The Influence of the Season and Market Class of Broiler Chickens on Breast Meat Quality Traits

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ABSTRACT The influence of the season and market class of broiler chickens on breast meat quality traits was determined on a total of 18 flocks reared and processed under commercial conditions. According to the Italian poultry production system the following classes of birds were considered: light size (1.2 kg of carcass weight; n = 90) and medium size (1.8 kg of carcass weight; n = 90), represented by females slaughtered at 40 and 52 d old, respectively, whereas heavy size were 57-d-old male broilers (2.4 kg of carcass weight; n = 90). After slaughter, 15 carcasses per flock (n = 270) were randomly collected during winter (n = 135) and summer (n = 135) seasons and used at 24 h postmortem to determine breast (pectoralis major) meat color (lightness, redness, and yellowness), pH, drip and cook loss, as well as Allo-Kramer (AK) shear values. Furthermore, pectoralis minor muscles were used to determine lipid, protein, moisture, and ash content. Finally, because the flocks included white- and yellow-skinned broilers, the color of the carcass skin was measured to assess the relationship between skin and raw breast meat color. With regard to the season, breast meat from birds slaughtered during summer exhibited a paler and less red color, lower pH, higher drip and cook losses, lower AK-shear, and a higher content of moisture and a lower content of protein and ash. In respect to medium and heavy birds, light broilers produced breast meat with higher values of redness, lower pH and cook loss, higher AK-shear values, and a higher content of moisture and ash. Finally, a positive correlation (r = +0.92; $P \leq 0.001$) between skin and breast meat yellowness was found. These results indicate that during summer, broiler breast meat undergoes a depression of its functionality and quality. Moreover, the market class of birds also determined some differences in breast meat quality attributes.

Key words: season, broiler chicken, market class, breast meat quality

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INTRODUCTION

The dramatic changes in the market forms for poultry in recent years, from a predominantly whole bird commodity to modern highly diversified industry focused on cut-up, deboned meat, and ready-to-eat further processed products, has resulted in a change of quality expectation. The major poultry meat quality attributes are appearance, texture, juiciness, flavor, and functionality (Fletcher, 2002). With trends increasing toward in further processing, meat functionality has increased in relative importance, especially because of its key role in determining the sensory quality of complex ready-to-eat products. Water-holding capacity (**WHC**) and water-binding capacity of meat are also critical attributes for successful product formulation and process control. Traditionally, less consideration has been given to the functional properties of poultry meat such as WHC and texture (Barbut, 1998). Loss in functionality of poultry breast meat is often associated with pale meat and is often referred to as pale, soft, exudative (**PSE**) or PSE-like (Bianchi et al., 2005). Some researchers have indicated that significant variations in breast meat color exist during processing as well as at the retail level, depending on the flock, type of birds, processing factors, and seasonality (Barbut, 1997; Owens et al., 2000; Wilkins et al., 2000; Woelfel et al., 2002; Petracci et al., 2004; Bianchi et al., 2006). Genetics also has been reported as a relevant factor for determining quality characteristics of the meat (Berri et al., 2001; Debut et al., 2003). Some factors other than biological variations have been considered to affect poultry meat quality. The environmental conditions during transport and holding of the birds have been shown to affect processing yield and meat quality (Northcutt, 1994; McKee and Sams, 1997; Petracci et al., 2001; Bianchi et al., 2004). During the summer months, high antemortem temperatures can affect muscle acidification, or rigor development, and subsequent meat quality via adrenal or other physiological responses or simply by fatigue of the birds (Lambooij, 1999; Warriss et al., 1999).

The production system of broiler chickens in Italy is mainly characterized by the separate rearing of females and males to obtain 3 different market classes of birds:

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light-size, medium-size, and heavy-size broilers. The light birds are females reared up to 1.5 to 1.7 kg of live weight (37 to 40 d old) to yield 1.0- to 1.2-kg carcasses for rotisserie-type products; medium birds are usually females (but might also be males) reared up to 2.3 to 2.5 kg of live weight (45 to 52 d old) to produce 1.5- to 1.6-kg carcasses mainly used for cut-up products. Finally, heavy birds are male broilers reared up to 3.4 to 3.6 kg of live weight (54 to 58 d old) to yield 2.5- to 2.6-kg carcasses for the production of cut-up and further processed products. Furthermore, according to special regional consumer preferences, the carcass skin color can be white (southern Italy) or yellow (northern Italy) by using natural or synthetic pigments in bird feed. Because of the differences in sex and age at slaughter, meat quality characteristics of these classes of chickens might differ from each other.

Therefore, a study was conducted to determine the influence of the season and market class of broiler chickens on breast meat quality traits.

MATERIALS AND METHODS

Animals and Experimental Design

The study was conducted on a total of 18 flocks of broiler chickens (Ross 508 strain) reared under commercial conditions in 3 different farms. The birds varied in sex and age at slaughter according to the Italian poultry production system whereby light (1.2 kg of carcass weight; n = 90) and medium (1.8 kg of carcass weight; n = 90) classes of birds were represented by females slaughtered at an average age of 40 and 52 d, respectively, whereas heavy male broilers (2.4 kg of carcass weight; n = 90) were 57 d old. Moreover, according to the Italian regional market need, 8 of the considered flocks were fed corn-soybean multiphase diets (total xanthophyll content: 12 to 15 mg/kg of feed) or wheat/sorghum-soybean diets (total xanthophyll content: 2 to 3 mg/kg of feed) to obtain yellow- or white-skinned carcasses, respectively. Prior to slaughter, broilers were subjected to a total feed withdrawal of 8 to 12 h, including a holding time at the processing plant of 2 to 3 h. The birds were subsequently processed under commercial conditions using electrocution (120 V, 200 Hz) as the stunning system. After chilling, 15 carcasses per flock (n = 270) were randomly collected and used for subsequent meat quality evaluation during winter (n = 135) and summer (n = 135) seasons. At 24 h postmortem the color of the carcass skin was measured and breast (pectoralis major) meat used to determine color [lightness (**L***), redness (**a***), and yellowness (**b***)], pH, drip loss, cook loss, and Allo-Kramer shear values of cooked meat. Finally, pectoralis minor muscles were frozen for subsequent determination of lipid, protein, moisture, and ash content.

Analytical Methods

Color Measurements. The CIE (1978) system color profile of L*, a*, and b* was measured by a reflectance colorimeter (Minolta Chroma Meter CR-300, Minolta Italia S.p.A., Milano, Italy) using illuminant source C. The colorimeter was calibrated throughout the study using a standard white (reference number 1353123. Y = 92.7, x = 0.3133, and y = 0.3193) ceramic tile. The carcass skin color was determined on the thickest part of the skin located on the pectoral apterium (the area between the pectoral and sternal feather tracts). For breast (pectoralis major) meat color evaluation, measurements were taken on the cranial, medial surface (bone side) in an area free of obvious color defects (bruises, discolorations, hemorrhages, full blood vessels, or any other condition that may have affected uniform color reading).

pH Measurement. The pH was determined using a modification of the iodoacetate method initially described by Jeacocke (1977). Approximately 2.5 g of breast meat was removed from the cranial end of each fillet, minced by hand, homogenized in 25 mL of a 5 m*M* iodoacetate solution with 150 m*M* potassium chloride for 30 s, and the pH of the homogenate was determined using a pH meter (pH meter HI98240 equipped with electrode FC230, Hanna Instrument S.p.A., Padova, Italy) calibrated at pH 4.0 and 7.0.

Drip and Cook Loss Determination. The 2 fillets from each whole breast were separated and used for the determination of drip and cook loss. Drip loss was carried out on 1 intact fillet kept suspended in a sealed glass box for 48 h at 2 to 4°C and expressed as percentage of weight loss during storage. Cook loss was measured on the other fillet by cooking the samples in a convection oven on aluminum trays at 180°C until 80°C at core sample. The fillets were then allowed to equilibrate to room temperature, reweighed, and cook loss was determined as percentage of weight loss.

Shear Value Determination. Shear values were determined using a TA.HDi Heavy Duty texture analyzer (Stable Micro Systems Ltd., Godalming, Surrey, UK) equipped with an Allo-Kramer shear cell using the procedure described by Papinaho and Fletcher (1996). A 25-mm diameter core were removed from the thickest part of each fillet, weighed, and sheared with the blades at a right angle to the fibers using a 250-kg load cell and cross head speed of 500 mm/min. Allo-Kramer shear values were reported as kilograms shear per gram of sample.

Chemical Analyses. The chemical composition (moisture, protein, lipid, and ash content) was carried out on frozen pectoralis minor muscles. The percentage of moisture was determined in duplicate according to the Association of Official Analytical Chemists (AOAC, 1990) procedure. Protein content was determined using a standard Kjeldahl copper catalyst method (AOAC, 1990). Total lipids were measured using the chloroform:methanol procedure described by Folch et al. (1957). Ash content was determined using the procedure described by the AOAC (1990).

Statistical Analysis

The influence of the season (winter vs. summer) and market class of broilers (light vs. medium vs. heavy) were

Table 1. Effect of the season on broiler breast meat quality traits and chemical composition

	Season			
Item	Winter	Summer	SEM	*P*-value
n	135	135		
Meat quality trait[1]				
Lightness, L*	52.58[b]	54.09[a]	0.20	0.000
Redness, a*	2.01[a]	1.50[b]	0.07	0.000
Yellowness, b*	4.28[b]	5.84[a]	0.23	0.001
pH	5.99[a]	5.95[b]	0.01	0.031
Drip loss (%)	0.88[b]	1.35[a]	0.04	0.000
Cook loss (%)	16.17[b]	17.02[a]	0.14	0.002
Allo-Kramer shear (kg/g)	3.29[a]	2.64[b]	0.08	0.000
Chemical composition[2]				
Moisture (%)	74.19[b]	75.24[a]	0.07	0.000
Protein (%)	23.22[a]	22.92[b]	0.04	0.000
Lipid (%)	1.15	1.19	0.02	0.282
Ash (%)	1.45[a]	1.36[b]	0.01	0.000

[a,b]Means within a row followed by differing superscript letters differ significantly ($P \leq 0.05$).

[1]Determined on pectoralis major muscles.

[2]Determined on pectoralis minor muscles.

separately evaluated by using 1-way ANOVA testing the season or the class of broilers as main effect, respectively. Means were separated using Duncan multiple range test option of the GLM procedure (SAS Institute, 1988). Pearson correlation coefficients (r), regression model (R^2), and probabilities were calculated to evaluate the relationships between the color parameters (L*, a*, b*) of skin and breast meat.

RESULTS AND DISCUSSION

In Table 1 the effect of the season (winter vs. summer) on broiler breast (pectoralis major) meat quality traits is reported. In respect to the broilers slaughtered during winter, the color of breast meat from birds processed during the summer season was significantly ($P \leq 0.01$) paler (L*, 54.09 vs. 52.58), less red (a*, 1.50 vs. 2.01), and more yellow (b*, 5.84 vs. 4.28). Moreover, the meat pH was lower during summer (5.95 vs. 5.99; $P \leq 0.05$) and was associated with higher ($P \leq 0.01$) drip (1.35 vs. 0.88%) and cook (17.02 vs. 16.17%) losses in respect to those observed during winter. These results indicate that broiler breast meat obtained from chickens reared and processed under warm temperature (summer) undergoes a significant deterioration in WHC properties with respect to birds kept at cool temperature (winter).

During the summer months, heat stress and excitement just prior to slaughter can affect the postmortem metabolism of muscle and subsequent meat quality characteristics such as color, WHC, and texture (Lambooij, 1999; Warriss et al., 1999). Babji et al. (1982) reported that heat stress resulted in significantly lower pH values for raw muscle and cooked meat, a reduced WHC, and increased lightness (L*) values. Petracci et al. (2001) showed that birds kept at higher temperatures prior to slaughter had significantly lower ultimate pH values than birds subjected to cooler temperatures. McKee and Sams (1997) observed that turkeys subjected to heat stress exhibit accelerated postmortem metabolism and biochemical changes in the muscle producing pale, soft, and exudative meat characteristics with lower pH values, paler color, as well as higher drip and cook losses. McCurdy et al. (1996) also observed that turkey breast muscle exhibited highest L* values in the summer season. In a further study, Bianchi et al. (2004), using the low-resolution nuclear magnetic resonance technique, concluded that paler color of turkey muscles during summer with respect to those collected in winter is associated with differences in low resolution nuclear magnetic resonance transversal relaxation properties of the water molecules of the muscle. In this study, it was also reported that during summer, turkey breast meat exhibits a lower WHC and an accelerated postmortem muscle metabolism, as indicated by the lower pH at 15 min postmortem. Northcutt (1994) reported that thermal preconditioning and heat shock in chicken resulted in breast meat that appeared to be PSE. Finally, other studies conducted on broiler chickens (Wilkins et al., 2000; Woelfel et al., 2002) did not outline clear effects of the season on meat color (L*).

When applying to our data the truncation value of L* = 56 previously suggested to classify the paler-than-normal (or PSE-like) broiler breast meat in the Italian production system (Petracci et al., 2004), it was established that the occurrence of pale meat is greater in birds slaughtered during summer (26.7%) with respect to birds processed during winter (5.9%). These results are consistent with those obtained by Petracci et al. (2004) who reported that the incidence of pale meat is greater during summer.

The tendency of the breast meat to show a lower redness when lightness increases observed in this study agrees with previous researchers (Van Laack et al., 2000; Qiao et al., 2001; Bianchi et al., 2005). Moreover, Petracci et al. (2001) also reported significantly lower breast meat redness (a*, 2.48 vs. 3.04) in broilers held at higher temperatures (34 vs. 25°C).

Shear values of cooked breast meat, were found significantly lower (2.64 vs. 3.29 kg/g; $P \leq 0.01$) in summer with respect to winter. Finally, concerning the chemical composition, the meat (pectoralis minor) produced during summer exhibited a higher content of moisture (75.24 vs. 74.19%; $P \leq 0.01$) and a lower content of protein (22.92 vs. 23.22%; $P \leq 0.01$) and ash (1.36 vs. 1.45%; $P \leq 0.01$). If we consider that the meat produced during summer is paler than that produced during winter, these results could be considered consistent with those reported by Qiao et al. (2002). These authors compared the chemical composition of broiler breast meat with lighter than normal, normal, or darker than normal color and found that meat from the light group had significantly lower protein content than the normal or dark meat as well as lower ash content than the dark group.

In Table 2 the effect of market class of broilers on breast meat quality traits is reported. The average carcass weights were 1.167, 1.779, and 2.387 kg for light, medium, and heavy broilers, respectively. As regard to the meat color, the breast meat from light birds was redder than medium and heavy broilers, whereas the yellowness was

Table 2. Effect of the market class on broiler breast meat quality traits and chemical composition

Item	Market class			SEM	P-value
	Light	Medium	Heavy		
n	90	90	90		
Carcass weight (kg)	1.167[c]	1.779[b]	2.387[a]	0.031	0.000
Meat quality trait[1]					
Lightness, L*	53.47	53.56	52.98	0.20	0.422
Redness, a*	2.14[a]	1.52[b]	1.59[b]	0.07	0.000
Yellowness, b*	4.75[b]	6.08[a]	4.35[b]	0.23	0.005
pH	5.92[b]	5.99[a]	5.98[a]	0.01	0.003
Drip loss (%)	1.07	1.05	1.22	0.04	0.246
Cook loss (%)	15.80[b]	16.83[a]	17.16[a]	0.14	0.000
Allo-Kramer shear (kg/g)	3.55[a]	2.74[b]	2.60[b]	0.08	0.000
Chemical composition[2]					
Moisture (%)	74.99[a]	74.66[b]	74.49[b]	0.07	0.008
Protein (%)	23.06	23.12	23.04	0.04	0.653
Lipid (%)	1.13	1.15	1.23	0.02	0.172
Ash (%)	1.45[a]	1.38[b]	1.38[b]	0.01	0.014

[a–c]Means within a row followed by differing superscript letters differ significantly ($P \leq 0.05$).

[1]Determined on pectoralis major muscles.

[2]Determined on pectoralis minor muscles.

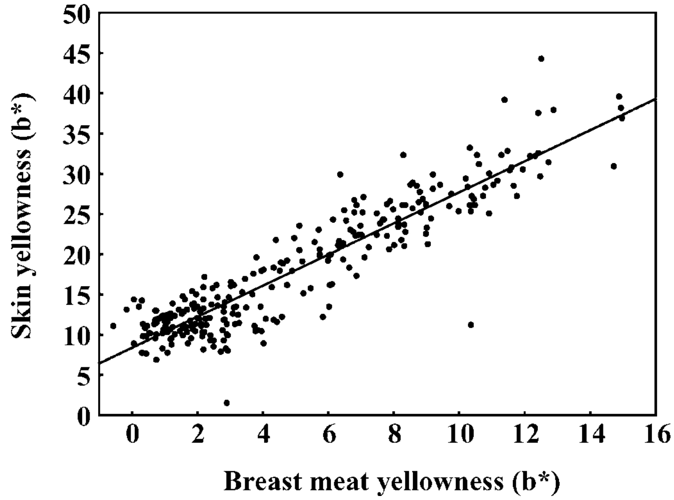

Figure 1. The relationship between the yellowness (b*) of the skin and the yellowness of breast meat (pectoralis major): ($b^*_{skin} = 8.38 + 1.93 \times b^*_{meat}$; n = 270; Pearson r = +0.92; regression model $R^2 = 0.85$; $P \leq 0.001$).

higher in medium compared with light and heavy birds. In another study, Bianchi et al. (2006) found that the heavier birds (>3.3 kg of live weight) produced darker breast meat (lower lightness values) in comparison with lighter birds (3.0 to 3.3 kg and <3.0 kg of live weight). However, no differences were found in the meat redness. Smith et al. (2002), comparing straight run broilers processed at various ages (from 42 to 52 d old) reported that color of broiler breast meat was not affected by age.

In light birds, the pH of breast meat was lower than medium and heavy broilers. However, despite the lower values of pH, cook loss was lower in light birds. These results might indicate that the differences in the WHC of the meat were more related to a physical than a pH-induced effect. It is well known that the diameter of muscle fibers increases as the age and the weight of the birds increase, thus changing the structural characteristics of the muscle (Dransfield and Sosnicki, 1999). This structural effect might also contribute to the differences found in shear values, which were higher in light birds (Table 2). Dransfield and Sosnicki (1999) reported that smaller fiber diameters might allow a higher packaging density and increase toughness of the meat even if this effect was not confirmed in all species. Finally, the meat from light broilers had a higher content of moisture and ash, which can be related to the younger age at slaughter.

Table 3. Pearson correlation coefficients (r) and probabilities between skin and breast meat (pectoralis major) color (n = 270)[1]

Item	L* skin	a* skin	b* skin
L* meat	+0.21***	–0.08[NS]	+0.01[NS]
a* meat	–0.05[NS]	+0.39***	–0.50***
b* meat	–0.17**	–0.58***	+0.92***

$^{**}P \leq 0.01$; $^{***}P \leq 0.001$.

[1]L* = lightness; a* = redness; b* = yellowness.

As previously described in the Materials and Methods section, the flocks of birds considered in this study included white- and yellow-skinned broilers, and the color of the skin was measured to evaluate the relationships between the color parameters of skin and meat. In Table 3 the Pearson correlation coefficients (r) and probabilities among skin and breast meat color are reported. The most interesting result is the correlation between the yellowness of the skin and breast meat (Figure 1; r = +0.92; $R^2 = 0.85$; $P \leq 0.001$), which indicates that the more yellow the color of the skin, the more yellow the color of raw breast meat.

In conclusion, the results found in this study indicate that broiler breast meat obtained from chickens reared and processed under warm temperature (summer) undergoes a significant deterioration in WHC properties in respect with birds kept at cool temperature (winter). Moreover, the market class of birds may also play a role in determining variations in breast meat quality attributes, especially when comparing light- with medium- and heavy-size birds.

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REFERENCES

AOAC. 1990. Meat and meat products. Pages 931–948 in Official Methods of Analysis. 15th ed. Vol. 2. Assoc. Off. Anal. Chem., Washington, DC.

Babji, A. S., G. W. Froning, and D. A. Ngoka. 1982. The effect of preslaughter environmental temperature in the presence of electrolyte treatment on turkey meat quality. Poult. Sci. 61:2385–2389.

Barbut, S. 1997. Problem of pale exudative meat in broiler chickens. Br. Poult. Sci. 38:355–358.

Barbut, S. 1998. Estimating the magnitude of the PSE problem in poultry. J. Muscle Foods 9:35–49.

Berri, C., N. Wacrenier, N. Millet, and E. Le Bihan-Duval. 2001. Effect of selection for improved body composition on muscle and meat characteristics of broilers from experimental and commercial lines. Poult. Sci. 80:833–838.

Bianchi, M., F. Capozzi, M. A. Cremonini, L. Laghi, M. Petracci, G. Placucci, and C. Cavani. 2004. Influence of the season on the relationships between NMR transverse relaxation and WHC in turkey breast. J. Sci. Food Agric. 84:1535–1540.

Bianchi, M., D. L. Fletcher, and D. P. Smith. 2005. Physical and functional properties of whole and ground pale broiler breast meat. Poult. Sci. 84:803–808.

Bianchi, M., M. Petracci, and C. Cavani. 2006. The influence of genotype, market live weight, transportation and holding conditions prior to slaughter on broiler breast meat color. Poult. Sci. 85:123–128.

CIE. 1978. International Commission on Illumination, Recommendations on uniform colour spaces, colour difference equations, psychometric colour terms. CIE Publication (No. 15 (E-1.3.1) 1971/(TO-1.3) (Suppl. 15). Bureau Central de la CIE, Paris, France.

Debut, M., C. Berri, E. Baeza, N. Sellier, C. Arnould, D. Guemene, N. Jehl, B. Boutten, Y. Jego, C. Beaumont, and E. Le Bihan-Duval. 2003. Variation of chicken technological meat quality in relation to genotype and preslaughter stress conditions. Poult. Sci. 82:1829–1838.

Dransfield, E., and A. A. Sosnicki. 1999. Relationship between muscle growth and poultry meat quality. Poult. Sci. 78:743–746.

Fletcher, D. L. 2002. Poultry meat quality. World's Poult. Sci. J. 58:131–145.

Folch, J., M. Lees, and G. H. Solane-Stanley. 1957. A simple method for the isolation and purification of total lipids from animal tissues. J. Biol. Chem. 226:497–509.

Jeacocke, R. E. 1977. Continuous measurement of the pH of beef muscle in intact beef carcasses. J. Food Technol. 12:375–386.

Lambooij, E. 1999. Handling of poultry before slaughter: some aspects of welfare and meat quality. Pages 311–323 in Proc. XIV Eur. Symp. Quality Poult. Meat, Bologna, Italy.

McCurdy, R. D., S. Barbut, and M. Quinton. 1996. Seasonal effect on pale soft exudative (PSE) occurrence in young turkey breast meat. Food Res. Int. 29:363–366.

McKee, S. R., and A. R. Sams. 1997. The effect of seasonal heat stress on rigor development and the incidence of pale, exudative turkey meat. Poult. Sci. 76:1616–1620.

Northcutt, J. K. 1994. Influence of antemortem treatment on postmortem muscle properties of poultry meat. PhD thesis North Carolina State Univ., Raleigh, NC.

Owens, C. M., E. M. Hirschler, S. R. McKee, R. Martinez-Dawson, and A. R. Sams. 2000. The characterization and incidence of pale, soft, exudative turkey meat in a commercial plant. Poult. Sci. 79:553–558.

Papinaho, P. A., and D. L. Fletcher. 1996. The effect of stunning amperage and deboning time on early rigor development and breast meat quality of broilers. Poult. Sci. 75:672–676.

Petracci, M., M. Bianchi, M. Betti, and C. Cavani. 2004. Color variation and characterization of broiler breast meat during processing in Italy. Poult. Sci. 83:2086–2092.

Petracci, M., D. L. Fletcher, and J. K. Northcutt. 2001. The effect of holding temperature on live shrink, yields and breast meat quality of broiler chicken. Poult. Sci. 80:670–675.

Qiao, M., D. L. Fletcher, J. K. Northcutt, and D. P. Smith. 2002. The relationship between raw broiler breast meat color and composition. Poult. Sci. 81:422–427.

Qiao, M., D. L. Fletcher, D. P. Smith, and J. K. Northcutt. 2001. The effect of broiler breast meat color on pH, moisture, water-holding capacity, and emulsification capacity. Poult. Sci. 80:676–680.

SAS Institute. 1988. SAS®/STAT Guide for Personal Computers. Version 6.03 ed. SAS Institute Inc., Cary, NC.

Smith, D. P., C. E. Lyon, and B. G. Lyon. 2002. The effect of age, dietary carbohydrate source, and feed withdrawal on broiler breast fillet color. Poult. Sci. 81:1584–1588.

Van Laack, R. L. J. M., C.-H. Liu, M. O. Smith, and H. D. Loveday. 2000. Characteristics of pale, soft, exudative broiler breast meat. Poult. Sci. 79:1057–1061.

Warriss, P. D., L. J. Wilkins, and T. G. Knowles. 1999. The influence of ante-mortem handling on poultry meat quality. Pages 217–230 in Poultry Meat Science. R. I. Richardson and G. C. Mead, ed. CABI Publishing, Oxon, UK.

Wilkins, L. J., S. N. Brown, A. J. Phillips, and P. D. Warriss. 2000. Variation in the colour of broiler breast fillets in the UK. Br. Poult. Sci. 41:308–312.

Woelfel, R. L., C. M. Owens, E. M. Hirschler, R. Martinez-Dawson, and A. R. Sams. 2002. The characterization and incidence of pale, soft, and exudative broiler meat in a commercial processing plant. Poult. Sci. 81:579–584.