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Evaluation of broiler breast meat color using the minolta Chroma Meter and Nix Color Sensor

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ABSTRACT

Instrumental color measurement is widely used in the poultry industry to ensure product uniformity and to provide rapid evaluation of meat quality. The objective of this study was to evaluate color measurements of broiler breast meat obtained using a conventional tristimulus colorimeter Minolta CR-400 Chroma Meter (Minolta Italia S.p.A., Milan, Italy) and a portable Nix Spectro 2 Color Sensor (NIX Sensor Ltd., Hamilton, ON, Canada), and to investigate the relationships between instrument-derived color parameters and key meat quality traits under commercial processing conditions. The *Pectoralis major* muscles from three homogeneous flocks of Ross 308 broilers were analyzed. In a preliminary screening (n = 450 fillets), samples were classified according to Minolta lightness (**L***) values into pale, normal and dark groups. Then 90 fillets per color group were selected and color using both instruments, ultimate pH, drip loss, and cooking loss, were measured. Moisture content, lipid (Thiobarbituric Acid Reactive Substances) and protein oxidation (carbonyl content) were also determined in 24 breasts per group. The Nix Spectro 2 reproduced the separation among color groups originally defined according to Minolta CR-400 L* values. Pale fillets exhibited higher lightness, oxidative indicators, drip and cooking losses and lower pH compared with normal and dark samples. Lightness measured by the two instruments was very strongly correlated ($\rho = +0.90$; $P < 0.001$), whereas strong correlations were observed for redness ($\rho = +0.66$; $P < 0.001$) and yellowness ($\rho = +0.51$; $P < 0.001$). For both devices, L* was strongly negatively correlated with pH and positively correlated with drip and cooking losses ($P < 0.001$), confirming the association between lightness and water holding capacity. Although absolute color values differed between instruments, the Nix Spectro 2 consistently reproduced relative color variation and its relationships with technological properties of the breast meat. In conclusion the Nix Spectro 2 represents a promising low-cost tool for assessing relative color variation in research and commercial poultry applications.

Introduction

The quality of poultry meat has gained increasing attention from both scientific and industrial perspectives, largely driven by the expanding commercialization of pre-packaged fresh and processed poultry products marketed through self-service food retailing, as well as by the increasing use of poultry meat in food service and catering operations, all of which must comply with stringent requirements for food safety, nutritional value, and sensory quality (Petracci, 2022). Among meat quality traits, color is one of the most critical attributes, particularly for broiler breast meat, as it is the first parameter evaluated by consumers at the point of purchase and strongly influences purchasing decisions (Fletcher, 2002; Altmann et al., 2023). Consequently, the poultry industry has devoted substantial efforts to minimizing color variability both within and among packages to ensure product uniformity and consumer acceptance (Barbut and Leishman, 2022). In addition, meat color is routinely used in processing plants as a criterion for raw material selection, since it is closely associated with processing performance and product quality consistency for products intended for both retail and food service markets (Lee et al., 2022; King et al., 2023).

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Deviations in meat color are often associated with quality defects such as pale, soft, and exudative (**PSE-like**) or dark, firm, and dry (**DFD**) conditions, which may negatively affect uniformity and processability thereby impairing product consistency and marketability (Petracci et al., 2017; Barbut and Leishman, 2022). In modern fast-growing broiler chickens, the occurrence of paler-than-normal and darker-than-normal breast meat is strongly linked to pre-slaughter and slaughter-related factors that influence peri-mortem muscle energy metabolism and biochemical processes (Petracci, 2022). Moreover, intensive genetic selection aimed at maximizing growth rate and breast yield has reduced the ability of birds to cope with pre-slaughter stress, thereby contributing over time to increased variability in breast meat color and a higher prevalence of color-related quality defects (Petracci et al., 2017; Barbut et al., 2024). This issue has been further exacerbated by the centralization of slaughtering operations into a limited number of highly specialized processing plants within vertically integrated companies, which has increased average transportation distances and lairage times as flocks are collected from farms distributed over wide geographic areas (Barbut and Leishman, 2022; Petracci, 2022). Under these conditions, the poultry industry frequently observes increased overall color non-uniformity and a higher incidence of darker-than-normal and especially paler-than-normal breast meat, particularly during cold and hot seasons, respectively (Petracci et al., 2017; Barbut and Leishman, 2022).

Consequently, considerable efforts have been devoted by meat scientists and poultry producers to improving color consistency and reducing the occurrence of extreme color deviations. Strategies aimed at optimizing poultry meat color include dietary supplementation with antioxidants, proper management of feed withdrawal, implementation of transport vehicles and lairage areas designed to prevent exposure to extreme temperatures and reduce stress, and optimization of carcass chilling rates (Petracci et al., 2010; Ramanathan et al., 2023). In this context, accurate, repeatable, and practical methods for color evaluation are essential for effective quality control, defect detection, and decision-making in both research and industrial processing environments, including retail and food service supply chains (Ramanathan et al., 2020; Barbut and Leishman, 2022; Ramanathan et al., 2023). Meat color can be evaluated either subjectively through visual scoring and classification or objectively using colorimetric instruments. In the latter category, the results of color evaluation are generally expressed by means of CIELAB color coordinates (CIE, 1978). Indeed, CIELAB is an international standard for color measurement where **L*** indicates the "lightness" component, ranging from 0 (black) to 100 (white), and the chromatic components **a*** and **b*** represent the green-red and blue-yellow axes (generally called "redness" and "yellowness"). Values of a* and b* variables range from −120 to +120, with negative values that refer to green and blue colorations and positive ones to red and yellow, respectively (Mancini and Hunt, 2005; King et al., 2023). This methodology is utilized by colorimeters such as the Minolta Chroma Meter, which is the most widely used instrument for assessing meat color, and the HunterLab colorimeter (Mancini et al., 2022). Minolta Chroma Meter is a hand-held colorimeter equipped with a controlled illumination, either average daylight illuminant C (6,774 K color temperature) or average daylight illuminant D65 (6,504 K color temperature). Even though color measurement with Minolta Chroma Meter is fast and accurate, such equipment is rather expensive, which can represent a limitation for some researchers or companies (Dang et al., 2021). Therefore, it has become important to find alternative and less expensive solutions for meat color assessment.

Recently, a new device known as the Nix Color Sensor has been proposed for the evaluation of color in foods, with particular emphasis on muscle foods (Dang et al., 2021). The Nix Color Sensor is a compact, pocket-sized colorimeter equipped with a user-friendly mobile application, which is characterized by a lower cost compared to previously mentioned colorimeters. In some studies, the Nix Color Sensor (Pro 2 model) has been used to assess the color profile of beef meat (Holman and Hopkins, 2019; Hernández et al., 2025) although inconsistent results have been reported regarding its agreement with conventional colorimeters (i.e. HunterLab colorimeter). Nevertheless, encouraging results regarding the potential use of the Nix Pro 2 model for chicken meat color evaluation as alternative to the Minolta CR 400 have been reported by Che et al. (2023). However, several models of the Nix Color Sensor, such as the Spectro 2, have been recently released on the market. As this new device presents different characteristics compared to the previous models (e.g., camera dimension), research is needed to evaluate the accuracy and the potential applicability of this new model.

Therefore, the objective of this study was to evaluate color measurements of broiler breast meat obtained using a conventional tristimulus colorimeter Minolta CR-400 Chroma Meter (Minolta Italia S.p.A., Milan, Italy) and a portable Nix Spectro 2 Color Sensor (NIX Sensor Ltd., Hamilton, ON, Canada), and to investigate the relationships between instrument-derived color parameters and key meat quality traits under commercial processing conditions. To this end, darker-than-normal, normal, and paler-than-normal breast fillets, representative of the color variability observed under commercial processing conditions, were collected at a commercial slaughterhouse and evaluated for color using both instruments, as well as for major technological quality traits.

Materials and methods

Sample collection

Three independent trials were conducted on boneless, skinless *Pectoralis major* muscles obtained from homogeneous flocks of broiler chickens (male Ross 308; 42 ± 1 days of age; average body weight: 3.2 ± 0.1 kg). Birds were fed the same diet formulated for white-skin broilers (mainly based on soybean meal, barley, and wheat), reared under similar intensive husbandry conditions and processed under the same commercial conditions, including controlled-atmosphere stunning (in accordance with EU Regulation 1099/2009), scalding (50 ± 2°C for 3 min), mechanical defeathering, and evisceration. After air chilling, carcasses were deboned and breast fillets were collected and analyzed within 24 h post-mortem. During the first trial, the color profile (L*: lightness; a*: redness; b*: yellowness; CIE, 1978; Fig. 1SM) of 450 fillets was initially assessed using a standard tristimulus Chroma Meter (CR-400, Minolta Italia S.p.A., Milan, Italy) at the processing plant. Based on the distribution of L* values, three color groups were established using the following thresholds: pale (L* > 59) normal (55 ≤ L* ≤ 57) and dark (L* < 54). Thirty fillets per color group were then selected, resulting in 90 fillets for the first trial. In the second and third trials, 30 fillets per color group were directly selected at the processing plant according to the same L* thresholds. Overall, 270 fillets were collected, corresponding to 90 *Pectoralis major* per color group. For each trial, once selected, fillets were bagged, and transported to the laboratory where color measurements using both the same tristimulus Chroma Meter and Nix Color Sensor (Model Spectro 2; NIX Sensor Ltd., Hamilton, ON, Canada), as well as pH, drip loss, and cooking loss were assessed. After vacuum-packaged storage at −24°C, additional analyses were performed, including moisture content, lipid oxidation (Thiobarbituric Acid Reactive Substances, **TBARS**), and protein oxidation (carbonyl content) (n = 24 samples per color group; 8 randomly selected per color group within each trial).

Color profile measurements by tristimulus Chroma Meter and Nix Color Sensor

The color profile (CIE, 1978) was assessed in parallel using the same tristimulus Minolta Chroma Meter (**L*$_m$, a*$_m$, and b*$_m$**) and a Nix Color Spectro 2 (**L*$_n$, a*$_n$, and b*$_n$**). For both instruments, measurements were taken in triplicate on the medial surface of each fillet using the same illuminant (i.e., C) and standard observer angle (i.e., 2°). The measurement aperture size was 8 mm for the Minolta Chroma Meter and 5

mm for the Nix Spectro 2. The physical illumination systems of the two instruments were different. The Minolta CR-400 uses a pulsed xenon lamp with diffuse illumination geometry and specular component included, whereas the Nix Spectro 2 employs an integrated LED-based illumination system with a 45°:0° ring illumination geometry. As reported in the Nix Spectro 2 (5 mm) Product specification – v3.2, this device was used in combination with the "Nix Toolkit" app, hardware version H3.2.6 and Firmware version F2.0.0. According to the manufacturer's technical specifications, spectral measurements are performed in the 400–700 nm range with a 10 nm reporting interval and the predefined setup for measurement models M0, which includes the UV components, was used.

Before color evaluation, breast fillets were removed from refrigerated storage and equilibrated at room temperature for approximately 1 h. This procedure was applied consistently to all samples. Prior to color analysis, fillet surfaces were gently blotted with absorbent paper to remove excess surface moisture. Measurement areas were selected to be free from visible defects (bruises, discoloration, hemorrhages, engorged blood vessels, picking damage, or any other condition that could affect uniform color readings) as recommended by Petracci and Baeza (2011). Although, as reported above, the two devices were characterized by different aperture sizes, the measurement locations were first identified and then marked to ensure that analyses performed with both Minolta CR-400 and Nix Spectro 2 were carried out on the same surface region to minimizing additional variability associated with tissue heterogeneity and localized color differences. Before measurements in each trial, both instruments were calibrated throughout the study using their respective manufacturer-supplied white ceramic calibration tile, according to the manufacturers' recommended procedures before sample analysis. Color measurements were performed by the same operator. For each breast fillet, color was first measured using the Minolta CR-400 and immediately thereafter using the Nix Spectro 2 to minimize any potential variation in sample conditions between measurements. Color coordinates (CIELAB) were automatically calculated by the devices using the CIE Standard Illuminant C and the CIE 2° Standard Observer for colorimetric calculations. These settings were applied only to the calculation of the color coordinates and do not represent the physical illumination conditions used during spectral acquisition.

Quality traits of breast meat

Meat ultimate pH (**pHu**) was measured 24 hours post-mortem using a portable pH-meter with a stainless-steel blade tip designed for meat penetration and temperature compensation (HI98163, Hanna Instruments Inc., Padova, Italy), previously calibrated with standard buffer solutions at pH 4.01 and 7.01. Water holding capacity (**WHC**) was assessed by estimating drip and cooking losses. From the same cranial portion of each *Pectoralis major* muscle, a parallelepiped-shaped meat cut (8 × 4 × 2 cm; approximately 70 g) was obtained, and drip loss (%) was calculated as weight difference before and after 24 hours of storage at 4 ± 1°C in plastic boxes placed over sieved plastic racks. Cooking loss was determined on the same samples, which were vacuum-packed and subjected to thermal treatment in a water bath (75°C) until the internal core temperature reached 72°C. Then, samples were chilled at room temperature, carefully blotted to remove surface moisture, and weighed. Cooking loss was calculated relative to the sample weight recorded immediately before cooking. Moisture content of pale, normal, and dark fillets was evaluated in duplicate following the standard method reported by the Association of Official Analytical Chemists (AOAC, 1990). Lipid oxidation was assessed through the Thiobarbituric Acid Reactive Substances (TBARS) assay according to Bao and Ertbjerg (2015), while protein oxidation was evaluated following a DNPH-based method reported by Soglia et al. (2016) in which protein-bound hydrazones are spectrophotometrically determined after derivatization with 2, 4-dinitrophenylydrazine.

Statistical analysis

Statistical analyses were performed in R environment (version 4.3.2; R Core Team, 2020). The effect of color group (pale, normal and dark) on meat quality traits was assessed using linear mixed-effects models (LMM), considering color group as a fixed effect and trial as a random effect to account for batch-to-batch variability. When significant differences were detected ($P < 0.05$), pairwise comparisons among groups were performed using Tukey-adjusted post-hoc tests. Model assumptions were evaluated through residual diagnostics, including residual histograms, normal Q-Q plots, and Shapiro–Wilk tests.

The relationships between the color coordinates measured with the Minolta CR-400 and the Nix Spectro 2 were evaluated using Spearman's rank correlation coefficients (ρ). Correlations were estimated using *cor()* and *cor.test()*, and *rcorr()* function from the "Hmisc" package. Scatterplots were generated using "ggpubr", "tidyverse" and "patchwork" packages for the corresponding L*, a*, and b* coordinates obtained using the two different devices to provide a visual assessment of the strength and direction of the associations across the entire range of observed values. Also, correlation plots between color variables (L*, a*, and b*) measured using the Minolta CR-400 and Nix Spectro 2 and meat quality traits (pHu, drip loss, and cooking loss, moisture content, TBARS, and carbonyls) were generated using the "corrplot" package. Correlation coefficients were considered significant at $P < 0.05$.

Results

Quality traits of pale, normal and dark breast meat

In Table 1, the color parameters detected through the Minolta CR-400 and the Nix Spectro 2, as well as the pH, drip loss and cooking loss are reported. Regarding lightness measured with the Minolta CR-400, pale breast meat showed a higher L* value compared with normal and dark meat which differed from each other (61.6 vs. 56.9 vs. 51.9, respectively; $P < 0.001$). The same differences were observed for the L* values measured with the Nix Spectro 2 (45.2 vs. 41.5 vs. 37.6, respectively; $P < 0.001$), even though with lower absolute L* values than the Minolta CR-400. Concerning the redness (a*) and yellowness (b*) parameters, significant differences among the three experimental groups were revealed by the Minolta CR-400. Dark breast meat was characterized by the highest a* value and the lowest b* value compared with normal and pale meat (3.24 vs. 2.49 vs. 2.00 and 2.42 vs. 3.95 vs. 4.67, respectively; $P < 0.001$). The Nix Spectro 2 also detected differences in color parameters, showing a lower a* value in pale meat

Table 1
Color parameters detected by both Minolta CR-400 (L^*_m, a^*_m, and b^*_m) and Nix Spectro 2 (L^*_n, a^*_n, and b^*_n) and ultimate pH, drip loss and cooking loss of chicken breast meat showing different color.

Parameter	Color group			SEM[1]	*P* value
	Pale	Normal	Dark		
Sample n.	90	90	90		
Color parameters – Minolta CR-400					
Lightness - L^*_m	61.6^{A}	56.9^{B}	51.9^{C}	0.30	<0.001
Redness - a^*_m	2.00^{C}	2.49^{B}	3.24^{A}	0.06	<0.001
Yellowness - b^*_m	4.67^{A}	3.95^{B}	2.42^{C}	0.08	<0.001
Color parameters – Nix Spectro 2					
Lightness - L^*_n	45.2^{A}	41.5^{B}	37.6^{C}	0.20	<0.001
Redness - a^*_n	-1.76^{B}	-1.57^{A}	-1.11^{A}	0.04	<0.001
Yellowness - b^*_n	2.45^{A}	2.33^{A}	1.75^{B}	0.07	<0.001
Ultimate pH	5.71^{C}	5.80^{B}	5.98^{A}	0.01	<0.001
Drip loss[2]	2.28^{A}	1.57^{B}	1.50^{B}	0.04	<0.001
Cooking loss[2]	20.4^{A}	16.9^{B}	14.0^{C}	0.30	<0.001

[1] Standard error of the mean.
[2] Expressed as %.
[A-C] Mean values followed by different superscript letters significantly differ among the groups ($P < 0.001$).

compared with normal and dark meat (–1.76 vs. –1.57 and –1.11, respectively; $P < 0.001$), as well as a lower b* value in the dark group compared with the normal and pale groups (1.75 vs. 2.33 and 2.45, respectively; $P < 0.001$). Significant differences were also observed in pHu, drip loss and cooking loss. Pale meat exhibited the lowest pHu (5.71 vs. 5.80 vs. 5.98, respectively; $P < 0.001$) and the highest values of both drip loss (2.28 vs. 1.57 and 1.50%; $P < 0.001$) and cooking loss (20.4 vs. 16.9 vs. 14.0%, respectively; $P < 0.001$) compared with normal and dark meat. In Table 2 the moisture content, TBARS and carbonyls level of breast meat are reported. No significant differences in moisture content were observed among groups. Pale breast meat showed the highest value for the TBARS, while normal and dark meat exhibited similar values (0.82 vs. 0.66 and 0.72 mg MDA/kg of meat, respectively; $P < 0.05$). Carbonyl levels were higher in pale than in normal meat (2.65 vs. 2.10, nmol/mg of protein; $P < 0.05$), whereas dark meat showed intermediate values that did not differ significantly from either group.

Correlations between the color parameters assessed by using the Minolta CR-400 and the Nix Spectro 2

The relationships between the color coordinates (L*, a*, and b*) measured by the Minolta CR-400 and the Nix Spectro 2 were evaluated using Spearman's rank correlation coefficients. Fig. 1 shows the paired measurements and the corresponding correlations between devices. Significant positive correlations were observed for all color coordinates evaluated. Specifically, the L* parameter showed a very strong positive correlation ($\rho = +0.90$, $P < 0.001$), whereas a* and b* parameters exhibited strong positive correlations ($\rho = +0.66$ and $+0.51$, respectively; $P < 0.001$).

Correlations between color parameters and technological properties of breast meat

The Spearman's rank correlation coefficients (ρ) between the color parameters measured using the Minolta CR-400 and Nix Spectro 2 device and the technological properties are presented in Fig. 2. For the Minolta CR-400, the L^*_m value showed a strong positive correlation with both cooking loss ($\rho = +0.64$; $P < 0.001$) and drip loss ($\rho = +0.53$; $P < 0.001$), while a strong negative correlation with pH was found ($\rho = –0.70$; $P < 0.001$). The a^*_m coordinate showed weak positive correlation with ultimate pH ($\rho = +0.18$; $P < 0.01$) and negative correlation with drip ($\rho = –0.12$; $P < 0.05$) and cooking losses ($\rho = –0.20$; $P < 0.001$), whereas b^*_m was negatively correlated with pH ($\rho = –0.48$; $P < 0.001$) and showed a moderate correlation with both drip loss (ρ +0.37; $P < 0.001$) and cooking loss ($\rho = +0.44$; $P < 0.001$), respectively. Regarding the color coordinates measured with the Nix Spectro 2 device, L^*_n was negatively correlated with pH ($\rho = –0.60$; $P < 0.001$) and showed a positive correlation with drip loss ($\rho = +0.48$; $P < 0.001$) and cooking loss ($\rho = +0.58$; $P < 0.001$). The a^*_n coordinate presented a weak positive correlation with pH ($\rho = +0.25$; $P < 0.001$) and a weak negative correlation with drip loss ($\rho = –0.15$; $P < 0.05$) and cooking loss ($\rho = –0.26$; $P < 0.001$), while b^*_n was negatively correlated with pH ($\rho = –0.29$; $P < 0.001$) and exhibited a very weak positive correlation with cooking loss ($\rho = +0.13$; $P < 0.05$). The Spearman's rank correlation coefficients (ρ) between color parameters measured using both devices (Minolta CR-400 and Nix Spectro 2) and moisture content, TBARS and carbonyls level of breast meat are shown in Fig. 3. No significant correlations were observed between the color coordinates measured by either device and the additional quality traits (moisture content and oxidation levels).

Table 2
Moisture content, Thiobarbituric Acid Reactive Substances (TBARS) and carbonyls of chicken breast meat showing different color.

Parameter	Color group			SEM[1]	*P* value
	Pale	Normal	Dark		
Sample n.	24	24	24		
Moisture[2]	75.1	75.0	75.3	0.20	0.357
TBARS[3]	0.82[a]	0.66[b]	0.72[b]	0.02	0.012
Carbonyls[4]	2.65[A]	2.10[B]	2.51[AB]	0.07	0.004

[1] Standard error of the mean.
[2] Expressed as %.
[3] Expressed as mg MDA/kg of meat.
[4] Expressed as nmol/mg of protein.
[A-C] Mean values followed by different superscript letters significantly differ among the groups ($P < 0.001$).
[a,b] Mean values followed by different superscript letters significantly differ among the groups ($P < 0.05$).

Discussion

Color parameters detected by Minolta CR-400 and Nix Spectro 2 and characterization of chicken breast meat showing different color

The present study assessed color measurements of broiler breast meat, representative of the variability which may be observed under commercial processing conditions, obtained using the Nix Spectro 2 and the Minolta CR-400. In accordance with the classification criteria applied at sampling, a wide range of variation in lightness was observed, allowing the classification of fillets into three experimental groups. These groups exhibited clearly distinct color profiles (L^*_m, a^*_m, and b^*_m) particularly in terms of lightness, which was the parameter used to define the experimental classification based on measurements obtained with the Minolta CR-400. It is well documented that paler meat is associated with lower redness and greater yellowness in broiler breast meat (Qiao et al., 2001; Petracci et al., 2004). Marked variability even within the same flock and particularly in terms of lightness, has been widely reported (Fletcher, 1999; Petracci et al., 2004; Petracci et al., 2017; Barbut and Leishman, 2022). Pre-slaughter conditions and slaughtering procedures, through their influence on the onset and extent of post-mortem acidification, have been identified as primary determinants of this variation (Petracci et al., 2010; Barbut and Leishman, 2022). In fact, during the pre-slaughter phase, birds may be exposed to multiple stressors, which can exacerbate pre-existing variability in meat quality traits, including color (Petracci et al., 2010). Direct comparison of color data across studies remains challenging, as substantial differences in absolute L* values have been reported worldwide (Petracci et al., 2009). Such variability likely reflects differences in production factors (e.g., genotype, feeding strategy, housing conditions, ante-mortem management, and processing techniques, etc.), as well as methodological discrepancies in sampling procedures and color measurement protocols (Wideman et al., 2026). Therefore, comparisons with previously published results should be made with caution. Among the available references, the study by Petracci et al. (2004), conducted in a commercial plant in Italy using the same Minolta colorimeter represents the most comparable investigation to the present one. In that study, L^*_m thresholds were proposed to classify breast meat as pale ($L^*_m > 59$) normal ($55 \leq L^*_m \leq 57$) and dark ($L^*_m < 54$), .

Compared with those reference ranges, the present results indicate generally higher lightness values, suggesting a possible shift toward lighter breast meat samples. More recently, Lee et al. (2022), evaluating 1,499 breast fillets, classified meat as dark, normal, and pale when L* values were < 56, between 56 and 62, and > 62, respectively. The variability in proposed cut-off values across studies further confirms the absence of universally accepted L* thresholds to discriminate among darker-than-normal, normal, and paler-than-normal breast meat (Zhang and Barbut, 2005; Lee et al., 2022). In this context, the classification criteria adopted in the present study (i.e., $L^*_m > 59$ for pale, $55 \leq L^*_m \leq 57$ for normal, and $L^*_m < 54$ for dark) fall within the ranges reported in the literature. When color parameters obtained with the Nix Spectro 2 were considered, a consistent and coherent pattern of differences among the three experimental groups emerged. In particular, L^*_n values were

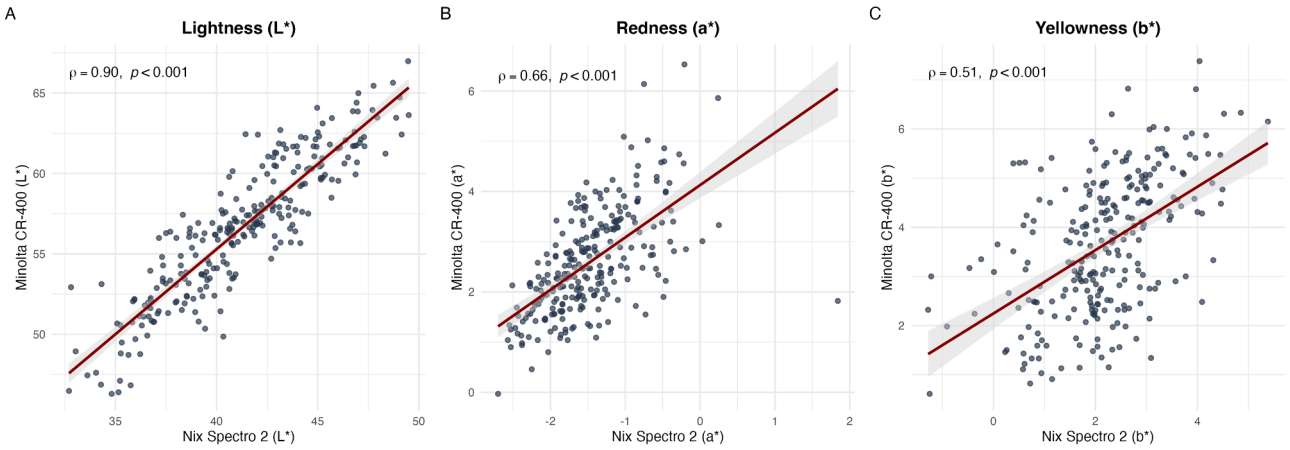

Fig. 1. Scatterplots illustrating the relationships between corresponding color coordinates obtained with the Minolta CR-400 and the Nix Spectro 2 by considering the entire dataset (90 samples per color group; N = 270). Panel A: L* (Lightness), Panel B: a* (redness), and Panel C: b* (yellowness). Spearman's rank correlation coefficients (ρ) and associated p-values are shown within each panel. Fitted lines are included for visualization purposes only.

significantly higher in pale breast meat compared with normal and dark samples, which also differ each other (45.2 vs. 41.5 vs. 37.6, respectively; $P < 0.001$), reflecting the trend observed with the Minolta device. Similarly, pale meat exhibited lower a^*_n and higher b^*_n values than normal and dark samples (−1.76 vs. −1.57 vs. −1.11 and 2.45 vs. 2.33 vs. 1.75, respectively; $P < 0.001$). In the present study, color coordinate values obtained with the Nix Spectro 2 were generally lower than those measured with the Minolta CR-400. This finding is consistent with previous reports. Dang et al. (2021), comparing the CR-400 and the formerly available Nix Color Sensor (i.e., Model Pro 2) across different food matrices, including muscle foods, observed lower L* and C* values with the Nix device, indicating darker and less saturated color measurements. Similarly, Che et al. (2023), evaluating chicken meat color using the same instruments, reported markedly lower absolute values with the Nix Color Sensor. Studies conducted on beef and lamb have likewise demonstrated that, although absolute values may differ, the Nix Color Sensor reliably captures relative color differences (Holman and Hopkins, 2019; Holman et al., 2021; Hernández et al., 2025).

The discrepancies in absolute color values observed between the two instruments may be partly explained by differences in their measurement principles and optical configurations, particularly measurement geometry, illumination conditions, and aperture size, all of which influence the interaction between incident light and the meat surface. Specifically, the difference in optical geometry between the Minolta CR-400 (d/0° geometry) and the Nix Spectro 2 (45°/0° geometry) may introduce systematic variations in color measurements because diffuse and directional illumination geometries differ in their treatment of specular reflection and surface appearance effects. In particular, the Minolta CR-400 operates in a specular component included (SCI) configuration. Consequently, the higher absolute color values obtained with the Minolta CR-400, compared with the Nix Spectro 2, may be partially attributed to the inclusion of surface specular reflection in the measurement. Because meat is a translucent material, instruments with directional measurement geometry are generally preferred for color assessment, as they minimize or exclude the contribution of specular reflection, thereby providing a more accurate evaluation of the intrinsic color of the sample (Warner, 2014). Concerning the illumination conditions, the Minolta CR-400 and the Nix Spectro 2 were both set to the same CIE standard illuminant (C) for colorimetric calculations, they employ different light sources (a pulsed xenon lamp and an LED-based light source, respectively). Although the technical documentation for both instruments does not provide details on their spectral power distributions (SPDs), it is plausible that differences in their SPDs contribute to variations in the measured color values.

Another important aspect to consider is the larger measurement aperture of the Minolta CR-400 (8 mm) compared with that of the Nix Spectro 2 (5 mm). Aperture size significantly influences colorimetric measurements by modulating light reflectance, particularly at wavelengths >450 nm, resulting in increased color coordinate values when larger apertures are used (Yancey and Kropf, 2008; Holman et al., 2015). Increasing aperture diameter also exacerbates edge-loss effects due to greater lateral light displacement beyond the measurement area. However, for heterogeneous surfaces such as meat, larger aperture sizes may provide a more integrated representation of sample color (Yancey and Kropf, 2008). However, it is important to note that the various differences between the Minolta CR-400 and the Nix Spectro 2 that influence color measurement occur simultaneously. Consequently, it is not possible to isolate and assess the effect of each individual factor. Despite differences in absolute values between instruments, the Nix Spectro 2 effectively discriminated among pale, normal, and dark breast meat samples, demonstrating a classification capability comparable to that of the Minolta CR-400.

As well established, color variations in chicken meat are strongly associated with pHu, with lighter muscles (higher L* values) typically exhibiting lower pH (Petracci et al., 2017; Barbut and Leishman, 2022; Petracci, 2022) and a reduced ability to retain water during storage and heat treatment due to the proximity to the isoelectric point of myofibrillar proteins. Moreover, the lower pHu observed in pale meat may promote partial denaturation of sarcoplasmic proteins, leading to an increased scattering of the incident light (Qiao et al., 2001; Petracci et al., 2009). This protein denaturation may also enhance the activity of endogenous proteolytic and lipolytic enzymes, thereby accelerating protein and lipid oxidation processes (De Avila Souza et al., 2022), which may explain the higher TBARS (0.82 vs. 0.66 and 0.72; $P = 0.012$) and carbonyl (2.65 vs. 2.10 and 2.51; $P = 0.004$) values observed in the pale group compared with normal and dark meat. These oxidative processes further impair technological properties such as WHC (De Avila Souza et al., 2022). Accordingly, in our study, pale meat exhibited higher drip and cooking losses than normal and dark meat.

Spearman's rank correlations among color parameters measured by Minolta CR-400 and Nix Spectro 2, and between color parameters and some key meat quality traits

Irrespective of absolute color differences, Spearman's rank correlation coefficients were calculated to assess the direct relationships between the color parameters measured using the Minolta CR-400 and the Nix Spectro 2. A strong positive correlation was observed for the L* variable, while moderate positive correlations were found for the a* and b* variables. These differences may be partially explained by the wider

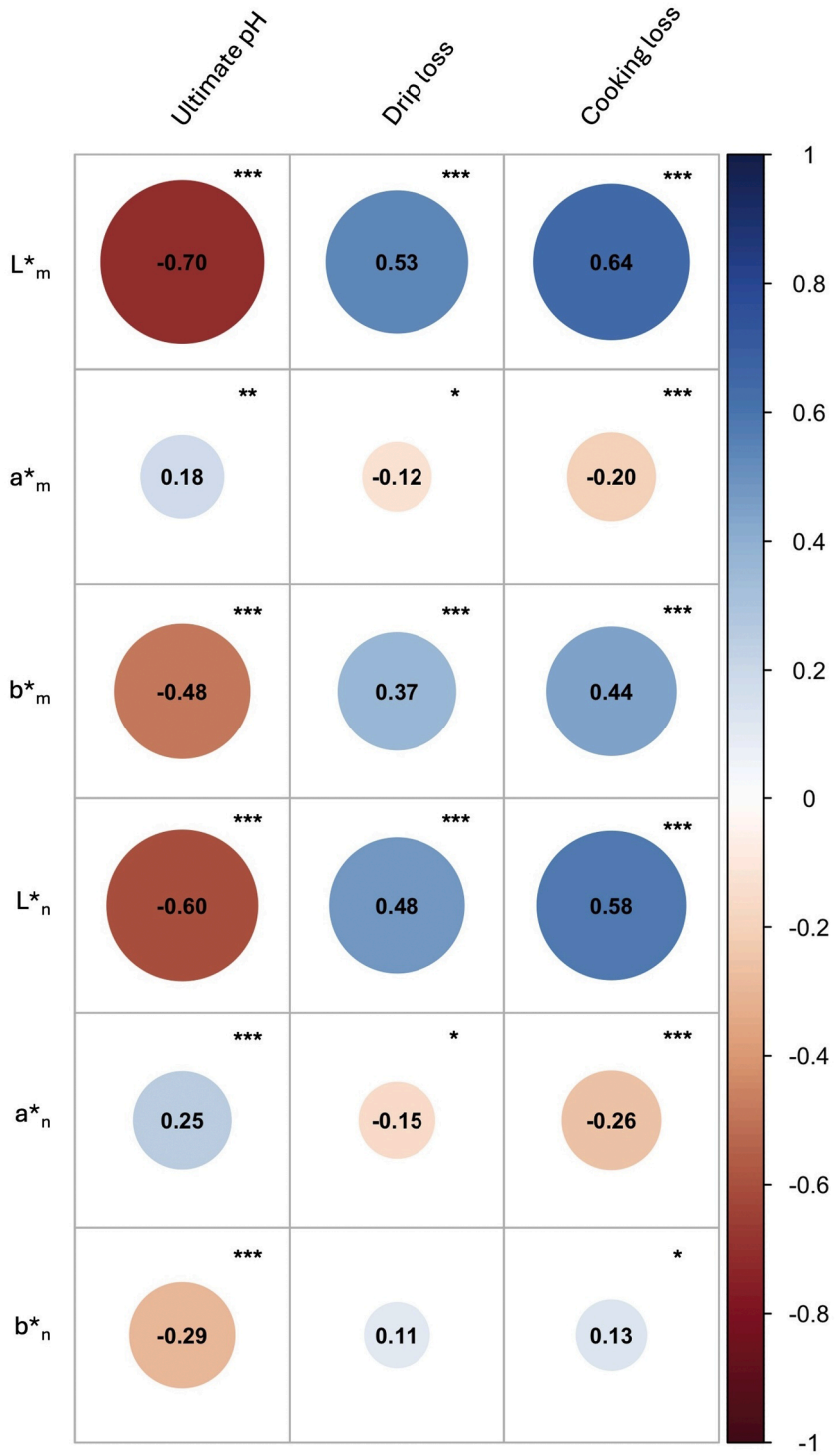

Fig. 2. Correlation plot showing the Spearman's correlation coefficients between the color parameters, assessed by using Minolta CR400 colorimeter (L^*_m, a^*_m, and b^*_m) and Nix Spectro 2 color sensor (L^*_n, a^*_n, and b^*_n), and other quality parameters assessed as part of this study (i.e., ultimate pH, drip loss, and cooking loss) by considering the entire dataset (90 samples per color group; n = 270). The correlation plot is color-coded: blue and red indicate positive and negative correlations, respectively. $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

range of variation observed for lightness compared with that found for redness and yellowness. However, these findings suggest that the two instruments describe the relative color differences among samples in a consistent manner and identify similar patterns of variation, although differences in absolute measurements may occur between devices.

Overall, these findings are consistent with those reported by Che et al. (2023), who, based on a smaller sample size (95 vs. 270 samples in the present study), observed strong positive correlations between the Minolta CR-400 and the formerly available Nix Color Sensor (Model Pro 2), with correlation coefficients of $\rho = +0.75$ for L*, $\rho = +0.72$ for a*, and $\rho = +0.80$ for b*. It should also be noted, however, that Che et al. (2023) used different illuminant for the two instruments (i.e., D65 for the Minolta CR-400 and D50 for the Nix Pro 2), whereas in the present study both devices operated using illuminant C. Colorimeter settings, particularly the illuminant source, significantly affect color measurements because perceived color depends on the spectral properties of the

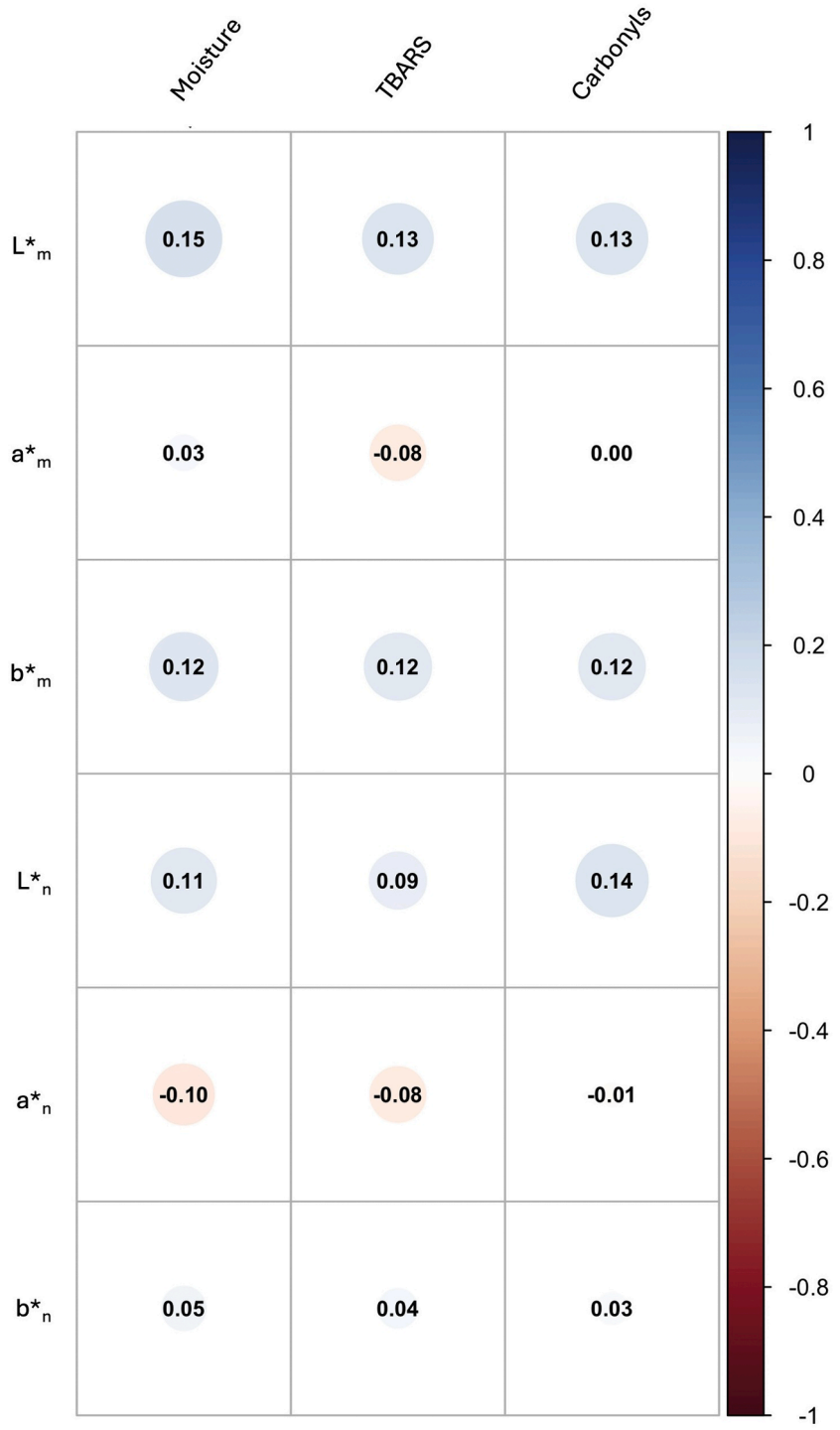

Fig. 3. Correlation plot showing the Spearman's correlation coefficients between the color parameters, assessed by using Minolta CR400 colorimeter (L^*_m, a^*_m, and b^*_m) and Nix Spectro 2 color sensor (L^*_n, a^*_n, and b^*_n), and the additional quality parameters assessed as part of this study (i.e., moisture, TBARS, and carbonyls) by considering a subset of samples (24 samples per color group; n = 72). The correlation plot is color-coded: blue to red colors indicate positive to negative correlation values. $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

light source (Salueña et al. 2019; Holman et al., 2021). In fact, the use of different illuminants (e.g., D50 and D65) can alter redness and yellowness values, highlighting the need for standardization (Güngören, and Güngören, 2025). Therefore, the use of illuminant C for both instruments in the present study may have contributed to the different outcomes observed for the a* and b* parameters compared with those reported by Che et al. (2023).

To evaluate the suitability of color coordinates measured by the Nix Spectro 2 with particular emphasis on lightness (L*) as indicators of meat quality, as is commonly done using a conventional colorimeter, the main meat quality traits were determined in the same set of samples grouped according to color. The correlations between the color parameters measured using both instruments and the main technological properties of the meat showed that the values obtained with the Nix Spectro 2 confirm the outcomes of the Minolta CR-400 regarding the scarce prediction capacity of meat color variables on moisture, TBARS

and carbonyls content. In accordance with these findings, previous studies (Allen et al., 1998; Qiao et al., 2001) conducted on chicken meat have demonstrated that L* values are not significantly correlated with moisture content. The literature consistently reports that elevated TBARS and carbonyl levels are associated with darker meat (Estévez, 2015). Nevertheless, although oxidative processes are known to influence meat color, no studies in chicken meat have established a correlation coefficient between TBARS or carbonyls and color coordinates. This lack of association likely reflects the complexity of the lipid and protein oxidation processes, which involve multiple stages from radical formation triggered by external factors (i.e., preslaughter stress) to the accumulation of secondary products such as aldehydes and carbonyls (Estévez, 2015). Endogenous muscle components, including iron and myoglobin and its redox forms (i.e., deoxymyoglobin, oxymyoglobin, and metmyoglobin), can catalyze oxidative reactions (Min and Ahn, 2005). Given that aldehydes and carbonyls are secondary oxidation products and that myoglobin actively participates in oxidative pathways, it is plausible that heme pigments are more directly associated with color variables than TBARS or total carbonyl content. However, when the meat heme pigment content is very low (i.e., pork or chicken meat) the color is influenced also by the muscular structure (Hernández et al., 2016). As muscle pH declines after slaughter, proteins denature and gaps form between myofibrils, increasing light scattering and making the meat appear lighter (Qiao et al., 2001; Petracci et al., 2009). During rigor mortis, myofibrils shorten, enlarging intracellular spaces and causing water to move out of cells, which increases drip and cooking loss (Warner, 2014). These changes explain why lower pH is associated with higher lightness (L*) and why lighter meat tends to show greater water loss (Warner, 2014). This result agrees with previous research reporting a positive correlation between L* and drip loss (Barbut, 1993; Allen et al., 1998; Lee et al., 2022) and a negative correlation between L* and WHC (Qiao et al., 2001). In the present study, drip loss and cooking loss were negatively correlated with a* and positively correlated with b*. The latter correlation was observed only when using the Minolta CR-400 color coordinates. To our knowledge, no studies in the literature support these findings; consequently, any statements about these relationships remain hypothetical.

Considering the mechanisms described above, which involve pH, L*, and WHC parameters, it is possible to hypothesize that the positive correlation between b* and drip and cooking losses, as well as the negative correlations between a* and these parameters, is a consequence of the increased light scattering resulting from the pH decreases and the L* increases. The relationships among pH, L*, a*, and b* are well documented when paler-than-normal and darker-than-normal chicken meat are described. Accordingly, in paler-than-normal meat, a rapid pH decline is observed, and the meat shows high L*, b*, and WHC values, as well as a low a* value. Conversely, in darker-than-normal meat, a high pH is observed, and the meat shows a high a* value, along with low L*, b*, and WHC values. The novelty of this study lies in the confirmation of these correlations even when the Nix Spectro 2 is used to assess the color profile of chicken meat. It is well established that L* represents a good predictor of the technological quality of the meat. In our study, the L* value provided by both instruments was positively correlated with drip and cooking loss and negatively correlated with pH. This supports the fact that the relationship between L* and the main meat quality traits is consistent between the two instruments. In particular, the strong correlation between L^*_m and L^*_n as well as the negative correlation showed between L^*_n and pH further support the finding that the Nix Spectro 2 could be considered as a promising alternative to the Minolta CR-400 to assess chicken meat color and predict some of its quality traits.

Conclusions

This study demonstrates that the Nix Spectro 2 was able to discriminate among pale, normal, and dark broiler breast meat samples collected under commercial processing conditions. Although systematic differences in absolute CIELAB coordinates were observed between Nix Spectro 2 and the Minolta CR-400, the Nix device consistently captured the relative variation in breast meat color, particularly in lightness, and showed relationships between L*, ultimate pH and water holding capacity comparable to those observed with the Minolta CR-400. In addition to its analytical performance, the Nix Spectro 2 offers several practical advantages, including its compact size, mobile-app integration, operational simplicity, and lower acquisition cost compared with conventional colorimeters. Standardization of instrumental settings and measurement procedures is nevertheless recommended to minimize methodological discrepancies and facilitate meaningful comparisons across studies and surveys, as previously emphasized for widely used tristimulus colorimeters.

Author Contribution

MP designed and supervised the project, secured funding, contributed to data interpretation, and critically reviewed and revised the manuscript. BGM, ELA participated in sample collection and analyses. MAG, FS, MB, ACM participated in samples collection, provided the quantitative data for statistical evaluation, with MB being additionally responsible for figure preparation, data analyses and data visualization. ALS critically reviewed and revised the manuscript. All authors have read and approved the final version and agree to be accountable for all aspects of the work.

Disclosures

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.psj.2026.107552.

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