Color Variation and Characterization of Broiler Breast Meat During Processing in Italy

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ABSTRACT The variation in broiler breast meat color (CIE values L*a*b*) that normally occurs during processing was evaluated on 6,997 broiler breast fillets (pectoralis major muscles) from 79 flocks using a Minolta Chroma Meter. The samples were randomly collected at 3 to 6 h postmortem from the deboning line at a single major Italian processing plant. In addition, 216 fillets were selected based on lightness (L*) values as being dark ($L^* < 50$), normal ($50 \leq L^* \leq 56$), or pale ($L^* > 56$), and were analyzed for ultimate pH, intact and ground meat cooking loss, and shear value. The overall range in measured lightness (L*) was considerable and varied from 40 (dark) to 66 (pale), indicating that high breast meat color variation during processing could exist. Broiler breast meat during summer was found to be paler (+1.7 L* unit), less red (–1.0 a* unit), and less yellow (–0.7 b* unit) than breast meat samples collected during the winter, confirming that the incidence of pale meat is greater during summer as indicated by nonscientific observations of plant personnel. It was also determined that paler ($L^* > 56$) breast meat is associated with lower ultimate pH and poorer water-holding capacity, whereas darker ($L^* < 50$) breast meat is associated with higher muscle pH and cooking yield.

(*Key words*: broiler, breast meat, color variation, lightness, water-holding capacity)

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INTRODUCTION

It is generally recognized that the 2 most important attributes for poultry meat are appearance and texture. Appearance is critical for consumers' initial selection of product as well as for final product satisfaction. Because appearance is so critical for consumers' selection, poultry producers go to great lengths to produce products with the appropriate color for a particular market and to avoid appearance defects, which will negatively affect product selection or price (Fletcher, 2002).

Some researchers have indicated that significant variation in breast meat color exists during processing as well as at the retail level (Barbut, 1997a; Fletcher, 1999a; Wilkins et al., 2000; Petracci and Fletcher, 2002; Woelfel et al., 2002). Moreover, Fletcher et al. (2000) showed that variations in raw breast meat color are sufficient to cause variations in cooked product appearance. Numerous researchers have demonstrated the relationship between raw breast meat color and functional meat properties in poultry (Boulianne and King, 1995; Van Laack et al., 2000; Qiao et al., 2001, 2002; Cavani et al., 2002). It has therefore been suggested that lightness (L*) values can be used as an indicator of poultry breast meat quality for further processing and for evaluating the incidence of the pale, soft, and exudative (PSE)-like condition in poultry (Barbut, 1993, 1997a,b; Owens et al., 2000; Wilkins et al., 2000; Woelfel et al., 2002; Galobart and Moran, 2004).

Barbut (1997a) carried out the first study with the aim to evaluate poultry color variation in a commercial processing plant in Ontario, Canada, using 700 broiler breasts belonging to 7 flocks. Wilkins et al. (2000), in a similar study conducted in UK, reported that using the cut-off point of $L^* = 50$ proposed by Barbut (1997a) to discriminate pale breast meat would mean that 90% of 7,538 broiler breast fillets analyzed would be sorted as PSE-like. More recently, Woelfel et al. (2002) conducted a study which first evaluated the relationship between drip loss and lightness (L*), and established that a cut-off of $L^* = 54$ could discriminate breast meat with PSE properties. Moreover, by using this cut-off value, approximately 47% of the 3,554 fillets were classified as pale and could potentially exhibit poor water-holding capacity (WHC). However, it has been suggested that each processing plant would have to determine its own lightness values for sorting PSE meat depending on type of birds, processing factors, and final product specifications (Barbut, 1997a; Wilkins et al., 2000; Woelfel et al., 2002). Among the many

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Abbreviation Key: a* = redness; b* = yellowness; CIE = International Commission on Illumination; L* = lightness; PSE = pale, soft, and exudative; WHC = water-holding capacity.

TABLE 1. Effect of season on L* value distribution in broiler breast meat

Season	Observations	Mean	SD	Minimum	Maximum	Skewness	Kurtosis
Summer	2,309	53.05^a	3.08	40.55	66.07	–0.10	0.82
Autumn	2,365	52.79^b	2.71	41.90	61.98	–0.06	0.36
Winter	2,323	51.31^c	2.57	41.25	66.33	0.00	1.28
All groups	6,997	52.38	2.89	40.55	66.33	–0.02	0.69

$^{a–c}$Means within a column followed by differing superscript letters differ significantly ($P \leq 0.001$).

factors affecting poultry meat color, stress immediately before and during slaughter has been considered a major factor implicated in increased color variation of breast meat. Environmental conditions during transport and holding of livestock have been shown to affect processing yield and meat quality (Northcutt, 1994; McKee and Sams, 1997; Petracci et al., 2001; Cavani et al., 2002). During the summer months, high antemortem temperatures affect the postmortem metabolism of muscle and subsequent meat quality via adrenal or other physiological responses or simply by fatigue of the birds (Lambooij, 1999; Warriss et al., 1999).

This study first evaluated the variation in broiler breast meat color that normally occurs during processing in Italy and how it is affected by season (summer, autumn, and winter) in a total of 6,997 fillets. Moreover, to characterize breast fillets with different colors, a total of 216 fillets were selected during 3 independent trials based on lightness (L*) as being dark (L* < 50), normal (50 ≤ L* ≤ 56), and pale (L* > 56) and were evaluated for color (L*a*b*), ultimate pH, intact and ground meat cooking loss, and shear value. The limit values of L* to discriminate the 3 fillet color groups (dark, normal, and pale) were established considering the mean and SD of L* value distribution as follows: dark (L* < mean – SD), normal (mean – SD ≤ L* ≤ mean + SD), and pale (L* > mean + SD).

MATERIALS AND METHODS

Experiment 1—Color Variation

The study was conducted in a single major commercial processing plant in Italy on 6,997 broiler breast fillets (pectoralis major muscles) from 79 flocks. A variable number of flocks and breast fillets were available on each day of sampling. The number of fillets measured for color per flock ranged from 46 to 119. To evaluate the seasonal effect, 24, 29, and 26 flocks were examined during June to July (summer) and October to November (autumn) in 2002, and January to February (winter) in 2003, respectively. The flocks varied in genotype (Ross 508 or Cobb 500), sex, and slaughter age (from 46 to 68 d). Whole breasts were collected at random from the deboning line at 3 to 6 h postmortem and the determination of color was carried out immediately on one fillet from each breast.

Experiment 2—Characterization

Three individual trials were conducted, using 108 boneless, skinless, 24-h postmortem whole breast muscles (216 breast fillets) from 8-wk-old male Cobb 500 broilers (3.5 kg live weight) selected from the deboning area of the same commercial processing plant based on lightness (L*) values as being dark, normal, and pale. The limit values of L* to discriminate the 3 fillet color groups (dark, normal, and pale) were established considering the mean and SD of L* value distribution obtained during experiment 1 as follows: dark (L* < mean – SD), normal (mean – SD ≤ L* ≤ mean + SD), and pale (L* > mean + SD). For practical purposes, the limit values L* = 50 and L* = 56 were adopted (L* < 50; 50 ≤ L* ≤ 56; L* > 56). In each trial, the whole breasts were bagged by color group (12 whole breasts, 24 fillets/color group), packed on ice, and transported to the laboratory. Upon receipt at the laboratory, the 2 fillets of each whole breast were separated, trimmed of excess fat and connective tissue, and held at 2 to 4°C throughout handling and measurements. Color (L*a*b*) was measured on the medial surface of each fillet and ultimate pH was determined on the cranial section. One fillet from each breast was kept intact and used to determine cooking loss, and the other was ground and used to assess cooking loss on a meat patty. After cooking, intact (fillets) and ground (patties) samples were analyzed for shear value.

Analytical Methods

Color Measurement. The CIE (1978) system color profile of lightness (L*), redness (a*), and yellowness (b*) was measured by a reflectance colorimeter[2] using illuminant source C. The colorimeter was calibrated throughout the study using a standard white ceramic tile. Color was measured in single on the cranial, medial surface (bone side) in an area free of obvious color defects (bruises, discolorations, hemorrhages, full blood vessels, picking damage, or any other condition which may have affected a 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

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[2] Minolta Chroma Meter CR-300, Minolta Italia S.p.A., Milano, Italy.

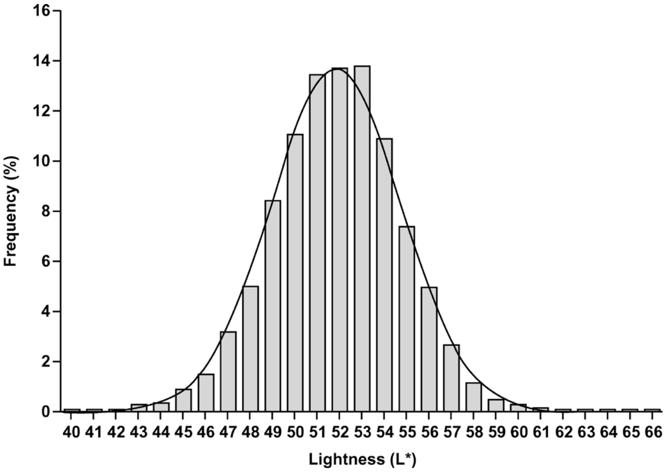

FIGURE 1. Distribution of lightness (L*) values in broiler breast meat (n = 6,997).

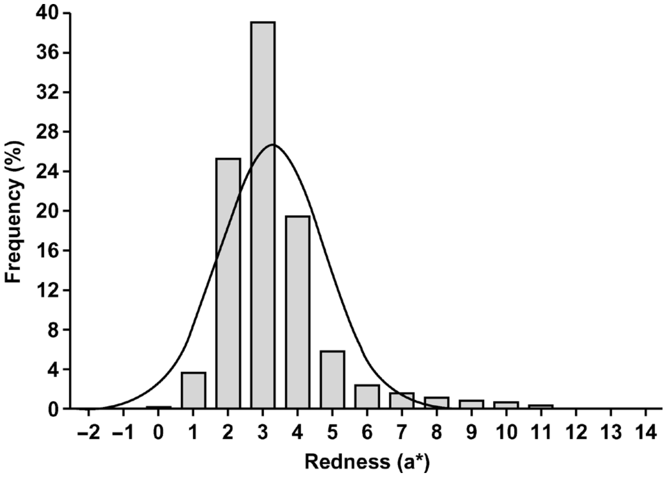

FIGURE 2. Distribution of redness (a*) values in broiler breast meat (n = 6,997).

the pH of the homogenate was determined using a pH meter[3] calibrated at pH 4.0 and 7.0.

Cooking Loss Determination—Intact Meat. One fillet from each whole breast was individually weighed and cooked in a convection oven on aluminum trays at 180°C until the core temperature reached 80°C. The fillets were then allowed to equilibrate to room temperature and reweighed, and cooking loss determined as percentage of weight lost by the sample.

Cooking Loss Determination—Ground Meat. Cooking loss on meat patties was determined by individually weighing and cooking individual patties (70 g; 8.5 cm diameter and 1.5 cm thick) in a convection oven at 180°C until the core temperature reached 80°C. The samples were then allowed to equilibrate to room temperature, reweighed, and cooking loss was determined as percentage of weight lost by the sample.

Shear Value Determination. Shear values were determined using an TA.HDi Heavy Duty texture analyzer[4] equipped with an Allo-Kramer shear cell using the procedure described by Papinaho and Fletcher (1996). A 25-mm (diameter) core was removed from the thickest part of each fillet and the center of each meat patty and weighed. Each sample was sheared with the blades at a right angle to the fibers using a 250-kg load cell and crosshead speed of 500 mm/min. Shear values are reported as kilograms of shear per gram of sample.

Statistical Analysis

Data from experiment 1 were analyzed by descriptive statistics (mean, standard deviation, minimum and maximum values, skewness, and kurtosis) for each color coordinate (L*a*b*) in overall data and within seasons (summer, autumn, and winter). Data were also analyzed using the ANOVA option of the GLM procedure of SAS software (SAS Institute, 1988) testing the season (summer, autumn, and winter) as main effect.

Data from experiment 2 were subjected to ANOVA using same procedure described above. The model tested the main effects for color group (dark, normal, and pale) and replication, as well as the interaction term, using residual error. When the interaction was significant, the interaction mean square error was used to determine the significance of the main effects (SAS Institute, 1988). In both experiments, means were separated using Newman-Keuls multiple range test option of the GLM procedure (SAS Institute, 1988).

RESULTS

The histogram showing the L* distribution in broiler breast meat during processing (Figure 1) exhibited a mean L* value of 52.38, SD 2.89, skewness –0.02, and kurtosis 0.69 (Table 1). The overall range in measured lightness was fairly large and varied from 40 (dark) to 66 (pale). Large variations were also observed for a* (range: 0 to 13) (Table 2) and b* (range: –3 to 12) (Table 3). Values of L* and b* showed a normal distribution (Figures 1 and 3), whereas the a* values showed a distribution with positive kurtosis and skewness indicating a relatively flatter peak and asymmetric tail extending toward more positive values than a normal distribution (Figure 2). Regarding the seasonal effect, the meat color of breast fillets collected during the summer, autumn, and winter were different from each other ($P \leq 0.001$) (Tables 1, 2, and 3). During the summer, the broiler breast muscle fillets exhibited higher ($P \leq 0.001$) lightness (53.05 vs. 52.79 and 51.31 for summer, autumn, and winter, respectively), lower redness (2.82 vs. 3.20 and 3.80), and lower yellowness (3.25 vs. 3.34 and 3.93) values compared with those collected during autumn and winter, respectively. The sea-

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[3] pH meter HI98240 equipped with electrode FC230, Hanna Instrument S.p.A., Padova, Italy.

[4] Stable Micro Systems Ltd., Godalming, UK.

TABLE 2. Effect of season on a* value distribution in broiler breast meat

Season	Observations	Mean	SD	Minimum	Maximum	Skewness	Kurtosis
Summer	2,309	2.82^{c}	1.01	0.42	10.39	1.50	6.31
Autumn	2,365	3.20^{b}	1.39	–0.43	10.94	1.92	5.40
Winter	2,323	3.80^{a}	1.71	–0.24	13.23	1.91	4.62
All groups	6,997	3.27	1.46	–0.43	13.23	2.05	6.47

[a–c]Means within a column followed by differing superscript letters differ significantly ($P \leq 0.001$).

sonal effect on breast meat lightness (L*) was also evident by considering the expected normal distributions of L* values in summer, autumn, and winter (Figure 4).

Table 4 summarizes the incidence of pale meat by using different L* cut-off values for sorting PSE-like meat during summer, autumn, and winter, respectively. When the L* cut-off value is greater than 52, the occurrence of pale meat is higher during summer with respect to autumn and winter.

Color (L*, a*, and b*), ultimate pH values, cooking loss, and shear value of intact and ground meat from the 3 color groups are presented in Table 5. Lightness and redness values were significantly different by color group and are consistent with the selection criteria (dark, L* < 50; normal, 50 ≤ L* ≤ 56; pale, L* > 56), whereas no differences were found in b* values. The ultimate pH values and cooking losses of intact and ground fillets from dark, normal, and pale groups were different from each other ($P \leq 0.01$). The pale meat (L* > 56) exhibited lower ultimate pH values (5.77 vs. 5.89 and 6.04; $P \leq 0.01$) and higher weight loss during cooking in intact fillets (23.84 vs. 21.13 and 18.84%; $P \leq 0.01$) and ground meat (27.69 vs. 24.66 and 21.02%; $P \leq 0.01$), compared with normal and dark groups. There were no treatment effects on shear values of breast meat kept either as intact or ground.

DISCUSSION

This study is the first survey carried out to evaluate the magnitude of broiler breast meat color variations during processing in Italy. Moreover, it was conducted in a major processing plant, which produces whole birds, cut-up, and further-processed products, and which can be considered representative of the Italian industry as a whole.

Considerable variation was detected in all color coordinates (L*, a*, and b*). The magnitude of the range of L* values (40 to 66) found in this study was comparable to the results reported in North America (Barbut, 1997a; Woelfel et al., 2002; Galobart and Moran, 2004) and the United Kingdom (Wilkins et al., 2000). The overall distribution suggests that breast meat lightness in Italy is similar to that reported by Woelfel et al. (2002) and Wilkins et al. (2000), whereas it is considerably higher and lower than the findings by Barbut (1997a) and Galobart and Moran (2004), respectively. These differences could be due to the different slaughter ages of broilers. In the present study, the breasts were randomly selected among flocks of birds slaughtered at different ages (from 43 to 68 d) to obtain the color variation existing in the overall Italian production. Wilkins et al. (2000) observed that the difference in mean value of observed lightness (8 L* units) in respect to the study conducted by Barbut (1997a) might be due to older ages. In the present study, breast meat lightness was negatively correlated with the live weight of birds (r = –0.30; $P \leq 0.001$), indicating a darker color in heavier birds. These data are not in agreement with those of Galobart and Moran (2004) who reported a positive correlation between breast meat lightness and the live weight of birds. Finally, it seems that color variation could not be explained only based on age or live weight at slaughter of the birds.

Color variation is a major problem in the retail environment because consumers are more sensitive to color variation than to absolute color, and they tend to reject multiple packaged fillets with noticeable color differences (Fletcher, 1999a). Fletcher (2002) further emphasized that raw poultry meat color variation is sufficient to cause variation in the appearance of cooked products.

In our study, season significantly affected the absolute color (L*, a*, and b*) as well as the shape of L* value distribution. Moreover, the color differences between summer and autumn (although statistically significant) are small, and they may be of relatively little practical importance. In contrast, the color coordinates of fillets measured during summer and winter were dramatically different, being paler (+1.7 L* unit), less red (–1.0 a* unit), and less yellow (–0.7 b* unit) in summer than in winter. Antemortem temperature stress and excitement immediately before slaughter have been shown to affect poultry meat color. McKee and Sams (1997) observed that sea-

TABLE 3. Effect of season on b* value distribution in broiler breast meat

Season	Observations	Mean	SD	Minimum	Maximum	Skewness	Kurtosis
Summer	2,309	3.25^{c}	1.32	–3.12	11.01	–0.23	1.71
Autumn	2,365	3.34^{b}	1.31	–2.38	8.37	–0.03	0.55
Winter	2,323	3.93^{a}	1.30	–2.35	12.04	0.06	1.37
All groups	6,997	3.51	1.34	–3.12	12.04	–0.06	1.16

[a–c]Means within a column followed by differing superscript letters differ significantly ($P \leq 0.001$).

TABLE 4. Comparison of the incidence of pale breast meat under different L* value limits during summer, autumn, and winter

	Season[1]		
L* value limit	Summer (%)	Autumn (%)	Winter (%)
L* >50[2]	84.4	85.7	70.7
L* >52	65.4	61.9	39.7
L* >54[3]	38.2	20.1	13.8
L* >56[4]	15.5	11.3	2.7
L* >58	4.1	2.2	0.4
L* >60	1.2	0.6	0.2
L* >62	0.6	0.0	0.1

[1] n = 6,997 (summer: n = 2,309; autumn: n = 2,365; winter: n = 2,323).

[2] Limit value proposed by Barbut (1997a).

[3] Limit value proposed by Woelfel et al. (2002).

[4] Limit value adopted in this study by calculating the sum of the mean and SD of L* obtained on 6,997 broiler breasts (see Table 1).

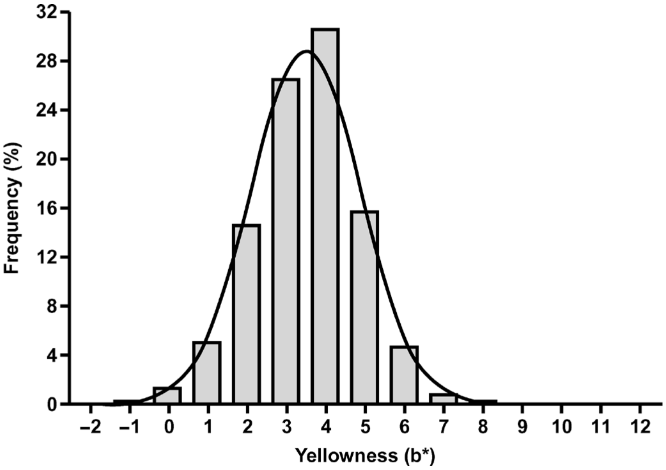

FIGURE 3. Distribution of yellowness (b*) values in broiler breast meat (n = 6,997).

sonal heat-stress accelerated postmortem metabolism and biochemical changes in the muscle, which produced PSE meat characteristics in turkey toms. These results agree with the report of McCurdy et al. (1996), who observed that turkey breast muscle had highest L* values in the summer season. In a subsequent study, Cavani et al. (2002), using a low-resolution nuclear magnetic resonance technique, concluded that paleness of turkey muscles during the summer compared with those collected in winter is associated with differences in nuclear magnetic resonance transversal relaxation properties of the water molecules of the muscle. However, no clear seasonal effect on meat color (L*) was observed in previous studies on broiler chickens (Wilkins et al., 2000; Woelfel et al., 2002). This could be because these studies were not specifically designed to investigate the effect of season. Nevertheless, Northcutt (1994) reported that thermal preconditioning and heat shock in chicken resulted in breast meat that had PSE characteristics. By considering the incidence of pale meat using different L* cut-off values for sorting PSE-like meat during summer, autumn, and winter, respectively, it was established that the occurrence of pale meat is greater during summer. By applying the L* cut-off value (L* = 56) adopted in experiment 2, the pale meat rejection rate would be 15.5, 11.3, and 2.7% in summer, autumn, and winter, respectively. Even if the difference in the L* average between summer and autumn was small (0.26 L* unit), the incidence of pale meat is 4.2% greater during summer. This suggests that breast meat color is more variable in summer months as shown by the higher standard deviation (Table 1) and the flatter expected normal distribution (Figure 4) of lightness values compared with color data recorded in autumn and winter. Because processing plant efficiency depends on product uniformity, variation can contribute to decreased product quality (Fletcher, 2002). If the lightness value (L* >54) indicated by Woelfel et al. (2002) to discriminate pale breast meat were applied to the present study, the rejection rates would be 38.2 (summer), 20.1 (autumn), and 13.8% (winter). By using the L* cut-off value of 50 as suggested by Barbut (1997a), the incidence of pale meat would be greater than 75% in each season. This indicates that care must be taken to use L* limit values established under different conditions.

Experiment 2 was aimed at characterizing pH, WHC, and texture of broiler breast meat with different color. The L* and a* values were significantly different and consistent with the selection criteria by color. The results agree with previous studies that reported pale meat as having lower redness than normal and dark meat (Van Laack et al., 2000; Qiao et al., 2001), although the yellowness (b*) values did not vary according to the color group. This indicates that the meat paleness (L*) is not highly correlated with b* and this finding is supported by previous research on pale broiler breast meat (Boulianne and King, 1995; Fletcher, 1999b; Van Laack et al., 2000; Qiao et al., 2001). However, others studies reported that paler meat is associated with higher b* values (Boulianne and King, 1995; Qiao et al., 2001). The color differences among dark, normal, and pale meat could be

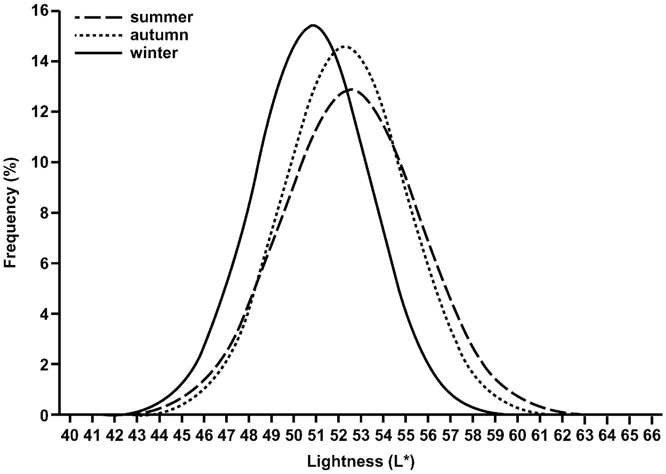

FIGURE 4. Expected normal distributions of lightness (L*) values in broiler breast meat during summer (n = 2,309), autumn (n = 2,365), and winter (n = 2,323).

TABLE 5. Effect of color group on color lightness (L*), redness (a*), yellowness (b*), ultimate pH, intact and ground cooking loss and shear value[1] of broiler breast meat (mean ± SEM)

Variable	Color group: Dark	Normal	Pale	*P*
n	72	72	72	
L*	48.29 ± 0.21^{c}	53.51 ± 0.18^{b}	57.53 ± 0.27^{a}	**[2]
a*	2.96 ± 0.07^{a}	2.05 ± 0.11^{b}	1.63 ± 0.12^{c}	**[3]
b*	1.07 ± 0.08	1.52 ± 0.09	2.08 ± 0.12	**[3]
Ultimate pH	6.04 ± 0.01^{a}	5.89 ± 0.01^{b}	5.77 ± 0.02^{c}	**[3]
Cooking loss of intact meat (%)	18.84 ± 0.43^{c}	21.13 ± 0.51^{b}	23.84 ± 0.51^{a}	**[2]
Shear value of intact meat (kg/g)	3.36 ± 0.33	3.36 ± 0.30	3.48 ± 0.25	NS
Cooking loss of ground meat (%)	21.02 ± 0.36^{c}	24.66 ± 0.31^{b}	27.69 ± 0.40^{a}	**[2]
Shear value of ground meat (kg/g)	2.05 ± 0.05	1.94 ± 0.05	2.09 ± 0.04	NS

$^{a\text{–}c}$Means within a row followed by differing superscript letters differ significantly ($P \leq 0.01$).

[1] For cooking loss and shear value measurements, n = 36 in each color group.

[2] Significance determined using residual error.

[3] Significance determined by replicate mean square error as the statistical test.

**$P \leq 0.01$.

considered sufficient to sort fillets by color before packaging to guarantee uniformity in presentation of multiple-fillet packages. The selection of breast fillets based on L* values resulted in a clear differentiation of the pH and WHC evaluated by the cooking loss method. Darker meat ($L^* < 50$) is associated with higher pH values and cooking yield, whereas paler meat ($L^* > 56$) is associated with lower muscle pH and WHC. These results are consistent with previous studies (Fletcher, 1999b; Fletcher et al., 2000; Van Laack et al., 2000; Qiao et al., 2001) and indicate that wide differences in raw broiler breast meat color are mainly due to differences in pH and they result in variations in the WHC of the meat. Nevertheless, there were no consistent effects on meat tenderness (shear value) according to the results obtained by Fletcher (1999a).

In conclusion, our study established that color variation of broiler breast meat during processing in Italy exists and is affected by season. A higher occurrence of pale meat observed during the summer months is associated with lower ultimate pH values and poorer water-holding capacity.

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REFERENCES

Barbut, S. 1993. Colour measurements for evaluating the pale, soft, exudative (PSE) occurrence in turkey meat. Food Res. Int. 26:39–43.

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

Barbut, S. 1997b. Occurrence of pale soft exudative meat in mature turkey hens. Br. Poult. Sci. 38:74–77.

Boulianne, M., and A. J. King. 1995. Biochemical and color characteristics of skinless boneless pale chicken breast. Poult. Sci. 74:1693–1698.

Cavani, C., M. Bianchi, F. Capozzi, M. A. Cremonini, L. Laghi, M. Petracci, and G. Placucci. 2002. Influence of season on Low-Resolution NMR relaxation properties and standard meat quality parameters in turkey breast. Proceedings of the XI European Poultry Conference, Bremen, Germany. Arch. Geflugelkd. 66:165.

CIE. 1978. International Commission on Illumination, Recommendations on uniform colour spaces, colour difference equations, psychometric colour terms. CIE Publication (15 (E-1.3.1) 1971/(TO-1.3) (Suppl. 15). Bureau Central de la CIE, Paris.

Fletcher, D. L. 1999a. Color variation in commercial packaged broiler breast fillets. J. Appl. Poult. Res. 8:67–69.

Fletcher, D. L. 1999b. Broiler breast meat color variation, pH, and texture. Poult. Sci. 79:1323–1327.

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

Fletcher, D. L., M. Qiao, and D. P. Smith. 2000. The relationship of raw broiler breast meat color and pH to cooked meat color and pH. Poult. Sci. 79:784–788.

Galobart, J., and E. T. Moran, Jr. 2004. Refrigeration and freeze-thaw effects on broiler fillets having extreme L* values. Poult. Sci. 83:1433–1439.

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 Proceedings of the XIV European Symposium on the Quality of Poultry 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. Ph.D. Thesis. North Carolina State University, 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., and D. L. Fletcher. 2002. Broiler skin and meat color changes during storage. Poult. Sci. 81:1589–1597.

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, 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.

Qiao, M., J. K. Northcutt, D. L. Fletcher, and D. P. Smith. 2002. Effects of raw broiler breast meat color variation on marination and cooked meat quality. Poult. Sci. 81:276–280.

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

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, Wallingford, 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.