Pajohi-alamoti et al., 2016), but similar oxidative and metabolic disturbances accompany the ensuing necrosis (Malila, 2023).

Despite the fact that the reported frequencies of broiler breast myopathies vary across studies, likely due to factors such as slaughter age (Kuttapan et al., 2017), gender (Trocino et al., 2015; Che et al., 2022), genotype (Hammemi et al., 2024), diet and feeding strategies (Trocino et al., 2015; Vieira et al., 2021) and final body weight (Aguirre et al., 2020), histological analyses have consistently revealed muscle fiber damage in more than 97% of examined breasts (Sihvo et al., 2014; Soglia et al., 2016; Radaelli et al., 2017). Consistent with these findings, all macroscopically unaffected broiler breast muscles in the current investigation showed mild myodegeneration and infiltration, with no evidence of fibrosis on histological examination. The microscopic lesions observed in broiler breast muscles affected by myopathies in this study are consistent with previously reported histological findings (Soglia et al., 2016; Trocino et al., 2015; Radaelli et al., 2017). In line with the findings of this study, several studies (Sihvo et al., 2014; Soglia et al., 2016; Malila et al., 2018) reported that broiler breast muscles affected by wooden breast exhibit reduced muscle fiber number, loss of the typical polygonal shape, abnormally rounded fibers with internalized nuclei, disrupted cross-striations, vacuolar degeneration and fiber necrosis, accompanied by fibrotic responses, such as proliferation and thickening of the endomysium and perimysium, as well as variable amounts of loose connective and granulation tissue. Additionally, Trocino et al. (2015) reported that a pathognomonic feature of wooden breast myopathy is the marked accumulation of fibrotic tissue in the endomysium and perimysium, resulting in firmer muscle consistency that requires greater compressive force to detect this anomaly by gross examination (Che et al., 2022). However, white striping can be distinguished by pronounced adipocyte accumulation, which can be associated with a substantial increase in fat content and a reduction in protein content due to muscle fiber degeneration (Kuttapan et al., 2012). The same authors further suggested that the reduction in protein content creates space for adipocyte deposition, which appears macroscopically as white striations on the muscle surface. Furthermore, histological analysis in this study confirmed that spaghetti meat is characterized by pronounced thinning of connective tissue in the endomysium and perimysium, which facilitated the separation of muscle fibers and compromises the structural integrity of the *musculus pectoralis major*, giving the muscle its characteristic "spaghetti-like" appearance (Baldi et al., 2018). Histological analysis in this study revealed that alterations in broiler breast muscles affected by deep pectoral myopathy (green muscle disease) are characterized by inflammation, edema, hyperemia, hemorrhage, fiber necrosis and replacement of muscle tissue by newly formed connective and adipose tissue. These findings can be ascribed to the impaired blood and oxygen supply, coupled with insufficient nutrient delivery to the affected area (Stancu et al., 2015). Increased physical activity such as wing flapping, excessive body weight and diverse stressors have been proposed as the main predisposing factors for the development of deep pectoral myopathy (Ozmen, 2017; Pajohi-alamoti et al., 2016).

In this study, the greatest breast muscle weight was recorded in unaffected broilers. The reduced breast muscle weight in affected birds can be explained by atrophy, fibrosis and necrosis of muscle tissue, with replacement by adipose and connective tissue, ultimately lowering meat yield in the most valuable part of the carcass (Mazzoni et al., 2015; Bošković Cabrol et al., 2023). These changes were most pronounced in green muscle disease, where, in addition to reduced weight, both width and length of the breast muscles were significantly reduced, highlighting its severe impact on breast muscle yield.

Analysis of meat quality characteristics revealed that meat from unaffected broilers exhibited optimal pH (5.9–6.2; Ristić and Damme, 2010) water-holding capacity (4–6%; Carvalho et al., 2017) and color (46 < L^*value < 53, Zhang and Barbut, 2005), which resulted in the highest frequency of RFN (normal) meat. These findings suggest that when broilers are in good health, free from myopathies, and not exposed to high stress, their physiological regulatory systems remain intact, and they are able to maintain homeostasis and normal metabolism (Kovačević et al., 2025). Under these conditions, post-mortem energy is allocated to regular metabolic processes in skeletal muscles, thereby supporting the production of high-quality meat (Kovačević et al., 2025). Conversely, changes in muscle morphology have been associated with alterations in meat quality characteristics (Soglia et al., 2016; Rajčić et al., 2024). In the present study, meat from broilers affected by wooden breast and white striping showed significantly higher ultimate pH, reduced cooking and thawing loss, darker color (lower L^* values) and a higher frequency of DFD meat. These results can be explained by the impact of degenerative muscle changes on carbohydrate metabolism, leading to reduced glycogenolysis, gluconeogenesis, tricarboxylic acid cycle activity, glycogen breakdown and pyruvate fermentation to lactate (Bošković Carbol et al., 2023). This reduction in glycolytic potential accounts for the elevated ultimate pH in affected meat

(Bošković Carbol et al., 2023). As a result of higher meat pH, protein denaturation is limited, preventing myoglobin loss via drip loss, and thereby contributing to a DFD meat quality defect (Font-i-Furnols et al., 2015). Compared to wooden breast and white striping, the presence of spaghetti meat myopathy was associated with increased thawing and cooking loss, which can be attributed to the compromised muscle integrity and fiber separation, which favor protein denaturation and diminished water-holding capacity (Baldi et al., 2018). Unlike broilers without myopathies and the previously mentioned myopathies, green muscle disease was characterized by the lowest cooking loss and the lightest meat color (the highest L^* and the lowest a^* values), resulting in the higher tendency towards PSE meat development. A previous study (Giampietro-Ganeco et al., 2021) has shown that green muscle disease depletes glycogen reserves in skeletal muscle, leading to higher postmortem pH and improved water-holding capacity, findings that were corroborated by the results of the present study. The higher frequency of PSE meat in broilers affected by deep pectoral myopathy (green muscle disease) can be attributed to the classification criterion applied in the present investigation, which relied on instrumentally measured L^* (lightness) values. The increased lightness and yellow hue of meat from affected broilers can be explained by the presence of multiple hemorrhages, followed by gradual degradation of hemoglobin and myoglobin in damaged muscle tissue, producing yellow-green breakdown products (Bilgili and Hess, 2008).

CONCLUSION

The obtained results indicate that macroscopic examination has the potential to be an effective tool for detecting all four types of studied myopathies, as histological analysis of breast muscle samples confirmed their presence. Morphometric trait analysis revealed that broilers affected by myopathies exhibit significantly reduced breast muscle yield compared to unaffected individuals. In addition, the frequent occurrence of myopathies, along with their characteristic macroscopic and histological alterations in breast muscles, resulted in markedly deteriorated broiler meat quality. Moreover, the presence of myodegenerative alterations negatively influenced meat quality characteristics, in terms of inadequate postmortem glycolysis (elevated pH), impaired water-holding capacity and unappealing color (either excessively pale or overly dark meat). Consequently, it can be concluded that meat from broilers affected by any of the studied myopathies does not fulfill the standards for market placement and is suitable only for processing into lower-quality meat products.

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Authors' contributions

Conceptualization and methodology, N.Č.; formal analysis, N.Č.; investigation, M.I., M.J., Dj.P., I.M., A.N., T.L.J. and N.Č.; validation, N.Č.; writing—original draft preparation, M.I., I.M. and N.Č.; writing—review and editing, M.I., I.M., N.K and N.Č.; supervision, N.Č.; project administration, N.Č and N.K.; funding acquisition, N.Č. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interest.

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HISTOLOŠKE KARAKTERISTIKE, MORFOMETRIJSKA SVOJSTVA I KVALITET MESA BROJLERA SA MIOPATIJAMA POREKLOM IZ JEDNE MALE KLANICE

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Kratak sadržaj

Drvenaste grudi, bela prugavost, špageti meso i bolest zelenih mišića su miopatije koje se javljaju na grudnoj muskulaturi brojlera usled ubrzanog rasta jedinki u toku uzgoja. Pomenute miopatije odlikuju se različitim histološkim promenam a i utiču na kvalitet mesa, pa dovode do velikih ekonomskih gubitaka. Cilj istraživanja bio je da se utvrde histološke karakteristike mesa brojlera sa miopatijama, kao i uticaj miopatija na pokazatelje kvaliteta mesa i morfometrijske osobine grudne muskluature. Prikupljeni su podaci od 80 pilećih filea, kod kojih je izvršen makroskopski pregled 24 časa nakon klanja i histološka analiza (n=46). U svim uzorcima grudne muskulature su određeni fizičkohemijski pokazatelji (pH vrednost i temperature), boja mesa, sposobnost vezivanja vode, kao i morfometrijske osobine (masa, širina, dužina i debljina). Drvenaste grudi su utvrđene kod 22,50% (n=18), bela prugavost kod 13,75% (n=11), špageti meso kod 16,25% (n=13), dok je bolest zelenih mišića utvrđena kod 10,00% (n=8) brojlera. Histološkom analizom utvrđene su degeneracija, nekroza, hipereozinofilija, gubitak poprečne prugavosti, vakuolizacija sarkoplazme, fregmentacija vlakana i prisustvo inflamatornih ćelija. Brojleri sa miopatijama imaju znatno manji prinos mesa u poređenju sa jednikama bez miopatija. Pojava miopatija negativno utiče na tehnološke karakteristike mesa brojlera, u smislu visoke pH vrednosti, lošije sposobnosti vezivanja vode (manji kalo odmrzavanja i kuvanja) i nepoželjnih promena u boji mesa. Na osnovu rezultata ovog istraživanja može se zaključiti da meso poreklom od brojlera sa miopatijama ne zadovoljava tržišne kriterijume za stavljanje u promet u svežem obliku, već se može korisititi samo za preradu u cilju dobijanja proizvoda slabijeg kvaliteta.

Ključne reči: brojleri, histološke karakteristike, kvalitet mesa, miopatije, morfometrijske osobine