Describing the relationships among meat quality traits in domestic turkey (*Meleagris gallopavo*) populations

Heather M. Hiscock,* Emily M. Leishman,† Ryley J. Vanderhout,† Sarah M. Adams,† Jeff Mohr,‡ Benjamin J. Wood,†,‡,§ Christine F. Baes,†,# and Shai Barbut[1],*

*Department of Food Science, University of Guelph, Guelph, Ontario N1G 2W1, Canada; †Centre for the Genetic Improvement of Livestock, Department of Animal Biosciences, University of Guelph, Guelph, Ontario N1G 2W1, Canada; ‡Hybrid Turkeys, Kitchener, Ontario N2K 3S2, Canada; §School of Veterinary Science, University of Queensland, Gatton, Queensland 4343, Australia; and #Institute of Genetics, Vetsuisse Faculty, University of Bern, Bern 3001, Switzerland

ABSTRACT The presence of meat quality defects is increasing in the turkey industry. While the main strategy for mitigating these issues is through improved housing, management, and slaughter conditions, it may be possible to incorporate meat quality into a turkey breeding strategy with the intent to improve meat quality. Before this can occur, it is important to describe the current state of turkey meat quality as well as the correlations among the different meat quality traits and important production traits. The main objective of the present study was to provide a descriptive analysis of 8 different meat quality traits for turkey breast meat from 3 different purebred lines (A, B, and C), and their correlation with a selection of production traits. Using a total of 7,781 images, the breast meat (N = 590−3,892 birds depending on trait) was evaluated at 24 h postmortem for color (L*, a*, b*), pH, and physiochemical characteristics (drip loss, cooking loss, shear force). Descriptive statistics (mean and standard deviation) and Pearson correlations were computed to describe the relationships among traits within each genetic line. A one-factor ANOVA and post hoc t-test were conducted for each trait and between each of the genetic lines. We found significant differences between genetic lines for some color traits (L* and a*), $pH_{initial}$, drip loss, and cooking loss. The lightest line in weight (line B) had meat that was the lightest (L*) in color. The heaviest line (line C) had meat that was less red (a*) with a higher $pH_{initial}$ and greater cooking loss. Unfavorable correlations between production traits and meat quality were also found for each of the genetic lines where increases in production (e.g., body weight, growth rate) resulted in meat that was lighter and redder in color and in some cases (line B and C), with an increased moisture loss. The results of this study provide an important benchmark for turkey meat quality in purebred lines and provide an updated account of the relationships between key production traits and meat quality. Although the magnitude of these correlations is low, their cumulative effect on meat quality can be more significant especially with continued selection pressure on growth and yield.

Key words: color, cooking loss, drip loss, pH, genetics

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INTRODUCTION

Global poultry meat consumption has significantly increased within the last few decades (Yalcin et al., 2019). Consumer demands for high protein, low fat, fresh meat, and poultry products has led to turkey meat ranking as the second most popular poultry meat around the world (Baéza et al., 2022). To efficiently meet consumer demands, the use of intense genetic selection for fast growth and higher meat yields have increased, resulting in higher body weight and breast meat proportions (Yalcin et al., 2019).

Along with the demand for poultry meat, consumers have high expectations for product quality. Product quality can be characterized through the physical, chemical, morphological, and nutritional attributes presented (Anadon, 2002; Mir et al., 2017). As the selection for larger, faster growing birds continues, there has been a noticeable increase in meat quality defects (Anadon, 2002; Yalcin et al., 2019). Defects such as myopathies (e.

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[1]Corresponding author: sbarbut@uoguelph.ca

g., white striping, woody breast), pale, soft, and exudative (**PSE**)- like meat, and dark, firm, and dry (**DFD**) meat, affect the color, water holding capacity (**WHC**), and texture of the product (Adzitey and Nurul, 2011; Leishman et al., 2021). All of these defects negatively affect consumer acceptance and could potentially lead to economic losses in the turkey industry (Werner et al., 2008). In particular, PSE meat is estimated to cost the US broiler and turkey industry $200 million per year (Barbut, 2009). Poultry products classified as PSE are characteristically paler and with reduced WHC. This phenomenon can occur immediately after slaughter during a rapid pH decline while the muscles are still warm (Werner et al., 2008). The rapid pH decline results in muscle proteins denaturation creating less ability for water to be held as well as a color change (lighter and more yellow). Raw meat color is the main factor affecting consumer preferences at the point-of-purchase, with texture and firmness being important for consumer satisfaction (Mir et al., 2017). Traits like WHC are less important from a consumer perspective, however they are the main interest for meat (Adzitey and Nurul, 2011; Mir et al., 2017). Overall, PSE impacts consumer acceptability also the ability for the industry to process high quality products with high yields. Using methods such as drip loss and cooking loss, we can assess the muscle's water holding capacity overtime. PSE meat can be classified with traits such as meat color, pH, and water-holding capacity and therefore these parameters represent important indicators for meat quality and meat quality defects (Leishman et al., 2021).

Currently, the main strategies to reduce the occurrence of these meat quality problems is through improved housing, management, and slaughter practices (Ali et al., 2008; Zampiga et al., 2020). However, an alternative strategy is to use genetic selection targeting meat quality traits (Bailey et al., 2020). The presence of noticeable physical changes in the meat caused by myopathies (e.g., white striping, woody breast) or other conditions (e.g., PSE, DFD) have been noted to be connected to the intensive selection for larger body weight and breast meat yield (Berri et al., 2001; Fernandez et al., 2001; Vanderhout et al., 2022). The impact of this intensive selection has also been proven to be a driving factor in the progression of myopathies and meat quality attributes (Werner et al., 2008; Zampiga et al., 2020). Due to the connections between meat color, pH, WHC, and certain myopathies and growth, it is possible that directional selection for some of these traits will improve meat quality and reduce the incidence of myopathies and PSE.

Before incorporating meat quality into a turkey breeding strategy, it is important to benchmark the meat quality traits in the population and describe how they are correlated with economically important components (Abdalla et al., 2021). Previous studies have demonstrated differences in meat quality attributes between different turkey genetic lines (Fernandez et al., 2001; Updike et al., 2005; Leishman et al., 2022) however this relationship is still unclear as other studies report no differences in meat quality traits between lines (Werner et al., 2008; Zampiga et al., 2019). It has been suggested that differences in meat quality between genetic lines relate to growth trajectories and physiologies and have a tendency for faster-growing lines to be different from slower-growing lines (Leishman et al., 2022). Faster-growing birds have muscles with larger fiber size, and higher proportion of glycolytic fibers (Dransfield and Sosnicki, 1999; Strasburg and Chiang, 2009). As the structure of the muscle changes with growth, it is important to establish if differences in meat quality exist between different genetic lines of turkeys and whether similar correlations among traits exist in the different lines.

The objective of the present study was to describe and compare meat quality traits (color, pH, drip loss, cooking loss, and shear force) in 3 purebred turkey lines with different breeding goals. A secondary objective was to describe correlations between the selected traits and body weights from birds of each genetic line. A good understanding of the relationship among the meat quality traits should aid in future breeding strategies to improve overall meat quality.

MATERIALS AND METHODS

Turkeys

Adult male turkeys from three purebred lines were used (N = 15,496). Line A is a female line selected primarily for growth and reproductive traits. Line B is also a female line selected mainly for reproductive traits. Line C is a male line, selected primarily for body weight and meat yield. All birds were processed over a 44-wk period from July 2018 to November 2019. The age of the turkeys at slaughter was between 20 and 24 wk. All birds were reared under similar housing and management conditions and were processed at the same commercial poultry abattoir under identical conditions (Vanderhout et al., 2022; Leishman et al., 2022). The turkeys were electrically stunned and exsanguinated, then scalded, defeathered, and eviscerated before being water chilled (2 h) and moved onto ice in refrigerated storage for 22 h.

All protocols complied with the guidelines of the Canadian Council on Animal Care and were approved by the University of Guelph Animal Care Committee (AUP 3782).

Production Traits

Body weight (kg) was measured on all birds 2 d before slaughtered (noted as final BW, varied between 20 and 24 wk based on the line). Average weekly gain (kg/wk, AWG) was calculated as the final BW (kg) divided by the age at slaughter.

At 24 h postmortem, carcasses were broken down into their components and boneless skinless whole breasts (fillets + tenders) were individually weighed. Breast meat yield (BMY) was calculated using the following formula,

$$BMY\ (\%) = \frac{Whole\ Breast\ (kg)}{BW20\ (kg)} \times\ 100$$

Meat Quality Evaluations

Initial pH was measured at 45 min postmortem on a 20 g sample of breast meat cut from the cranial region of the *Pectoralis major* muscle, prior to placing the birds in the 4°C water chiller (samples were also kept at 4°C). Ultimate pH was measured directly from the dorsal side of an intact deboned *Pectoralis major* at 24 h postmortem. A portable pH meter (Model H199163, Hanna Instruments, Woonsocket, RI) equipped with a spear probe was used for both measurements. The calibrated probe was inserted for about 30 sec until the reading stabilized.

Trichromatic coordinates (L*, a*, b*) (CIE, 2018) of the breast muscle were obtained by using a colorimeter (Nix Pro, Hamilton, ON, CA) employing D50 illumination. Color measurements were taken 24 h postmortem from the dorsal side of an intact skinned *Pectoralis major*.

Approximately 200 g samples of *Pectoralis major* were collected from each bird at 24 h postmortem, and transported on ice to the University of Guelph Meat Lab. A small portion (13 ± 1 g) was removed and placed in a drip loss collection tube. After 72 h at 4°C, the sample was reweighed, and percent drip loss was calculated as:

$$Drip\ loss\ (\%) = \frac{initial\ weight\ (g) - final\ weight\ (g)}{initial\ weight\ (g)} \times\ 100$$

Cooking loss was measured on intact muscle samples (7.5 cm W × 4.5 cm L × 4.5 cm H); weighing about 150g removed from the ventral areas. Samples were wrapped in aluminum foil and placed inside a metal cooking rack (4.5 cm wide) to prevent deformation while cooking. Samples were cooked in a preheated conventional oven set at 350°C until the internal temperature of 72°C was reached. Percent cooking loss was calculated as:

$$Cooking\ loss\ (\%) = \frac{initial\ weight\ (g) - final\ weight\ (g)}{initial\ weight\ (g)} \times\ 100$$

Cooked samples were cooled to room temperature and shear force was measured on the ventral side of the breast sample using a texture analyzer (TA.XT Plus Texture Analyzer, Stable Micro Systems, Godalming, Surrey, UK) equipped with a 30 kg load cell. Each cooked sample was sheared at six different locations on the sample surface (1 cm apart) perpendicular to the muscle fiber direction on the ventral surface using MORS blade (Morey and Owens, 2017). Samples were sheared to a depth of 20 mm at a speed of 1mm/s with a trigger force set at 0.1 N. Values from the 6 reading were averaged for each sample.

Statistical Analysis

Descriptive statistics (mean and standard deviation) and Pearson correlation coefficients between the traits, for each genetic line, were computed using R (version 1.3.1093, R Core Team, 2020). A one-factor ANOVA and post hoc t-test with Bonferroni adjustment were conducted for each of the traits to assess the differences between genetic lines. The α level for determination of significance was 0.05.

RESULTS

Production Traits

Table 1 shows the difference between the three lines for the assessed production traits: final BW, AWG, whole breast weight, and BMY. There were significant differences between the genetic lines for each of these production attributes ($P < 0.001$). Birds from line C demonstrated a higher final BW in comparison to the birds from lines A ($P < 0.0001$) and B ($P < 0.0001$). The AWG was also different between the genetic lines ($P <$

Table 1. Mean and standard deviation (SD) for production and meat quality traits under investigation within three purebred turkey lines (A, B, and C).

	Line A		Line B		Line C	
Trait	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD
FINAL BW (kg)	4,468	21.87 ± 1.53^{b}	5,285	19.11 ± 1.35^{c}	5,433	24.72 ± 1.79^{a}
AWG (kg/week)	4,468	1.34 ± 0.16^{b}	5,285	1.12 ± 0.11^{c}	5,433	1.63 ± 0.22^{a}
Whole Breast (kg)	4,639	5.21 ± 0.57^{b}	5,215	4.74 ± 0.50^{c}	5,442	6.08 ± 0.74^{a}
BMY (%)	4,448	23.78 ± 1.93^{c}	5,203	24.77 ± 1.71^{a}	5,347	24.58 ± 2.06^{b}
Lightness (L*)	3,369	37.36 ± 2.54^{c}	3,671	38.04 ± 2.58^{a}	3,892	37.64 ± 2.69^{b}
Redness (a*)	3,369	1.13 ± 0.68^{b}	3,671	1.21 ± 0.69^{a}	3,892	0.93 ± 0.64^{c}
Yellowness (b*)	3,369	2.00 ± 0.89^{a}	3,671	1.90 ± 0.93^{a}	3,892	1.89 ± 0.92^{a}
$pH_{initial}$	722	6.30 ± 0.24^{b}	1,340	6.31 ± 0.24^{b}	1,034	6.43 ± 0.23^{a}
$pH_{ultimate}$	714	5.74 ± 0.11^{a}	1,340	5.77 ± 0.10^{a}	1,061	5.79 ± 0.11^{a}
Drip loss (%)	699	1.95 ± 1.60^{a}	1,347	1.36 ± 1.32^{c}	1,065	1.56 ± 1.36^{b}
Cooking loss (%)	718	29.67 ± 3.94^{b}	1,385	30.08 ± 4.08^{b}	1,065	30.76 ± 4.59^{a}
Shear Force (N)	590	9.95 ± 3.05^{a}	1,048	9.53 ± 2.49^{a}	939	9.70 ± 2.54^{a}

[a-c]Within a given trait, means that do not share a letter superscript are significantly different ($P < 0.05$).

Table 2. Phenotypic correlation matrix for the evaluated turkey meat quality traits for Line A (N = 590−3,369 depending on trait).

Traits	FINAL BW[1]	AWG	Whole Breast	BMY	L*	a*	b*	$pH_{initial}$	$pH_{ultimate}$	Drip loss	Cooking loss	Shear force
Final BW (kg)		0.704**	0.687**	0.070*	0.194**	0.135**	0.194**	0.177*	0.087	0.012	0.035	−0.159*
AWG (kg/week)			0.425**	−0.03	0.112**	0.017	0.098**	0.163*	0.133*	0.013	0.078	−0.183*
Whole Breast (kg)				0.771**	0.275**	0.008	0.203**	0.111	−0.006	0.073	0.089	−0.087
BMY (%)					0.217**	−0.121**	0.107**	−0.031	−0.117	0.110	0.102	0.051
L*						−0.148**	0.166**	−0.049	−−0.360**	0.147**	0.164*	0.127
a*							0.290**	0.060	0.122	0.034	0.064	−0.046
b*								0.089	−0.011	0.054	0.038	0.007
$pH_{initial}$									0.206**	−0.055**	−0.068	−0.085
$pH_{ultimate}$										−0.137	−0.082*	−0.222
Drip loss (%)											0.133	0.113**
Cooking loss (%)												0.017
Shear force (N)												

[1]FINAL BW = body weight measured two days before slaughter (20−24 weeks of age).Significance is denoted by superscripts *and **, at $P < 0.05$ and $P < 0.001$ respectively.

*$P < 0.05$.

**$P < 0.001$.

0.05). Specifically, line C demonstrated an AWG of 1.63 kg/wk, which was significantly higher ($P < 0.05$) than that of line A and B, which had an AWG of 1.34 kg/wk and 1.12 kg/wk respectively. Similarly, both traits, whole breast, and BMY were significantly different ($P < 0.05$) between all genetic lines. Line C, selected predominately for growth, had the heaviest whole breast weight (6.08 kg) in comparison to both lines A (5.21 kg) and B (4.74 kg). Interestingly, lines did not have the same trend for BMY. The highest percent yield (BMY) was collected from line B at a value of 24.77%, whereas line A had a percent yield of 23.78% while line C had a percent yield of 24.58%.

Meat Quality

Descriptive statistics for the studied meat quality traits are shown in Table 1. The results from the ANOVA and post hoc show that there were differences between genetic lines for L*, a*, $pH_{initial}$, drip loss, and cooking loss (adjusted pairwise $P < 0.05$).

Both L* and a* were influenced by genetic line ($P < 0.0001$). Line B produced meat with a higher L* value in comparison to lines A and C ($P < 0.0001$). Line C had a lower a* than lines A ($P > 0.05$) and B ($P > 0.05$). There was no difference in b* between the genetic lines ($P > 0.05$).

At 45 min postmortem ($pH_{initial}$), line C had the highest mean at 6.43 ± 0.23 which was significantly different than lines A ($P < 0.0001$) and B ($P < 0.0001$). The $pH_{initial}$ was not different between lines A and B ($P = 1.000$). There was no difference in the $pH_{ultimate}$ between the three genetic lines ($P > 0.05$).

Line A had the highest mean drip loss compared to line B ($P < 0.0001$) and line C ($P < 0.0001$) with the drip loss for line C being higher than line B ($P = 0.012$). For cooking loss, line C had significantly higher cooking loss compared to lines A ($P = 0.0041$) and B ($P = 0.0196$). There was no difference in the mean shear force between the genetic lines ($P > 0.05$).

Correlations

Tables 2, 3 and 4 show the Pearson correlation matrices created for each of the three lines, A, B, and C respectively. Due to the high number of variable correlations, only significant ($P < 0.05$) correlations will be

Table 3. Phenotypic correlation matrix for the evaluated turkey meat quality traits for Line B (N = 1,048−3,671 depending on trait).

Traits	FINAL BW[1]	AWG	Whole Breast	BMY	L*	a*	b*	$pH_{initial}$	$pH_{ultimate}$	Drip loss	Cooking loss	Shear force
FINAL BW (kg)		0.737**	0.780**	0.183**	0.135**	0.091**	0.048	0.089	−0.048	0.081	0.101*	−0.026
AWG (kg/week)			0.527**	0.059*	0.066*	0.082**	0.057*	0.073	−0.06	0.166**	0.076	−0.025
Whole Breast (kg)				0.756**	0.191**	0.068*	0.120**	0.043	−0.001	0.061	0.169**	−0.055
BMY (%)					0.160**	0.000	0.143**	−0.028	0.064	−0.001	0.163**	−0.046
L*						−0.116**	0.147**	−0.02	−0.251**	0.127*	0.133**	0.056
a*							0.094**	−0.031	0.039	0.072	0.116*	−0.195**
b*								0.032	0.069	0.105*	0.088	0.023
$pH_{initial}$									0.169**	−0.074	−0.061	−0.056
$pH_{ultimate}$										−0.142**	−0.098*	−0.132*
Drip loss (%)											0.107*	0.054
Cooking loss (%)												−0.047
Shear force (N)												

[1]FINAL BW = body weight measured two days before slaughter (20−24 weeks of age).
Significance is denoted by superscripts *and **, at $P < 0.05$ and $P < 0.001$ respectively.

*$P < 0.05$.

**$P < 0.001$.

Table 4. Phenotypic correlation matrix for the evaluated turkey meat quality traits for Line C (N = 939−3,892 depending on trait).

	FINAL BW[1]	AWG	Whole Breast	BMY	L*	a*	b*	$pH_{initial}$	$pH_{ultimate}$	Drip loss	Cooking loss	Shear force
FINAL BW (kg)		0.720**	0.751**	0.237**	0.206**	0.199**	0.188 **	0.058	0.134*	0.033	0.162**	−0.250**
AWG (kg/week)			0.454**	0.042	0.137**	0.181**	0.175**	0.149*	0.236**	0.084	0.035	−0.155*
Whole Breast (kg)				0.818**	0.257**	0.156**	0.189**	0.032	0.006	0.044	0.256**	−0.232**
BMY (%)					0.206**	0.055*	0.113**	0	−0.115*	0.035	0.250**	−0.121*
L*						−0.149**	0.103**	0.018	−0.249**	0.166**	0.130*	0.060
a*							0.299**	−0.064	0.034	0.039	0.074	−0.136*
b*								0.015	0.129*	0.095	0.031	−0.091
$pH_{initial}$									0.077	−0.008	−0.005	0.048
$pH_{ultimate}$										−0.209**	−0.096	−0.147*
Drip loss (%)											0.086	0.027
Cooking loss (%)												−0.04
Shear Force (N)												

[1]FINAL BW = body weight measured two days before slaughter (20-24 weeks of age).
Significance is denoted by superscripts * and **, at $P < 0.05$ and $P < 0.001$ respectively.
*$P < 0.05$.
**$P < 0.001$.

discussed. All correlations regardless of p-value are reported in these tables.

Production and Meat Quality

In general, correlations between production traits (final BW, AWG, whole breast, and BMY) and breast meat color (L*, a*, b*) were consistent across the genetic lines. Final BW was significantly positively correlated with L* (r = 0.135−0.206), and a* (r = 0.091 −0.199). Similarly, AWG was positively correlated with L* (r = 0.066−0.137), a* (r = 0.082−0.181), and b* (r = 0.057−0.175). Whole breast weight was also positively correlated with L* (r = 0.191−0.275), a* (r = 0.068−0.156), and b* (0.120−0.203). Lastly, BMY was positively correlated with L* (r = 0.160−0.217) and b* (r = 0.107−0.143), however the correlations with a* were either very weak (line C: r = 0.055, $P < 0.05$, Table 4) or negative (line A: r = −0.121, $P < 0.0001$, Table 2). The strongest correlations between the production traits and meat color were observed for line C compared to lines A and B.

The relationships between the pH traits (initial and ultimate) and the production traits differed between the 3 lines. For line A, $pH_{initial}$ was significantly correlated with final BW (r = 0.177) and AWG (r = 0.163) and $pH_{ultimate}$ was significantly correlated with AWG (r = 0.133). For line B, neither $pH_{initial}$ or $pH_{ultimate}$ were significantly correlated with any of the production traits (Table 3). For line C, $pH_{initial}$ was significantly correlated with AWG (r = 0.149) and $pH_{ultimate}$ was significantly correlated with final BW (r = 0.134), AWG (r = 0.236) and BMY (r = −0.115) (Table 4).

For the physiochemical traits (drip loss, cooking loss, and shear force), the correlations with production traits differed slightly among the genetic lines. There were no significant correlations between any of the production traits and drip loss for line A or line C (Tables 2 and 4). For line B, drip loss was significantly correlated with AWG (r = 0.166, $P < 0.0001$, Table 3). Cooking loss was significantly correlated with final BW (r = 0.101 −0.162), whole breast (r = 0.169−0.256), and BMY (r = 0.163−0.250) for lines B and C (Table 3 and 4). Shear force was significantly negatively correlated with final BW (r = −0.159) and AWG (r = −0.183) for line A (Table 2). For line C, shear force was significantly negatively correlated with final BW (r = −0.250), AWG (r = −0.155), whole breast (r = −0.232), and BMY (r = −0.121) (Table 4). Shear force was not significantly correlated with any of the production traits for line B (Table 3).

Correlations among Meat Quality Traits

The relationships among the color traits were similar for each genetic line. L* is significantly positively correlated with b* (r = 0.103−0.166) and significantly negatively correlated with a* (r = (−0.116)−(−0.149)). There is also a significant positive correlation between a* and b* for each genetic line (r = 0.094 − 0.294).

Meat lightness (L*) was significantly negatively correlated with $pH_{ultimate}$, but not $pH_{initial}$. Correlations between L* and $pH_{ultimate}$ ranged from −0.249 to −0.360 depending on the genetic line. Lightness was also significantly positively correlated with drip loss (r = 0.127 −0.166) and cooking loss (r = 0.130−0.164), however no significant correlations were observed between L* and shear force in any genetic line. Interestingly, a* was significantly correlated with shear force for both lines B (r = −0.195, Table 3) and C (r = −0.136, Table 4), however, this relationship was not seen in line A.

As we predicted, $pH_{initial}$ and $pH_{ultimate}$ were significantly positively correlated for Lines A and B (r = 0.129 −0.206). The relationships between the pH traits and the physiochemical traits however, were different between the three genetic lines. For line A, there was a significant correlation between pH_{inital} and drip loss (r = −0.055) and $pH_{ultimate}$ and cooking loss (r = −0.082) (Table 2). For line B, there were no significant correlations between $pH_{initial}$ and the physiochemical traits, however $pH_{ultimate}$ was significantly negatively correlated with drip loss (r = −0.142), cooking loss (r = −0.098), and shear force (r = −0.132) (Table 3). For line C, there were no significant correlations between $pH_{initial}$ and the physiochemical traits, however $pH_{ultimate}$ was significantly negatively correlated with drip loss ($r = -0.209$) and shear force ($r = -0.147$).

DISCUSSION

The objective of the present study was to describe and evaluate differences in breast meat quality in three purebred turkey lines and to describe how these meat quality traits are phenotypically correlated within each genetic line. In general, we found the lines differed significantly for the studied production traits. Line C is the fastest growing line with an AWG of 1.63 ± 0.22 kg/wk resulting in the heaviest body weight before slaughter (24.72 ± 2.06 kg). Line B is the slowest growing line with an AWG of 1.12 ± 0.11 kg/wk resulting in the lightest average body weight before slaughter (19.11 ± 1.35 kg). Line A falls in the middle with an AWG of 1.34 ± 0.16 kg/wk and a body weight before slaughter of 21.87 ± 1.53 kg. We see that line C has the heaviest whole breast weight, followed by line B which had the highest BMY and then finally line A. It should be noted that the difference in BMY between line B and line C is <1%. These differences in production are potentially a reflection of the selection goals of each line. Line C is a male line selected predominantly for growth, efficiency, and yield. Line A is a female line; however, it is selected predominantly for body weight as well as reproductive traits. Line B is a female line whose selection is focused primarily on reproductive traits. The lack of selection pressure on growth and yield in line B is likely why it is smaller compared to line A which incorporates some pressure on growth and line C which has the most emphasis placed on growth and yield. Ultimately, these different selection goals have resulted in genetic lines with different growth trajectories. Given the previously reported relationship between growth and meat quality (Chiang et al., 2008), the following section will discuss the differences in meat quality between these three lines. Since these genetic lines were raised under similar housing and management conditions and slaughtered at a similar age, we can infer that observed differences in meat quality could be due to the previously mentioned differences in production traits.

Differences Between Genetic Lines

In the present study, we found differences between the genetic lines for several meat quality traits. In particular, there were differences between genetic lines for L*, a*, $pH_{initial}$, drip loss, and cooking loss based on the adjusted pairwise comparisons. Line B had the highest L* and a* compared to lines A and C. Similarly, Fernandez et al. (2001) reported that a slow-growing turkey line had paler meat compared to faster growing lines. Conversely, other turkey studies have found no differences in meat color between different genetic lines (Werner et al., 2008; Zampiga et al., 2019). Conditions such as PSE, characterized in part by high L*, are increasing throughout the industry, and causing issues in the fast growing lines that are used for further processing (Werner et al., 2008; Barbut, 2009). Line C was the heaviest and fastest growing line here and interestingly did not show the highest L* values. Meat from poultry genotypes with increased meat yield have been reported to have lower hematic pigments meaning the meat presented as less red and more pale (Berri et al., 2001).

For $pH_{initial}$, the fastest growing line (line C), had the highest average $pH_{initial}$ compared to lines A and B. The normal acidification process in meat postmortem is dependent on the amount of stored glycogen in the muscle because of the anaerobic breakdown of glycogen into lactic acid (Duclos et al., 2007). In broiler chicken lines with greater breast muscle mass, it has been shown that birds from these lines have lower muscle glycogen stores and therefore higher ultimate pH due to the reduced glycolytic potential postmortem (Berri et al., 2001). Debut et al. (2003) also observed that a fast-growing broiler genotype had a slower rate of pH decline postmortem which resulted in lower drip loss compared to a slow-growing genotype. However, it is also worth noting here that the correlations between whole breast weight and breast yield with pH was inconsistent between the genetic lines. Additionally, Werner et al. (2008) found no difference in pH taken at 20 min postmortem between turkey genetic lines, however some differences between lines were observed when pH was measured at 4 h postmortem. In particular, the smallest line had the lowest pH compared to the heavier lines (Werner et al., 2008). Due to the conflicting results reported across several studies further longitudinal research is likely needed to untangle this relationship.

The muscle's ability to retain water can be influenced by the rate at which the bird grows (Barbut et al., 2005; Mir et al., 2017; Zampiga et al., 2020). Line B had the lowest average drip loss compared to lines A and C. For cooking loss, lines A and B had a lower average cooking loss compared to line C. These results indicate that slower growing lines may have improved water-holding capacity compared to larger, faster growing lines. Conversely, Fernandez et al. (2001) found that slower growing turkey lines had greater drip loss compared to faster growing lines. Other turkey studies have found no difference in drip loss (Werner et al., 2008) cooking loss (Updike et al., 2005; Zampiga et al., 2019) between genetic lines.

Biologically, it would be expected that the genetic line with the lowest pH, would have the highest L*, highest drip and cooking loss, and highest shear force (Barbut, 2015). This is the proposed biological mechanism behind the development of PSE meat where rapid declines in postmortem pH, in combination with the warm muscle, results in the degradation of muscle proteins and pigments (Pietrzak et al., 1997; King and Whyte, 2006; Duclos et al., 2007; Carvalho et al., 2014). However, we did not observe these consistent biological relationships between our lines. Line A had the lowest initial and ultimate pH. However, line B also had a similar initial pH to line A, as well as all lines demonstrated similar ultimate pH values. Similarities can be explained by the decline in pH post mortem where values are known to become more consistent 24 h post mortem (Barbut, 2015). Line B had the highest L*, Line A had the highest drip loss, and line C had the highest cooking loss. Although these relationships are inconsistent, it is also important to note that the magnitude of the differences between lines are not large and may not be noticeable from a processing perspective.

It is possible that some of our results do not align with previously published studies as external factors (e.g., temperature stress, physical stress, etc.) were not assessed during the current study which are well established to influence meat quality (Owens and Sams, 2000; Leishman et al., 2021). Although external factors were not measured, birds from each line were raised under similar housing, management, and processing conditions. Research conducted using broiler chickens indicated that environmental stressors preslaughter, causing a longer duration of wing flapping contribute towards shifts in pH (Debut et al., 2003). Moreover, studies of postmortem wing flapping in turkeys demonstrated that flapping could affect breast meat color (a*), drip loss, and shear force (Leishman et al., 2022). External factors should be considered in future research regarding meat quality traits to better gauge the progression of meat quality within the 3 lines.

Correlations

Phenotypic correlations among the production and meat quality traits were similar within each of the genetic lines. Within each line, unfavorable correlations were observed between production and meat color with increased production (e.g., higher body weight, breast weight) associated with meat that is lighter, more yellow and more red (increased L*, b*, a*). Studies of the genetic and phenotypic correlations between growth and turkey meat quality traits also report positive correlations between body weight and particularly L* and b* (Aslam et al., 2011; Vanderhout et al., 2022). This unfavorable relationship between growth and meat color could be due to the faster pH decline reported in some studies of fast-growing turkey lines (Berri et al., 2001; Werner et al., 2008). However, as pointed out by Vanderhout et al. (2022), the size of the bird at processing can influence the time required to chill the carcass with larger birds required a longer duration of chilling. These longer chilling times can result in meat that is lighter and more yellow compared to meat that chills faster because of the positive relationship between temperature and the rate of glycolysis (Mckee and Sams, 1998; Rathgeber et al., 1999).

As the meat gets lighter in color there is an increase in light scattering occurring (Owens and Sams, 2000; Adzitey and Nurul, 2011). When there is more light scattering throughout the meat, there is a decrease in light absorbed and an increase in the difference between the refractive indices of the sarcoplasm and the myofibrils (Owens and Sams, 2000; Adzitey and Nurul, 2011). Pale meat will have a much larger difference between these indices, and as a result the meat will appear reduced in the pink color that is more visually acceptable to consumers. The relationship between growth and meat color is important to consider since cut-up poultry products are typically packaged on trays covered with clear film, displaying the meat color as the most prominent characteristic to the consumer (Min and Ahn, 2012; Font-i-Furnols and Guerrero, 2014) and consumers can be very sensitive to color variation in packaged poultry products (Fletcher, 1999). Although there may be cultural differences in preference for meat color, Western consumers avoid purchasing chicken meat with greater yellowness (Kennedy et al., 2005). Since North America accounts for 58% of global poultry consumption (Daniel et al., 2011), the unfavorable relationship between heavier faster growing birds and meat lightness and yellowness is important for breeding companies to be aware of.

Interestingly, the correlations between the production traits and both the ultimate and initial pH traits varied among genetic lines, with correlations between both pH initial and pH ultimate and final BW being relatively weak ($r = 0.13-0.17$). Therefore, we do not have any substantial evidence to show a relationship between the traits. Similar to what was discussed in the previous section, the relationship between growth and turkey meat quality is not clear. Some studies of chickens have found that greater breast muscle mass is associated with lower glycogen stores and thus higher meat pH (Berri et al., 2001). However, some turkey studies report negative correlations between body weight or breast weight and meat pH (Wang et al., 1999; Updike et al., 2005; Aslam et al., 2011;Vanderhout et al., 2022). Similarly, for the physiochemical traits, the correlations with production traits differed between the genetic lines. Since our correlation results varied between traits and lines, we cannot conclusively predict with confidence the relationship between traits and production.

The correlations observed among the meat quality traits were in line with previous studies (Barbut, 1993; Le Bihan-Duval et al., 2003; Aslam et al., 2011; Leishman et al., 2021; Vanderhout et al., 2022). Similar correlations were reported by a previous meta-analysis of poultry meat quality which synthesized the results of 48 studies (Leishman et al., 2021). Similar to what was found by previous studies, we found that L* is significantly correlated to pH as well as the physiochemical traits. As suggested by other studies, the results of this study provide further evidence that L* could be an appropriate indicator trait for overall turkey meat quality that could be included as a phenotype in a breeding program (Barbut, 1993; Petracci et al., 2004;Leishman et al., 2021). With modern technology, it is feasible to incorporate the collection of L* measurements on the processing line and have the potential to be an accurate, feasible, nondestructive, and cost-effective indicator trait (Barbut, 1997; Leishman et al., 2021). Incorporating these measures into turkey breeding strategies is especially relevant given the rise in PSE meat (Werner et al., 2008; Dewez et al., 2018). In some studies, the development of PSE meat has been linked to growth rate which indicates that without intervention, PSE may become more prevalent due to the continued selection pressure on growth and yield (Werner et al., 2008).

Benchmarking these traits and their correlations with key production traits in turkey pedigree lines will be an important factor to consider for future breeding programs. The unfavorable relationships between intense selection for growth and meat quality have been reported for many decades as well as the key role that breeding for improved meat quality may play (Anthony, 1998). We provide an updated report that these unfavorable relationships exist to some degree in modern purebred turkey lines. However, the cumulative effect of these low correlations on overall meat quality may be more substantial. These results should be replicated in future studies; however, this may indicate that more balanced selection indices including more emphasis on health and livability traits may be reducing the negative effects of growth on meat quality (Neeteson et al., 2016).

CONCLUSION

This study provides an updated description and analysis of turkey breast meat quality in purebred lines selected for different breeding goals and reports phenotypic correlations among important production and meat quality traits. Differences in meat quality were observed between the genetic lines for L*, a*, $pH_{initial}$, drip loss, and cooking loss, however these differences were not consistent. The smallest line (line B) had the palest meat compared to the other two lines whereas the heaviest line (line C) had the lowest redness (a*), highest $pH_{initial}$ and cooking loss. Drip loss was the highest in the intermediate weight line (line A), followed by line C and then line B. For all three genetic lines, we report unfavorable correlations between production traits (final BW, AWG, whole breast weight, and BMY) and meat quality which is in line with previous studies. Among the meat quality traits, we observed significant correlations between meat color, pH, and physiochemical traits where meat with increased L* is associated with a lower pH and increased moisture loss. Although we report many differences between genetic lines and significant correlations it should be acknowledged that the magnitude of these differences and correlations is relatively low. This is potentially due to the environmental factors that are known to influence meat quality which were not evaluated in this study (e.g., temperature, antemortem behavior). However, this study provides an important benchmark of the current state of turkey meat quality in purebred lines as well as an indication of how selection for increased growth and meat yield may influence meat quality.

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DISCLOSURES

J.M. and B.W. were employees of Hybrid Turkeys at the time of the study. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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