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Board Invited Review

BOARD INVITED REVIEW

A review on the woody breast condition, detection methods, and product utilization in the contemporary poultry industry

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Abstract

In recent years, the global poultry industry has been facing increasing and challenging myopathies such as the woody breast (**WB**) condition that has caused significant economic losses. Even though the etiological causes of WB myopathy are still unknown or partially understood, the intensive genetic selection for rapid-growth rates and high yields in broilers may be the main factor associated with the development of this abnormality. The severity of this anomaly and its incidence rates are associated with fast-growing and heavier broilers, especially with those from high breast yielding strains. Such WB myopathy is primarily characterized by a notorious hardness in broiler breast muscles, which exhibit morphometric and histopathological alterations coupled with physicochemical abnormalities that result in undesired sensory, nutritional, and technological properties. In this negative context, although scientists are trying to solve or reduce the prevalence of this meat quality problem, the poultry industry needs noncontact and rapid in-line methods for WB detection at the fillet and/or carcass level that could help to establish automated objective grading or sorting systems according to its severity. Another need is the development and selection of profitable alternatives for the utilization of WB meat once poultry carcasses or deboned fillets affected by this abnormality are objectively detected and sorted. Indeed, there is a need for studies to expand the industrial applications of WB meat in further processed products, optimizing the incorporation of this affected chicken meat based on sensorial, technological, and nutritional profile evaluations. Even though a better understanding of the contribution of genetic and nongenetic factors to the development of growth-related myopathies can be the main strategy to mitigate their negative effects, the poultry industry could benefit from meeting the aforementioned needs.

Key words: broiler, meat quality, myopathy, poultry products, processing, woody breast

Introduction

In the United States, poultry is widely popular by consumers and is the top protein consumed; in 2019, it is expected that Americans will consume approximately 44 Kg per capita, more than any other country (NCC, 2020). A majority of that consumption consists of boneless broiler breast meat. With rising incomes around the world, consumers usually select more premium products and this includes breast meat along with further processed products.

To meet these demands, geneticists have selected broilers for rapid growth and greater breast yield among other traits (Petracci et al., 2015). Zuidhof et al. (2014) reported that that from 1957 to 2005, broiler weights quadrupled and breast meat

Abbreviations

CVS	computer vision system
HYB	high breast yielding
NIR	near-infrared
OCT	optical coherence tomography
SBY	standard breast yielding
SM	spaghetti meat
TBARS	thiobarbituric acid reactive substances
WB	woody breast
WS	white striping

yield (*Pectoralis major*) increased by approximately 80%. In the last decade along with improvements in growth performance (including breast yield), producers have extended growth periods, all in efforts to increase the bird size. The increased size allows for more kilograms per man hour to be processed, thereby reducing cost and improving process efficiency. In the United States, the average live weight of broilers is now approximately 2.8 Kg, but almost 60% of the U.S. market is made up of broilers ranging from 2.7 to 4.5+ Kg (based on the number of head produced), a market that has doubled in size over the past 20 yr (Alonzo, 2020). Though there is some consumer demand for smaller birds and/or slower-growing birds, the large bird segment is likely to remain a significant proportion of birds produced in the U.S. market in the future.

Producing an adequate supply of broiler meat is a primary goal of the industry, but producing high-quality meat is also an important goal. The overall evolvement of the industry and shift toward a large bird market has resulted in product quality changes as well. Meat quality can be defined in many ways but mostly is related to appearance, water holding capacity, color, and texture/tenderness. These attributes affect sensory properties, or eating quality, and acceptance by consumers. Changes in quality characteristics can be directly related to the broiler and its environment, while others are related to processing methods. This review will focus primarily on the woody breast (**WB**) condition that the broiler industry has been challenged with over the past several years. It is a condition that develops in the live bird and can have negative implications on meat quality. This condition can occur in varying degrees of severity. A recent survey conducted over a 3-yr period showed that moderate and severe WB ranged from approximately 25% to 35% in high breast yielding (**HYB**) flocks with another 30% made up of mildly affected WB (de Almeida Mallmann, 2019). These severe cases can result in unnecessary condemnations, decreased meat quality and yield, changed nutritional content, and continued reduced customer/consumer acceptance, leading to losses of US $200 million per year (Kuttappan et al., 2016).

Myopathies in the Contemporary Poultry Industry

Over the past few years, the global poultry industry has been facing increasing and challenging myopathies, such as white striping (**WS**), **WB**, and spaghetti meat (**SM**). Although the etiology of these abnormalities is still unknown or partially understood, the intensive genetic selection of broilers for fast-growth rates and high yields could be the principal factor associated with the development of these myopathies (Petracci et al., 2019). At the macroscopic level, the muscles affected by these myopathies display distinctive characteristics, whereas microscopic analyses show similar histological abnormalities (Soglia et al., 2019). Currently, the most common myopathy is the WS condition that is characterized by noticeable white striations parallel to the orientation of muscle fibers on broiler breast, tenders, and thighs (Kuttappan et al., 2013). The WB condition is characterized by an abnormal hardness with pale protuberances mainly affecting the *Pectoralis major* muscle (Sihvo et al., 2014), and the most recent myopathy is the SM condition, which is characterized by an altered structural integrity of the broiler breast muscle (Baldi et al., 2018). These fillets affected by WS, WB, and SM disorders exhibit histological and physicochemical anomalies that result in unwanted sensory, nutritional, and technological properties (Soglia et al., 2016a, 2016b; Petracci et al., 2017; Baldi et al., 2018, 2019). These negative implications along with significant levels of occurrence can result in serious economic losses (Kuttappan et al., 2016; Hanning et al., 2018; Petracci et al., 2019). There is an association between WB and WS defects (Sihvo et al., 2014; Tasoniero et al., 2016; Radaelli et al., 2017; Griffin et al., 2018) that can be often detected in the same sample exerting similar influence on muscle histology and proximate composition (Kuttappan et al., 2013; Soglia et al., 2016b). Nevertheless, the strength of the positive relationship between WS and WB in terms of incidence and degree of severity is only moderate and weak as breast fillet weight increase (Bowker et al., 2019). Although these abnormalities can occur simultaneously, they may have different etiologies (Velleman, 2015). In parallel, recent and crucial challenges are the early detection and objective grading of these myopathies using noncontact and fast methods as well as the use of affected chicken meat in other processing lines such as further processed poultry products (Petracci et al., 2019).

WB myopathy

WB myopathy is one of the most challenging meat quality problems in the modern global poultry industry. It is characterized by a noticeable hardness with swollen and pale sections, and it may be covered with clear viscous fluid, as well as scattered petechiae or hemorrhages in severely affected chicken breast fillets (Sihvo et al., 2014; Mudalal et al., 2015) from modern commercial broilers intensively selected for rapid growth and high yields (Petracci et al., 2015, 2019; Hanning et al., 2018). Morphological changes due to WB myopathy start to develop in affected broilers at about 2 wk of age (Sihvo et al., 2017). This myopathy exhibits histological signs of muscle fiber degeneration, muscle fiber necrosis, lymphocytic vasculitis, lipidosis, muscle fiber regeneration, and fibrosis or interstitial accumulation of connective tissue extensively cross-linked (Sihvo et al., 2014, 2017; Velleman and Clark, 2015; Velleman et al., 2018). These changes result in chicken meat with higher levels of fat, collagen, moisture, and thus, lower levels of protein and ash (Soglia et al., 2016a, 2016b; Wold et al., 2017; Velleman et al., 2018; Baldi et al., 2019). Furthermore, WB has resulted in downgrades, condemnations, and changes in meat quality (Tijare et al., 2016; Hanning et al., 2018; Petracci et al., 2019).

One of the most critical negative implications of WB anomaly is the poor functional properties exhibited mainly by severely affected breast fillets (Tijare et al., 2016; Petracci et al., 2019). Muscle fiber degeneration and resultant changes in muscle composition have led to impaired technological properties, which are reflected in low further processing yields, reduced water holding capacity, and textural changes (Mudalal et al., 2015;

Soglia et al., 2016b; Kuttappan et al., 2017; Bowker et al., 2018; Dalgaard et al., 2018).

There are live production factors that have an effect on the incidence and severity of WB condition in broiler breast fillets, such as the genotype (high > standard breast-yield) (Petracci et al., 2013; Mazzoni et al., 2015), gender (males > females) (Trocino et al., 2015; Brothers et al., 2019), growth rate (higher > lower) (Sihvo et al., 2014; Kuttappan et al., 2017), and age (older > younger) (Kuttappan et al., 2017; Radaelli et al., 2017; Sihvo et al., 2017) or slaughter weight (heavier > lighter) (Cruz et al., 2017; Papah et al., 2017). Thus, it would be suitable to consider these factors when evaluating the WB myopathy.

Factors involved in the development and incidence of WB myopathy

The intensive genetic selection of broilers for rapid growth rates and greater breast yields may be the main factor associated with the development of current myopathies such as the WB condition (Petracci et al., 2015, 2019; Kuttappan et al., 2016). In this regard, Hubert et al. (2018) concluded that WB myopathy is a possibly polygenic, complex syndrome, with molecular similarities to neoplastic disorders. Lilburn et al. (2019) stated that the evident increase in the occurrence of modern myopathies such as WB abnormality is related to multiple causative factors, such as genetics, management, and muscle growth and development. Even though the etiological causes of WB disorder are still unknown or partially understood, there are several live broiler production factors, such as broiler strain, gender, and age or body weight at slaughter, that can be associated with the incidence and severity of WB condition; therefore, those factors may need to be considered when performing WB-related studies.

Strain

Rapid growth rates and greater breast yields in commercial broiler strains have been related to the occurrence of emerging myopathies such as WB condition (Sihvo et al., 2014). Indeed, there are studies reporting that HBY hybrids present higher degrees of myopathic anomalies along with altered meat quality attributes in comparison with standard breast-yielding (**SBY**) strains (Petracci et al., 2013; Mazzoni et al., 2015). Similarly, Bailey et al. (2015) report a higher incidence of WB in an HBY strain compared with a moderate-yielding strain; nevertheless, they also argue that there is a considerable nongenetic component associated with breast muscle myopathies highlighting that environmental and/or management factors might contribute to more than 90% of the variance in the incidence of WB abnormality. On the other hand, higher frequency of WB disorder has been reported for broilers produced from an HBY strain male compared with broilers produced from a fast-growing strain male, which suggest that male genetic background and growth rate play a significant role in the development of WB syndrome (Livingston et al., 2019). In fact, Velleman and Clark (2015) suggest that the etiology of the WB disorder could vary between fast-growing commercial broiler strains.

Gender

There are reports confirming that male broilers present a higher WB occurrence and severity with differentiated biological characteristics that could make them more susceptible to WB condition than female broilers (Trocino et al., 2015; Brothers et al., 2019). Indeed, Trocino et al. (2015) found that the incidence of WB condition was affected by sex factor and it was approximately two times higher in male broilers (16.3%) compared with females (8.0%), which could be related to the fact that male broilers grow faster and bigger than female broilers. In this regard, a more advanced and detailed study was conducted by Brothers et al. (2019), who reported that a total of 260 genes were differentially expressed between male and female broilers from which 189 were upregulated in males (103 genes located on the Z-chromosome). There was an increased expression of genes involved in fat metabolism, oxidative stress response, anti-angiogenesis, and connective tissue proliferation in male birds. They concluded that there are biological features in male broilers that could make them more vulnerable to WB anomaly.

Live weight/age at slaughter

The etiology of contemporary abnormalities may not be related to a single causative factor; nevertheless, any factor that decreases body weight or breast muscle accretion would probably reduce the frequency of these defects (Lilburn et al., 2019). Thus, live weight and age at the slaughter of commercial broiler chickens are important factors to be considered when analyzing current myopathies. A recent study established that WB disorder displays an age-dependent gene expression pattern in fast-growing broiler strains, with molecular signatures and phenotypic markers becoming more noticeable in older birds (Hubert et al., 2018). Results from histological evaluations have shown that myodegeneration progress related to the development of broiler breast anomalies such as WB myopathy is associated with the birds age at slaughter (Papah et al., 2017; Radaelli et al., 2017; Sihvo et al., 2017; Griffin et al., 2018). Indeed, it has been reported high levels of occurrence and severity of WB in older broiler chickens (Kuttappan et al., 2017), which is consistent with another study showing that the prevalence of broilers with muscle fiber degeneration increases with age (Radaelli et al., 2017). On the other hand, it has also been reported that the incidence and severity of modern myopathies such as WB condition increase with an increase of slaughter weight of broilers (Cruz et al., 2017; Papah et al., 2017). However, there is also a report showing that broilers affected by WB condition do not necessarily present higher body weights during the rearing period, particularly after about 5 wk of age (Kawasaki et al., 2018); in fact, Bailey et al. (2015) found that the estimated heritability for WB disorder as well as the genetic and phenotypic correlations between this anomaly and body weight was low.

Morphometric changes in breast fillets affected by WB myopathy

Even though there are morphometric changes in the breast muscle intrinsic to the selection of broilers for rapid growth and greater yields (Godfrey and Goodman, 1956; Reddish and Lilburn, 2004; Griffin et al., 2018), significant physical dimension changes have been found in broiler breast fillets with WB myopathy compared with normal samples (Mudalal et al., 2015; Zambonelli et al., 2016; Kuttappan et al., 2017). There is a consensus on the argument that occurrence and severity of current muscle abnormalities such as WS, WB, and SM are linked to thicker and heavier broiler breast fillets (Mudalal et al., 2015; Kuttappan et al., 2017; Baldi et al., 2018; Petracci et al., 2019). Particularly, samples affected by WB and WB/WS exhibit higher height at cranial, medial, and caudal sections of the breast in comparison with normal broiler breast dimensions (Mudalal et al., 2015; Zambonelli et al., 2016;

Kuttappan et al., 2017). These findings are consistent with macroscopic characteristics of breast fillets with WB disorder that present bulged areas or ridge-like bulges at the caudal end (Sihvo et al., 2014; Griffin et al., 2018), which could be used as a discriminant parameter to identify broiler breast fillets exhibiting WB abnormality (Mudalal et al., 2015). Griffin et al. (2018) also reported WB characteristics in the *Pectoralis minor* muscle in 46-d-old broilers, such as the ridge-like protuberance at the caudal region. Furthermore, some authors assert that broiler breast width and length increase with the severity of WB condition (Zambonelli et al., 2016; Griffin et al., 2018); however, there are few authors who did not find significant differences in these dimensions between normal and WB fillets (Mudalal et al., 2015). It could be inferred that differences in breast fillet height, length, and width between normal and affected samples may be the result of multiple WB-related muscle alterations. The most recurrent changes start with the muscle hypertrophy due to the selection of broilers for fast growth and higher yields coupled with an irregular growth of supportive connective tissue that derives in a compromised blood supply and hypoxia, which may speed up the development of oxidative stress that would contribute to tissue inflammation and myodegeneration (Petracci et al., 2019). In addition, there is variability in size, shape, and diameter of the muscle fibers (Sihvo et al., 2014, 2017), and the high occurrence of WB disorder could be associated with pathological mechanisms involving edema and inflammation (Petracci et al., 2019).

Detection and Classification of WB Myopathy

The identification, characterization, and categorization of broiler breast fillets by WB severity are commonly estimated by subjective visual and tactile evaluations or laborious and time-consuming instrumental techniques (Chatterjee et al., 2016; Tijare et al., 2016). Thus, one of the most urgent needs in the global poultry industry is the objective and rapid detection and sorting of chicken with WB defect using nondestructive methods (Petracci et al., 2019). Recent studies have been conducted to evaluate objective and fast techniques for identification and grading of breast fillets with WB, such as the computer vision system (**CVS**; Geronimo et al., 2019), the near-infrared (**NIR**) spectroscopy (Wold et al., 2017, 2019; Geronimo et al., 2019), and the fusion of optical coherence tomography (**OCT**) and hyperspectral imaging (Yoon et al., 2016). However, these methods cannot anticipate potential problems caused by WB anomaly on preceding operations such as portioning and deboning as reported by Hanning et al. (2018). Therefore, the study of the objective detection and classification of broiler carcasses by WB severity would be a reasonable option. Alternatively, biochemical and histological assays could be applied accurately; nevertheless, they may involve the carcass removal from the processing line (Petracci et al., 2019).

Subjective methods

Tactile and visual or macroscopic evaluations are the most typical subjective methods to identify and characterize broiler breast fillets with WB condition. Sihvo et al. (2014) carried out a detection and characterization of WB disorder using a palpation assessment to determine the degree of hardness of breast fillets in addition to macroscopic evaluations of shape, color, consistency, and presence of exudate or hemorrhages or both. Later, Tijare et al. (2016) also applied the tactile evaluation to categorize breast fillets based on the level of hardness or WB condition using a 4-point scoring scale (0 = normal, 1 = mild, 2 = moderate, and 3 = severe). Similar scoring scales with some modifications have been widely used in several studies. Kuttappan et al. (2016) pointed out that it is imperative to score fillets under similar conditions, such as postmortem time, surface wetness, and sample temperature as well as humidity, lighting, and temperature in the room. They also assert that it is more complex to define the scoring scale for WB myopathy in comparison to the visual scoring applied for WS condition. In fact, Bowker et al. (2019) conclude that visual characteristics (WS, fillet shape, and hemorrhaging) could not be accurate indicators of WB incidence and severity since they might cause high misclassification rates. Thus, the standardization of the scoring system to detect, characterize, and classify fillets by WB condition would be required. A recent study has been carried out to provide a standardized 3-point scoring scale (no, moderate, and severe WB) for the classification of WB myopathy based on the hardness of *Pectoralis major* muscle determined by palpation, which correlated with meat quality characteristics that are known to be altered by this disorder (Dalgaard et al., 2018). Although a sorting system based on tactile traits of broiler breast fillets could provide an accurate evaluation of the WB defect (Bowker et al., 2019), this scoring process would depend on the knowledge and expertise of the analyst. Therefore, objective, rapid, and nondestructive in-line methods are required to identify and sort more accurately broiler fillets with WB abnormality.

Objective methods

Objective methods have been applied to detect and characterize the WB myopathy in broiler breast fillets, such as instrumental texture analyses (Mudalal et al., 2015; Chatterjee et al., 2016; Soglia et al., 2017; Dalgaard et al., 2018; Sun et al., 2018; Baldi et al., 2019), and meticulous evaluations, such as metabolomics analysis and differential gene expression and pathway analysis (Mutryn et al., 2015; Abasht et al., 2016; Zambonelli et al., 2016). Petracci et al. (2019) suggest that the application of biomarkers to detect myopathies in live broilers using biological specimens such as plasma could be a considerable alternative for WB diagnosis. However, there is still a need for fast and objective in-line identification of WB myopathy for automatic quality classification (Wold et al., 2017).

The aforementioned objective techniques may involve labor-intensive and time-consuming procedures of sample preparation and analysis. Thus, advanced and rapid methods have been assessed to detect and grade the WB myopathy in broiler breast fillets (Yoon et al., 2016; Wold et al., 2017, 2019; Geronimo et al., 2019). Yoon et al. (2016) studied the potential of advanced techniques such as OCT and hyperspectral imaging to measure subsurface microstructure and optical properties of broiler breast fillets with WB myopathy. These authors concluded that although the capability of these methods to detect the WB defect was limited, a fusion of OCT and hyperspectral imaging is suggested to rapidly and accurately identify and grade broiler breast fillets with WB disorder. Later, a NIR spectroscopy method was evaluated to detect and classify WB abnormality in broiler breast fillets; it was applied on-line in an industrial hyperspectral imaging scanner and could sort samples passing by on a conveyor belt based on protein content (Wold et al., 2017). However, Wold et al. (2019)

pointed out that the depth and location on the breast fillets where the NIR measurement is carried out are critical due to the heterogeneous distribution of the WB abnormality. The authors also concluded that the principal reason why NIR spectroscopy is successful at discriminating between normal and WB fillets is that NIR can measure both the protein content and how loosely the water is bound to the muscle matrix, which are two established markers for WB condition. Similarly, Geronimo et al. (2019) suggested that NIR spectroscopy and CVS can be used as fast and nondestructive techniques for detecting and grading the WB disorder. Nevertheless, they also affirmed that CVS and NIR spectroscopy have advantages and disadvantages, and the application of these advanced techniques is rigorously associated with the specialist knowledge and solution setup.

Potential in-line control technologies for WB detection and grading

One of the current contributing factors to the economic losses in the poultry industry worldwide is the increased labor cost for the detection and grading of WB myopathy, which is typically performed by manual palpation based on a subjective scale that depends on the training, sensitivity, and knowledge of the scorer (Wold et al., 2017; Sun et al., 2018; Geronimo et al., 2019). In fact, Petracci et al. (2019) assert that the weakness of the methods such as tactile evaluation for identifying the WB defect is the main justification to evaluate rapid and nondestructive techniques for WB detection. These authors also highlight important contributing factors to the financial losses in the poultry industry caused by the WB anomaly, such as condemnation/trimming, reduced yield and value, as well as decreased consumer acceptance due to unwanted sensory properties. Thus, one of the most immediate and current needs in the global poultry industry is the development of objective, reliable, noninvasive and rapid in-line methods to detect WB myopathy, so that affected broiler fillets can be automatically sorted out from the processing lines (Yoon et al., 2016; Wold et al., 2017, 2019; Petracci et al., 2019). Addressing this need, some attempts have been recently made with positive results as well as limitations. Yoon et al. (2016) suggest an amalgamation of OCT and hyperspectral imaging techniques for fast and nondestructive identification and grading of boneless, skinless broiler breast fillets with WB anomaly. However, these authors also report some disadvantages of both techniques. One of the disadvantages of the OCT method would be related to the sample, since the excessive adipose and connective tissues including noticeable white stripes would make the detection of WB defect more complex and complicated due to normal breast fillets could also have excessive adipose and connective tissues on their surfaces after trimming. In addition, the scanning time of a broiler breast fillet would be very long. With respect to the hyperspectral imaging, results from the spectral analysis revealed that there was no clear difference between the mean spectra of normal and WB samples (Yoon et al., 2016).

The application of NIR spectroscopy as a potential method for the detection and grading of WB defect has also been evaluated. Wold et al. (2017) conducted a research study to assess if a NIR imaging system can be applied in-line to identify and categorize the WB abnormality in broiler breast fillets based on NIR spectra only and NIR spectra coupled with the estimated concentrations of protein showing high levels of accuracy (99.5% to 100%). The authors used an optimal decision limit or threshold of 21.9% (protein); fillets below 21.9 were sorted as WB due to the low protein content, which is a distinctive feature of broiler breast fillets with WB condition. This approach was also tested in-line using the protein calibration that was implemented in the NIR scanner showing levels of WB incidence of 0.1%, 6.6%, and 8.5% for volumes of 9,063, 6,330, and 10,483 fillets, respectively. Nevertheless, the authors also reported that the estimation of protein content could vary if the NIR system measures deeper than 1 cm. In addition, they pointed out that the regression model included neither WB samples nor spectral shifts because of the degree of water binding in the muscle. Concerning this matter, Wold et al. (2019) stated that the depth and location on the breast fillets where the NIR measurement is performed are important because the morphological changes in the muscles affected by WB anomaly are unevenly distributed throughout the fillets. They also emphasize that the primary reason why NIR spectroscopy is effective at discriminating between normal and WB fillets is that NIR can measure both the protein content and the degree of water binding in the muscle, which are two established markers for WB syndrome. However, the authors found that both markers did not differentiate well between fillets exhibiting moderate and severe levels of WB condition, which can be attributed to a weak correlation between hardness and either protein content or bound water index, and the heterogeneous nature of the WB myopathy.

Recently, Geronimo et al. (2019) recommended that CVS and spectral information from the NIR region can be used to identify and categorize the WB abnormality. They reported an accuracy of 91.8% using a classification approach that involves a combination of image analysis and support vector machine model, whereas the NIR spectral information displayed 97.5% accuracy. However, these authors also reported some drawbacks of both methods. They argue that CVS outcomes depend on the quality of images, which could be influenced by external factors such as ambient illumination or sample handling. In fact, another study highlights that vision color would not be adequate to detect the WB condition (Yoon et al., 2016). Bowker et al. (2019) also point out that visual characteristics might not be accurate indicators of WB incidence and severity since they could lead to significant misclassification rates. On the other hand, Geronimo et al. (2019) suggested that the NIR spectroscopy technique has some limitations, such as the lower sensitivity for detecting smaller food constituents and the complexity of selection of spectral data processing, as well as time-consuming calibration procedures.

Regardless of the effectiveness of aforementioned objective and rapid in-line methods, the effect of skin on the detection of the WB condition remains unknown because those techniques were developed for boneless, skinless broiler breast fillets. Therefore, there would be a limitation in the application of these methods on skin-on carcasses (Petracci et al., 2019). On this subject, Geronimo et al. (2019) asserted that inadequate sample handling can have a negative effect on the CVS performance for WB detection because skin sections from carcasses could be interpreted as striations or repetition patterns. Similar to Wold et al. (2017) with respect to the benefits of a potential automatic identification and classification of WB in breast fillets, an in-line detection and automatic sorting of broiler carcasses with WB condition would be also a useful tool for mapping occurrence rates of WB defect at a large scale and provide information upstream to production chain in order to identify and remove potential causes of WB myopathy linked to production factors. Vision grading systems for poultry carcasses have been commercially implemented for many years to identify carcass defects using image analysis, yet there is limited research available on its use to detect WB condition in broilers (Hanning et al., 2018).

Potential application of image analysis to predict WB condition

The poultry industry has had an increasing interest in the use of image analysis because of its clarity, low-cost, and high speed of inspection to reduce or solve problems of subjective visual evaluations and time-consuming analysis of laboratory (Barbin et al., 2016). Indeed, automatic inspection systems are based on camera and computer technology (computer vision), which include image processing and analysis. Currently, there are companies that offer advanced in-line vision grading systems, which can evaluate the whole carcass or parts of slaughtered broilers and sort them conveniently at distinct locations in the processing plants.

Among the studies carried out for selection and inspection of poultry carcasses based on image analysis are the discrimination of abnormal carcasses from normal carcasses (Park and Chen, 1994), real-time examination of broiler carcasses with fecal contaminants (Yoon et al., 2011), and in-line wholesomeness inspection of broilers (Chao et al., 2002, 2010). Martel and Paris (2007) also developed an artificial vision method and system for the inspection and sorting of poultry carcasses. These authors proposed a system, including image acquisition and processing, verification of processed digital images to detect the presence of at least one defect (missing carcass, missing leg, missing wing, hole in a leg, and skin condition), and classification of the carcass according to predefined quality parameters. The image analysis has also been studied to perform other important tasks in the poultry industry. For example, Mollah et al. (2010) used the image analysis to estimate the live weight of broilers at various stages of their growth with promising results to assist producers in the tedious weighing operation. The authors examined their collected pictures using an imaging software to define the chicken body surface section and generate a linear equation to calculate the weights of the bird.

Chao et al. (2010) reported that the use of the multispectral system, which mechanically identifies the region of interest on broiler carcass images, can be incorporated into commercial high-speed inspection systems. Hanning et al. (2018) developed a method for detecting WB in broiler carcasses with intent to use with existing vision grading technology. One major region of interest in this work was the caudal region of the breast area on the carcass, which showed strong a relationship to moderate and severe levels of WB as indicated by hand palpation scoring and instrumental evaluation of hardness. Caldas-Cueva (2020) developed strong predictive models where over 90% of broiler carcasses (based on multiple strains, gender, and ages) were classified correctly as WB or normal.

Barbin et al. (2016) asserted that the poultry processors might benefit from a protocol that can predict differences in distinctive color attributes or even categorize samples with quality issues in accordance with visual characteristics. According to Sihvo et al. (2014), broiler breast muscles exhibiting WB characteristics were significantly paler and were covered with a narrow layer of clear, viscous material, as well as spots of hemorrhages. These superficial features that show specific colors could be obtained from image processing and analysis, which might also be used to determine whether the color difference of specific sections on broiler carcass or fillet surfaces are related to WB features. However, Yoon et al. (2016) found that the visual difference between normal and severe WB fillet images was not significant, which suggests that color vision would not be appropriate to detect the WB abnormality.

Researchers have started to apply techniques based on image analysis to detect WB in broiler breast fillets (Yoon et al., 2016; Geronimo et al., 2019). Most recently, Yoon et al. (2020) described a system to determine the shape characteristics of boneless fillets, including the bending properties of the fillet (based on shape) in efforts to identify and sort WB fillets in the processing plant. Fillets that presented with WB showed less ability to bend due to the increased fillet hardness than those that were normal that presented with flexible fillets.

Potential Use of Chicken Meat with WB Condition

Another urgent need in the global poultry industry is the development and selection of cost-effective alternatives for the use of WB meat once the carcasses or breast fillets affected by this myopathy are detected and classified (Petracci et al., 2019; Santos et al., 2019) due to these abnormal fillets showing unwanted nutritional and sensorial characteristics that can negatively impact the consumer acceptability (Petracci et al., 2015, 2017). Indeed, the WB anomaly has a detrimental effect on broiler breast meat quality by changing functional properties of the affected meat that exhibits an altered composition, such as higher levels of fat, collagen and moisture, and lower levels of protein and ash (Soglia et al., 2016a, 2016b; Wold et al., 2017; Velleman et al., 2018; Baldi et al., 2019). In that context, the preparation of further processed products using chicken meat affected by WB abnormality could be a possible alternative. The chemical composition can be modified during formulation (Petracci et al., 2015) and further processing operations can modify meat properties (Aberle et al., 2001), which could mitigate or minimize undesirable effects on final product quality (Petracci et al., 2019) providing processors options to face this meat quality problem. In this regard, some attempts have been made to evaluate the use of WB meat in poultry meat products, such as marinated whole muscle product (Mudalal et al., 2015; Soglia et al., 2016b; Tijare et al., 2016; Bowker et al., 2018; Maxwell et al., 2018), sausages (Qin, 2013; Madruga et al., 2019), nuggets (Qin, 2013), and patties (Sanchez-Brambila et al., 2017; Santos et al., 2019). In addition, functional properties of meat batters prepared from WB meat have been evaluated (Xing et al., 2017a, 2017b; Chen et al., 2018). However, it is still necessary to expand potential applications of chicken meat with WB condition in further processed products.

One of the most common methods of adding value to poultry meat is the marination process; however, various studies have demonstrated that the negative effects of WB condition on quality attributes of breast fillets with this myopathy are not eliminated by vacuum-tumbling marination (Mudalal et al., 2015; Soglia et al., 2016b; Tijare et al., 2016; Bowker et al., 2018; Maxwell et al., 2018). The profound degeneration of muscle fibers accompanied by fibrosis, lipidosis, and alterations in fiber membrane integrity caused by the WB anomaly would explain the poor ability to bind water observed in WB fillets (Soglia et al., 2016b; Petracci et al., 2019). In fact, changes in the chemical composition (Soglia et al., 2016a, 2016b; Wold et al., 2017; Baldi et al., 2019) and reduction in muscle fiber number (Sihvo et al., 2014; Mazzoni et al., 2015) play an important role in the reduction of water holding capacity in breast fillets affected by WB defect. On the other hand, it has been demonstrated that the severity of WB myopathy depends on the muscular depth and location because the WB defect is heterogeneously distributed throughout the breast fillet, and the superficial section is more affected (Soglia et al., 2017; Bowker et al., 2018; Baldi et al., 2019; Wold et al., 2019). Thus, it has been suggested the portioning of downgraded breast fillets to separately process the superficial and deep layers (Bowker et al., 2018; Petracci et al., 2019). However, remaining surface portions along with potential costs generated by the portioning process could be still a problem; therefore, it may require further processing solutions for alleviating negative implications on product quality caused by WB condition.

The first study found in this review related to the preparation of further processed meat products using broiler breast fillets with WB condition was conducted by Qin (2013), who suggested that percentages of WB meat could be used in sausage and chicken nuggets without causing a perceived quality defect. The formulation that Qin (2013) used to prepare the chicken nugget made from ground WB meat included food additives, such as whole egg liquid, soy protein isolate, salt, and phosphate, which could have masked the effect of WB myopathy on this product by the interaction between WB meat and those additives that can modify functional properties, such as water holding capacity and texture attributes of cooked meat products (Sanchez-Brambila et al., 2017). For example, soy proteins are commonly used as binders in products, such as meat patties, meatloaves, and sausages (Barbut, 2015). Thus, the study of the effect of WB condition on further processed products using only chicken meat at varying degrees of WB severity may be a suitable approach to evaluate the real negative impact of this meat quality problem and subsequently optimize formulas for industrial applications including adequate ingredients.

In another study, Sanchez-Brambila et al. (2017) evaluated the effect of WB anomaly on the texture and cook loss of chicken patties made from ground broiler breast fillets. These authors reported that there were no significant differences in shear force and cook loss between normal and WB cooked patties. They also observed that average scores for sensory attributes of hardness, cohesiveness, juiciness, fibrous, and rate of breakdown were not significantly different between normal and WB patties; however, WB patties showed the lower intensity of springiness and chewiness than normal samples. Thus, this research suggests that unwanted differences in sensory texture features between intact cooked normal and WB fillets can be minimized in a ground product. However, the benefits of grinding broiler breast fillets with WB abnormality may be related to several factors such as the meat particle size. Qin (2013) reports that ground chicken nuggets containing WB meat (replacing the 30% of the total lean meat in the formulation) processed in a pilot plant using a grinder with a 3-mm plate showed higher cook loss levels compared with the control, whereas Sanchez-Brambila et al. (2017) did not find significant differences in cook loss between normal and WB cooked patties prepared using a grinder with a chopper plate of approximately 6-mm square hole. Madruga et al. (2019) also observed that although the cook loss values showed increasing trends for WB sausages produced using a grinder with a 10-mm plate, there was no significant difference compared with normal samples. In contrast, Chen et al. (2018) found significant differences in cook loss levels between normal and WB meatballs processed using a grinder with a 6-mm plate. Because of these contrasting results in terms of cook loss levels coupled with a large standard deviation of this parameter for WB patties found by Sanchez-Brambila et al. (2017), additional research is needed to confirm the effect of WB myopathy on cook loss levels of ground products prepared at different meat particle sizes.

Recent studies have been conducted by Santos et al. (2019) and Madruga et al. (2019) who assessed the influence of WB anomaly on quality parameters of emulsified chicken patties and sausages, respectively. Santos et al. (2019) evaluated the effect of WB on physicochemical and sensory characteristics of emulsified chicken patties during frozen storage for 90 d. This research demonstrated that there was a significant effect of storage time and WB myopathy on the instrumental color parameters of chicken patties, exhibiting the WB samples paler colors with a reduction in redness, which could be attributed to the typical pale color of WB fillets (Sihvo et al., 2014). Santos et al. (2019) also reported a significant increase in the instrumental hardness that was observed in normal and WB chicken patties over storage time, where the normal samples were tougher in comparison with WB samples. These authors also claimed that 2-thiobarbituric acid reactive substances (**TBARS**) values for WB patties were higher than those for normal samples at the first 30 d and at the end of frozen storage; however, peroxide index, *p*-anisidine index, and carbonyl content values for WB samples were lower than those for normal patties at the end of the storage period. Despite these significant alterations in lipid and protein oxidation indicators throughout the storage period, Santos et al. (2019) did not find a significant effect of WB anomaly on sensory acceptability (odor and color liking). They also observed that a mixture of 50% of normal breast fillets with 50% of WB fillets may be the most suitable combination for the development of emulsified chicken patties. In this line, Madruga et al. (2019) suggested that chicken meat with WB defect could be used to produce chicken sausages, mixed with or without normal chicken meat, because there were no significant differences in the water holding capacity levels; L*, a*, and b* color parameters; and TBARS levels. Furthermore, there were no significant differences in texture profile analysis parameters as well as sensory attributes, the acceptability, and purchase intention between normal and WB chicken sausages. However, they also reported that sausages prepared using entirely WB meat showed a lower amount of protein and higher values of moisture and collagen content in comparison with normal sausages, which indicates that there is a significant effect of WB condition on the chemical composition of meat products. Therefore, appropriate ingredients may be used to compensate alternations caused by WB on the chemical composition and oxidative stability of meat products due to it has been reported that WB fillets are also more susceptible to oxidation (Soglia et al., 2016a).

However, Chen et al. (2018) affirmed that WB meat may not be appropriate to produce gel-type meat products because WB meat showed inferior functional properties through processing. Their research highlighted defects caused by WB condition, such as decreased ability to bind water, increased water purge during gelation, and impaired textural properties that were observed in meatballs prepared from WB meat. These findings are consistent with those reported by Xing et al. (2017a, 2017b) who also suggested that WB meat could not be suitable to produce gel-type meat products with low salt levels. The use of high salt levels (≥3%) may improve the quality of WB products; however, it is not a commercial alternative due to health concerns associated with high-salt foods (Xing et al., 2017b). Therefore, the effectiveness of the utilization of WB meat without causing a perceived quality defect in further processed products could be associated with several factors, such as the replacement rate of normal chicken meat in the formulation, the meat particle size (whole muscle, ground, and coarsely or finely chopped), and the use of nonmeat ingredients, particularly the concentration of salt.

In summary, poultry producers and processors are expressing growing concerns about the incidence of emerging broiler breast myopathies such as WB condition that have been causing important economic losses to the poultry industry worldwide. The intensive improvements in genetic selection for fast growth and high yields in broiler chickens could be the principal factor related to the development of these poultry meat quality problems. Even though the etiology of WB condition is still unknown or partially understood, WB fillets exhibit morphometric and histopathological alterations along with physicochemical abnormalities that result in impaired sensory, nutritional, and technological properties. These negative implications along with increasing levels of WB prevalence for moderate and severe cases can negatively affect consumer preference. Thus, one of the most urgent challenges and areas for further research is the development of objective, noncontact, and fast in-line inspection methods and systems to detect and sort broiler carcasses or fillets affected by WB myopathy. Another area for further research is the development of cost-effective alternatives for the utilization of WB meat. For instance, the expansion of applications of WB fillets in further processed products is needed based on technological, sensorial, and nutritional profile assessments. Additionally, the optimization of the inclusion of WB meat into product formulations needs to be investigated, considering the influence of factors, such as the meat particle size and the addition of adequate food additives for industrial applications. The poultry industry could mitigate the negative effects of the WB condition on meat quality by overcoming these challenges, even though a better comprehension of the influence of genetic, environmental, nutrition, and management factors on the development of these growth-related myopathies can be the main strategy for that purpose.

Conflict of interest statement

The authors declare no real or perceived conflicts of interest.

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