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Chapter

An Overview of Poultry Meat Quality and Myopathies

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Abstract

The increased demand for poultry meat and the shift toward portioned and further processed products has been accompanied by genetic improvement and progress in nutrition and management to increase growth rates and improve feed efficiency. Animal protein continues to be the most demanded and expensive protein source worldwide. Poultry is an animal protein commonly accepted among different faith groups and relatively more affordable than other animal protein sources. In addition, poultry meat has lower fat, cholesterol, and sodium content compared to red meat. This review aims at summarizing the available information about skeletal muscle structure, conversion of muscle to meat and how it affects poultry meat quality, the different myopathies historically been identified and other emerging myopathies, then discussing how meat quality affects consumer perception and consumption trends, and finally discussing few of the proposed solutions to overcome the issues of decreased meat quality, including nutritional strategies.

Keywords: meat quality, nutrition, muscle myopathies, color, poultry

1. Introduction

The poultry industry has witnessed significant improvements over the past several decades achieving higher market weight with improved feed efficiency, thus reducing production cost. During the past 60 years, the amount of time and quantity of feed per pound of meat required to reach broiler market weight had been reduced by 50% [1]; furthermore, according to the National Chicken Council [2], modern broiler chickens can achieve market weight 16 days earlier with 35% higher weight compared to the 1960s broiler chicken. These improvements have resulted from a combination of genetic improvement and progress in nutrition and poultry management.

The U.S. is considered the world's largest producer of poultry meat; the U.S. provides approximately 17% of the global poultry meat output, followed by Brazil and China, mainly dominated by broiler meat followed by turkey meat and a small fraction for other poultry meat. The production and consumption of poultry meat have increased rapidly worldwide and are expected to continue to grow [3] due to its relatively low price compared to other meats, the absence of cultural or religious obstacles, and its dietary and nutritional properties as it has lower fat, cholesterol, and sodium content [4] with an increased preference of white chicken meat [5, 6].
Additionally, consumers have shifted from the consumption of whole chicken toward portioned (especially breast fillets) and further processed products [7, 8]. These changes were driven by the need for convenience with meal preparation in a fast-paced industrialized era and meeting consumer preference of specific carcass parts. The poultry industry has responded to these changing demands by further enhancing genetic selection for increased breast yield, faster growth rate, and improved feed efficiency. Meanwhile, feed cost has increased, and ethanol production has forced producers to use alternative feed ingredients such as the distiller's dried grains with solubles (DDGS) produced as byproducts of ethanol production. However, since the selection of broiler chickens initially focused on increasing growth performance and improving body composition [9], this has led to indirect and often deleterious effects on meat quality traits, such as excessive deposition of abdominal fat, the formation of which represented the inefficient use of feed [10, 11]. Coincidently, several studies have shown an increased incidence of abnormalities, mainly in breast muscles [12, 13]. In the early 1980s, Wight and Siller [14] recognized an abnormal condition in the pectoralis minor, in which the muscle is basically “suffocated” leading to ischemic necrosis; this condition known as deep pectoral muscle myopathy is only the first in a list of fast-growth-related muscle abnormalities that eventually affect meat quality and its functional properties.

In poultry meat, appearance and texture have been considered the two most important attributes responsible for initial consumer meat evaluation and final product acceptance [15], so consumers are expected to reject meat with observed defects such as bruises and hemorrhages. Several appearance defects have been reported in the poultry industry, such as pinking of raw and cooked meat, bone darkening, red/bloody discoloration, white striping, wooden breast, spaghetti meat, and pale, soft, exudative appearance of breast meat. However, many of the underlying causes of appearance defects have not been fully explained. Understanding the structural organization of the muscle fibers and physiology can help in explaining some of these defects.

2. Overview of skeletal muscle structure

The basic structural unit of a muscle has been defined as the muscle fiber, which is constituted of several myofibrils (contractile units). Each muscle fiber is surrounded by a connective tissue called the endomysium; muscle fibers are then grouped into fascicles and surrounded by another layer of connective tissue called the perimysium. Then, the whole muscle is made up of a group of fascicles and surrounded by epimysium that connected the muscle to bones. Collagen is the major constituent of these connective tissues. These connective tissues influenced muscle development and subsequent meat quality.

Skeletal muscles growth was achieved by increasing the size of preexisting muscle fibers (hypertrophy). The number, size, and type of fibers vary with the function and anatomical location of the muscle. Meat quality is also affected by these factors. A muscle that contained high proportion of oxidative fibers tends to have red color due to a greater amount of myoglobin (e.g., thigh muscles) as compared to glycolytic fibers, which tended to appear white in color, which affected the appearance of muscle/meat (e.g., chicken breast muscle). Glycolytic fibers are larger and have lower rate of protein turnover. Therefore, the white muscles are larger and more efficient. In poultry, genetic selection for increased breast yield resulted in pale breast meat color in broilers [16], ducks [17], and turkeys [18], which could result in poor meat quality.
Collagen is the most abundant protein in the body and in connective tissues. The structure of collagen supports its function of providing strength to muscle and other tissues with more than 20 different types of collagen identified in vertebrates [19]. Glycine constitutes about one-third of all the amino acids found in collagen, while proline, which has been classified as an imino acid, and its analog hydroxyproline also constituted about one-third of all amino acids in collagen [20]. Lysine has been considered to be another constituent of collagen where both proline and lysine are covalently modified to hydroxyproline and hydroxylysine, respectively. A collagen molecule (tropocollagen) is composed of three left-handed polypeptide helices coiled around each other to form a right-handed supercoil where glycine is found at every third residue [19].

The strength of the collagen fibrils is due to the covalent bonds formed between and within tropocollagen triple helices, where collagen is cross-linked by lysine side chains that contribute to the strength of the collagen in meat, which has an essential role in the development of meat tenderness [21]. Furthermore, in a recent study, it has been shown that muscle with spaghetti meat abnormality had an altered immunoreactivity to specifically procollagen type III (precursor of collagen type III) suggesting a possible defect in the collagen turnover and synthesis process [22], while Sanden et al. [23] reported that spaghetti meat has poorly packed thin, loose, and immature collagen fiber bundles.

2.1 Conversion of muscle to meat

The process of converting muscle to meat in poultry starts immediately upon sacrificing the bird. Exsanguination results in blood/oxygen supply removal, during which the muscle tries to maintain its functions even after oxygen depletion through the anaerobic glycolysis of its glycogen reserves to produce adenosine triphosphate (ATP), but in the absence of blood supply to remove waste, the accumulated heat and lactic acid in the muscle decreases the pH. Owing to ATP depletion, the muscle remains contracted due to actin and myosin binding that leads to muscle stiffness (rigor mortis). This marks the onset of rigor mortis and the conversion of muscle to meat, where muscle proteins start to denature due to high temperature and low pH. Temperature and pH are the main postmortem factors influencing meat quality through affecting the onset and progression of rigor mortis and subsequent resolution [24–27]. During resolution, the proteolysis of Z-disk proteins takes place, and myofibrillar proteins degrade into myofibrillar fragments by proteolytic enzymes that affect meat tenderness. In chickens, the process of converting muscle to meat has been found to start immediately after slaughter and be resolved within 2–4 h. The extent of meat tenderization postmortem could be altered by the conditions under which the meat is processed. Factors include temperature and chilling duration, deboning time, postchill aging/holding duration, and marination.

2.2 Poultry meat quality

Meat quality is a collective term used to describe the indicators of a meat product wholesomeness and freshness, such as color, texture, flavor, pH, and juiciness. The two most important quality attributes for poultry meat are appearance and texture since they influence the initial consumer selection of a product as well as final satisfaction [15]. Appearance quality attributes include skin color, meat color, and appearance defects such as bruises and hemorrhages. Any deviation from a normal
appearance would result in meat product rejection, subsequently leading to consumer complaints. Despite the importance of these quality attributes, the poultry grading system used is still based on aesthetic attributes, such as conformation, presence or absence of carcass defects, bruises, missing parts, and skin tears, without taking into consideration the functional properties of meat [28], which have been important for the further processing industry that was mainly interested in the functional properties of meat; the importance of incorporating functional properties and quality indicators is becoming increasingly important as the recent muscle myopathies not only affect consumer acceptance based on appearance but also the quality of further processed meat manufactured using meat with such defects.

Many factors influence poultry meat quality, including sex, strain, age, environmental factors, exercise, diet, and processing practices mainly focused on chilling, deboning time, marination, and electrical stunning [29–32].

Another important quality attribute that influences customer perception is the tenderness of the meat. This attribute comes second after appearance; consumers usually correlate acceptable appearance with better quality and tenderness. Tenderness development is a function of myofibrillar protein denaturation, connective tissue content, and juiciness. Deboning time, age, and strain are some of the major factors that affect poultry meat tenderness [31, 33]. Lyon and Lyon [34] reported that as the time before deboning increased from 0 to 24 h postmortem, consumer acceptability of the meat texture increased, with fillets deboned at 0 and 2 h postmortem considered tough by a consumer panel, and samples deboned at 6 and 24 h postmortem considered slightly tender to moderately tender. Liu et al. [35] reported a decreased shear force of chicken breast as deboning time increased from 2 to 24 h postmortem. Similar results were also reported by Cavitt et al. [33].

Furthermore, Mehaffey et al. [8] reported that fillets deboned 2 or 4 h postmortem from broilers raised to 7 weeks were significantly tougher than those raised to 6 weeks, indicating that age affected tenderness when deboning was performed shortly after harvest. Northcutt et al. [31] reported that breast fillets harvested at less than 2 h postchill aging were tenderer when taken from broilers slaughtered at 42 or 44 days of age than those harvested from birds 49 or 51 days of age, irrespective of any sex effect. On the other hand, Young et al. [36] reported that females had greater fillet yields than males.

Connective tissue content has been reported to increase with age and is correlated with tenderness; as mentioned earlier, collagen is the most abundant protein in the body, making up the majority of the connective tissue proteins [37, 38]. In young broilers (6–8 weeks), it is expected that connective tissue would not affect tenderness since mature cross-links should have not yet formed between tropocollagen molecules, which are the structural units of the collagen fibril. On the other hand, the contraction of myofibrillar protein, which depends upon time and rate of rigor mortis development after the bird is sacrificed, is related to processing rather than intrinsic factors [15]. Furthermore, tenderness, indirectly associated with connective tissue, is one of the quality attributes that are negatively affected by the emerging muscle myopathies emphasizing the importance of further investigating and attempting to mitigate the negative impacts.

Another important meat quality attribute is meat juiciness, or water-holding capacity, which refers to the ability of raw meat to retain its inherent water during force application and/or processing [39]. Water in muscle has been divided into three general types: bound, immobilized, and free. Bound water is held tightly via myofibrillar protein charges and represents 4–5% of water in muscle [39, 40]; it is resistant
to freezing and could only be removed by severe drying processes, not including conventional cooking [41]. Immobilized water is found within the muscle ultrastructure (within the space between actin and myosin), but it is not bound to myofibrillar proteins as in the case of bound water. Immobilized water accounts for the largest portion of muscle-bound water (88–95%). Finally, free water is held within muscle by weak capillary forces [42].

2.3 Poultry meat color

Poultry has been determined to be the only species known to have muscles/parts with apparent differences in color, as meat from poultry has been classified as either white or dark. In chicken, fresh raw breast meat is expected to have a pale pink color, while the raw thigh and leg meat are darker and redder. Meat color plays a significant role in consumer purchase decisions [43–45]. Consumers tend to associate color with flavor, tenderness, safety, storage time, nutritional value, and satisfaction level [46], and as an indicator of freshness and wholesomeness.

Meat color is what the human eye sees as light is reflected from the meat surface. Poultry meat absorbs most blue and green color spectra and reflects most of the yellow, orange, and red color spectra, which is what the human eye perceives.

The most commonly used colorimetric scale is the CIE Lab [47], even though other color scales have been used, such as the Hunter L, a, b, and YXZ space. However, the accuracy of these instruments has depended upon thickness, background color, and illuminant wavelengths [48, 49].

The CIE Lab system components measures include L* that refers to lightness and has a range from 0 to 100 (black to white), component a* had a range from –60 to +60 (green if negative to red if positive), and b* has the same range as a* (blue if negative to yellow if positive) [50, 51]. Another more recent system used for color measurement is the computer vision system, which has been shown to give reproducible results with the ability to measure the color of the entire sample instead of specific spots, as has been the case with widely used colorimeters [52]; in fact, Tomasevic et al. [53] recommended using computer vision program as a superior approach for poultry color determination.

Meat color is mainly related to the myoglobin pigment present in the muscle fibers. Myoglobin consists of a protein (globin) and a nonprotein heme ring, which has an iron molecule in its center. Iron can bind one of several ligands (e.g., oxygen, carbon monoxide, and nitric oxide) on its sixth coordination site. The forms of myoglobin (deoxymyoglobin, oxymyoglobin, carboxymyoglobin, and metmyoglobin) differ depending upon the ligand bound to iron and on the redox state of the iron. Thus, myoglobin and iron states are the two main ways through which meat color changes.

Myoglobin (or deoxymyoglobin) has a red-purple color in its nature when not bound to any ligands; the state of myoglobin changes to oxymyoglobin when oxygen is present and to carboxymyoglobin when carbon dioxide is present. In both the forms, the color is bright red (bloom), and iron is in the reduced ferrous form (Fe++). The oxidation of myoglobin changes the form to metmyoglobin and the iron to the oxidized ferric form (Fe+++), which has a brown color. These myoglobin color changes are reversible; however, if heat-treated, metmyoglobin becomes denatured and color changes irreversibly to grayish-brown. Curing with nitrites/nitrates causes an irreversible color change to red color that, upon heating, converts to pink. The replacement of iron with zinc results in a stable red color of myoglobin due to the
formation of Zn-protoporphyrin IX (ZPP), which has been shown to give Parma ham its stable, bright red color [54, 55]. Within a chicken carcass, chicken breast muscles are mainly composed of white fibers (glycolytic) that have low myoglobin content. Thus, breast meat appears white, while thigh muscles are composed of red fiber (oxidative) and appears darker. Fleming et al. [56] reported a myoglobin concentration of 0.16 and 0.30 mg/g in broiler breast and thigh muscles, respectively. Furthermore, Miller [57] said a lower myoglobin content of 0.01 and 0.40 mg/g in white and dark meat of 8-week-old broilers, respectively.

Froning [58] classified the factors influencing meat color into three main categories (Table 1). Smith et al. [59] investigated the effect of age, diet (carbohydrate source), and feed withdrawal on broiler meat color by slaughtering birds each day from 42 to 45 and 49 to 52 days of age with a carbohydrate source that was either corn, milo, or wheat, with feed withdrawal times of either 0 or 8 h. Color was not affected by age. Still, feed withdrawal increased fillet lightness (L*) from an average of 46.1 to 48.9, decreased redness (a*) from 4.1 to 3.1, and increased yellowness (b*) from 2.8 to 3.7. Fillets from the birds fed the wheat diet were lighter than fillets from the corn or milo fed birds. The milo diet resulted in redder fillets than corn or wheat diets, while the corn diet produced more yellow fillets than milo or wheat diets.

In addition to meat color, skin color has been considered a critical quality attribute, mainly in a whole carcass and skin-on cuts sale. The color of poultry skin has varied from cream-colored to yellow. This variation is primarily the result of genetic variation and natural pigments in feed. Birds had differed in their ability to deposit the black melanin pigment in the epidermis and dermis layers of the skin and varied in their ability to deposit carotenoids from the feed as the combinations of different amounts of melanin and carotenoids produced different skin colors. However, in commercial strains, the ability to deposit melanin has been eliminated through genetic selection. Different skin colors as adopted from [60] are illustrated in Table 2.

| Heme pigments | • Myoglobin, hemoglobin, cytochrome c, and their derivatives  
| • Presence of ligands complexing with heme pigments |
| Pre slaughter factors | • Genetics (fast growing strains)  
| • Feed (e.g., moldy feed)  
| • Feed withdrawal time  
| • Hauling and handling stress  
| • Heat and cold stress  
| • Pre slaughter gaseous environment of the bird |
| Slaughter, chilling, and further processing | • Stunning techniques  
| • Presence of nitrates  
| • Additives and pH (e.g., phosphates, salt)  
| • End-point cooking temperature  
| • Reducing conditions  
| • Washing surimi-like processing of mechanically  
| • deboned poultry meat (MDPM)  
| • Irradiation |

Table 1.  
Factors influencing poultry meat color [58].
However, considerable variation in color and discoloration of poultry meat has occurred and remains of great concern for the industry. Discoloration may occur in the entire muscle or only in a portion of a muscle due to bruising or broken blood vessels [58]. Possible poultry color defects are presented in Table 3.

### 2.4 Poultry meat color defects

#### 2.4.1 Pink discoloration of cooked white meat

The pinking of cooked white meat has been an undesirable color defect found in poultry; its occurrence was noticed sporadically and has negatively influenced consumer purchasing decisions (Maga, 1994). According to Maga [61], pink color might have resulted from the presence of high levels of myoglobin that were not completely denatured during heat processing, incidental nitrate/nitrite contamination either in feed or water or during processing. The presence of carbon monoxide and nitric oxide gases in oven gas while roasting has caused pink color on the surface of turkey.

### Table 2.
Combination of possible skin colors due to dietary xanthophyll deposition in epidermis or melanin production in either dermis or epidermis [60].

<table>
<thead>
<tr>
<th>Skin color</th>
<th>Dermis</th>
<th>Epidermis</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Black</td>
<td>Melanin</td>
<td>Melanin</td>
</tr>
<tr>
<td>Yellow</td>
<td>None</td>
<td>Xanthophyll</td>
</tr>
<tr>
<td>Green</td>
<td>Melanin</td>
<td>Xanthophyll</td>
</tr>
<tr>
<td>Blue (Slate)</td>
<td>Melanin</td>
<td>None</td>
</tr>
</tbody>
</table>

### Table 3.
Summary of poultry color defects [60].

<table>
<thead>
<tr>
<th>Defect and hemorrages</th>
<th>Description</th>
<th>Possible causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bruises and hemorrhages</td>
<td>Classic bruises, pin-point blood spots in meat, blood accumulation along bones and in joints</td>
<td>Physical trauma, nutrient deficiencies, mycotoxins, stunning</td>
</tr>
<tr>
<td>Overscaling</td>
<td>Incomplete removal of epidermis, cooked discoloration on surface of meat</td>
<td>Too high scalding temperature, too long in scaler</td>
</tr>
<tr>
<td>Surface drying</td>
<td>Mottled appearance of skin or meat due to surface dehydration</td>
<td>Incomplete removal of epidermis, exposed meat, poor packaging, freezer burn</td>
</tr>
<tr>
<td>Heme reactions</td>
<td>Normal color ranges from raw pink meat, tan to brown raw meat, grey to brown cooked meat, pink cooked meat, cured meat color</td>
<td>Oxidative or redox state of the myoglobin, myoglobin complexing with nitrates/ nitrites or other compounds such as carbon monoxide</td>
</tr>
<tr>
<td>Dark meat</td>
<td>Darker than normal appearing meat, possible motting</td>
<td>High muscle pH due to antemortem depletion of muscle glycogen</td>
</tr>
<tr>
<td>Light meat</td>
<td>Pale breast meat</td>
<td>Low muscle pH (PSE-like condition)</td>
</tr>
<tr>
<td>Dark bones</td>
<td>Dark brown to black bones</td>
<td>Freezing, blood accumulation around bone</td>
</tr>
</tbody>
</table>
meat, with carcasses from younger turkeys more susceptible than older ones [62]. The proposed mechanism for pink color development of fully cooked is related to the ligands to which the denatured myoglobin was bound, such as amino acids, denatured proteins, and nitrogen-containing compounds that form denatured hemochromes globin. Therefore, depending on the ligand to which the denatured heme will bind, different pink shades would result.

Binding of nitric oxide to myoglobin from preslaughter contamination (feed and water and gases from the truck exhaust) or during/after processing (processing water, ice, spice mix, and oven gas) has formed the pink nitric oxide myoglobin that, upon cooking, was converted to pink nitrosohemochrome. Furthermore, carbon monoxide binding to myoglobin has led to pink carboxymyoglobin developing upon cooking in oven gases or during irradiation.

Cooking meat harvested from birds before rigor mortis resolution could also cause pink color when meat is cooked when pH was higher than 6.0. At this high pH, myoglobin is not denatured, and cytochrome C (electron transport protein), which is heat stable, increases and contributes to the delayed denaturation of myoglobin since cytochrome C is still able to deliver electrons to myoglobin. Ahn and Maurer [63] showed that a pH above 6.4 leads to binding of myoglobin and hemoglobin with most naturally present ligands, such as histidine, cysteine, methionine, nicotinamide, and solubilized proteins, which leads to pink color of the meat. At high pH, amino acids and protein ligands can donate electrons to Fe, resulting in stable pink ferro-hemochrome. High pH also reduces the susceptibility of meat pigments and lipids to oxidation resulting in a cooked pink color [64].

2.4.2 Bone darkening or discoloration

Bone darkening has been described as a dark reddish brown or black discoloration on the surface of bone and muscle adjacent to the bone after cooking. The darkening was due to bone marrow passing from inside the bone onto the bone surface and adjacent tissue, usually after freezing the meat [65, 66] and after cooking of the frozen meat [67]. Lyon and Lyon [30] described the variation in bone discoloration due to different preparation methods (precook, freeze, and reheat). They found that freezing before cooking increased the severity of discoloration more than cooking followed by freezing and reheating. Lyon et al. [65] demonstrated that meat and bone darkening of thigh pieces was related to pigment migration from the femur to muscle tissue. The commercial further processing industry has reported that redness was usually accompanied by blood in bone-in chicken carcasses and parts, which consumers could reject as the product appears undercooked and unsafe for consumption [59].

The migration of pigments from the femur to muscle tissues has created darkening that was more prevalent in younger birds since their bones were less calcified, were more porous, and had more red marrow than older birds. The epiphysis of long bones in older birds is more calcified than young birds, so the pigment is more difficult to escape from bones onto surrounding tissue. However, bone darkening only affects the appearance and not the organoleptic properties of the meat product [67].

Smith and Northcutt [59] studied discoloration prevalence in commercially fully cooked breasts, thighs, and drumsticks from various market sources. They speculated that about 11% of products could face consumer complaints or rejection since they were severely discolored. Furthermore, cooking chicken breast samples with bone marrow collected from femurs increased the darkness and redness of both raw and cooked broiler meat [68].
2.4.3 Red discoloration of white meat

Red and/or bloody discoloration of poultry meat, raw or cooked, has been a chronic yet sporadic problem for the poultry industry. Raw breast meat with red discoloration is objectionable to many customers, and cooked white or dark meat with red defect is unacceptable to consumers due to the perception that it is undercooked. Red discoloration of white meat is closely related to bone darkening but with higher redness. Little research has been available concerning this red discoloration defect in poultry meat [59]. According to Smith and Northcutt [66], bone marrow is an effective inducer of red, bloody discoloration in breast meat samples. In a previous investigation conducted concerning the color of different parts of chicken, Lyon et al. [65] reported that the initial color of breast was lighter and less red than thighs because breasts had a lower proportion of total bone area to muscle mass, fewer large, calcified bones, a lower proportion of blood vessels per muscle mass (less hemoglobin), or lower myoglobin content than thighs or drums [66].

The bright red color development has been investigated in Parma ham, where this north Italian traditional dry-cured ham “Prosciutto di Parma (Parma ham)” has been made from only the legs of fattened pigs and was salted with sea salt, dried, and matured over 1 year [69]. It was initially postulated that sea salt used was contaminated with nitrate/nitrite. However, that was later investigated, and results showed that this pigment was also formed in a nitrate/nitrite-free environment and that endogenous enzymes as well as microorganisms were involved in this pigment formation [54, 55]. These results suggested that the bright red color in Parma ham is caused by Zn–protoporphyrin IX (ZPP), in which the iron in heme was substituted by zinc heme separated from the native heme protein. Investigations on this lipophylic myoglobin derivative showed that it was a stable red pigment that increased with aging [70]. This process has now been patented for producing red pigments for food use that were heat-stable [71]. The addition of salt accelerated the reaction and increased redness [72]. The process has also occurred in live animals, including humans, as lead poisoning and iron deficiency caused an increase of ZPP in blood as zinc replaced the iron in hemoglobin. The level of ZPP can be evaluated with a simple screening test using a hematofluorometer. The measurement of ZPP has been used with ducks to test for lead poisoning [73]. An increased ZPP/heme ratio indicates that Zn has replaced Fe in the heme, thus changing the color of hemoglobin and myoglobin. Based on findings in Parma ham, ZPP may be responsible for the red discoloration in poultry meat, which could be formed in myoglobin found in muscles or hemoglobin stored in bone marrow. Thus, ZPP leaking out of the bones could cause the increased stable redness observed in white meat.

2.4.4 Green discoloration

Green discoloration of live muscles, raw meat, and cooked deli products can be produced by various mechanisms that lead to condemnation by the industry and consumers. In live muscles, green muscle disease (deep muscle myopathy) is caused by the lack of blood supply to the deep pectoral muscle that results in the death of the muscle fibers, thus giving the muscle a green appearance. The bruising of live birds has caused a rupture of blood capillaries and blood accumulation under the skin or in the meat. The color of the bruise subsequently developed over time and turned either yellow or green depending upon heme degradation. Using lactic acid as a decontamination approach resulted in the greening of chicken skin color [74]. The irradiation
of fresh beef and pork meat has been thought to affect the stability of iron in the myoglobin and cause the breakdown of the porphyrin molecule and/or the formation of sulfmyoglobin that caused green pigments to appear [75].

In cooked meat, contamination with microorganisms such as Pseudomonas fluorescens has produced a shiny transparent greenish exudate on the meat surface due to microbial degradation of the heme pigment. In sausage-type products, the presence of green rings is an indicator of microbial contamination where the microorganisms oxidized the heme pigment before applying thermal treatment.

Iridescence, which is the appearance of a green-orange color on the surface of meat products such as deli meat, is mainly associated with the meat surface microstructure that could be interpreted as a color diffraction problem related to the ability of certain muscles to split the white light into its component. Thus, the reflection of the meat surface would appear in green-orange. If a sharp knife was used to cut the meat, the smooth surface resulting from the cut causes this color diffraction, but if a dull knife was used instead, this problem would be eliminated.

3. Existing and emerging muscle myopathies

3.1 Breast muscle myopathy

Deep pectoral muscle myopathy, also known as green muscle disease and Oregon disease, was first identified in turkeys [76] and later in broiler breeders [77] and 7-week-old broiler chickens [78]. This disease affected the wing elevating muscle (M. supracoracoideus or pectoralis minor) and was characterized by the death of the muscle (tenders) but did not cause the death of the bird. Dead muscle decay, while the bird was still alive, resulted in the appearance of a yellowish-green color due to the breakdown of hemoglobin and myoglobin to bile salts; muscle myopathy could affect just one (unilateral) or both (bilateral) pectoralis minor muscles. Since affected tenders were located deep in the breast, this defect resulted in consumer complaints when the carcasses were sold as a whole.

The pectoralis minor muscle is confined in a tight space between the sternum and the pectoralis major muscle (large breast fillet). It is also encased in a rigid fibrous sheath that restricts any increase in muscle volume in response to any physiological changes caused by muscle exercise such as wing-flapping [79] which requires increased blood flow to supply the oxygen and nutrients needed by the muscles. The incidence of green muscle disease has also been reported to be higher in high yielding crosses, especially males.

On the other hand, the incidence of focal pectoral myopathy has increased, and it has been associated with increased growth rate and muscle size [12, 80]. Further investigation is required to determine the causes of this muscular defect since focal myopathy has an even more detrimental effect on the poultry industry. It has affected the pectoralis major muscle leading to consumer complaints and industry economic loss.

3.2 Pale, soft, and exudative-like condition in poultry muscles

The incidence of pale, soft, and exudative (PSE) meat has been well-documented in swine, where meat has a very light gray color, soft texture, and cannot hold water
An Overview of Poultry Meat Quality and Myopathies
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This condition has been associated with heavy muscling [83]. In poultry, similar PSE characteristics have been reported in turkey meat [84, 85], chickens [86, 87], and ostriches [88]. However, it is more difficult to distinguish and identify these characteristics in poultry meat compared to pork. This condition has been referred to as PSE since characteristics were similar to PSE in pork, which is misleading since both conditions were not exactly the same. Poultry researchers have preferred to refer to the condition in poultry as “PSE-like” or “Pale poultry muscle syndrome” [86, 89]. The PSE and PSE-like conditions are detrimental to the industry profitability since it affects important meat quality attributes involved in the production of value-added products and further processed meat. Affected muscles have been reported to lose their rheological properties and become unable to hold water. For example, mortadella prepared with PSE-like chicken meat has reduced water-holding capacity, altered texture, diminished emulsion stability, and required additives to restore the functional properties of normal meat [90]. In addition, poultry processors have been concerned with the appearance of PSE-like meat in fresh tray packs. The pale color affected color uniformity within the package and, thus, consumer acceptance. The occurrence of PSE-like in poultry meat has been believed to be the result of accelerated postmortem glycolysis (rapid pH decline), while the carcass was still warm [91]. In poultry, normal pH values at 15 min postmortem ($\text{pH}_{15}$) are around 6.2–6.5 [92, 93], whereas normal ultimate pH ($\text{pH}_{u}$) values are approximately 5.8 [60, 88, 94]. If the $\text{pH}_{15}$ value is low (below 6.0) when the muscle is still warm, the proteins are subject to denaturation, which leads to a decreased water-holding capacity and a lighter color of the meat.

The reasons for PSE-like condition have remained unclear, but up to 30% of broiler breast meat and up to 40% of turkey breast meat have shown this defect in commercial processing plants [95–97]. Furthermore, it has been reported that the occurrence of PSE-like meat in birds may be affected by alteration to the intracellular calcium homeostasis caused by a mutation in the ryanodine receptor gene, which is different from the ryanodine receptor gene in swine, and also depends upon the several aspects of preslaughter and postslaughter management practices [98, 99]. It is thought that the application of “snow chilling” with carbon dioxide intensified meat quality abnormalities [100]. In addition, other factors have been thought to contribute to this problem, such as heat stress during the finisher period or the preslaughter period [86], and stress and struggling before slaughter [101].

Differentiating PSE-like meat from normal meat has been based on the instrumental or visual assessment of color lightness ($L^*$). However, the cutoff value for classifying meat as PSE-like has differed among researchers. Petracci et al. [102] considered an $L^*$ value of 56 as the cutoff, while Barbut [28, 103, 104] suggested classifying turkey breast meat as PSE-like when $L^*$ values were greater than 52 at 24 h postmortem. Fraqueza et al. [105] classified breast meat as PSE-like when the $L^*$ was greater than 50 and $\text{pH}_{u}$ was less than 5.8, while Woelfel et al. [106] used $L^*$ values greater than 54 in broilers as their standards.

Using $L^*$ per se as an indicator of PSE-like condition has not been considered accurate and could be misleading because several factors influence poultry meat color. Feed ingredients used in poultry have been reported to change breast meat color (e.g., wheat-based versus corn-based diets). In addition, it has been shown that genetic selection for increased growth and breast meat yield resulted in a marked increase in muscle fiber size [107, 108] with a shift toward a greater proportion of white fibers (glycolytic) and reduced dark fibers (oxidative), which produced meat that appears
pale but still has a high pH. Muscle thickness [48, 49] and color measurement position on the fillet [109] also affects color measurement. Therefore, color, pH, and water-holding capacity should be considered when classifying poultry as PSE-like meat.

### 3.3 White striping, woody breast, and spaghetti meat

White striping, woody breast, and spaghetti meat can be collectively referred to as the myopathies of modern broiler. These nomenclatures were simply based on the appearance of the defective muscles. White striping is a condition described in broiler chickens and characterized by white striations parallel to the direction of muscle fibers on both breast fillets and thighs of broilers. White striping is considered to be an emerging issue by the poultry meat industry that could be associated with enhanced growth rate and heavier body weight in birds [110–112], especially in the age of 6–8 weeks [110], and higher fat content in broiler breast fillets [111]. The incidence of white striping was evaluated under commercial conditions, and the overall incidence in broiler breast meat was 12.0%, of which 3.1% had severe striping [113]. It is possible that the intense selection for rapid growth rate in birds could have accidentally been accompanied by the selection for inadequate capillary/fascial growth or muscle fiber defects leading to myopathic changes referred to as growth-induced myopathy [13], under which these three different myopathies can be classified.

The precise etiology of white striping has not been defined yet [114]; however, several speculations have been reported. In turkeys, Wilson et al. [80] reported that rapid growth rate may have led to the limited ability of muscle support systems leading to a condition called focal myopathy, which affected the major pectoral muscle. Ischemia could also result from a rapid growth rate and lead to muscular damage in turkeys [115]. It is also possible that reduced oxygen supply to breast meat resulted from lower capillary density in fast-growing chickens [116]. A higher growth rate could also lead to defective cation regulation in muscles leading to an increased sodium, potassium, magnesium, and calcium in muscle tissue [117]. An increased level of calcium in muscle tissue could initiate several tissue changes, including the activation of intracellular proteases or lipases resulting in myopathic changes [13, 118–120]. Kuttappan et al. [114] reported that breast fillets showing severe white striping had reduced protein content and myopathic lesions, while Petracci et al. [113] observed poor cohesion beneath the striation area.

Poultry producers started noticing and complaining about woody breast in the late 1990s [12, 121]. The woody breast muscle is usually characterized by increased firmness in all or parts of the pectoralis major muscle that can start in the live birds and can be detected by palpating the breast muscle. Sihvo et al. [121] reported that woody breast might result from fibrosis, which leads to an accumulation of interstitial connective tissue. This myopathy affects consumer acceptability and meat quality; even when trying to mitigate by diverting to further processed poultry products, woody breast meat is still required to be mixed with normal meat to maintain the quality of the further processed product [122, 123].

Spaghetti meat, or previously known as mushy breast, is the most recent emerging myopathy of breast meat in poultry. As the name implies, the breast muscle loses its structure and firmness. One distinct feature the spaghetti meat has that would differentiate it from white striping and woody breast is the loss of endomysial and perimysial connective tissue that compromises the fiber bundles cohesion, coupled with a loose connective tissue deposition [124] leading to the separation of the fascicles into “spaghetti” strings.
Sanden et al. [23] investigated the collagen of muscles with either woody breast or spaghetti meat abnormalities. They showed that collagen in woody breast muscle was a mix of thin and thick fibers, whereas spaghetti meat had thinner, fewer, and shorter. However, both myopathies generally resulted in a higher content in connective tissue (mainly in perimysium) compared to normal muscle.

Several researchers have investigated these myopathies to understand their etiology and effect on meat products quality [114, 121, 124, 125]. It is believed that cellular stress and hypoxia (ischemia) caused by muscle hypertrophy are the main triggering factors behind white striping and woody breast, in addition to being strapped within a relatively rigid connective tissue that limits the hypertrophy capabilities. However, what is interesting is that spaghetti meat, where the opposite issue is faced concerning connective tissue, started appearing. It is possible that geneticist, while trying to reduce the rigidity of the connective tissue, led to the emergence of the most recent abnormality of spaghetti meat, which is worth investigating in the future with poultry strain companies.

4. Nutrition and muscle myopathies

Researchers have investigated multiple factors that may have either contributed or helped in eliminating the emerging myopathies starting at different incubation conditions [126] all the way to management during growing [127, 128] and nutritional manipulations [129–133].

Several white muscle defects and myopathy have been reported. According to the literature, these problems spiked in the 1970s and 2000s concurrent with increased feed prices. It was suggested that producers were driven to use less expensive feed and use alternative feed ingredients (e.g., DDGS) to control costs. One significant consequence of feeding less expensive feed was that the essential amino acids (e.g., lysine and methionine) became a primary concern when formulating these diets, while the nonessential amino acids (e.g., arginine, glycine, and proline) were neglected despite their essential role in connective tissue formation, which may have contributed to the emerging of muscle defects as genetics for enhanced growth and muscle accretion were improved even further.

The spectacular advancements in genetics witnessed by the broiler industry have resulted in broilers with a higher growth rate, while the role of nutrition has become even more critical in supporting the increased growth demands of what may have become a relatively fragile animal. Profit-driven decisions about formulating feed in a least-cost manner while neglecting the essentiality of nonessential amino acids in nutrition would eventually be evidenced by increased condemnation at the processing plant and increased consumer complaints.
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