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# Meat Quality and Cooking Characteristics in Broilers Influenced by Winter Transportation Distance and Crate Density

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A study was conducted to determine the effect of transportation distance and crating density on meat quality traits during winter. ROSS-308 broilers aged 35 days were divided into 10 treatment groups based on three transportation distances (80, 160, and 240 km) with three crating densities (10, 12, and 15 birds per crate) along with birds slaughtered on farm without crating as a control group. Each treatment was replicated 10 times and placed at various locations in the truck. The birds were transported in plastic crates of 0.91 m × 0.55 m × 0.30 m at ambient temperature and relative humidity of 3.6–9.5℃ and 63.3–78.8%, respectively. The breast meat quality parameters including pH, color, drip loss, shear force, marinade uptake and retention, cooking losses, and yield were determined. The results showed significantly higher pH 15 min post-slaughter (PS), drip loss, lightness, marinade uptake, raw meat cooking yield, and shear force in birds slaughtered on farm without any transportation. The birds transported for 240 km had significantly higher pH at 2 hours (h) PS, marinade retention, and cooking yield. Whereas, pH at 24 h PS, meat redness, yellowness, chroma, and marinated meat cooking yield were significantly higher in all transported treatments compared to the control group. Among different crating densities, the birds transported with 10 birds per crate showed significantly higher meat redness, marinade retention, and cooking yield. The crating density of 15 birds per crate had significantly higher lightness, hue, cooking loss, and shear force. However, no effect of crating density was observed on meat pH, drip loss, and marinade uptake. It can be concluded that an increase in transportation distance and low crating density during winter can negatively affect physical quality of meat with significant improvement in marination and cooking characteristics.

**Key words**: cooking, crating, marination, meat quality, transportation, winter

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## Introduction

Broiler welfare and meat quality traits are serious concerns for the global poultry industry. After spending the growing phase in an environment-controlled poultry house, the sudden exposure of broilers to physiological stress, during their transportation to processing plants negatively affects their well-being (Savenije *et al*., 2002). The major factors associated with stress during transportation include feed and water deprivation, catching, crating density, thermal variations, and duration and distance of transportation (Delezie *et al*., 2007; Orlic *et al*., 2007). The interaction of these factors not only cause economic losses due to mortality and live weight shrinkage but can also deteriorate meat quality traits (Kannan *et al*., 1997; Nijdam *et al*., 2004).

The ambient temperature during transportation affects muscle metabolism by inducing physiological changes and fatigue in birds (Petracci *et al*., 2001). Higher temperatures are associated with higher carcass temperature and faster postmortem pH decline (Mitchell and Kettlewell, 2004; Guarnieri *et al*., 2004). Conversely, low environmental temperature coupled with air drafts due to movement of the truck can cause cold stress (Minka and Ayo, 2015). The cold stress can deteriorate meat quality traits because of depletion in body glycogen due to increased energy metabolism to maintain body temperature (Dadgar *et al*., 2010). The subsequent effect of these variables varies according to the

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length of journey due to depression in liver and muscle glycogen contents (Warriss *et al*., 1993; Kannan *et al*., 1997). Lower glycogen contents before slaughtering can cause low lactic acid production in birds (Gregory, 1994; Lawrie, 1998). Meat with low lactic acid content is expected to have higher ultimate pH ($pH_u$) than normal (Dadgar *et al*., 2010).

Investigating the effect of transportation distance, different studies have reported that an increase in transportation distance has been associated with higher $pH_u$, lower lightness, shear force, drip, and cooking losses (Yalçin and Güler, 2012; dos Santos *et al*., 2017). On the other hand, Zhang *et al*. (2009) reported no effect of transportation (up to 3 h) on meat quality traits in broilers. Similarly, Sowińska *et al*. (2013) also reported no effect of winter transportation (0–300 km) on meat pH and color parameters except water holding capacity (WHC), which increased with higher transportation distance. These studies suggest that variations in climatic conditions in different geographical regions of the world are associated with contradictory effects of transportation distance on meat quality. The ambient environment or climate during transportation changes the microclimate of the vehicle. The season of transportation, length of journey, and crating density are the major determinants of the microclimate of the vehicle (Barbosa filho *et al*., 2008).

The optimal loading density varies according to ambient temperature and bird size (Elrom, 2000; Whiting *et al*., 2007). Provision of more space will affect the transporter economically as well as produce chilling during winter, while less space can cause welfare issues (Watts *et al*., 2011). The space and traveling distance can also cause physical consequences such as bruising, injury, and death due to fighting, trampling, or suffocation (Moran and Bilgili, 1995; Elrom, 2000). The effect of elevated temperature transportation is comprehensively reviewed by many studies. However, data regarding meat quality under the influence of crating densities in the winter season and its interaction with journey length are scarce. Therefore, this study aimed to investigate the effects of winter transportation under various crating densities.

## Materials and Methods

### *Experimental Birds*

The study was conducted at the Department of Poultry Production, University of Veterinary and Animal Sciences, Lahore-Pakistan. ROSS-308 broilers (body weight 1900–2050 g; age: 35 days) were selected from a commercial farm after four hours of feed withdrawal before catching. During the growing phase, the broilers were fed with standard broiler rations and raised on a litter floor in an environmental controlled broiler house under optimum management conditions. The sampling was based on transportation distance and crating density (3×3=9 treatments+1 control group). Transportation distance was categorized as short (80 km), medium (160 km), and long (240 km) under three crating densities: 10 birds (0.050 $m^2$/ bird), 12 birds (0.042 $m^2$/ bird), and 15 birds (0.033 $m^2$/ bird) per crate. The control group comprises birds slaughtered on farm ($n$=30) without crating and transportation while applying four hours of feed withdrawal. The birds were transported in commercial trucks (capacity 144 crates) in loose plastic crates (Engi Plastic Industries Pvt. Ltd., Sundar, Lahore-Pakistan) having a dimension of 0.91 m (length)×0.55 m (width)×0.30 m (height). To reduce the effect of the microenvironment, each treatment was replicated 10 times and placed at various locations in the trucks and the meat sample(s) were collected randomly from all locations. All the protocols and birds handling were performed in accordance with the laws and regulations of Pakistan and approved by the Ethical Review Committee of the University of Veterinary and Animal Sciences, Lahore-Pakistan (No: DR/916 - 2017).

### *Climatic Indices*

The experiment was conducted during the winter season (January) and the birds were transported in the vicinity of Kasur and Lahore district, in Punjab, Pakistan. The birds subjected to transportation distances of 160 and 240 km were first transported in laps of 40 km from the farm and then transported to a slaughtering facility located almost 80 km from the farm. The birds transported 80 km were directly sent for slaughtering. The temperature and relative humidity were recorded with the help of a digital weather tracker (Kestrel 4500 NV, Nielsen-Kellerman, USA). The temperature range and relative humidity measured at various times and distances remained between 3.6–9.5℃ and 63.3–78.8%, respectively. There were patches of mild to severe fog at several locations along the journey.

### *Meat Quality Measurements*

Upon reaching the slaughtering facility, three tagged birds from each replicate were randomly picked and slaughtered manually with a knife following halal slaughtering. Birds were then defeathered and eviscerated. After recording some initial parameters, carcasses were placed in chilled water to reduce the temperature and the following meat quality parameters were recorded.

### *pH Measurement*

The pH of individual breasts was measured from three different places at 15 min (initial pH), 2 h and 24 h {ultimate pH ($pH_u$)} post-slaughtering using an electronic pH meter (ProfiLine pH 3110 SET 2, WTW, Germany). The probe was rinsed with deionized water after every reading and between the samples. The pH was measured from warm carcass at 15 min, while pH was recorded from deboned breast samples stored at 4℃ in display chiller at 2 h and 24 h (S80100VVC, Tecnodom S.P.A., Italy).

### *Meat Color*

The breast meat (*pectoralis major*) was separated from the carcass and placed in polystyrene food grade trays covered with cling film (250 mm thickness) and kept in a display chiller (S80100VVC, Tecnodom S.P.A., Italy) at 4℃. The meat color ($L^*$=lightness, $a^*$=redness, $b^*$=yellowness, chroma=saturation, and hue=angle that the metric chroma line makes with the+a* axis) was measured at 24 h postmortem employing the Commission International de l'Eclairage (CIE, 1976) L*a*b* system using a chroma meter (Minolta® CR-410, Konica Minolta, Inc. Japan). The color was measured by placing the Minolta head at cranial, middle, and caudal region (skin side) of the breast free of any obvious color defects such as bruises, discolorations, hemorrhages or any other condition that may have affected the uniform color reading.

***Drip Loss (%)***

Following Honikel (1998), the drip loss (%) was measured by hanging the breast muscle (weight 165–174 g) by a thread in a polythene bag under atmospheric pressure for 24 h at 4℃.

***Marination***

One day after slaughtering, the marination of six breast fillets per treatment (kept at 4℃) with 4% brine solution (chilled overnight) was performed. Marination was carried out by immersing a batch of 10 fillets (pre-weighed w1) in marinade solution and manually tumbling by hand for 15 minutes for maximum absorption of brine. After performing marination, the individual fillets were reweighed (w2) to determine the brine uptake. The fillets of each treatment were placed in polystyrene trays and held overnight at 4℃ before individual fillets were reweighed (w3) to calculate marinade retention using the formulas.

$$\text{Marinade uptake (\%)} = (w2 - w1)/w1 \times 100$$

$$\text{Marinade retention (\%)} = 100 - (w2 - w3)/w2 \times 100$$

***Cooking***

The breast meat samples, with and without marination (having uniform weight in each type of meat), were individually packed in labeled polythene zipper bags (food grade). The bags were placed in a water bath (WNB45 Memmert GmbH, Schwabach, Germany) operating at 80℃. The samples were cooked until the core temperature reached 72℃. The temperature was monitored at the thickest part of the breast using a hand-held digital thermometer (TP-101, China). The cooked fillets were cooled on ice, drained, blotted dry, and reweighed (w4) to calculate the cooking loss and yield of raw and marinated breast fillets using the formula:

$$\text{Cooking Loss (\%)} = (w3 - w4)/w3 \times 100$$

$$\text{Cooking Yield (\%)} = (w4)/(w1) \times 100 \text{(marinated)};$$
$$(w4)/w3100 \text{(without marination)}$$

***Shear Force***

The Warner Bratzler Shear Force value (N/cm$^2$) of raw and marinated meat was analyzed using a texture analyzer (TA.XT plus® texture analyzer, Stable Micro System, UK). Three rectangular blocks, each with a cross section of 1×1 cm and fiber direction parallel to a long dimension of 2 to 3 cm, were cut from each cooked fillet (Dadgar *et al*., 2010). The fibers were cut with a V slot blade perpendicular to their direction.

***Statistical Analysis***

The data collected were analyzed using the two-way analysis of variance (ANOVA) technique under completely randomized design. The means were considered significant at a p value of 0.05. For the separation of means, Tukey's HSD test was used with the help of SAS 9.4 (SAS Institute, 2013).

## Results

In the present experiment, the pH of the meat measured at 15 min, 2 h and 24 h PS remained significantly different ($P<0.05$) among different transportation distances (Table 1). At 15 min PS, the birds in the control group showed the highest pH compared to all the transported treatments. On the other hand, at 2 h PS, the same control group had the lowest pH compared to the rest of the treatments. At 24 h PS (ultimate pH) the birds transported up to 240 km had the highest pH followed by those transported for 160 and 80 km and the least in the control group (Table 1). The findings revealed non-significant differences ($P>0.05$) among various crating densities for PS pH but the differences were significant in

Table 1. **Meat pH and drip loss % under transportation distance and crating densities**

| Treatments | pH 15 min | pH 2 h | pH 24 h | Drip Loss % |
|---|---|---|---|---|
| Distance | | | | |
| 0 Km | 6.68±0.04$^a$ | 6.14±0.03$^b$ | 5.81±0.02$^c$ | 1.87±0.07$^a$ |
| 80 Km | 6.55±0.03$^b$ | 6.27±0.02$^a$ | 6.01±0.02$^b$ | 1.62±0.03$^b$ |
| 160 Km | 6.49±0.02$^b$ | 6.26±0.02$^a$ | 6.04±0.02$^b$ | 1.17±0.03$^c$ |
| 240 Km | 6.48±0.02$^b$ | 6.30±0.03$^a$ | 6.12±0.02$^a$ | 0.99±0.03$^d$ |
| Density | | | | |
| 10 birds/crate | 6.49±0.02 | 6.31±0.02 | 6.10±0.02 | 1.21±0.07 |
| 12 birds/crate | 6.50±0.02 | 6.25±0.03 | 6.03±0.02 | 1.27±0.08 |
| 15 birds/crate | 6.53±0.03 | 6.27±0.02 | 6.03±0.02 | 1.31±0.09 |
| P-value | | | | |
| Distance | 0.0001 | 0.0134 | <0.0001 | <0.0001 |
| Density | 0.4898 | 0.2566 | 0.066 | 0.6311 |
| Interactions | 0.0094 | 0.0373 | <0.0001 | <0.0001 |

Note: Different alphabets ($^a$, $^b$, $^c$) on means showing significant differences ($P<0.05$) among treatment groups (Mean±S.E.M.)

Table 2. **Meat color under various transportation distance and crating density**

| Treatments | Lightness (L*) | Redness (a*) | Yellowness (b*) | Chroma (c) | Hue (h) |
|---|---|---|---|---|---|
| Distance | | | | | |
| 0 km | 56.73±0.26[a] | 13.20±0.53[b] | 14.68±1.23[b] | 19.79±1.15[b] | 47.69±1.95 |
| 80 km | 50.90±0.55[b] | 16.86±0.41[a] | 16.55±0.30[a] | 23.67±0.31[a] | 44.54±0.98 |
| 160 km | 51.54±0.56[b] | 16.09±0.31[a] | 16.92±0.26[a] | 23.36±0.32[a] | 46.46±0.59 |
| 240 km | 50.02±0.40[b] | 17.32±0.34[a] | 17.22±0.38[a] | 24.47±0.34[a] | 44.82±0.89 |
| Crating Densities | | | | | |
| 10 birds/crate | 49.96±0.43[b] | 17.53±0.32[a] | 16.58±0.24 | 24.15±0.30 | 43.433±0.65[b] |
| 12 birds/crate | 50.50±0.55[ab] | 16.53±0.38[ab] | 17.25±0.38 | 23.94±0.39 | 46.23±0.91[a] |
| 15 birds/crate | 52.01±0.44[a] | 16.20±0.33[b] | 16.86±0.31 | 23.41±0.32 | 46.16±0.80[a] |
| p-value | | | | | |
| Distance | <0.0001 | <0.0001 | 0.0106 | <0.0001 | 0.1705 |
| Crating Density | 0.0121 | 0.0255 | 0.3287 | 0.2890 | 0.0245 |
| Interaction | <0.0001 | 0.0001 | 0.0058 | 0.0001 | 0.0272 |

Note: Different alphabets ([a], [b], [c]) on means showing significant differences ($P<0.05$) among treatment groups (Mean±S.E.M.)

Table 3. **Meat marination, cooking, and shear force as affected by transportation distance and crating density**

| Treatments | MU[1] % | MR[2] % | Cooking loss (%) | | Cooking yield (%) | | Shear Force (N/cm$^2$) | |
|---|---|---|---|---|---|---|---|---|
| | | | Raw | Marinated | Raw | Marinated | Raw | Marinated |
| Distance | | | | | | | | |
| 0 Km | 20.02±1.69[a] | 95.34±0.25[c] | 12.23±0.47[b] | 23.07±0.36[a] | 87.77±0.47[a] | 88.01±0.91[b] | 11.71±0.36[a] | 8.88±0.07[a] |
| 80 Km | 15.68±0.72[b] | 96.66±0.39[b] | 13.66±0.48[a] | 15.86±0.52[b] | 86.34±0.48[b] | 94.04±0.58[a] | 10.27±0.48[b] | 7.41±0.18[bc] |
| 160 Km | 13.34±0.57[c] | 97.42±0.22[ab] | 12.04±0.38[b] | 16.05±0.45[b] | 87.96±0.38[a] | 92.68±0.56[a] | 10.66±0.37[ab] | 7.97±0.21[b] |
| 240 Km | 11.21±0.24[d] | 97.74±0.19[a] | 10.82±0.35[b] | 14.28±0.34[c] | 89.18±0.35[a] | 93.17±0.45[a] | 9.03±0.15[c] | 7.33±0.15[c] |
| Crating density | | | | | | | | |
| 10 birds/crate | 13.12±0.63 | 97.84±0.19[a] | 11.02±0.42[b] | 14.83±0.37 | 88.98±0.42[a] | 94.22±0.31[a] | 9.44±0.26 | 7.16±0.20[b] |
| 12 birds/crate | 13.55±0.85 | 96.78±0.43[b] | 12.91±0.55[a] | 16.02±0.38 | 87.09±0.55[b] | 92.22±0.21[b] | 10.37±0.32 | 7.62±0.21[ab] |
| 15 birds/crate | 13.57±0.60 | 97.20±0.15[ab] | 12.59±0.37[a] | 15.34±0.61 | 87.41±0.37[b] | 93.44±0.80[ab] | 10.16±0.54 | 7.93±0.11[a] |
| p-value | | | | | | | | |
| Distance | <0.0001 | 0.0002 | 0.0001 | <0.0001 | 0.0001 | <0.0001 | 0.0010 | 0.0001 |
| Density | 0.8783 | 0.0367 | 0.0108 | 0.2061 | 0.0108 | 0.0274 | 0.2155 | 0.0135 |
| Interaction | <0.0001 | 0.0003 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.006 | <0.0001 |

Note: Different alphabets ([a], [b], [c]) on means showing significant differences ($P<0.05$) among treatment groups (Mean±S.E.M.)
Marinated: Breast marinated with 4% brine solution for 15 minutes
[1] MU: Marinade uptake (% of water absorbed by breast meat during marination)
[2] MR: Marinade retention (% of water retained by breast during 24 h storage at chilling temperature)

transportation distance×crating density interaction (Table 1).

Similarly, the drip loss % was also found to be significantly different ($P<0.05$) among different transportation distances and interactions of transportation distance×crating density while the differences remained non-significant ($P>0.05$) among different crating densities (Table 1). Among different transportation distances, the birds slaughtered on farm had the highest drip loss % and a gradual decrease was observed with increase in transportation distance (Table 1).

Among different meat color parameters, the lightness (L*) of the meat was found to be significantly higher in the control group while the redness (a*), yellowness (b*), and chroma was significantly lowest in the control group compared to all transported treatments (Table 2). Similarly, among different crating densities, the birds transported with 15 birds per crate had the highest ($P<0.05$) lightness and lower redness compared to birds transported at 12 and 10 bird/crate density. The meat hue was found to be higher in the birds transported at 12 and 15 birds per crate density compared to those having 10 birds per crate density (Table 2). There was no significant difference in meat yellowness and chroma among different crating densities.

The meat marination showed a significantly higher ($P<$

0.05) marinade uptake (%) in the bird slaughtered on farm without any transportation. Whereas, a gradual decrease in marinate uptake % was observed with the increase in transportation distance (Table 3). On the other hand, the marinade retention was significantly higher ($P<0.05$) in birds transported for 240 km and decreased gradually with decrease in transportation distance. The cooking losses % in raw meat was found to be significantly higher in birds transported up to 80 km, followed by those in the control group and slaughtered after 160 km transportation, and lowest in those transported up to 240 km. In the marinated breast meat, the birds in the control group had the highest cooking losses while those in 240 km had the lowest (Table 3). Among different crating densities, marinade uptake % was non-significantly different ($P>0.05$), but marinade retention % and cooking yield %, both in raw and marinated breast meat, were found to be the highest in birds transported at 10 birds per crate density and lowest in those transported at 15 birds per crate density. The interactions showed significant differences among all treatments.

Shear force ($N/cm^2$) in raw and marinated breast meat was found to be significantly higher in the control group and lowest in those transported up to 240 km (Table 3). Among different crating densities, non-significant differences were observed among different treatments for raw meat shear force. Birds transported at 15 birds per crate density had the highest shear force for marinated meat and those having 10 birds per crate had the lowest (Table 3).

## Discussion

Results revealed that the initial pH of the meat was significantly higher ($P<0.05$) in birds that were slaughtered on farm compared to the rest of the treatments. The pre-slaughter cold stress and struggle in birds may have resulted in the production of more lactic acid before slaughtering and a relatively lower initial pH of the meat (Lee *et al*., 1976; Debut *et al*., 2005). Similarly, Yalçin and Güler (2012) also reported lower initial pH in birds transported for longer journeys, that is, 6.53 compared to those transported for relatively shorter periods with a pH of 6.58, but the differences were non-significant ($P>0.05$) among treatments. The pH at 2 h postmortem was significantly higher in all transported groups compared to those in the control group. The findings revealed a lower rate of pH fall in birds subjected to transportation compared to the control group. Furthermore, the ultimate pH was higher in birds transported up to 240 km (Table 1). It has been reported that during rigor mortis development, substrates such as glycogen and glucose are converted into lactate, which accumulates to acidify the meat (Price and Schweigert, 1987). The amount of glycogen in muscle will determine the ultimate pH of the meat (Lawrie, 1998). Therefore, due to a significant decrease in the muscle glycogen reserves with the stress associated to the length of journey (Lin *et al*., 2004) and increase in feed withdrawal period (Nijdam *et al*., 2004), the ultimate pH of transported birds was higher than the control group. Similarly, a significant increase in the pH of the meat with the increase in the length of transportation journey was also reported in many studies (Zhang *et al*., 2009; Yalçin and Güler, 2012). However, crating densities had no effect on the PS pH of the meat. Similarly, Delezie *et al*. (2007) also reported no effect of different crating densities on ultimate pH. However, significant differences were observed in the interaction of transportation distance and crating density (Table 1). The lower number of birds in each crate during the winter season resulted in cold stress in birds due to relatively less metabolic heat accumulation (Watts *et al*., 2011). Therefore, the struggle to maintain body temperature combined with the long transportation journey resulted in relatively higher $pH_u$ of these treatments. Similarly, Dadgar *et al*. (2012) also reported significantly higher $pH_u$ in treatments kept at low ambient temperature before slaughter.

Color is one of the most important sensorial characteristics influencing the acceptability or rejection of the meat (Fletcher, 2002). In the meat color characteristic observed at 24 h postmortem, the birds transported for various distances had significantly lower lightness and higher redness, yellowness, and chroma compared to birds slaughtered on farm without transportation (Table 2). Previous studies classified the meat with the aforementioned conditions as dark meat (Barbut *et al*., 2005; Bianchi *et al*., 2007). The color development in meat is dependent on denaturation of muscle proteins due to $pH_u$ and rate of pH fall (Lawrie, 1998). The low $pH_u$ ($<6$) of meat will result in greater lightness (L*) due to an increase in scattering of light while higher $pH_u$ ($\geq 6$) will lead to darker meat (low L*) due to less light scattering (Swatland, 1994; Barbut, 1997; Barbut *et al*., 2005). Similarly, in the present trial, the longer transportation has probably resulted in depletion of glycogen reserves and higher $pH_u$ of the meat causing darker meat color (Owens and Sams, 2000; Lin *et al*., 2004). Our findings are supported by several previous studies (Yalçin and Güler, 2012; dos Santos *et al*., 2017) that also reported lower lightness and higher redness in birds transported for long distances. Among different crating densities, the birds transported with crating density of 10 birds per crate had the lowest lightness and higher redness compared to the other treatments (Table 2). Although there is lack of published data regarding effect of winter crating densities on meat quality, it is likely that the birds transported at lower crating densities during winter experienced relatively higher chilling effects compared to those transported with relatively higher crating densities. In agreement with the findings of the present study, Petracci *et al*. (2004) reported darker (low L*) breast meat in birds transported during the winter season compared to summer. Similarly, Dadgar *et al*. (2012) also reported higher redness in meat of birds exposed to lower crating temperatures. Similarly, Bianchi *et al*. (2006) also reported higher redness and saturation of meat kept for longer periods in crates at relatively lower temperatures. Moreover, Adzitey and Nurul (2011) reported that chronic stress can cause to dark-firm-dry (DFD) -like conditions in poultry.

The ability of meat to hold water is one of the most important parameters related to processor's economics and consumer perception of meat. The results of the present experiment revealed that the drip loss (%) and cooking loss (%) of raw and marinated breast meat were significantly higher in the control group and lowest in birds transported 240 km (Table 1, 3). Cooking yield was found to be higher in birds transported compared to the control group. Different crating densities had non-significant differences for drip loss % and marinated breast cooking loss %. However, the raw meat cooking loss was higher in the birds transported with 12 and 15 birds per crate compared to the control group (Table 3). The cooking yield was higher in the birds transported at 10 birds per crate. The water binding capacity of proteins and release of water from muscles are dependent on the isoelectric point of the meat, that is, the pH at which there is no net charge on muscle proteins (Offer and Knight, 1988; Le Bihan-Duval *et al*., 2001), which has been reported to be approximately 5.5 (Swatland, 1994). The farther the muscle pH from the isoelectric point, the higher the net charge on the proteins will be and more intracellular spaces will be available for water (Van Laack *et al*., 2000; Huff-Lonergan and Lonergan, 2005). Similarly, the birds in the control group had lower $pH_u$ and higher losses % (Table 1, 3). The low transportation crating densities may have resulted in cold stress in broilers due to relatively lower metabolic heat production. These two factors therefore interact in such a way that the longer transportation of broilers under lower numbers of birds per crate resulted in depletion of muscle glycogen, an increase in the $pH_u$ of the meat associated with an increase in water binding capacity and a reduction in drip loss %, particularly in colder environments (Zhang *et al*., 2009; Dadgar *et al*., 2012; Sowińska *et al*., 2013). Similarly, dos Santos *et al*. (2017) compared two transportation distances (15 and 90 km) in two different seasons (Rainy: 25℃+67% RH and Dry: 19℃+44% RH) in Brazil and reported higher $pH_u$ and lower drip losses in birds subjected to long-term transportation in both seasons. Furthermore, Yalçin and Güler (2012) reported a significant decrease in meat thawing and cooking loss % with the increase in transportation distance from 65 to 165 km in Turkey. Delezie *et al*. (2007) reported no effect of different crating densities on drip loss of meat.

The present experiment showed significantly ($P<0.05$) higher marinade uptake in the meat of birds slaughtered on farm without transporting, whereas marinade uptake was lowest in birds transported for 240 km (Table 3). However, non-significant differences were observed within different crating densities. Reduction in marinade uptake with the increase in transportation distance may be due to higher WHC of meat with higher $pH_u$ (Le Bihan-Duval *et al*., 2001), as shown in Table 1. The muscle-bound water content will be higher in meat having lower drip losses and there will be less space for new water molecules to add to muscle structure during marination. Furthermore, the results of marinade retention % also confirm the above-mentioned findings. The higher ($P<0.05$) marinade retention observed in longer transportation birds may be due to low $pH_u$, which increases the water binding capacity of meat (Van Laack *et al*., 2000; Huff-Lonergan and Lonergan, 2005). Owens and Sams (2000) also reported that 3 h transportation of male turkeys caused a significant increase in breast pH and marinade retention and reduction in cooking losses. Among different crating densities, the higher marinade retention in birds transported at lower crating densities could be attributed to chilling/cold stress due to lack of metabolic heat accumulation inside crates. The cold stressed birds had relatively higher ultimate pH (as shown in Table 1) and WHC (Dadgar *et al*., 2012). However, no previous studies have focused on the effect of crating densities on marinade retention, but an increase in water retention capacity of meat in birds transported at low ambient temperature has been reported by Bianchi *et al*. 2007.

A gradual decrease in shear force ($N/cm^2$) was observed with the increase in transportation distance (Table 3). Lower $pH_u$ in the control group may have caused inhibition of proteolytic enzymes resulting in more drip loss % and higher shear force (Khan and Cohen, 1977). Similar findings were also reported by dos Santos *et al*. (2017), who observed a significant decrease in shear force with the increase in transportation distance of broilers. Our experiment revealed an increase in shear force of broilers at a transportation distance of 160 km compared to 80 and 240 km. Similarly, Ehinger (1977) also reported that broiler meat tenderness and WHC were reduced after 2 h of transportation but improved after 4 h of transportation. Among different crating densities, the shear force of marinated breast meat was higher in the birds transported at 15 birds per crate (Table 3). The differences in marinade retention in different crating densities (Table 3) may have resulted in variation in shear force of marinated breast samples only. The treatments with higher marinade retention showed lower shear force (Table 3). A similar decrease in meat shear force due to the enrichment of muscle water content was also reported by Silva *et al*. (2011).

The current study demonstrated that transportation of broilers is associated with economic losses due to depression in meat quality and physical appearance. However, the cooking characteristics of the birds transported for longer distance during winter were improved. Thus, the meat from birds subjected to long-term transportation can be used for further processing operations. Similarly, the birds transported at crating density of 15 birds per crate had better physical appearance and those transported at 10 birds per crate had better yield and tenderness. Thus, transportation at a crating density of 12 birds per crate ($0.042\ m^2$/ bird) during the winter season is recommended for producing meat with better physical appearance, yield, and tenderness.

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## Conflicts of Interest

Authors certify that there is no conflict of interest.

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