Current meat quality issues for broiler chickens - Summary

Sensory attributes and nutritional composition of broiler chicken meat

Intensification of broiler production has increased the amount of chicken meat available on the market but the costs to the health and welfare of the chickens have been considerable. In standard intensive chicken production, broiler breeds are selected primarily for performance traits. In contrast, strains of broilers kept in more enriched and less restrictive rearing environments (e.g., higher welfare indoor, free range, organic) are typically selected for better welfare outcomes, such as better leg strength, increased activity and enhanced behavioural expression. The selection pressure for fast growth and high meat yield (especially breast meat) not only has detrimental consequences on birds welfare, but also affects the quality of their meat – two issues which have been shown to be increasingly important for consumers[1].

Additionally, broilers in standard production systems typically live in barren and crowded environments, with little opportunities to perform highly motivated behaviours such as perching and foraging for food. These environmental factors are also known to influence meat quality.

Most research to date looking at the impact of breed and rearing environment on the sensory and nutritional attributes of the meat cannot be directly compared, due to the large variation amongst studies in the strains used and the husbandry conditions. However, a number of studies have linked some meat quality parameters with factors related to the housing environment and the genetics used. For example, slower-growing breeds tend to have a higher percentage of abdominal fat, higher protein content and lower pH values compared to fast-growing breeds, while outdoor access improves PUFA’s composition and vitamin E content.

Breast muscle myopathies

The composition of the carcass and the amount of meat that is acceptable for consumption, has been showed to be heavily influenced by the fast metabolism of the fast-growing breeds. Selection for fast growth and high breast yield has increased the incidence of Breast Muscle Myopathies (BMMs), raising both welfare and economic concerns.

The most frequent BMMs affect the two main muscles that form the breast. The issues affecting the Pectoralis major (white striping, wooden breast, and spaghetti meat) and Pectoralis minor (deep pectoral myopathy, pale-soft-exudative meat and gaping of P. minor) muscles are more likely to develop in birds where the muscle attempts to cope with the continuously high growth demands. This means that these conditions are more likely to be found in heavier, fast-growing birds.

The breast meat affected by these BMMs can be unsuitable for sale as whole fillets and can also be unfit for further processing due to high levels of connective tissue, hardened muscle, and/or easily fragmented muscle fibres. Research has also shown that white striping changes the nutritional composition of meat, resulting in higher levels of fat and less protein. This altered nutritional profile may not appeal to traditional consumer expectations of chicken meat as a healthy and lean protein source, often resulting in economic losses and food waste. The breast muscle myopathies not only lead to a decline in meat quality, but research indicates that these conditions also lead to poor animal health and welfare, appearing as chronic underlying tissue inflammation early in the chickens' lives, and inhibiting their normal movements, by interfering with wing flapping and walking ability.

TAKE HOME MESSAGES

- Chicken meat quality is influenced by the breed, the diet, the husbandry techniques, and the stocking density:
    - Slower-growing breeds tend to have higher polyunsaturated fatty acid (PUFA) content in the meat than fast-growing breeds.
    - Slower-growing breeds tend to have a higher percentage of abdominal fat, a higher protein content and lower pH values.
    - Outdoor access improves PUFA's composition.
    - Free range access increases vitamin E content.
    - Lower stocking density decreases intramuscular fat content, lowers cooking and drip loss, and increases carcass and breast yields.
- Fast-growing breeds with larger breast yields are more prone to suffer from BMMs than slower-growing breeds.
- BMMs are associated with welfare issues such as:
    - Chronic muscle inflammation.
    - Increased incidence of mortality.
    - Increased incidence of pulmonary disease.
    - Muscle hypercontraction leading to impaired wing movement.
    - Poorer walking abilities.

Current meat quality issues for broiler chickens – Scientific review

Introduction

Meat quality is a term used to describe the general characteristics of meat, including its physical, chemical, morphological, biochemical, microbial, sensory, technological, hygienic, nutritional and culinary properties[2]. Broiler farming is the fastest-growing animal production sector and broiler meat is the second most-consumed meat in the world[3]. There are numerous factors that can affect the quality properties of chicken meat. Genetics, age, sex, type of muscle, structure of muscle fiber, production system, feeding, feed and water withdrawal, transport, slaughter process and postmortem aging time are responsible of most of the differences in the physical, sensorial and nutritional quality of the meat[4]. Most of these factors, such as age, sex or genetics are associated with specific husbandry methods.

This information sheet provides an overview of the current literature covering meat quality topics in modern broiler chicken production. The first section covers the impact of factors such as breed (i.e., selection primarily for performance traits vs strains bred for higher welfare outcomes) or rearing environment on the sensory attributes, nutritional composition, and consumer acceptance of broiler meat. The second section describes the different myopathies that affect the breast meat of broiler chickens, their distinct impacts on meat quality, and their growing prevalence in commercial broilers given the heavy selection for fast growth, high breast meat yields and heavy body weights in these breeds. The final section highlights the links between these breast muscle myopathies (BMM) and the health and welfare of the affected broiler chickens.

I. Husbandry factors affecting the sensory attributes and nutritional composition of broiler chicken meat

1. Genetics

The most common breeds of commercial broiler chickens have been selected mainly for performance (i.e., fast growth, low feed conversion ratio (FCR), high white breast meat yield, and heavy slaughter weights). However, this selection has had negative consequences on the health and welfare of the birds. In contrast, other, slower growing, strains have been selected for higher welfare outcomes including better leg health, lower mortality, better immune function, increased activity, and improved natural behavioural expression.

Some meat properties seem to have a genetic component (e.g., the fillets of chicken carrying a certain allele (GG) have a yellower tone[5]). However, direct comparison of the meat quality of today's commercial strains of broilers bred for fast grow with those bred for higher welfare outcomes is often confounded by many other factors related to their rearing environment. Whereas fast-growing breeds are most commonly used in standard industry production, where they are housed in large indoor barren sheds with artificial light and high stocking densities, slower growing breeds are more commonly used in higher welfare indoors, free-range or organic systems, where they typically benefit from greater space allowances, enrichment and outdoor access in the free-range and organic systems.

Slow-growing breeds are usually slaughtered at a later age than fast-growing breeds, as they take longer to reach market weight. This can be a confounding factor when looking at the effect of breed on meat quality, as the age of the birds is also a factor that will influence some of the meat quality parameters. For example, younger slaughter ages are associated with a decrease in meat flavor and an increase of the tenderness and the juiciness[4]. Additionally, the content of haem pigments in the muscle increases with age, and the meat becomes redder and darker [5]. Protein, lipids, and fatty acids content is also mainly influenced by the slaughter age[5].

Most studies to date have jointly evaluated the impact of breed and rearing environment on broiler meat quality, and the considerable variation in the strain genotypes, housing, and management of chickens has led to inconsistent findings and made direct comparisons of those research findings quite difficult. Additionally, the results analysing the organoleptic and nutritional characteristics of meat from slow-growing breeds vary depending on the chosen breed, as most of the studies establishing these comparisons used different breeds with different characteristics and grow rates[3].

Examples of studies that have compared fast with slower-growing breeds by rearing both genotypes under identical environmental conditions can be found below:

The first study by Doğan and colleagues[6] compared the physical meat characteristics and carcass composition of 200 fast-growing Ross-308 (AGR= 52.6 gr/day) and 200 slow-growing local T2-Y2 broilers (AGR= 27.8 gr/day) when both breeds were at the same market weight (2 kg). Overall, broilers from the slower-growing T2-Y2 genotype had a higher leg yield, more abdominal fat, brighter and redder breast meat, and had lower pH values in both their breast and leg meat. No differences were detected in leg and breast meat cooking loss between the two genotypes, but the T2-Y2 chickens had a poorer water holding capacity in the leg meat than the Ross 308 broilers, which is linked to the lower pH in this tissue in the slow-growing genotype.

A more recent study comparing the breast meat quality of 20 fast-growing Ross 308 (FG), 20 slower-growing JA 757 and 20 slow-growing dual purpose breed ISA Dual (SG) (both breeds including males and females, slaughtered at 2kg live weight), reported that both slower-growing breeds had higher abdominal fat, higher dry matter and protein content and a lower shear force value and lower intramuscular fat. The JA757 had the lowest water holding capacities after freezing and the ISA Dual the highest. Ross 308 carcasses had higher lightness and yellowness values compared with the other two[7].

Similarly, Devatkal and colleagues [8] evaluated differences in the meat quality, composition, and consumer preferences between a slow-growing Indbro strain (AGR= 40 gr/day) and common commercial broiler breed (Vencobb, AGR= 55.6 gr/day) at 2.0kg final weights. The breast meat yield and meat-to-bone ratio were higher in the commercial broiler line, but the cooking yield of drumstick and breast meat did not differ significantly between the two genotypes. Although the breast meat pH was not measured in this study, the thigh meat from the Indbro breed had a higher pH, shear force value, and protein content than the commercial Vencobb birds. However, the water holding capacity was lower in the Indbro than Vencobb broiler thigh and drumstick meat. The Indbro breast meat also had significantly lower saturated fatty acid contents. Furthermore, a significant percentage of consumers preferred the meat and meat products prepared from slow-growing Indbro broiler meat.

An earlier study by Sirri and colleagues[6] compared the nutritional attributes of meat from a slow-growing egg laying breed (Brown Classic Lohmann, ADG= 18.8 gr/day), a broiler breed that they identified as intermediate growth (Naked neck Kabir, ADG=32.6 gr/day) and a fast-growing breed (Cobb 700, ADG= 64.2 gr/day). Results indicated that meat from the egg laying breed (Brown Classic Lohmann) appeared to have "healthier" nutritional attributes (i.e., lower content of lipids in meat but higher proportions of polyunsaturated fatty acids). Those attributes have been reported to align more with consumer expectations for organic products than broiler breeds with intermediate (Naked neck Kabir) or fast growth rates (Cobb 700), even when all breeds were reared organically with pasture access.

Although the experimental designs are different, some of the common findings of these studies are a higher percentage of abdominal fat, a higher protein content and lower pH values in slow growing breeds. Despite of the difficulties to extract clear conclusions, the FAO described in its report "*Contribution of terrestrial animal source food to healthy diets for improved nutrition and health outcomes*" (FAO, 2023) some of the effects of genetic selection on the nutritional values of broiler meat, which we have summarized in Annex 1.

2. Environment

Most of the studies published to date have examined the effects of outdoor access on chicken meat quality. Additionally, some of them have studied a potential effect of perches but no other environmental enrichment devices[3].

2.1. Outdoor access

A 2023 meta-analysis[3] reported that outdoor access had no effect on the meat pH in most of the studies. Additionally, it reports inconsistent results when looking at moisture, proteins, fat and lipids content. However, most authors reported either no effect or a positive effect of outdoor access on the protein content and an overall positive effect on the lipid composition. Most authors also reported an increased water holding capacity and reduced cooking loss in chickens with outdoor access.

A study examining the impact of the rearing environment alone[9] found that outdoor access negatively affected slaughter weight, but positively affected the meat quality, taste, and composition of slow-growing Sasso T451 72-day old chickens compared to chickens from the same breed housed solely indoors.

Regarding the organoleptic qualities, and specifically the colour of the meat, there are contradicting results involving outdoor access on meat lightness (L*) and yellowness (b*) while no effect has been reported on meat redness (a*). No differences or a positive effect of the outdoor access have been reported regarding taste, odour and texture[3].

Many studies have evaluated the combined impact of both bird genotype and type of production system on broiler meat quality[10,11]. For instance, a large-scale analysis of 28 experiments included a comparison of the effects of pasture access on the meat quality of 16 fast, two medium, and 14 slow-growing breeds[12]. They found that providing access to pasture was associated with a reduction in the fat concentration in breast, thigh and drumstick meat, and a tendency towards increased protein concentration in these cuts. However, the same study also reported that broiler genotype (i.e., slow, medium or fast growth rate) was, within this meta-analysis, unsuitable as a variable for comparing carcass yields and meat quality due to the widely variable conditions in the studies (i.e., different categorisation of different growth rates, different diets, housing systems, etc.).

2.2. Use of perches

None of the studies included in the 2023 meta-analysis[3] reported an effect of the perches on pH, moisture, or lipids content. Regarding the physical properties of the meat, no effect of perches' provision has been found on water holding capacity, cooking loss or drip loss. Two studies reported a reduction on the L* colour when perches or cooled perches were provided[13].

3. Stocking density

Lower stocking densities are normally associated with better meat quality[3]. The cooking and drip loss of fast-growing Arbor Acres have been reported to be lower for lower (8 birds/m^2) or medium (14 birds/m^2) stocking densities, compared with higher ones (18 birds/m^2) [14]. Lower water holding capacities (WHC) were described in Cobb chickens at lower stocking densities (9 birds/m^2), kept constant during the last 2 weeks of life of the chickens, compared with higher ones (18 birds/m^2) [15]. The same study also reported a higher L* of the meat colour at lower densities compared with higher ones. Wu and colleagues[14] found a similar effect in at 14 birds/m^2, compared with 18 birds/m^2.

Better meat tenderness and juiciness were also associated with lower stocking densities. This is negatively correlated with intramuscular fat, which was lower for birds reared at a lower stocking density[16].

There is conflicting evidence in the scientific literature regarding the relationship between carcass and breast muscle yields and stocking densities. However, the majority of the papers have reported higher yields at stocking densities ranging from 10-15 birds/m^2 compared with 16-20 birds/m^2 [3].

I. Breast muscle myopathies

Over the last 50 years, the time for broilers to reach slaughter weight has reduced by approximately 50%, with a final weight of the modern broiler being approximately 2kg at 40 days of age or less[17]. The body weight of a modern fast-growing broiler (Ross 308) at 42 days of age is more than 4 times higher than one of the most commonly raised breeds in the 1950's[18].

However, achieving this rapid increase in final body weight and muscle yield in such a short amount of time has not been without consequences to the health, welfare and the composition of the carcass of commercial broilers[19]. Fast-growing breeds have shown higher rates of post-mortem rejections due to different issues affecting the carcass such as ascites, discolouration, cellulitis andperihepatitis[20,21]. In a recent commercial study comparing the carcass condemnation of Ross 308 (FG) and JA787 (SG), results showed that the prevalence of ascites and discoloration was 6.5 and 2 times higher, respectively, in Ross 308 birds compared to the JA787 (Figure 1)[22].

	Hubbard	IQR		Ross	IQR	
Condemnation cause	Median (%)	Q1 (%)	Q3 (%)	Median (%)	Q1 (%)	Q3 (%)
Ascites	0.08	0.05	0.12	0.54	0.34	0.85
Fractures	0.03	0.01	0.05	<0.00	0.00	0.01
Peritonitis	0.03	0.01	0.06	0.12	0.07	0.21
Cardiac disease	<0.00	0.00	0.00	<0.00	0.00	0.00
Skin lesions	0.06	0.03	0.13	0.17	0.09	0.32
Arthritis	0.01	0.00	0.01	0.01	0.00	0.02
Lesions/bleeding	<0.00	0.00	0.00	<0.00	0.00	0.01
Hepatitis	0.04	0.02	0.09	0.16	0.08	0.33
Discolouration	0.12	0.07	0.19	0.21	0.11	0.40
Small	0.09	0.05	0.16	0.32	0.18	0.54
Tumours	<0.00	0.00	0.01	<0.00	0.00	0.00
Other rejects	<0.00	0.00	0.00	<0.00	0.00	0.00
Total rejects	0.56	0.42	0.77	1.96	1.48	2.67

Figure 1*: Relative frequency of condemnation causes within-slaughter batch recorded at the abattoir for Hubbard JA787 and Ross 308 (n = 2436 and 1859 slaughter batches respectively)*

The most frequents issue affecting the integrity of the carcass in broilers remains the range of inflammatory conditions affecting the breast muscles, known as Breast Muscle Myopathies (BMM). Fast growth and selection for higher muscle yield are believed to play a central role in the recent increase in these BMMs in modern broilers, affecting mainly the breast muscles Pectoralis major and Pectoralis minor. Selection pressure for fast growth and high breast yield have altered the birds' metabolism and muscular structure, leading to longer muscle fibres with larger diameters (3-5 times larger), higher density of hypercontracted muscle fibres, and fewer blood vessels (capillaries). This has resulted in a reduced ability to provide nutrients and remove metabolites and waste products from the muscle tissue[23].

Breast muscle myopathies (BMMs) are more likely to develop in birds where the muscle attempts to cope with the continuously high growth demands. Although BMMs present distinct phenotypic changes in the appearance and structure of the muscle, they are all the result of disruption or malfunction in the structure, metabolism, or repair mechanisms of the breast muscle tissue [24]. The most common BMMs reported in commercial broilers are summarised in the annexes 2 and 3.

BMMs, as they result in lower carcass yield, downgrading and even carcass condemnation, have a significant economic impact. If the BMM is severe and accompanied by inflammatory signs (e.g., petechial/pin-point hemorrhaging, gelatinous fluid), the regulatory authorities may require the entire carcass to be discarded (Europe) or trimming of the affected areas[25]. In 2020 it was estimated that white striping resulted in a loss of approximately 1 billion USD in North America, due to decreased breast meat yields (e.g., as a result of trimming, drip loss, cook loss) and/or lost value from downgraded or discarded meat [24].

1. White striping

White striping (WS) is characterised by the infiltration of white striations of fat and connective tissue parallel to the muscle fibre on the skin-side of breast fillets and is less commonly found in the thigh muscles. The white lines may vary in quantity and thickness amongst affected birds and affect most frequently the cranial area of the muscle. They rarely extend to the caudal area. WS can be scored for severity, based on the frequency and thickness of the white lines[26] (Figure 2).

- *Risk factors*

Although it has been suggested that WS is only moderately heritable ($h^2 \leq 0.338$)[27], a more recent study[28] showed that WS had a strong genetic basis in two broiler strains, divergently selected for breast meat pH. In this study, the increased incidence and severity of WS was also shown to be highly correlated with higher body weights, breast meat yields, and the amount of intramuscular fat in the Pectoralis major. Incidence and severity of WS have been shown to be higher in breeds with higher breast meat yields[29–31]. For example, in a study comparing purebred broiler lines with moderate vs. high breast yield, 49% of high yield broilers had some degree of WS, whereas only 14% of moderate yield birds were affected[27].

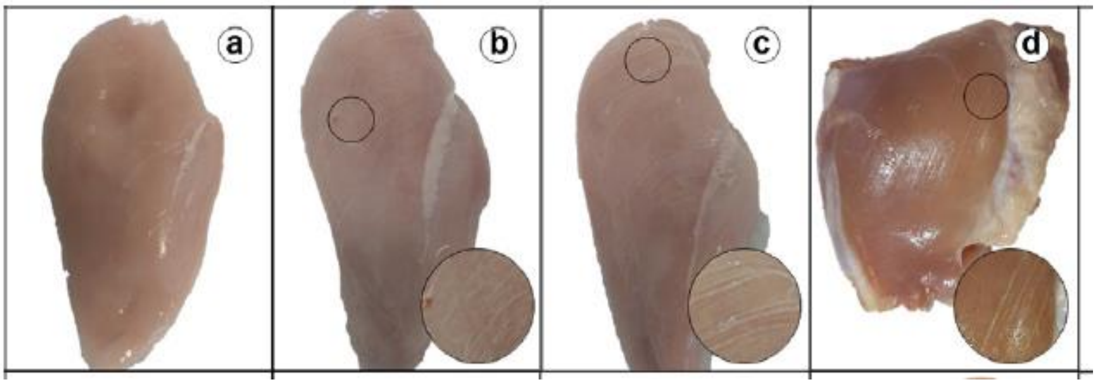


Figure 2. *(a) A normal chicken breast with no myopathies, (b) a breast with moderate white striping (striations < 1mm extensively covering the muscle surface), (c) a breast with severe white striping (striations > 1mm extensively covering the muscle surface), and (d) a thigh muscle with moderate white striping (Taken from Petracci et al., 2019*

- *Occurrence*

White striping has been present since the 1990's but reports of WS in broiler meat is increasing and it is currently the most prevalently breast meat myopathy[25]. WS is reported to affect up to 50% of chicken breasts in Italy, Spain, France and Brazil[23], while an assessment by Kuttappan and colleagues found 98% of breasts from nine-week-old broilers in the US showed some degree of WS[26].

- *Organoleptic and nutritional consequences*

Due to its visual appearance, WS breast can be considered undesirable by the consumers. For example, intention of buying raw WS meat has been shown to be lower compared to non-affected parts[18]. The participants in this study identified the white stripes as uncommon for a chicken breast even before being informed about the cause. Additionally, consumers' acceptance decreased with the severity of the lesions[32]. The flavor precursors of the umami taste in meat have been found to decrease significantly in chicken breasts affected by WS[33].

Meat with WS has higher fat and lower protein content in addition to a higher overall pH. The higher levels of collagen in WS meat may make it less digestible, and it may be deficient in certain amino acids[34–36].

2. Wooden (Woody) breast

Wooden (or woody) breast (WB) is characterised by hard, bulging, pale breast meat, which starts focally as a mild lesion (often on the cranial portion of the muscle) and then diffuses to the entire muscle as the birds age and grow (Figure 3). Visually, WB can also be characterized by petechial haemorrhaging and a gelatinous liquid on the skin-side surface of the muscle, but these features are not present in all WB cases (Aviagen, 2019). Although WB mostly affects the P. major muscle, these hardened areas can also appear in the P. minor[23].

***Figure 3**. Image of a breast muscle without (left) or with severe WB (right) (Taken from Aviagen, 2019)*

Biopsy samples taken from two-week-old Cobb 500 broilers showed that chickens that went on to develop WB showed dysregulation of genes, which is linked to the development of metabolic disorders in humans, such as diabetes. Although more research is needed, these preliminary findings suggests that WB is first and foremost a metabolic disorder characterized primarily by the abnormal accumulation of fat in the P. major[37].

- *Risk factors*

Like WS, selection for larger body weights and breast meat yields appears to be particularly correlated to the incidence of WB in modern broiler strains. Broilers with faster weight gain from the outset (1-2 weeks of age) are more likely to develop WB as they approached marketable weight[38,39]. Accordingly, Mailia and colleagues[40] found that increasing breast weight by one percent increased the likelihood of a severe WS and WB score in the breast muscle of Ross 208 (FG) by 50.9% and 61.0%. Additionally, delaying the slaughter age from 6 to 7 weeks was linked to a 56.3% higher risk of a more severe WS score.

It has been suggested that significant flock-level reductions in WB might be best achieved by identifying environmental and management factors (e.g., incubation temperatures) contributing to its occurrence given the low heritability reported for WB in their study[27]. However, research also suggests that management practices such as limiting feed intake or dietary nutrient availability in early life, leads to a similar[41] or an increased incidence/severity[42] of myopathies in broiler flocks at slaughter.

- *Occurrence*

The incidence of WB is not exactly known but some studies have reported figures as high as 38% of broilers in the most used commercial breeds[43], 53.2% of high-breast-yielding chickens at a commercial broiler processing plant in Italy[39] or 61.9% of breast fillets in a Chinese processing plant[44].

- *Organoleptic and nutritional consequences*

Wooden breast affected meat is harder and crunchy to chew. Additionally, it presents reduced water holding capacity, reduced marinade uptake and higher drip loss and cooking loss[25].

Nutritionally, WB meat contains lower protein levels and is deficient in some essential amino acid while presenting an abnormal mineral profile[25].

3. Spaghetti meat

Spaghetti meat (SM), also known as stringy-spongy or mushy breast, is characterized by the loss of structural connective tissue in the P. major. This results in the loosening and separation of the muscle fibres with the individual muscle fibres resembling the cylindrical, long, thin appearance of spaghetti[23,25] (Figure 4).

- *Risk factors*

In comparison to the other breast muscle myopathies, reports of SM in broilers are more recent, so research is ongoing into the casual factors resulting in its development.

One hypothesis suggests that selection for faster growing chickens has contributed to the increasing appearance of SM[45]. Broilers continue to be slaughtered at increasingly younger ages and therefore are less developmentally mature at processing. For instance, Baldi and colleagues[46] showed that SM-affected breast meat had less superficial collagen cross-linking than normal fillets, meaning the tissue lacks a suitable connective tissue framework, resulting in the muscle fibres being easily pulled apart.

Figure 4. *Breast muscle fillet exhibiting a severe case of the spaghetti meat myopathy as shown by extensive superficial lacerations. (Taken from Baldi et al., 2021).*

In the Aviagen guide on BMMs, it is also hypothesized that the accumulation of lactic acid in the muscle tissue after death is linked to the development of SM[25]. The acidic conditions produced by the lactic acid accumulation is thought to cause several damaging effects to the structural integrity of the connective tissue, which ultimately results in the separation of the muscle fibre bundles. However, research has showed that breast meat exhibiting SM had higher pH levels than unaffected fillets, which suggests that SM affected tissue is more basic (i.e. less acidic) than normal breast meat[45,46].

The feeding of plant-based diets to broiler chickens with insufficient concentrations of amino acids (e.g., proline), necessary for proper connective tissue growth, has also been implicated in the increased incidence of SM[25].

- *Occurrence*

The incidence of SM is unclear due to different classification criteria being used between abattoirs and due to the comorbidity between SM and other more studied myopathies, but it can reach up to 20%[45]. A Italian study analysed 16,000 chicken breast and reported a prevalence of 21%[47], while a Brazilian study found that approximately 10% of the 5,580 breasts examined were affected by SM[48].

- *Organoleptic and nutritional consequences*

SM affected meat can be difficult to slice and have a softer texture after cooking[25,46]. At processing, breast meat with SM cannot be used for products requiring normal structural integrity. Muscles severely affected are normally downgraded and incorporated into the formulation of further processed products. However, the increasing consumer demand for thinly sliced chicken breast has made the emergence of SM a particular challenge for the processing industry, since SM is often only detected after the slicing process[45].

Regarding nutrient composition, SM meat has a higher moisture and lower protein levels (10% less) throughout the breast tissue (superficially and deep) when compared to unaffected muscles[45]. The occurrence of SM is also associated with higher meat yellowness values and greater drip and cooking losses in SM samples compared to normal ones[45].

4. Co-occurrence of spaghetti meat, white striping and wooden breast

The occurrence of abnormalities affecting the Pectoralis major muscle has been observed and studied for more than 10 years. The underlying histological changes of these conditions are non-specific, and often overlap[49]. For example, despite their different phenotypic manifestations, White Striping (WS), Wooden Breast (WB) and Spaghetti Meat (SM) have been hypothesized to have common histological features[50] (Figure 5). Consequently, these pathologies often occur together[34,50].

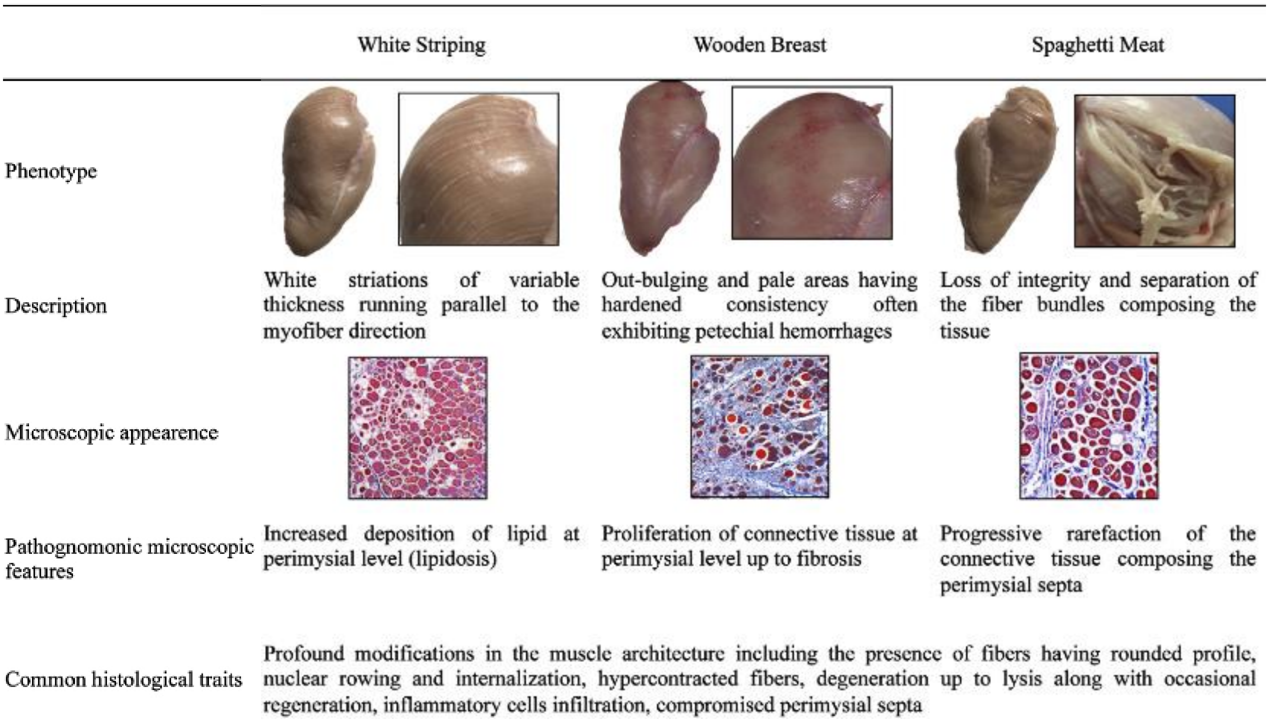


***Figure 5**: Phenotype and microscopic features of the Pectoralis major muscles affected by White Striping, Wooden Breast and Spaghetti Meat (From Soglia et al., 2021)*

Co-occurrence of WS, WB, and SM was investigated in a 2022 study[49] that included 179 chicken breast fillets belonging to mixed-sex Ross 708, mixed sex Cobb 500 and male Ross 708. In this study, SM, WB, and WS showed similar histological characteristics (i.e myodegeneration, inflammation, interstitial accumulation of fat, and fibrous tissue) and overlapping severity. Regeneration process occurring in WS and WB-affected tissues does not produce new muscle fibres, but instead deposits fat and connective tissue within the breast muscle[25]. All muscle tissues show a degree of degeneration and regeneration. However, in the case of WS and WB, sustaining continuously high growth puts a large demand on the resources needed to maintain health muscle metabolism. This ultimately results in the breakdown of the tissues and haemorrhaging.

- *Risk factors*

Several recent studies have reported that high-breast-yielding strains are more likely to be associated with higher WB and WS scores[51,52]. The percentage of chickens displaying muscle fibre degeneration (characteristic of both WS and WB) in their P. major muscles also increases as birds age[41] (Figure 2). These BMMs are more likely to develop (or develop more severely) as the muscle attempts to cope with the continuously high growth demands, which means broilers grown to older ages and with heavier breasts are more affected by WB and WS[26,41,52].

Research has shown that the incidence of WS[29] and WB[30] is higher in male vs. female broilers. However, the increased prevalence is possibly confounded by males typically reaching higher final body weights[30]. In contrast, a different study has found a similar incidence of muscle fibre degeneration in both male and female broiler breast tissue sampled from 14 to 46 days of age[41].

- *Occurrence*

Since WS and WB have been studied for a long period of time, there is abundant evidence of concomitance of the two abnormalities. For example, a study showed that from the 2600 individual chicken breasts inspected at an American slaughter facility, 94.2% of the breast muscles affected with WB were also affected with WS[53].

- *Organoleptic and nutritional consequences*

Along with the higher shear force for WB affected breast fillets, which indicates a reduced tenderness, breasts with severe WB and WS myopathies are affected by inflammatory processes which lead to fluid accumulation (edema), explaining their increased water content compared with normal breasts[19,54] but a lower water holding capacity (and a higher drip/moisture loss during cooking). Additionally, a higher pH reduces the usefulness of the muscle for further processing [26,30,34,35,47]. A summary of the main combined effects of WS and WB on meat quality can be found in figure 6.

Category*	pH (at 24 h)	Drip loss (%)	PHEM scores	b* values	Fillet yield (%)	Fillet height (mm)	
						Cranial	Caudal
6 wk							
NORM (n = 28)	$5.89^{b} \pm 0.03$	$0.49^{b} \pm 0.19$	$0.07^{c} \pm 0.00$	$2.2^{b} \pm 0.3$	$21.4^{c} \pm 0.3$	$34.4^{b} \pm 0.8$	$20.0^{c} \pm 0.8$
SEV-WS (n = 48)	$5.96^{a,b} \pm 0.02$	$0.92^{b} \pm 0.15$	$0.83^{b} \pm 0.08$	$3.8^{a} \pm 0.2$	$24.4^{b} \pm 0.3$	$43.5^{a} \pm 0.6$	$30.0^{b} \pm 0.6$
SEV-WB (n = 24)	$6.04^{a} \pm 0.03$	$2.14^{a} \pm 0.19$	$1.00^{a,b} \pm 0.12$	$3.7^{a} \pm 0.3$	$25.7^{a} \pm 0.4$	$43.9^{a} \pm 0.8$	$30.9^{a,b} \pm 0.8$
SEV-WS/WB (n = 39)	$6.02^{a} \pm 0.02$	$1.70^{a} \pm 0.15$	$1.21^{a} \pm 0.09$	$4.4^{a} \pm 0.2$	$25.1^{a,b} \pm 0.3$	$44.6^{a} \pm 0.6$	$32.5^{a} \pm 0.6$
9 wk							
NORM (n = 40)	$5.93^{b} + 0.02$	$0.51^{b} + 0.15$	$0.03^{c} + 0.07$	$3.4^{c} \pm 0.3$	$23.8^{b} \pm 0.3$	$44.8^{b} \pm 0.7$	$27.1^{b} \pm 0.7$
SEV-WS (n = 16)	$5.94^{b} + 0.04$	$0.45^{b} + 0.24$	$0.31^{b} + 0.12$	$4.7^{b} \pm 0.4$	$24.9^{a,b} \pm 0.4$	$47.1^{a,b} \pm 1.1$	$28.6^{b} \pm 1.1$
SEV-WB (n = 12)	$6.15^{a} + 0.04$	$2.06^{a} + 0.27$	$1.00^{a} + 0.14$	$5.0^{a,b} \pm 0.5$	$25.5^{a} \pm 0.5$	$48.7^{a,b} \pm 1.3$	$33.3^{a} \pm 1.3$
SEV-WS/WB (n = 31)	$6.12^{a} + 0.03$	$1.31^{a} + 0.17$	$1.32^{a} + 0.08$	$6.1^{a} \pm 0.3$	$26.0^{a} \pm 0.3$	$50.1^{a} \pm 0.8$	$36.5^{a} \pm 0.8$

[a–c]Different superscripts indicate significant ($P < 0.05$) difference within each column.
*NORM: no or mild WS (0/1) and WB (0/1); SEV-WS: severe or very severe WS (2/3) and normal or mild WB (0/1); SEV-WB: moderate or severe WB (2/3) and normal/mild WB (0/1); SEV-WS/WB: moderate or severe WS (2/3) and WB (2/3).

Figure 6. *Effect of WS and/or WB on various carcass and meat quality parameters in six- and nine-week-old broilers from a high breast meat yielding strain (Taken from Kuttappan et al, 2017).*

A 2019 study reported that WB, WS, and WS/WB-affected breast fillets had more fat and collagen contents, coupled with reduced protein and total heme pigments levels[36]. Additionally, in an evaluation of 96 single breast samples from male Ross 308 broilers, Baldi and colleagues[34] found that SM, WS, and both WS/SM affected meat had significantly lower protein and ash contents, but higher moisture levels. However, the fat content of the breast tissue was only impacted in muscles affected by both the SM and WS myopathies.

II. BMMs affecting Pectoralis minor

1. Deep pectoral myopathy

Also known as "green muscle disease", Deep Pectoral Myopathy (DPM) is a degenerative disease of the breast muscle, characterised by the necrosis and atrophy of the Pectoralis minor, which adopts a green colour (Figure 7). This muscle is surrounded by an inelastic membrane (fascia) and its location (between the sternum and the P. major) limits expansion during exercise, resulting in an elevated pressure that restricts blood flow and causes ischemic necrosis[55].

Figure 7. *A chicken breast with the P. minor muscles exhibiting deep pectoral myopathy (DPM) (Taken from Aviagen, 2019)*

- *Risk factors*

DPM appears to be more frequent in high-efficiency, high muscle yield breeds[56]. Bailey and colleagues reported that the development of DPM appeared to be more influenced by environmental factors than genetics in lines of moderate and high breast meat-yielding broilers[27]. However, the incidence of DPM may continue to increase as breast meat yield continues to be a primary focus of the industry and broilers are taken to heavier market weights[57].

The onset of DPM is mainly triggered by increased bird activity that results in wing flapping – particularly after 35 days of age[57]. Under commercial rearing conditions, broilers are mostly inactive so the breast muscle and surrounding connective tissue become relatively inelastic from a lack of use. However, these birds are still prone to sudden bouts of wing flapping when startled by, for example, human activity, unexpected noise, lighting change, handling during catching, or disruption of feed and water access, which can results in DPM in the breast tissue[58,59]. Higher breast meat yields mean broilers are physiologically and structurally incapable of coping with increased muscular activity in their Pectoralis muscles (for instance, during an environmental disturbance that causes the birds to flee via wing assisted running). Wing flapping has been used to experimentally induce DPM in Ross × Cobb 500 broilers (FG), suggesting that this activity combined with their physical conformation put high-breast-yield broilers at a greater risk of damaging their tissues[57].

- *Occurrence*

DPM is not detected until the deboning stage of the processing line, where DPM can present a significant meat quality issue, as fillets affected by DPM are trimmed causing downgrading of breast meat[60]. The occurrence of DPM seems to be lower than other BMMs, with reports ranging from <1-17% of flocks[57,59].

- *Organoleptic and nutritional consequences*

Meat with later stages of DPM becomes tougher and more fibrous. The colour of the breast fillets is also affected as the meat turns green. This can have a negative economic impact as the consumer primarily evaluates the colour and the texture of the meat[60].

A higher moisture percentage and water holding capacities, lower protein and ashes percentage and higher values of lipids (as damaged fibres are replaced by adipose tissue) have been found in muscles affected by DPM compared with unaffected muscles. Additionally DPM affected meat presented an altered composition of fatty acid profile, which results in a decreased nutritional value [60]. Even though DPM affects the P. minor, it has been reported that, in animals affected by DPM, P. major may also present lower water holding capacity and degenerative changes[58].

2. Pale-soft-exudative meat:

Pale, soft and exudative (PSE) meat (Figure 8) usually has a pH value below 5.8 due to a rapid post-mortem drop in pH while the carcass temperature remains high, resulting in the denaturation of myofibrillar and sarcoplasmic proteins[61]. There are two types of PSE meat: "fast-acidifying", in which pH drops below 6 within 1 h post-mortem, and so-called 'acid meat', in which the rate of acidification is more or less normal but the final pH is lower than normal (less than 5.8).

Figure 8. *Broiler breast fillet classified as normal (left) or PSE meat by the pH and L* (colour) values measured 24 hours post-mortem (Original source: Soares, 2002; Taken from Shimokomaki et al, 2017)*

- *Risk factors*

In addition to the genetic selection for production traits, management factors also play a role in the development of PSE breast meat in broilers. Several studies have linked the occurrence of PSE meat in broilers to the thermal stress (both cold and hot temperatures) and other conditions contributing to pre-slaughter stress, including catching, placement and waiting times in transport containers, transport, and unloading[62].Therefore, minimizing stress at this end-of-life stage for commercial broilers will not only lead to better welfare, but improved meat quality[61].

The onset of PSE can also be decreased by incorporating high levels of lysine in the diet, but this may limit the use of other amino acids for energy purposes.

Fast-growing, heavier birds are prone to developing PSE meat as they have reduced thermoregulatory capacity[25]. While it is possible to select birds for high breast yield and a decreased incidence of PSE meat (by selecting for birds which produce higher ultimate meat pH), this could unintentionally result in dry, firm, and dark (DFD) meat that would have detrimental effects on microbial and sensory traits (e.g., shorter shelf life and lower water holding capacity)[25].

- *Occurrence*

Occurrence of PSE has been recorded since the 1990's. The prevalence varies considerably depending on the environmental conditions such as time of the year or conditions associated with transportation[63]. However it has been reported to vary from a 2% to a 20%[64], with one Brazilian study reporting 25%-37% of their broilers showing some degree of PSE[65].

- *Organoleptic and nutritional consequences*

PSE-type meat may be downgraded during processing due to drip loss and pale colour, and the ability of meat to hold and bind to water during processing is reduced. Consumers can differentiate PSE meat from normal meat both visually and from taste, and they prefer the visual appearance and the taste of normal meat[61].

Compared to normal meat, pale breast meat has significantly lower pH, higher colour L* value, higher drip loss, lower marinade absorption and lower cooking yield. Protein solubility in the affected samples was lower than in the normal samples, suggesting higher protein denaturation in the pale breasts[64].

Some processing strategies such as including alkaline agents (e.g., phosphates) can help overcome the low pH in PSE affected meat.

3. Gaping' of P. minor muscle

In 2019, an Italian study[66] described a new, emerging breast meat myopathy called 'gaping' in which the muscle fibre bundles of the P. minor appear visually separated (or torn) between each other at one or more points along the external ventral surface (Figure 9), with a similar appearance to the gaping defect seen in fish fillets.

- *Risk factors*

Soglia and colleagues[66] hypothesized that gaping of the P. minor could result from the selection for high breast muscle yield, which has reduced the space within the chest cavity for the P. minor muscle to develop as the P. major muscle grows larger. Additionally, because of the selection for fast growth rate, broilers continue to be slaughtered at increasingly younger ages, meaning the collagen-rich connective tissue within and surrounding the breast muscle tissue does not have enough time to mature, so the P. minor is more prone to tearing during processing.

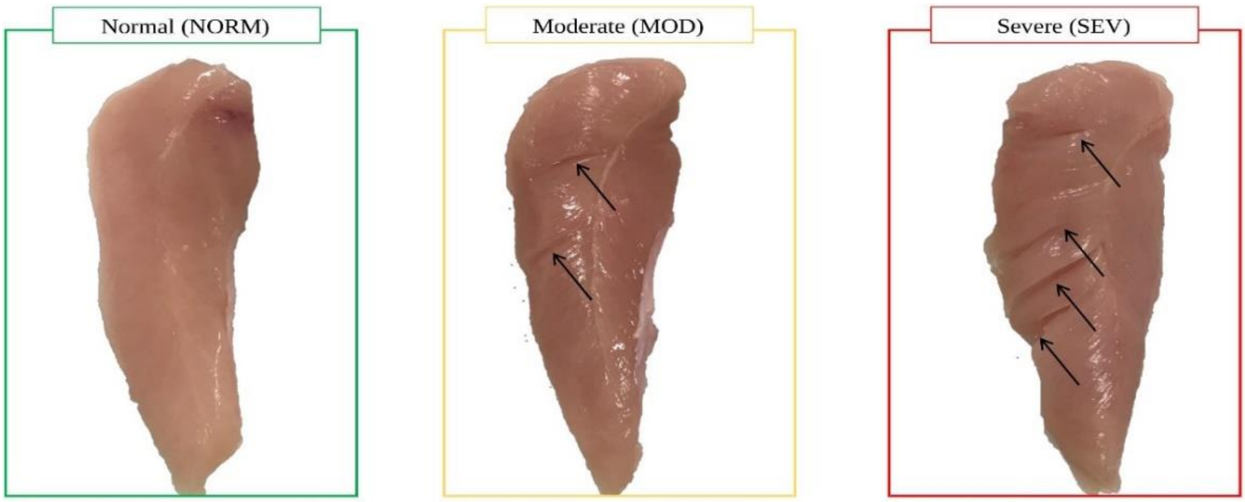


Figure 9. *Criteria adopted to classify the severity of the gaping defect of the Pectoralis minor muscles in broiler chickens (taken from Soglia et al, 2019).*

Occurrence

In their study, Soglia and colleagues randomly sampled 200 P. minor fillets from 43 commercial flocks. Gaping was detected in 16.8% of sampled P. minor muscles, but the incidence of gaping between flocks was relatively large ranging from 7.5-29.5%. The impaired appearance of P. minor affected by gaping often results in these affected muscles being downgraded from whole muscle tenders to chopped or ground processed products, resulting in an economic loss[66].

- *Organoleptic and nutritional consequences*

In terms of meat quality, a reduction in meat pH was observed as the severity of gaping increased with severely affected muscles showing a significantly lower pH than unaffected normal P. minors. The pH of moderately affected tenders was intermediate between the unaffected and severely affected P. minors[66]. Additionally, the muscles were lighter, more yellow and had a lower water holding capacity in comparison to unaffected muscles. However, no significant differences were found in the nutritional content (e.g., protein, collagen, fat, ash) in normal vs. P. minor muscles with gaping. The absence of significant variations in the nutritional composition, coupled with lower pH, suggests the underlying mechanism(s) responsible for the development of gaping in the P. minor differ from the occurrence of spaghetti meat in the P. major muscle (i.e., higher pH, lower protein, and ash content).

III. The welfare impacts of breast muscle myopathies

The breast muscle myopathies described above not only represent downgrades in meat quality, but research indicates that these conditions also result in poor health and alter the normal movement of affected broilers. However, there are only a few studies that have investigated the impact of BMMs on the welfare of broilers, and most of these have focused on wooden breast.

Wooden breast (WB) first appears as muscle fibre inflammation (myositis) and the immune cells can be detected in the muscle within the first two weeks of age. The hardening of the breast tissue starts at 4 weeks of age, meaning that affected birds experience chronic underlying inflammation weeks before WB can be detected through palpation[38].

The occurrence of WB has also been shown to be correlated with a higher incidence of mortality and pulmonary disease amongst growing broilers. A 2019 US study by Gall and colleagues investigated the mortality at 40-56 days of age from a 4000-bird flock of Ross 708 broilers. 68% of the birds that died during that period showed both severe WB and pulmonary disease (defined by the presence of lung congestion, edema, and/or pneumonia), including in 21 of the 22 dead birds found on their backs[67].

In addition, WB has also been linked to impaired wing movement and poorer walking ability[68]. Like other avian species, the breast region of broiler chickens is composed of two muscles. Together these muscles are responsible for producing the upstroke and downstroke needed to move (flap) the wings. While the P. minor is responsible for raising the wing during flight, the much larger and more powerful P. major is needed for pulling the muscle down.

In a small-scale pilot study, Kawasaki and colleagues first identified that the back-to-back wing contact test could be used to diagnose WB in affected broilers (Figure 9). In broilers with WB, limited motion range in the wings was found[68]. This is supported by Larsen and colleagues who found that broilers with WB had reduced wing mobility at 30 days[69].

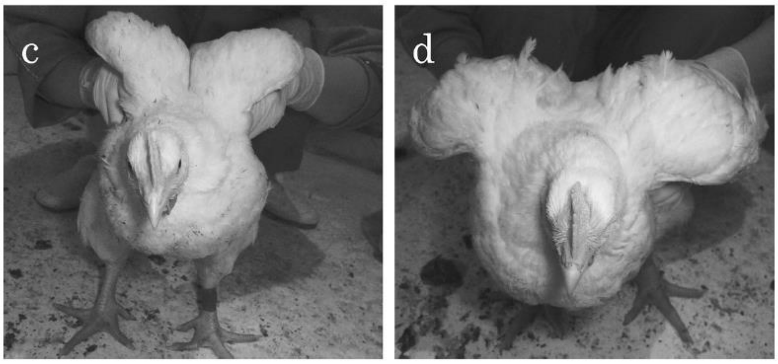


Figure 10. *Back-to-back wing contact test on 2 broiler chickens: an unaffected control bird (c) and a bird with WB (d) as detected as a firm/hard breast by physical palpation at 43 days of age. The control bird can lift its wings easily to achieve back-to-back wing contact. The affected bird is unable to lift its wings sufficiently to achieve back-to-back wing contact (Taken from Kawasaki et al., 2016).*

A 2019 study investigated the occurrence of the "dorsal recumbency" position, in which broilers fell over for an unknown reason and were unable to right themselves without assistance[67] (Figure 11). In this study, 95% of birds found dead in dorsal recumbency had both WB and pulmonary disease and were heavier than target weights. The authors hypothesized that broilers with WB are unable to right themselves when on their backs because WB causes the P. major muscle to be in a constantly hypercontracted state. This state makes it difficult for WB-affected birds to contract the P. minor muscle to elevate their wings. This association between dorsal recumbency and WB was also found in a 2022 study[70]

Figure 11. *A live broiler chicken found in dorsal recumbency (Taken from Gall et al, 2019).*

The walking ability of broilers with WB has also been shown to be significantly reduced at several points throughout the rearing[43]. In addition to having heavier weights and higher breast meat yields, WB-affected birds made fewer movements while they were lying down. The authors suggested that these behavioural differences may reflect increased breast tissue sensitivity of broilers with WB, resulting in them reducing any movements (e.g., shifting, crawling) while lying down to avoid any associated discomfort or potential pain.

While no studies to date have definitively shown that BMM are painful, severe myodegenerative lesions in humans, similar to those present in WB, are known to cause substantial pain, which suggests that the birds may be experiencing pain or discomfort in the breast area[71]. Additionally, the association between these myopathies and chronic tissue inflammation, a reduced physical capacity, and a higher incidence of mortalities demonstrates that the presence of these BMM represent a significant impairment to the overall health and welfare of affected broiler chickens.

SUMMARY OF THE WELFARE IMPACT OF THE BBMS

The presence of wooden breast has been associated with:

- Chronic muscle inflammation
- Increased incidence of mortality
- Increased incidence of pulmonary disease
- Increased incidence of dorsal recumbency syndrome
- Muscle hypercontraction leading to impaired wing movement
- Poorer walking abilities

References

1. Augère-Granier, M. L. (2019). The EU poultry meat and egg sector: Main features, challenges and prospects.

2. Ingr, I. Meat quality. Defining the term from the modern angle. Fleischwirtsch. Ger. FR (1989).

3. Marchewka, J., Sztandarski, P., Solka, M., Louton, H., Rath, K., Vogt, L., ... & Horbańczuk, J. O. (2022). Linking key husbandry factors to the intrinsic quality of broiler meat. Poultry Science, 102384.

4. Tougan, P. U., Dahouda, M., Salifou, C. F. A., Ahounou, S. G. A., Kpodekon, M. T., Mensah, G. A., ... & Karim, I. Y. (2013). Conversion of chicken muscle to meat and factors affecting chicken meat quality: a review. International Journal of Agronomy and Agricultural Research, 3(8), 1-20.

5. Baéza, E., Guillier, L., & Petracci, M. (2022). Production factors affecting poultry carcass and meat quality attributes. Animal, 16, 100331.

6. Sirri, F., Castellini, C., Bianchi, M., Petracci, M., Meluzzi, A., & Franchini, A. (2011). Effect of fast-, medium-and slow-growing strains on meat quality of chickens reared under the organic farming method. Animal, 5(2), 312-319.

7. Chodová, D., Tůmová, E., Ketta, M., & Skřivanová, V. (2021). Breast meat quality in males and females of fast-, medium-and slow-growing chickens fed diets of 2 protein levels. Poultry Science, 100(4), 100997.

8. Devatkal, S. K., Naveena, B. M., & Kotaiah, T. (2019). Quality, composition, and consumer evaluation of meat from slow-growing broilers relative to commercial broilers. Poultry science, 98(11), 6177-6186.

9. Stadig, L. M., Rodenburg, T. B., Reubens, B., Aerts, J., Duquenne, B., & Tuyttens, F. A. (2016). Effects of free-range access on production parameters and meat quality, composition and taste in slow-growing broiler chickens. Poultry Science, 95(12), 2971-2978.

10. Mikulski, D., Celej, J., Jankowski, J., Majewska, T., & Mikulska, M. (2011). Growth performance, carcass traits and meat quality of slower-growing and fast-growing chickens raised with and without outdoor access. Asian-Australasian Journal of Animal Sciences, 24(10), 1407-1416.

11. Cömert, M., Şayan, Y., Kırkpınar, F., Bayraktar, Ö. H., & Mert, S. (2016). Comparison of carcass characteristics, meat quality, and blood parameters of slow and fast grown female broiler chickens raised in organic or conventional production system. Asian-Australasian Journal of Animal Sciences, 29(7), 987.

12. Sales, J. (2014). Effects of access to pasture on performance, carcass composition, and meat quality in broilers: A meta-analysis. Poultry Science, 93(6), 1523-1533.

13. Fidan, E. D., Kaya, M., Nazligul, A., & Türkyilmaz, M. K. (2020). The effects of perch cooling on behavior, welfare criteria, performance, and litter quality of broilers reared at high temperatures with different litter thicknesses. Brazilian journal of poultry science, 22.

14. Wu, Y., Wang, Y., Wu, W., Yin, D., Sun, X., Guo, X., ... & Yuan, J. (2020). Effects of nicotinamide and sodium butyrate on meat quality and muscle ubiquitination degradation genes in broilers reared at a high stocking density. Poultry science, 99(3), 1462-1470.

15. Goo, D., Kim, J. H., Park, G. H., Delos Reyes, J. B., & Kil, D. Y. (2019). Effect of heat stress and stocking density on growth performance, breast meat quality, and intestinal barrier function in broiler chickens. Animals, 9(3), 107.

16. Skřivanová, V., Tůmová, E., Englmaierová, M., Chodová, D., & Skřivan, M. (2017). Do rearing system and free-range stocking density affect meat quality of chickens fed feed mixture with rapeseed oil?. Czech Journal of Animal Science, 62(4), 141-149.

17. Petracci, M., Mudalal, S., Soglia, F., & Cavani, C. (2015). Meat quality in fast-growing broiler chickens. World's Poultry Science Journal, 71(2), 363-374.

18. De Carvalho, L. M., Ventanas, S., Olegario, L. S., Madruga, M. S., & Estévez, M. (2020). Consumers awareness of white-striping as a chicken breast myopathy affects their purchasing decision and emotional responses. LWT, 131, 109809.

19. Kuttappan, V. A., Hargis, B. M., & Owens, C. M. (2016). White striping and woody breast myopathies in the modern poultry industry: a review. Poultry Science, 95(11), 2724-2733.

20. Rayner, A. C., Newberry, R. C., Vas, J. & Mullan, S. Slow-growing broilers are healthier and express more behavioural indicators of positive welfare. Sci. Rep. 10, 15151 (2020).

21. Baxter, M., Richmond, A., Lavery, U., & O'Connell, N. E. (2021). A comparison of fast growing broiler chickens with a slower-growing breed type reared on Higher Welfare commercial farms. PloS one, 16(11), e0259333.

22. Forseth, M., Moe, R. O., Kittelsen, K., Skjerve, E., & Toftaker, I. (2023). Comparison of carcass condemnation causes in two broiler hybrids differing in growth rates. Scientific Reports, 13(1), 4195.

23. Petracci, M., Soglia, F., Madruga, M., Carvalho, L., Ida, E., & Estévez, M. (2019). Wooden-breast, white striping, and spaghetti meat: causes, consequences and consumer perception of emerging broiler meat abnormalities. Comprehensive Reviews in Food Science and Food Safety, 18(2), 565-583.

24. Barbut, S. (2020). Understanding the woody breast syndrome and other myopathies in modern broiler chickens. In Australian Poultry Science Symposium. Sydney, Australia (pp. 99-102).

25. Aviagen (2019) Breast Muscle Myopathies (BMM). In-house publication, global. Aviagen Ltd., Newbridge UK.

26. Kuttappan, V. A., Owens, C. M., Coon, C., Hargis, B. M., & Vazquez-Anon, M. (2017). Incidence of broiler breast myopathies at 2 different ages and its impact on selected raw meat quality parameters. Poultry Science, 96(8), 3005-3009.

27. Bailey, R. A., Watson, K. A., Bilgili, S. F., & Avendano, S. (2015). The genetic basis of pectoralis major myopathies in modern broiler chicken lines. Poultry Science, 94(12), 2870-2879.

28. Alnahhas, N., Berri, C., Chabault, M., Chartrin, P., Boulay, M., Bourin, M. C., & Bihan-Duval, L. (2016). Genetic parameters of white striping in relation to body weight, carcass composition, and meat quality traits in two broiler lines divergently selected for the ultimate pH of the pectoralis major muscle. BMC genetics, 17(1), 1-9.

29. Lorenzi, M., Mudalal, S., Cavani, C., & Petracci, M. (2014). Incidence of white striping under commercial conditions in medium and heavy broiler chickens in Italy. Journal of Applied Poultry Research, 23(4), 754-758.

30. Trocino, A., Piccirillo, A., Birolo, M., Radaelli, G., Bertotto, D., Filiou, E., ... & Xiccato, G. (2015). Effect of genotype, gender and feed restriction on growth, meat quality and the occurrence of white striping and wooden breast in broiler chickens. Poultry science, 94(12), 2996-3004.

31. Dixon, L. M. Slow and steady wins the race: The behaviour and welfare of commercial faster growing broiler breeds compared to a commercial slower growing breed. PLOS ONE 15, e0231006 (2020).

32. Kuttappan, V. A., Lee, Y. S., Erf, G. F., Meullenet, J. F., McKee, S. R., & Owens, C. M. (2012). Consumer acceptance of visual appearance of broiler breast meat with varying degrees of white striping. Poultry Science, 91(5), 1240-1247.

33. Kong, F., Bai, L., He, Z., Sun, J., Tan, X., Zhao, D., ... & Liu, R. (2023). Integrated metabolomics and lipidomics evaluate the alterations of flavor precursors in chicken breast muscle with white striping symptom. Frontiers in Physiology, 13, 1079667.

34. Baldi, G., Soglia, F., Mazzoni, M. & Sirri, F. Implications of white striping and spaghetti meat abnormalities on meat quality and histological features in broilers. Animal 12, (2017)

35. Petracci, M., Mudalal, S., Babini, E., & Cavani, C. (2014). Effect of white striping on chemical composition and nutritional value of chicken breast meat. Italian Journal of Animal Science, 13(1), 3138.

36. Soglia, F., Laghi, L., Canonico, L., Cavani, C., & Petracci, M. (2016). Functional property issues in broiler breast meat related to emerging muscle abnormalities. Food Research International, 89, 1071-1076.

37. Lake, J. A., Papah, M. B., & Abasht, B. (2019). Increased expression of lipid metabolism genes in early stages of wooden breast links myopathy of broilers to metabolic syndrome in humans. Genes, 10(10), 746

38. Papah, M. B., Brannick, E. M., Schmidt, C. J. & Abasht, B. Evidence and role of phlebitis and lipid infiltration in the onset and pathogenesis of Wooden Breast. (2017).

39. Dalle Zotte, A., Tasoniero, G., Puolanne, E., Remignon, H., Cecchinato, M., Catelli, E., & Cullere, M. (2017). Effect of" wooden breast" appearance on poultry meat quality, histological traits, and lesions characterization. Czech Journal of Animal Science, 62(2), 51-57.
40. Malila, Y., Juthawut, U., Srimarut, Y., Chaiwiwattrakul, P., Uengwetwanit, T., Arayamethakorn, S., ... & Visessanguan, W. (2018). Monitoring of white striping and wooden breast cases and impacts on quality of breast meat collected from commercial broilers (Gallus gallus). Asian-Australasian Journal of Animal Sciences, 31(11), 1807.
41. Radaelli, G., Piccirillo, A., Birolo, M., Bertotto, D., Gratta, F., Ballarin, C., ... & Trocino, A. (2017). Effect of age on the occurrence of muscle fiber degeneration associated with myopathies in broiler chickens submitted to feed restriction. Poultry Science, 96(2), 309-319.
42. Meloche, K. J., Fancher, B. I., Emmerson, D. A., Bilgili, S. F., & Dozier III, W. A. (2018). Effects of reduced dietary energy and amino acid density on Pectoralis major myopathies in broiler chickens at 36 and 49 days of age. Poultry science, 97(5), 1794-1807.
43. Norring, M., Valros, A., Valaja, J., Sihvo, H. K., Immonen, K., & Puolanne, E. (2019). Wooden breast myopathy links with poorer gait in broiler chickens. Animal, 13(8), 1690-1695.
44. Xing, T., Zhao, X., Zhang, L., Li, J. L., Zhou, G. H., Xu, X. L., & Gao, F. (2020). Characteristics and incidence of broiler chicken wooden breast meat under commercial conditions in China. Poultry Science, 99(1), 620-628.
45. Baldi, G., Soglia, F., & Petracci, M. (2021). Spaghetti meat abnormality in broilers: current understanding and future research directions. Frontiers in Physiology, 12, 684497.
46. Baldi, G., Soglia, F., Laghi, L., Tappi, S., Rocculi, P., Tavaniello, S., ... & Petracci, M. (2019). Comparison of quality traits among breast meat affected by current muscle abnormalities. Food Research International, 115, 369-376
47. Baldi, G., Soglia, F., & Petracci, M. (2020). Current status of poultry meat abnormalities. Meat and Muscle Biology, 4(2).
48. Montagna, F. S., Garcia, G., Nääs, I. D. A., Lima, N. D. D. S., & Caldara, F. R. (2019). Practical assessment of spaghetti breast in diverse genetic strain broilers reared under different environments. Brazilian Journal of Poultry Science, 21.
49. Che, S., Wang, C., Iverson, M., Varga, C., Barbut, S., Bienzle, D., & Susta, L. (2022). Characteristics of broiler chicken breast myopathies (spaghetti meat, woody breast, white striping) in Ontario, Canada. Poultry science, 101(4), 101747.
50. Soglia, F., Petracci, M., Davoli, R., & Zappaterra, M. (2021). A critical review of the mechanisms involved in the occurrence of growth-related abnormalities affecting broiler chicken breast muscles. Poultry Science, 100(6), 101180.
51. Aguirre, M. E., Leyva-Jimenez, H., Travis, R., Lee, J. T., Athrey, G., & Alvarado, C. Z. (2020). Evaluation of growth production factors as predictors of the incidence and severity of white striping and woody breast in broiler chickens. Poultry science, 99(7), 3723-3732.

52. Santos, M. N., Rothschild, D., Widowski, T. M., Barbut, S., Kiarie, E. G., Mandell, I., ... & Torrey, S. (2021). In pursuit of a better broiler: carcass traits and muscle myopathies in conventional and slower-growing strains of broiler chickens. Poultry Science, 100(9), 101309.

53. Bowker, B., Zhuang, H., Yoon, S. C., Tasoniero, G., & Lawrence, K. (2019). Relationships between attributes of woody breast and white striping myopathies in commercially processed broiler breast meat. Journal of Applied Poultry Research, 28(2), 490-496.

54. Dalle Zotte, A., Ricci, R., Cullere, M., Serva, L., Tenti, S., & Marchesini, G. (2020). Research Note: Effect of chicken genotype and white striping–wooden breast condition on breast meat proximate composition and amino acid profile. Poultry Science, 99(3), 1797-1803.

55. Lien, R. J., Bilgili, S. F., Hess, J. B., & Joiner, K. S. (2012). Induction of deep pectoral myopathy in broiler chickens via encouraged wing flapping. Journal of Applied Poultry Research, 21(3), 556-562.

56. Stangierski, J., Tomaszewska-Gras, J., Baranowska, H. M., Krzywdzińska-Bartkowiak, M. & Konieczny, P. The effect of deep pectoral myopathy on the properties of broiler chicken muscles characterised by selected instrumental techniques. Eur. Food Res. Technol. 245, 459–467 (2019).

57. Lien, R.J., Bilgili, S.F., Hess, J.B., Joiner, K.S. (2011) Finding answers to 'green muscle disease'. Watt AgNet. https://www.wattagnet.com/articles/8761-finding-answers-to-green-muscle-disease

58. Yalcin, S., Şahin, K., Tuzcu, M., Bilgen, G., Özkan, S., Izzetoğlu, G. T., & Işik, R. (2019). Muscle structure and gene expression in pectoralis major muscle in response to deep pectoral myopathy induction in fast-and slow-growing commercial broilers. British poultry science, 60(3), 195-201.

59. Huang, X. & Ahn, D. U. REVIEW The Incidence of Muscle Abnormalities in Broiler Breast Meat – A Review. 38, (2018).

60. Giampietro-Ganeco, A., Owens, C. M. & Borba, H. Impact of deep pectoral myopathy on chemical composition and quality parameters of chicken breast fillet. Poult. Sci. 100, 101377 (2021).

61. Droval, A. A., Benassi, V. T., Rossa, A., Prudencio, S. H., Paião, F. G., & Shimokomaki, M. (2012). Consumer attitudes and preferences regarding pale, soft, and exudative broiler breast meat. Journal of Applied Poultry Research, 21(3), 502-507.

62. Wang, X., Li, J., Cong, J., Chen, X., Zhu, X., Zhang, L., ... & Zhou, G. (2017). Preslaughter transport effect on broiler meat quality and post-mortem glycolysis metabolism of muscles with different fiber types. Journal of agricultural and food chemistry, 65(47), 10310-10316.

63. BARBUT, S. (1998). Estimating the magnitude of the PSE problem in poultry. Journal of Muscle Foods, 9(1), 35-49.

64. Van Laack, R. L. J. M., Liu, C. H., Smith, M. O., & Loveday, H. D. (2000). Characteristics of pale, soft, exudative broiler breast meat. Poultry Science, 79(7), 1057-1061.

65. Carvalho, R. H., Soares, A. L., Grespan, M., Spurio, R. S., Coró, F. A. G., Oba, A., & Shimokomaki, M. (2015). The effects of the dark house system on growth, performance and meat quality of broiler chicken. Animal Science Journal, 86(2), 189-193.

66. Soglia, F., Mazzoni, M., & Petracci, M. (2019). Spotlight on avian pathology: current growth-related breast meat abnormalities in broilers. Avian Pathology, 48(1), 1-3.

67. Gall, S., Suyemoto, M. M., Sather, H. M., Sharpton, A. R., Barnes, H. J., & Borst, L. B. (2019). Wooden breast in commercial broilers associated with mortality, dorsal recumbency, and pulmonary disease. Avian Diseases, 63(3), 514-519.

68. Kawasaki, T., Yoshida, T., & Watanabe, T. (2016). Simple method for screening the affected birds with remarkably hardened pectoralis major muscles among broiler chickens. The Journal of Poultry Science, 53(4), 291-297.

69. Larsen, H. D., Blaabjerg, L. O., Brandt, P., Young, J. F., Rasmussen, M. K., Pedersen, J. R., & Brandborg, D. N. (2016, September). The occurrence of wooden breast in a danish flock of broiler chickens. In Proceedings of the XXV World's Poultry Congress (WPC2016), Beijing, China (pp. 5-9).

70. Che, S., Weber, L., Novy, A., Barbut, S., & Susta, L. (2023). Characterization of dorsal recumbency syndrome associated with woody breast in broiler flocks from Ontario, Canada. Poultry Science, 102(2), 102307.

71. Baltic, M., Rajcic, A., Lau danovic, M., Nesic, S., Baltic, T., Ciric, J., & Lazic, I. B. (2019, September). Wooden breast–a novel myopathy recognized in broiler chickens. In IOP Conference Series: Earth and Environmental Science (Vol. 333, No. 1, p. 012037). IOP Publishing.

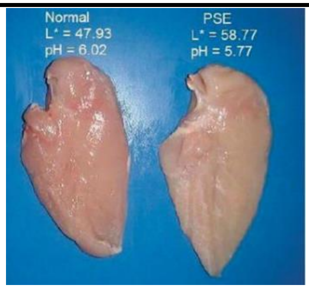
ANNEX 1: Factors affecting the nutritional value of broiler meat *(based on FAO, 2023)*

Fat and fatty acids	**Genetics**	◦Commercial hybrids with slower growth rates generally have a higher fat content than cross-bred fast-growing genotypes and have higher total PUFA (polyunsaturated fatty acid) content in the meat.	Baéza, Guillier and Petracci, 2021; Mahiza,Lokman and Ibitoye, 2021
		◦Genetic selection to promote weight gain and higher productivity increases the fat content and decreases the omega-3 DHA content of broiler meat.	Wang et al. (2010)
		◦Lipid content in indigenous pure-bred chickens is about one-third of that in hybrid chickens. Higher levels of lipid and protein oxidation (which curtails protein bioavailability) have been found in those pure-bred chickens.	Dalle Zotte et al., 2020
	Diet	◦Increasing lipid content of feed and decreasing its energy/protein ratio leads to an increase in intramuscular lipid content. ◦Saturated fatty acids (SFA)-rich diet (e.g. palm, copra oil) increases SFA proportion. ◦ PUFA-dense oil from marine animals increases the proportions of long-chain omega-3 PUFAs	Baéza, Guillier and Petracci, 2021
	Husbandry methods	◦Confinement of animals indoors with ad libitum access to high-energy feed and the use of growth promoters lead to higher fat content. ◦Lower stocking density decreases intramuscular fat content.	Marchewka et al. 20239
Protein and amino acid	**Genetics**	◦Significantly lower protein content (3–14% less) can be found in a high breast-yield strain compared to a standard breast-yield hybrid. ◦Higher protein content present in indigenous chickens.	Dalle Zotte et al., 2020; Petracci et al., 2013
		◦Decrease of slaughter age due to genetic selection for growth rate leads to increase in moisture/protein ratio.	Baéza et al., 20214
		◦Quality defects such as “white striping” or “wooden breast” are associated with a 7-18% decrease in muscle protein content and an increase of up to 11% in collagen content with genetic selection for growth rate in broilers.	Baéza, Guillier and Petracci, 2021
Moisture and Water Holding Capacities (WHC)	**Genetics**	◦Decrease of slaughter age due to genetic selection for growth rate leads to increase in moisture/protein ratio.	Baéza et al., 2021
	Husbandry Methods	◦Lower stocking density lowers cooking and drip loss. ◦Outdoor access increases WHC and reduces cooking loss.	Marchewka et al. 2023
Vitamins	**Husbandry methods**	◦Free-range access increases vitamin E content.	Baéza, Guillier and Petracci,

ANNEX 2: Summary of the most common breast muscle myopathies affecting the Pectoralis major in broiler chickens.

Condition	Appearance	Description	Histopathology	Risks Factors	Organoleptic changes	Nutritional changes
White Striping		◦Infiltration of white striations of fat and connective tissue parallel to muscle fibre on the skin-side	◦Necrosis and lysis of muscle fibres ◦Lipidosis ◦Vacuolar degeneration	◦Higher body weights ◦Breast meat yields	◦Visually unappealing ◦Decreased precursors of Umami flavour	◦Higher fat content ◦Lower protein content ◦Higher pH ◦Higher collagen content ◦Deficient in some aminoacids
Wooden Breast		◦Hard, bulging, pale breast meat ◦Sometimes petechial haemorrhaging and a gelatinous liquid on the skin	◦Localized infiltration of immune cells ◦Vasculitis ◦Muscular fibre inflamma-tion and degeneration ◦Muscle fibre replaced with adipose and connective tissue	◦Higher body weights ◦Breast meat yields	◦Reduced water holding capacity ◦Reduced marinade uptake ◦Higher drip loss Increased cooking loss	◦Decreased protein levels ◦Deficient in some essential amino acids ◦Abnormal mineral profile
Spaghetti meat		◦Loosened and separated of the muscle fibres. ◦The individual muscle fibres resemble spaghetti	◦Loss of structural connective tissue ◦Tissue degeneration and regeneration ◦Some of the muscle fibres appear hypercontracted	◦Fast-growing breeds ◦Plant-based diets	◦Difficult to slice and have a softer texture after cooking ◦Abnormal integrity resulting in downgrading ◦Higher meat yellowness ◦Higher moisture ◦Higher drip and cooking losses	◦Decreased protein levels

ANNEX 3: Summary of the most common breast muscle myopathies affecting the Pectoralis minor in broiler chickens.

Condition	Appearance	Description	Histopathology	Risks Factors	Organoleptic changes	Nutritional changes
Deep Pectoral Myopathy		◦Degenerative disease of the breast muscle, resulting in haemorrhaging and green discoloration	◦Characterised by necrosis and atrophy of the muscle	◦Higher breast meat yields	◦Tougher and more fibrous meat ◦Higher moisture percentage ◦Higher water holding capacities	◦Decreased protein and ashes percentage ◦Higher values of lipids ◦Altered fatty acid profile
Pale-Soft-Exudative (PSE) Meat		◦Pale meat result of denaturation of proteins, due to sudden drop on pH while the carcass is still warm	◦Denaturation of myofibrillar and sarcoplasmic proteins	◦Thermal stress ◦Stress during transport and slaughter	◦Pale colour ◦Less tender and juicy than normal breast meat ◦Lower pH ◦Higher colour L* value ◦Higher drip loss ◦Lower marinade absorption ◦Lower cooking yield	◦Decreased protein levels
"Gaping" of P. Minor		◦The muscle fibre bundles appear visually separated (or torn) between each other at one or more points along the external ventral surface	◦Collagen-rich connective tissue within and surrounding the breast muscle tissue does not have enough time to mature, so the P. minor is more prone to tearing during processing.	◦High breast muscle yield ◦Slaughter at young age	◦Reduced pH ◦Lighter muscle ◦Higher yellow colour ◦Lower Water Holding Capacity	◦No differences found in the nutritional content (e.g., protein, collagen, fat, ash)