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ARTICLE

Effect of Different Packaging Atmosphere on Microbiological Shelf Life, Physicochemical Attributes, and Sensory Characteristics of Chilled Poultry Fillets

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Abstract This trial was conducted to evaluate the effect of overwrap, vacuum, and modified atmosphere packaging (MAP) on poultry breast fillets' microbiological, biochemical shelf life and sensory attributes. The fillets were divided into 4 groups, and each of the treatments was replicated 3 times with 60 breast fillets. The first group was a control group with overwrap packaging; the second group was vacuum packed (VP); the third and fourth groups were MAP-1: 0% O_2, 40% CO_2, 60% N_2, and MAP-2: 20% O_2, 40% CO_2, 40% N_2. The microbiological and biochemical analyses were performed for the total viable count, coliform count, *Pseudomonas* count, *Salmonella* count, total volatile basic nitrogen (TVB-N), pH, cooking loss, color, lipid oxidation, tenderness, and sensory analysis. The data were analysed through two-way ANOVA by Minitab (Minitab 17.3.1). Meat treated with understudy MAP compositions and vacuum packaging reduced total viable count, *Pseudomonas* count, and total coliform count than control ($p<0.05$). TVB-N remained below the recommended limit throughout storage except aerobic packaging ($p<0.05$). Cooking loss (%) was lowered and showed non-significant results ($p>0.05$) between vacuum packaging and both MAP concentrations. The meat stored in MAP-2 was characterised by higher ($p<0.05$) visual scores. Whilst MAP-1 showed higher ($p<0.05$) L* values and overall acceptability. Sample packaged under aerobic packaging showed significant ($p<0.05$) results for b* and thiobarbituric acid reactive substances (TBARS). Meat stored in aerobic packaging showed higher ($p<0.05$) shear force values. The outcome of this trial may help to promote the application of understudy MAP compositions and rapid detection of microbes by biochemical analysis under local conditions.

Keywords poultry breast fillets, packaging methods, modified atmosphere packaging (MAP), vacuum packaging, total volatile basic nitrogen

Introduction

Poultry meat stands among immensely consumed meat worldwide. This global relevancy to the consumer is due to its short production time, ease of preparation, nutritional profile, and comparatively, low price compared to red meat (Nääs et al., 2015; Wiedemann et al., 2017). In developing countries, the traditional wet markets hold a significant share of total processed poultry meat, with no added value. These markets are primarily present at every corner of the street as consumers perceive that meat procured from these wet markets is free from adulteration and halal at relatively low cost as the slaughtering is done at the spot. Despite consumers' perception, these wet markets harbour unhygienic processing conditions, and food safety issues are of significant concern under such an environment (Fang et al., 2017). However, this trend has been shifting towards purchasing packed meat over the past few years due to food-borne illness's frequent occurrence (Rahman et al., 2019). This packed meat fraction is comparatively low; however, increased awareness among the common masses regarding food quality and safety has encouraged modern processing plants to invest and market poultry meat and meat products through a hygienic supply chain at a competitive price (Aslam et al., 2020).

The intervention related to modern packaging technologies holds the ability to ensure longer shelf life correlated to safety and quality (Chiavaro et al., 2008). The meat industry commonly utilizes styrofoam trays with oxygen permeable (OP) wrapping, traditionally known as PVC foil packaging, vacuum packaging, and enhanced or protective atmosphere modified atmosphere packaging (MAP) (Latou et al., 2014; Patsias et al., 2006). These packaging technologies not only ensure the quality and safety of the food but also have the potential to reduce environmental impact and enhance the acceptability of the retailers and the consumers whilst conserving the organoleptic properties of the product (Arvanitoyannis and Stratakos, 2012; Fang et al., 2017; Kerry et al., 2006; Realini and Marcos, 2014). The most commonly adopted method for chicken meat is oxygen permeable packing; however, its shelf life is of few days only as compare to vacuum and modified atmosphere packing; moreover, this packing may not protect the product for the long term against external factors like meat color changes and drip loss (Byrd et al., 2011; Fraqueza et al., 2008).

The prolificacy and plentitude of microorganisms present in food and allied products are vital in ensuring product safety, shelf life, and consumer health. Poultry meat can host a diversified microbiological profile altering with seasonal changes; pathogenic and spoilage bacteria such as *Pseudomonas* spp., *E. coli* spp., *Salmonella* spp., *Campylobacter* spp. proliferate (Cohen et al., 2007). The presence of these pathogenic and spoilage microorganisms should be minimized to ensure the safety of meat and meat products (Álvarez-Astorga et al., 2002). Generally, the meat's microbial spoilage is classified as aerobic or anaerobic in nature, however, depending on the circumstances under which it occurs and the microorganisms involved (Hedrick et al., 1989).

Besides microbial spoilage, lipid oxidation is considered another leading cause for the deterioration of meat quality (Singh et al., 2011). Other important factors associated with shelf life and packaging are dehydration, loss of aroma, and discoloration (Kerry et al., 2006). Packaging plays a vital role in minimising meat contamination and quality deterioration issues, and various packaging systems are available for meat according to their applications (Mangalassary, 2019).

For the extended shelf life of fresh chicken meat and consumers' demands for minimally processed meat, vacuum packaging and modified atmosphere packaging techniques are utilised. To the extent of current knowledge, the results of is this trial under the local conditions are the first report on chicken breast meat that correlates the vacuum and overwrap packaging with understudy MAP compositions (O_2=0 & 20%, N_2=60 & 40%, CO_2=40%) under the retail display case [simulating the conditions of retail display at chilled (4°C) temperature requirements and presence of light].

Materials and Methods

Ethical statement

All experimental procedures were pre-approved (vide letter no. DR/74, 14 January 2020) by the Institutional ethical review committee/institutional review board in accordance with the Helsinki Declaration of 1975 on human experimentation, Office of Research, Innovation, and Commercialization (ORIC), University of Veterinary and Animal Sciences (UVAS), Lahore, Pakistan.

Sample collection and packaging

For this experiment, a total of 180 poultry breast fillets (165 g±10 g) were procured from the local retail wet market and shifted to the departmental meat technology laboratory under the control conditions. Samples were stored at 4°C and randomly selected for the treatments. These samples were kept under different packaging conditions at 2±2°C for 10 days. Samples were packed using overwrap packaging, modified packaging MAP-1: 0% O_2, 40% CO_2, 60% N_2, MAP-2: 20% O_2, 40% CO_2, 40% N_2, and vacuum packaging at retail temperature. Two fillets for each group were taken at day 0, 2, 4, 6, 8, and 10 of the storage period. Each treatment was replicated 3 times, with 60 breast fillets each time.

For overwrap packaging, meat was wrapped by FDA-approved food-grade PVC cling stretch film (Shindy, Jiangsu, China). Vacuum packaging was performed by a C300 twin vacuum packer (AGW, Serial no. 219528, Multivac, Wolfertschwenden, Germany) with packing material made of polyamide/polyethylene (150×200, PA/PE 90) holding the transmission rate of moisture vapors 2.6 g/m^2.d while O_2, CO_2 and N_2 permeability were 50 cm^3/m^2, 150 cm^3/m^2, and 10 cm^3/m^2, respectively. For modified atmosphere packaging, T200 gas packer (AGW, Serial no. 219529, Multivac, Germany) was utilised. Gases were mixed by a manually controlled gas mixer (MAP Mix 9001 ME, Dansensor A/C, Ringster, Sjælland, Denmark) with a 20–200 L/min (40–425 SCFH) for three gases. PET-PVDCPE packaging film was used for MAP with the transmission rate of 5 cm^3/24 h/m^2/atm O_2, 20 cm^3/24 h/m^2/atm CO_2, and 4 g/24 h/m^2 water vapours, respectively. Polypropylene trays were utilized.

Sample preparation

The meat sample preparation for microbial analysis was performed according to international standards (ISO 17604, 2015). For bacterial enumeration, whole fillets were transferred to a sterile bag, and an equal amount of buffered peptone water (BPW) (Merck Life Science, Marvasodo, Ponda, Goa, India) was added. The samples were rinsed by the rocking movement for 5 min for maximum recovery, as Cossi et al. (2012) described.

Microbiological analysis

For total viable count (ISO 4833-2, 2013), a 1 mL sample was taken from tubes containing the mixed sample, and 10-fold dilutions were performed with 0.1% BPW. The 0.1 mL of the diluted sample was shifted to plates containing nutrient agar (1.05450, Merck KGaA, Darmstadt, Germany). The visible colonies were counted using the JP Selecta Digital S colony counter (4905002, Spain). For the total coliform count (ISO 4832, 2006), a 1 mL sample was diluted as mentioned above. A diluted sample, 0.1 mL, was transferred by a pipette and uniformly spread on MacConkey agar (Merck KGaA, 1.05465). Pink colonies appear on the agar that was counted through the colony counter. For *Pseudomonas* count (ISO 13720, 2010), 0.1 mL from the diluted sample was shifted and spread on Cetrimide agar (1.05284, Merck KGaA) as per protocol. The Green water-

soluble pigment of both colonies and the media was an indication of the presence of *Pseudomonas*. Plates were incubated for 48 h at 37°C. The visible colonies were counted using the colony counter. For *Salmonella* count (ISO 6579, 2002), the sample was diluted, and 0.1 mL for the diluted sample was transferred to *Salmonella shigella* (SS) agar (1.07667, Merck KGaA) and is spread uniformly on the plates. Colorless to black-centered colonies appeared, indicating the presence of *Salmonella*.

pH

The postmortem pH was recorded using a pH meter (ProfiLine, pH 3210, Portable pH Meter, WTW, London, UK) according to ISO 2917 (1999). The pH meter was calibrated by using buffer sets 4–7 (WTW, Technical Buffers). The probe was cleaned with distilled water after every sample reading. The pH of meat was measured from the *pectoralis major* muscle, as described by López et al. (2011).

Total volatile basic nitrogen

For total volatile basic nitrogen (TVB-N), 10 g of the meat was taken from each sample and homogenized with 100 mL of double-distilled water. A 5 mL of filtrate was obtained from homogenate and mixed with 5 mL of 1% magnesium oxide solution (10 g/L). The distillate solution was prepared by dissolving boric acid (2%), methyl red (0.1 g), and methylene blue (0.1 g) in 10 mL of ethanol solution. Distillation was performed by Behrotest steam distillation unit (Behr S1-B00218025, Labor-Technik™, Düsseldorf, Germany). The distillate was absorbed by 20 mL of boric acid solution. The sample was titrated against a 0.01 N hydrochloric solution. TVBN values were determined by the following formula (Song et al., 2011).

$$\text{TVB-N} = (\text{Vol. of HCl used} \times \text{Normality of acid} \times 14) \times 100$$

Cooking loss (%)

To calculate the cooking loss, the samples were weighed, vacuum-packed, and put under a pre-warm water bath (WNB45, Memmert, Buchenbach, Germany) for cooking purposes. The operating temperature of the water bath was 80°C. Breast fillets were cooked until they attained a core temperature of 72°C (Barbut et al., 2005). The core temperature was achieved in approximately 30 min, recorded by using a digital food-grade thermometer (TP 101, Cixi Sinco, Zhejiang, China). Breast fillets were then placed in polystyrene trays and overwrapped by cling film. To cool down, samples were set in a horizontal display chiller (ALVO, Model MD-12, Technosight, Lahore, Pakistan) working at 0°C–4°C. Cooked fillets were re-weighed. The cooking loss was calculated as performed by Yusop et al. (2010).

$$\text{Cooking loss (\%)} = (W_{initial} - W_{final}) \,/\, W_{initial} \times 100$$

Subjective color (visual color scoring)

The sensory panel members consisted of a trained panel of judges, took the subjective color by visualising the packs before opening the packaging at the display chiller on 0, 2, 4, 6, 8, and 10 days. The panellists evaluated the color of meat in the packed conditions, owing to purchasing decisions and overall meat color, by a 9-point hedonic scale (AMSA, 2012). The description of the hedonic scale for visual color scoring is present in Table 1.

Table 1. Description of hedonic scale for visual color scoring

Score	Description
9	Extremely desirable or acceptable color
8	Very desirable or acceptable color
7	Moderately desirable or acceptable color
6	Slightly desirable or acceptable color
5	Neither acceptable or unacceptable color
4	Slightly undesirable or unacceptable color
3	Moderately undesirable or unacceptable color
2	Very undesirable or unacceptable color
1	Extremely undesirable or unacceptable color

Instrumental color

The data recording of the instrumental color of the samples was conducted immediately after opening the pack. Readings were documented on the 0, 2, 4, 6, 8, and 10 day using Minolta Chroma meter (CR-410, Konica Minolta, Osaka, Japan) with 50 mm port size and D65 illuminant. The colorimeter was calibrated before recording the observations with standard white tile CR-410 with a 2-degree standard observer (Rodríguez-Calleja et al., 2012). Calibration value were L*=94.93, a*=0.13, b*=2.55 and C=2.55. Color parameters like lightness (L*), redness (a*) and yellowness (b*) were recorded. Three readings were taken from each sample, and mean values were used for statistical analysis.

Thiobarbituric acid reactive substances (TBARS; lipid oxidation)

Thiobarbituric acid reactive substances (TBARS) analysis was performed on the 0, 2, 4, 6, 8, and 10 day using the protocol described by John et al. (2004) with few amendments. A 0.5 grams meat sample was mixed in 2.5 mL of a solution containing 0.375% TBA (Sigma-Aldrich Chemical, St. Louis, MO, USA), 0.25N HCl, and 15% trichloroacetic acid (Merck KGaA). The mixture was heated in a water bath at 100°C (WNB45, Memmert) for 10 min and was cooled with tap water. Then the mixture was centrifuged at 3,720×g for 25 min (Z 326 K, HERMLE Labortechnik GmbH, Wehingen, Germany). The tube supernatant was collected from the test, and absorbance was recorded at 532 nm against the blank containing stock solution through a UV-160 spectrophotometer (Specord 200 plus, Jena, Germany). Using the malonaldehyde standard curve, the TBARS value was calculated and expressed as milligrams of MDA/kg of poultry meat.

Tenderness

Tenderness recording of samples was carried out on day 0, 2, 4, 6, 8, and 10 of storage. After weighing, the samples were vacuumed packed by using a vacuum packaging machine (C300Twin, AGW, Serial no. 219528, Multivac, Germany) using plastic bags (SR 150×200, PA/PE 90) for cooking in a water bath (WNB45, Memmert) operating at 80°C temperature. The samples were cooked until the samples attained the core temperature of 72°C; the temperature was recorded by using a digital food-grade thermometer (TP 101, Cixi Sinco), as carried out by Moczkowska et al. (2017). After cooking, the samples were placed in polystyrene trays and cooled down in a walk-in chiller maintained at 4°C±1°C. Cooked samples were sliced into strips having a dimension 1 cm long×1 cm high×1 cm wide alongside the muscle fibers and sheared under the 'V-Slot' blade

of Texture Analyzer (TA. XT plus texture analyser, Stable Micro Systems, Surrey, UK, Serial no. 41851) to obtain shear force values which indicate the tenderness of meat affected by various packaging technologies. Minimum 3 values were recorded from each sample in Newton per centimeter square (N/cm^2).

Sensory analysis

Sensory analysis of poultry breast samples was conducted in the sensory analysis laboratory at Central Laboratory Complex, UVAS, by a semi-trained sensory panel. The panel consisted of 15 members of faculty staff and postgraduate students. Before the start of the sensory trials, all the panelists were made aware of the study trial. After opening the tray, samples from each treatment were cooked without salt and any spices on a hot plate until it attained the core temperature of 72°C. The core temperature was recorded using a digital food-grade thermometer (TP 101, Cixi Sinco). The specimen was cut and subdivided into uniform parts to serve all the panelists. All the samples were served warm, and in between subsequent samples, the panelists had a facility to rinse their mouths to remove any carry-over effect. The panelists evaluated color appearance, flavor, juiciness, tenderness, and overall acceptability by following an 8-point hedonic scale (Berry and Leddy, 1984), whereas, 8=extremely flavor intensity, extremely tender, extremely juicy, and high overall acceptance while, 1=extremely weak flavor intensity, extremely tough, extremely dry, and extremely low overall acceptance (Marcinkowska-Lesiak et al., 2016).

Statistical analysis

The data were analysed under a complete randomised design through two-way ANOVA by Minitab (Minitab 17.3.1). Tukey's test was used to differentiate significant means. The significant difference was considered at $p<0.05$.

Results and Discussion

Microbiological changes under vacuum and modified atmosphere packaging

The microbial profile of samples under vacuum and modified atmosphere packaging is illustrated in Table 2.

Aerobic plate count (APC)

The aerobic plate count (APC), *Pseudomonas* count, and total coliform increased with duration regardless of the treatment. For APC, the initial bacterial load at 0 days ranged between 5.48±0.05 to 5.59±0.02 Log CFU/g. Treatment and storage time has a significant influence on APC. MAP-1 showed a lower bacterial count as compared to vacuum packed (VP) and control.

ICMSF (1986) stated that 7 Log CFU/g is the recommended TVC limit. Control and VP samples results crossed the recommended limit at 6 and 8 days, respectively, while both MAP-1 and MAP-2 packaging had lower bacterial profiles till day 10. The overall trends for APC were following the findings of Balamatsia et al. (2007) and Patsias et al. (2008), who investigated the combined effect of MAP and freeze chilling on raw chicken fillets.

Comparatively insignificant difference ($p>0.05$) was reported by Rossaint et al. (2014), who performed high O_2 (70% O_2, 30% CO_2) vs. high N_2 (70% N_2 and 30% CO_2) MAP composition, suggesting that high O_2 packing had no supplementary positive results on quality preservation and shelf-life extension of fresh broiler meat. Meredith et al. (2014) found that *Campylobacter* count was reduced on chicken fillets with a combination of 40:30:30, CO_2: O_2: N_2, respectively, extended the shelf-life in MAP for more than 14 days. Similarly, a higher concentration of CO_2 does not allow the growth of Enterobacteriaceae, including

Table 2. Effect of aerobic, vacuum and different modified atmosphere packagings on microbiological profile of poultry breast fillets

Packaging methods		Storage time (d)						p-value		
		0	2	4	6	8	10	d	trt	d×trt
Total plate count (Log CFU/g)	Control	$5.59^{l}\pm0.02$	$5.86^{k}\pm0.06$	$6.86^{ef}\pm0.05$	$7.84^{c}\pm0.11$	$8.20^{b}\pm0.07$	$10.35^{a}\pm0.12$	<0.0001	<0.0001	<0.0001
	VP	$5.43^{lm}\pm0.05$	$5.89^{jk}\pm0.02$	$6.42^{i}\pm0.05$	$6.72^{fgh}\pm0.04$	$7.32^{d}\pm0.09$	$8.17^{b}\pm0.08$			
	MAP-1	$5.35^{m}\pm0.08$	$5.89^{jk}\pm0.01$	$5.96^{jk}\pm0.08$	$6.64^{gh}\pm0.11$	$6.82^{fg}\pm0.03$	$6.88^{ef}\pm0.08$			
	MAP-2	$5.48^{lm}\pm0.05$	$5.92^{jk}\pm0.08$	$6.09^{ij}\pm0.04$	$6.53^{hi}\pm0.10$	$6.92^{ef}\pm0.05$	$7.08^{e}\pm0.04$			
Total coliform count (Log CFU/g)	Control	$2.52^{gh}\pm0.07$	$2.59^{efgh}\pm0.11$	$2.77^{defg}\pm0.07$	$3.09^{bc}\pm0.05$	$3.19^{b}\pm0.01$	$3.53^{a}\pm0.05$	<0.0001	<0.0001	<0.0001
	VP	$2.36^{h}\pm0.10$	$2.36^{h}\pm0.10$	$2.59^{efgh}\pm0.11$	$2.80^{def}\pm0.04$	$2.94^{bcd}\pm0.03$	$3.11^{bc}\pm0.03$			
	MAP-1	$2.42^{h}\pm0.10$	$2.46^{h}\pm0.15$	$2.55^{fgh}\pm0.13$	$2.77^{defg}\pm0.07$	$2.86^{cde}\pm0.03$	$2.92^{bcd}\pm0.03$			
	MAP-2	$2.46^{h}\pm0.15$	$2.36^{h}\pm0.10$	$2.40^{h}\pm0.17$	$2.63^{efgh}\pm0.06$	$2.94^{bcd}\pm0.03$	$2.94^{bcd}\pm0.03$			
Pseudomonas count (Log CFU/g)	Control	$5.46^{m}\pm0.06$	$5.95^{jk}\pm0.09$	$6.47^{gh}\pm0.09$	$6.97^{cd}\pm0.10$	$7.53^{b}\pm0.06$	$8.13^{a}\pm0.06$	<0.0001	<0.0001	<0.0001
	VP	$5.43^{m}\pm0.10$	$5.75^{k}\pm0.07$	$5.95^{jk}\pm0.08$	$6.36^{ghi}\pm0.10$	$6.86^{cde}\pm0.08$	$7.04^{c}\pm0.05$			
	MAP-1	$5.46^{m}\pm0.05$	$5.73^{kl}\pm0.06$	$5.86^{k}\pm0.10$	$6.16^{ij}\pm0.07$	$6.59^{fg}\pm0.13$	$6.76^{def}\pm0.08$			
	MAP-2	$5.46^{lm}\pm0.07$	$5.73^{k}\pm0.10$	$5.91^{jk}\pm0.03$	$6.27^{hi}\pm0.10$	$6.62^{efg}\pm0.11$	$6.88^{cde}\pm0.09$			

Control, aerobic packaging; VP, vacuum packaging; MAP-1, modified atmosphere packaging 1 (0% O_2, 40% CO_2, 60% N_2); MAP-2, modified atmosphere packaging 2 (20% O_2, 40% CO_2, 40% N_2).

$^{a–m}$ Superscripts indicate a statistical significant difference between days and treatment ($p<0.05$).

Salmonella spp. (Phillips, 1996). A higher concentration of CO_2, i.e., 20%–40%, inhibits aerobic microorganisms' growth, and a high concentration of O_2 is used to maintain cherry red color (O'Grady et al., 2000). Patterson et al. (1984) reported that lower temperature restrict psychrotrophic Enterobacteriaceae spp. growth than storage at 4°C or 5°C. The absence of oxygen in vacuum-packed meat may permit conditions favorable for developing toxin production by anaerobic pathogens such as *Clostridium botulinum* if the temperature is not maintained. So, vacuum meat safety is still a deal under temperature abuse, but it can be enhanced by proper preservation systems coupled with hurdle technology (Akhtar and Pandey, 2015).

Total coliform count

The recommended limit for the total coliform count is 3 Log CFU/mL. Results showed that MAP had a significantly lower ($p<0.05$) coliform count compared to VP and control. MAP-1 and MAP-2 did not cross the maximum limit during the study, while control and VP achieved and crossed the limit on days 6 and 10, respectively. Irkin et al. (2011) studied the effect of different MAP compositions and VP on coliform bacteria in minced beef found that MAP restricted coliform growth, especially when meat was packed in a higher amount of CO_2. The same results were obtained in *red claw crayfish* by Chen et al. (2007) using 80% CO_2/ 10% O_2/ 10% N_2 restricted coliform count compared with VP and AP stored at 2°C. Pettersen et al. (2004) also stated that coliform colonies were reduced when higher CO_2 was used in poultry breast fillets packaging.

Pseudomonas count

In vacuum packaging, CO_2 is produced because of oxygen utilization by the food products, slowing down aerobic bacteria's growth that leads to spoilage odor and off-flavor. The higher concentration of CO_2 and the anaerobic atmosphere of the package inhibits or lowers the multiplication of *Pseudomonas* spp. (Höll et al., 2016). In this study, *Pseudomonas* surpassed the recommended limit on day 10 in VP with an increase in shelf-life up to 4 days compared to AP. In contrast,

MAP-1 concentrations illustrated remarkably lower ($p<0.05$) values until the experiment's end. The recommended bacterial population of *Pseudomonas* spp. in meat is 7 Log CFU/g.

Zhang et al. (2015) performed experiments using 30% CO_2 and N_2 as filler gas showed a similar overall result as the present study and found that *Pseudomonas* spp. remained below the recommended limit throughout the storage. It was observed that the growth of *Pseudomonas* spp. was delayed in an atmosphere containing CO_2 and N_2. The reason for this could be the possible prolonged lag phase of bacterial growth and restricted proliferation during the logarithmic phase (Patsias et al., 2006). On the other hand, aerobic environments provide a suitable environment for *Pseudomonas* spp. to gradually grow in control even in VP because the transmission rate of the packaging material of 1% of the oxygen level is enough to support the growth of *Pseudomonas* spp. (Balamatsia et al., 2007). Therefore, the significant ($p<0.05$) growth was still observed, which supports the results of the study by Meredith et al. (2014) and Patsias et al. (2008), indicating that besides the anaerobic environment, the temperature played a crucial role in supporting the proliferation of *Pseudomonas* spp. (Fernández et al., 2009).

In contrast with an overwrap, the low oxygen supply in vacuum packaging restricted the growth of some typical spoilage-causing bacteria, i.e., *Pseudomonas* spp. (Cayré et al., 2003). A very low oxygen level is obtained with good vacuum packing, linked with carbon dioxide (CO_2) production in the bag, slowing down aerobic bacteria's growth that leads to spoilage odor and off-flavor. So, the aerobic growth of *Pseudomonas* spp. lessened, and anaerobic microorganisms predominate. This was because of the higher concentration of CO_2 that inhibited or lowered the multiplication of *Pseudomonas* spp. While the lactic acid bacteria growth is promoted, that has a low potential of deterioration at low temperature (Hernández-Macedo et al., 2011). Pennacchia et al. (2011) revealed that *Pseudomonas* spp. and *Brochothrix thermosphecta* reduced in number when packed in vacuum packaging.

Salmonella count

Salmonella was evaluated on their presence or absence in poultry breast fillets. According to the ISO standard (ISO 6579, 2002) and Veterinary Procedural Notices (VPN15), *Salmonella* should be undetectable in 25 g of meat (NDVQPH, 2010). In our study, 23% of samples (33 out of 144) were *Salmonella* positive, while 77% (111 out of 144) were *Salmonella* negative (Table 3). The higher number of detections was because of the slaughtering procedures adopted in retail markets. Good hygiene practices can improve the microbial profile of poultry meat. (data is present in the supplementary datasheet).

Effect of packaging techniques on the pH of poultry breast fillets

The initial pH was ranged between 5.93–5.95. No significant difference ($p>0.05$) was obtained among the different packaging techniques throughout the period (Table 4). However, samples treated with MAP-2 had lower pH on days 6 and 8. Similar results were reported in poultry under different MAP compositions (Patsias et al., 2006; Patsias et al., 2008; Vongsawasdi et al., 2008). The change in muscle pH is affected by various factors. Among them, lactic acid formation by the LAB metabolism caused a decline in pH. Higher amounts of CO_2 lower the pH by dissolution in breast fillets, forming carbonic acid (HCO_3–) (Al-Nehlawi et al., 2013). But the buffering capacity of meat tissues might be responsible for stabilising pH in different packaging atmospheres (Zhang et al., 2015).

Effect of packaging techniques on the TVB-N of poultry breast fillets

The freshness of the meat is an utmost quality attribute that is always demanded and preferred by the customers. TVB-N

Table 3. *Salmonella* presence in poultry breast fillets

Sample no.	*Salmonella* present Yes/No	Sample no.	*Salmonella* present Yes/No	Sample no.	*Salmonella* present Yes/No	Sample no.	*Salmonella* present Yes/No
1	No	37	No	73	Yes	109	No
2	No	38	Yes	74	No	110	No
3	No	39	No	75	No	111	No
4	No	40	No	76	No	112	No
5	No	41	No	77	No	113	No
6	No	42	No	78	No	114	Yes
7	No	43	Yes	79	No	115	No
8	Yes	44	No	80	No	116	No
9	Yes	45	No	81	Yes	117	No
10	No	46	No	82	No	118	No
11	No	47	No	83	Yes	119	Yes
12	No	48	No	84	No	120	No
13	No	49	No	85	No	121	No
14	No	50	No	86	No	122	Yes
15	No	51	Yes	87	No	123	No
16	Yes	52	No	88	Yes	124	Yes
17	No	53	No	89	No	125	Yes
18	Yes	54	No	90	No	126	No
19	No	55	Yes	91	No	127	No
20	No	56	No	92	Yes	128	No
21	No	57	No	93	No	129	No
22	No	58	Yes	94	No	130	No
23	No	59	No	95	No	131	No
24	No	60	Yes	96	No	132	No
25	No	61	No	97	Yes	133	Yes
26	No	62	Yes	98	No	134	Yes
27	Yes	63	No	99	No	135	Yes
28	No	64	No	100	No	136	No
29	No	65	Yes	101	Yes	137	No
30	No	66	No	102	No	138	No
31	No	67	No	103	No	139	No
32	No	68	No	104	Yes	140	No
33	No	69	No	105	No	141	No
34	Yes	70	Yes	106	Yes	142	No
35	No	71	No	107	Yes	143	No
36	Yes	72	No	108	No	144	No

Table 4. Effect of aerobic, vacuum and different modified atmosphere packagings on pH, T-VBN and cooking loss of poultry breast fillets

Packaging methods		Storage time (D)						p-value		
		0	2	4	6	8	10	d	trt	d×trt
pH	Control	5.93±0.01	5.89±0.01	5.90±0.01	5.89±0.00	5.90±0.01	5.93±0.05	<0.071	<0.342	<0.218
	VP	5.94±0.01	5.89±0.01	5.89±0.01	5.89±0.01	5.91±0.01	5.93±0.01			
	MAP-1	5.95±0.01	5.87±0.01	5.88±0.01	5.91±0.00	5.92±0.01	5.92±0.00			
	MAP-2	5.94±0.00	5.88±0.00	5.89±0.01	5.79±0.01	5.81±0.01	5.89±0.00			
T-VBN (mgN/ 100 g)	Control	18.67^{k}±0.80	21.00^{hijk}±1.40	22.87^{ghij}±0.80	31.73^{cd}±0.80	40.13^{b}±0.80	49.00^{a}±1.40	<0.0001	<0.0001	<0.0001
	VP	19.13^{jk}±0.80	19.13^{jk}±0.80	23.33^{ghi}±0.80	28.00^{def}±1.40	29.40^{cde}±1.40	33.13^{c}±0.80			
	MAP-1	18.67^{k}±0.80	18.67^{k}±0.80	19.60^{ijk}±1.40	24.27^{fgh}±0.80	24.27^{fgh}±0.90	26.60^{efg}±1.40			
	MAP-2	19.13^{jk}±0.80	22.87^{ghij}±1.62	21.467^{hijk}±2.14	21.93^{hijk}±0.80	24.27^{fgh}±2.13	28.00^{def}±1.40			
Cooking loss (%)	Control	20.49^{ghi}±0.53	23.48^{c}±0.44	22.69^{cde}±0.19	27.50^{b}±0.43	29.03^{ab}±0.99	30.79^{a}±0.40	<0.0001	<0.0001	<0.0001
	VP	19.63^{hi}±0.66	21.22^{efgh}±0.60	22.54^{cdef}±0.49	21.82^{cdefg}±0.67	20.69^{fghi}±0.45	20.35^{ghi}±0.39			
	MAP-1	19.12^{i}±0.56	20.70^{efghi}±0.60	21.53^{cdefgh}±0.28	21.43^{defgh}±0.7	20.84^{efghi}±1.10	20.18^{ghi}±0.17			
	MAP-2	20.70^{efghi}±0.64	21.93^{cdefg}±0.89	23.31^{cd}±0.34	21.77^{cdefg}±0.63	20.84^{efghi}±0.71	22.05^{cdefg}±1.14			

Control, aerobic packaging; VP, vacuum packaging; MAP-1, modified atmosphere packaging 1 (0% O_2, 40% CO_2, 60% N_2); MAP-2, modified atmosphere packaging 2 (20% O_2, 40% CO_2, 40% N_2).
[a–k] Superscripts indicate a statistical significant difference between days and treatment ($p<0.05$).
TBARS, thiobarbituric acid reactive substances.

contains volatile compounds, mainly trimethylamine $(CH_3)_3N$, dimethylamino $(CH_3)_2N$, and ammonia (NH_3), produced as a result of spoilage causing bacteria such as *Pseudomonas* (Fraqueza et al., 2008). TVB-N levels describe spoilage and real-time freshness (Pacquit et al., 2006). The test is low cost and rapid to access the freshness of poultry meat with established limits by European communities (European Commission, 1995).

Poultry breast fillets were evaluated for TVB-N count for different packaging techniques. The recommended limit for TVB-N in fresh poultry meat is 40 mgN/100 g proposed by Balamatsia et al. (2007). MAP and VP showed statistically significant ($p<0.05$) results compared to control, and their values remained below the recommended limit (Table 4). The final values were 33.13, 26.60, and 28 mgN/100 g for VP, MAP-1, and MAP-2, respectively. In TVBN, proteins and non-protein nitrogenous compounds break down to volatile amines indicating the freshness of the meat (Liu et al., 2013).

Few studies (Abdullah et al., 2017; Balamatsia et al., 2007; Rahman et al., 2019) have been published on the application of TVB-N as an indicator of spoilage in poultry breast fillets as compared to the information available on various species of fish (Castro et al., 2012; Chong et al., 2013; Goulas and Kontominas, 2007; Hsiao and Chang, 2017; Hwang et al., 2012; Lalitha et al., 2005). TVB-N result values for MAP and VP were in the recommended limit in the current study until the storage period lasted, which seconds the results of Balamatsia et al. (2007).

Effect of packaging technique on the cooking loss (%) of poultry breast fillets

The maximum cooking loss (%) was observed in the control group. In contrast, VP, MAP-1, and Map-2 showed non-significant ($p>0.05$) results among treatments, and their values remained the same till day 10 (Table 4). The highest VP, MAP-1, and MAP-2 values were 20.35%, 20.18%, and 22.50%, respectively. Slightly higher values for MAP-2 were because of the presence of oxygen in packaging. The reason behind higher values may be the increase in protein oxidation with the

rise in oxygen concentration (Wang et al., 2019). Similar results were obtained by Shen et al. (2022). Marcinkowska-Lesiak et al. (2016) used 30% CO_2 in MAP and found lower cooking loss with the storage time till day 10. The results were the same for vacuum packaging.

The decrease in cooking loss with increased storage time resulted from increased exogenous enzymes (Jama et al., 2008). Collagenase is an exogenous enzyme produced by ionic solubilization that increases water holding capacity because of the disintegration of myofibrillar proteins (Bruce et al., 2004). While according to Iwanowska et al. (2010), there was an increase in cooking loss after day 10 because of the advanced transformations in the muscle tissues affecting muscle protein structures.

Effect of packaging technique on the visual color of poultry breast fillets

Visual color scores for overall meat color of poultry breast fillets stored under VP, MAP-1, MAP-2, and aerobic packaging were evaluated at 0, 2, 4, 6, 8, and 10 day of the retail display are shown in Table 5. For visual color scoring, the breast fillet samples were evaluated on 9 points hedonic scale, as aforementioned in Table 1. It was observed that the treatments and storage time have shown a significant influence on the visual color scores. Among the treatment groups, MAP-2 showed significantly higher scores than MAP-1, VP, and control groups.

However, a significant decline is observed in the visual color scores with the extension in the storage duration. On day 0, MAP-2 showed significantly higher visual colour scores compared to control, MAP-1, and VP. On day 2, VP showed significantly higher scores as compared to MAP and control. On day 6, control samples showed significantly lower scores for

Table 5. Effect of aerobic, vacuum and different modified atmosphere packagings on color of poultry breast fillets

Packaging methods		Storage time (D)						p-value		
		0	2	4	6	8	10	d	trt	d×trt
Visual color acore	Control	8.13^{cde}±0.08	7.47^{hi}±0.10	6.01^{k}±0.10	3.96^{m}±0.12	2.56^{n}±0.07	1.00^{o}±0.00	<0.0001	<0.0001	<0.0001
	VP	8.49^{ab}±0.08	8.44^{ab}±0.10	7.67^{gh}±0.08	7.58^{ghi}±0.10	6.89^{j}±0.13	5.51^{i}±0.12			
	MAP-1	8.38^{abc}±0.07	8.33^{bcd}±0.07	8.11^{cde}±0.09	7.76^{fg}±0.09	7.76^{fg}±0.07	6.84^{j}±0.11			
	MAP-2	8.62^{a}±0.07	8.31^{bcd}±0.07	8.00^{ef}±0.06	8.07^{de}±0.04	8.00^{ef}±0.00	7.36^{i}±0.09			
L*	Control	55.11^{h}±1.26	57.87^{bcdefgh}±1.26	59.96^{abcde}±1.92	57.63^{cdefgh}±0.12	56.55^{efgh}±0.84	58.28^{bcdefgh}±1.35	<0.0001	0.0033	0.075
	VP	55.39^{gh}±1.05	58.39^{bcdefgh}±1.08	58.14^{bcdefgh}±1.09	59.46^{abcdef}±0.83	60.43^{abcd}±0.94	57.14^{defgh}±1.08			
	MAP-1	56.18^{fgh}±1.21	59.50^{abcdef}±0.50	58.71^{abcde}±0.70	59.78^{abcde}±0.92	62.01^{a}±0.94	61.15^{ab}±1.17			
	MAP-2	55.97^{gh}±1.31	58.60^{abde}±0.74	60.50^{acde}±0.53	60.96^{abc}±0.19	58.16^{bcdefgh}±1.36	60.77^{abc}±0.76			
a*	Control	14.27^{a}±0.60	14.48^{a}±0.81	15.01^{a}±1.44	12.18^{abcd}±0.81	11.40^{bcde}±0.15	11.16^{cde}±0.46	<0.0001	0.1467	0.105
	VP	13.93^{abc}±0.84	13.25^{abc}±0.63	13.45^{abc}±0.69	12.37^{abcd}±1.09	12.97^{abc}±0.98	13.09^{abc}±0.36			
	MAP-1	13.84^{abc}±0.41	13.63^{abc}±0.38	14.22^{ab}±0.39	13.83^{abc}±0.53	9.82^{de}±1.02	11.38^{bcde}±0.52			
	MAP-2	14.12^{ab}±0.52	12.89^{abc}±0.75	12.98^{abc}±0.79	13.59^{abc}±0.79	10.17^{de}±1.40	9.26^{e}±0.72			
b*	Control	14.34^{defgh}±0.40	17.87^{abcde}±0.62	19.82^{a}±0.77	17.70^{abcde}±1.43	18.65^{a}±0.62	18.26^{abcd} ±1.42	<0.0001	<0.0001	0.271
	VP	14.56^{cdefgh}±1.42	14.04^{efgh}±1.41	16.68^{abcdef}±2.31	14.49^{cdefgh}±1.73	14.49^{cdefgh}±1.33	11.07^{h}±0.77			
	MAP-1	13.38^{fgh}±0.70	16.13^{abcdefg}±0.98	18.01^{abcde} ±1.61	14.79^{bcdefgh}±0.78	13.32^{fgh}±0.60	12.31^{gh}±0.70			
	MAP-2	14.67^{cdefgh}±1.05	16.73^{abcdef}±1.59	18.41^{abc}±1.42	18.91^{a}±0.71	14.86^{bcdefgh}±0.98	14.78^{bcdefgh}±1.06			

Control, aerobic packaging; VP, vacuum packaging; MAP-1, modified atmosphere packaging 1 (0% O_2, 40% CO_2, 60% N_2); MAP-2, modified atmosphere packaging 2 (20% O_2, 40% CO_2, 40% N_2).
$^{a–h}$ Superscripts indicate a statistical significant difference between days and treatment ($p<0.05$).

visual color.

Whereas, as the storage period lasted, the samples under MAP-2 showed higher visual color scores. The order of visual color scores for samples under various treatments was MAP-2>MAP-1>VP>Control. The results of this trial's visual color scores showed significant differences ($p<0.05$) among various packaging environments along with the storage days. The assessment of color by visual evaluation is closely related to the purchasing behavior of consumers. MAP-2 showed the highest score (8.6) as compared to other groups (Table 5). All samples' initial color score was 8, indicating "very desirable color", followed by a gradual decrease in visual color scores along the storage days in all the packaging treatments. It was also observed that when the panelists were provided with the information regarding the day at which the samples were displayed, they assign the higher scores owing to the degree freshness of samples as the days passed, and this, consequently, could bias their assessment in assigning the visual color. The differences in visual scores at the same sampling day could be influenced by personal preference, the vision of sensory panelists, and environmental factors (AMSA, 2012).

Effect of packaging technique on the instrumental color of poultry breast fillets

The result of instrumental color values (L*, a*, and b*) for all the poultry fillet samples stored under VP, MAP-1, MAP-2, and aerobic packaging were analyzed and recorded at day 0, 2, 4, 6, 8, and 10 of the retail display are illustrated in Table 5. The storage duration and conditions significantly influenced the L* (Lightness) value of MAP samples. On day 0, MAP-1 had a significantly higher L* value. However, control, VP, and MAP-2 exhibited a similar pattern for L*. A significant increase in L* value was noticed on day 6, 8, and 10 in contrast to the control group stored under MAP. As the storage period completed, MAP-1 has shown a significantly higher L* value, whereas the VP samples had exhibited a significantly lower L* value. The order of lightness (L*) value was MAP-1>MAP-2>VP>Control. All the treatments had similar results for a* (redness) value. However, the storage duration has shown a significant effect on a* value among all treatments. There was a significant decrease in a* value noted as the storage time passed. It was observed that whilst the storage period was completed, VP had a significantly higher a* value than MAP and control treatment. MAP-2 showed a significantly lower a* value. On day 0, all the groups exhibited similar results for the b* (yellowness) value. It was concluded that the storage duration significantly influenced the b* value compared to the storage conditions.

In treatment groups, VP and MAP-1 showed significantly lower b* values than control and MAP-2. On day 2, the control samples illustrated markedly higher b* figures than other groups. However, a lower b* value across all the treatment groups was noticed in contrast to the control group. The exhibiting order of b* value was recorded to control>MAP-2>VP and MAP-1. Whilst assessing the integrity of meat color during the extended days of meat storage, the samples of MAP-2 treatment were rated as "moderately desirable color," whereas the meat in the control group was rated as having "extremely undesirable color". These results stand agreeable with the findings of Rotabakk et al. (2006), which stated that the samples treated under the aerobic packaging could develop unacceptable attributes at day 5 of storage time. Another study by Rossaint et al. (2015) reported that poultry meat's shelf life packed under MAP ranged around 10 days based on the visual colour analysis. Furthermore, Jongberg et al. (2014) observed a significant deterioration in poultry breast meat's sensory color characteristics after 10 days of storage under MAP (80% O_2 and 20% CO_2).

The instrumental color readings of all treatments recorded during the sampling are given in Table 5. The lightness value of samples (L*) had shown a significant ($p<0.05$) increasing trend during the ending phase of storage duration, i.e., the 10 day, indicating that the color of fillets became lighter as the storage duration extended. A significant inclination among the L* values of samples stored under MAP was noticed to be varied between 55.97 and 61.15. However, the VP and control

samples showed slightly non-significant results regarding L* values which ranged between 55.11 and 57.14 without any profound pattern to be observed. This study's results are consistent with the findings reported by Contini et al. (2014), which illustrated the effect of active packaging on the L* value of cooked turkey meat.

The initial a* values of the samples under treatment groups, i.e., control, VP, MAP-1, and MAP-2, were 14.27, 13.93, 13.84, and 14.12, respectively. On day 2 and 4 control group indicated a significant ($p<0.05$) hike in a* value compared to VP and MAP groups, which might be mainly due to the exposure to O_2. A significant ($p<0.05$) regression in a* value was observed along the storage time among all the treatments except VP; however, VP manifested a notably higher a* value than MAP and control at the end of the storage period. Control samples expressed an inclining pattern in the b* value, which varied between 14.34 and 18.26. VP revealed a decrease in b* value, and the values ranged between 14.56 and 11.12, Whereas a slight decline in the b* value of MAP-1 samples was observed as the storage period diminished. VP and MAP-1 samples exhibited non-significant results with each other. MAP-2 samples indicated a narrow increase in b*. In a similar study, Jouki and Khazaei (2012) stated that a considerable increase in b* value was due to changes in the pigment configuration of meat during the sample holding period. Metmyoglobin is synthesized during extended cold storage, consequently which can alter the meat color. In their study, Ahn and Lee (2004) reported no notable change in L* and a* values under aerobic and vacuum-packed turkey fillets during 2 weeks of storage time. However, they reported a significant ($p<0.05$) increase in b* values in aerobically-packaged samples. Angsupanich and Ledward (1998) proposed that this change in muscle color may be associated with sarcoplasmic proteins and myofibrillar denaturation.

Effect of packaging technique on lipid oxidation of poultry breast fillets

A significant amount of malondialdehyde formation was observed in the packed poultry breast fillets (Table 6) under the influence of storage duration and packaging methods (VP and MAP). Storage conditions and storage span exhibited a remarkable change in TBARS values. With the extended storage time, it was observed that the TBARS values of control and MAP-2 treatments showed a significant ($p<0.05$) increase as compared to MAP-1 and VP as both control and MAP-2 contain 20% O_2, which helps in the increase of lipid oxidation. Whereas at day 10, as sample holding time lasts, the control group samples were characterised by significantly highest values, whereas vacuum-packed samples manifested significantly lower TBAR values with no significant hike from the normal range. MAP-2 poultry meat samples during the storage indicated higher TBARS values than MAP-1 and VP samples on day 6, 8, and 10. The order of lipid oxidation for poultry breast fillets was appeared to be as Control>MAP-1>MAP-2>VP.

Lorenzo and Gómez (2012) stated that lipid oxidation and off-flavour development are serious problems for quality integrity during the storage of meat and allied products. TBARS index shows the extent of progression of the lipid oxidation process. In this study, the chicken fillet samples packed under VP and MAP exhibited significantly lower ($p<0.05$) lipid oxidation values as compared to the control (Table 6). On day 10, the meat from the control group displayed the highest values (1.92 mg MDA/kg meat). Similar outcomes by Orkusz et al., (2017), Rogers et al. (2014), Zakrys et al. (2008) illustrated that lipid oxidation can be triggered under the influence of O_2 used in the MAP. Other factors including, exposure to light and temperature fluctuations, may intensify this phenomenon of lipid oxidation. Meredith et al. (2014) stated that high O_2-MAP is responsible for increasing the TBARS values of chicken meat during chill storage, whereas the meat from organically reared chicken stored without high O_2-MAP was also influenced the formation of secondary lipid oxidation during 14 days storage. A similar study by Patsias et al. (2006) concluded that TBARS values decrease to day 8 of storage at 4°C. Whereas the VP samples showed no notable increase in TBARS value. VP meat was characterised by significantly

Table 6. Effect of aerobic, vacuum and different modified atmosphere packagings on TBARS and tenderness of poultry breast fillets

Packaging methods		Storage time (D)						p-value		
		0	2	4	6	8	10	d	trt	d×trt
TBARS	Control	0.40^{i}±0.00	0.40^{i}±0.00	0.79^{de}±0.01	0.89^{cd}±0.05	1.25^{b}±0.00	1.92^{a}±0.04	<0.0001	<0.0001	<0.0001
	VP	0.40^{i}±0.00	0.40^{i}±0.00	0.42^{i}±0.00	0.47^{hi}±0.04	0.49^{ghi}±0.04	0.51^{gh}±0.03			
	MAP-1	0.39^{i}±0.01	0.39^{i}±0.01	0.51^{cd}±0.05	0.45^{hi}±0.03	0.63^{fg}±0.10	0.69^{ef}±0.08			
	MAP-2	0.39^{i}±0.00	0.40^{i}±0.00	0.49^{ghi}±0.02	0.56^{gh}±0.05	0.72^{ef}±0.01	0.87^{cd}±0.02			
Tenderness	Control	24.63^{a}±2.72	14.84^{cde}±1.24	12.60^{de}±0.68	14.14^{cde}±1.48	13.66^{de}±0.29	13.39^{de}±0.31	<0.0001	0.0136	0.1408
	VP	16.57^{bcd}±2.26	14.14^{cde}±0.47	11.34^{e}±0.52	11.54^{e}±0.59	13.69^{de}±0.29	13.45 ^{de}±0.29			
	MAP-1	19.02^{b}±2.69	12.91^{de}±1.17	12.48^{de}±0.62	11.76^{e}±0.48	14.04^{cde}±0.62	14.15^{cde}±0.49			
	MAP-2	17.67^{bc}±2.35	13.77^{cde}±0.93	12.56^{de}±0.40	11.58^{e}±0.70	13.53^{de}±0.31	13.23^{de}±0.31			

Control, aerobic packaging; VP, vacuum packaging; MAP-1, modified atmosphere packaging 1 (0% O_2, 40% CO_2, 60% N_2); MAP-2, modified atmosphere packaging 2 (20% O_2, 40% CO_2, 40% N_2).
$^{a–i}$ Superscripts indicate a statistical significant difference between days and treatment ($p<0.05$).
TBARS, thiobarbituric acid reactive substances.

lower values ($p<0.05$) (0.51 mg MDA/kg meat). VP samples on days 4, 6, and 8 showed tendencies similar to those results concluded by Cayuela et al. (2004), Lorenzo and Gómez (2012). Abdullah et al. (2017) described that even vacuum packing might not prevent the initiation of lipid oxidation, which indicates that the formation of rancid off-flavor is more likely related to the storage span than the packaging atmosphere.

Effect of packaging technique on the tenderness of poultry breast fillets

According to Kozačinski et al. (2012) and Koohmaraie et al. (2002), meat tenderness is remarkably influenced by the post mortem proteolytic degradation of myofibrillar proteins function is to preserve the structural integrity in the muscle fiber. This degradation weakens the muscle fibers alignment and thus contributes to meat tenderisation.

The tenderness is expressed instrumentally as the Warner Bratzler shear force (WBSF). Tenderness (Warner-Bratzler Shear Force/WBSF values (N/cm^2) of sample fillets stored under VP, MAP-1, MAP-2, and aerobic packaging were evaluated at day 0, 2, 4, 6, 8, and 10 of the retail display are shown in Table 6. It is observed that the storage time has significantly influenced the tenderness values of all fillet samples. On day 0, control samples showed significantly higher shear force values. The control showed relatively higher WBSF values among the treatment groups than VP, MAP-1, and MAP-2. On day 4 and 6, VP and MAP samples had significantly higher tenderness values than control. There was a gradual decrease in shear force values with the extended time. However, MAP-1 on days 8 and 10 showed higher shear force values. The order of tenderness for poultry breast fillets was control>VP, MAP-1, and MAP-2. The findings of this trial illustrated that the control treatment group was characterised by significantly ($p<0.05$) higher WBSF values comparative to VP and MAP at day 0 (Table 6). Chen and Xiong (2008) reported similar results on days 6 and 14 when analysing the WBSF in the red claw crayfish (*Cherax quadricarinatus*) meat under the influence of the packaging environment. A non-significant difference among treatment groups was noticed in the shear force value.

Effect of packaging technique on sensory attributes of poultry breast fillets

Changes in color appearance, tenderness, flavor, juiciness, and overall acceptability of cooked poultry breast fillets stored

under VP, MAP-1, MAP-2, and control group were evaluated at day 0, 2, 4, 6, 8, and 10 of retail display. The storage conditions and time exhibited a noticeable influence on the sensory properties of samples. As storage time increased, the sensory quality degraded, color, flavor, and juiciness appeared to decline under each packaging method. At the same time, there was an increase in the tenderness scores in all the treatment groups compared to the control. Treatment groups, MAP-1and MAP-2, showed similar results for all the quality attributes. Flavor and juiciness scores deteriorated promptly than other indicators among all the treatment groups. The control group samples became unacceptable on day 8 and thus were excluded from the sensory analysis conducted on day 10. MAP-1 and MAP-2 samples had similar scores for all the sensory attributes except the juiciness. VP samples had significantly higher scores for juiciness. On day 0, control samples showed significantly higher scores for the color appearance of cooked poultry breast fillets as compared to treatment groups. On day 2 and day 6, MAP-1 showed significantly higher scores for color. As the storage period ended, MAP-1 and MAP-2 samples showed significantly higher scores for color than VP and control. A decrease in flavor score was observed in all groups, but on day 8, control samples became unacceptable. Along with the storage duration, a significant increase in tenderness scores was noted. On day 0, MAP-2 samples showed significantly higher scores for tenderness. On day 2, 4, 6, and 8, all treatment groups showed significantly higher tenderness scores than control. On day 10, VP and MAP-1 showed higher scores as compared to MAP-2. On day 0, VP samples showed significantly higher scores for juiciness as compared to MAP and control. However, there is a decrease in juiciness scores along the storage time. At the end of the storage period, VP and MAP-1 showed significantly higher results for juiciness. Throughout the storage period, VP and MAP samples illustrated significantly higher scores (compared to control) for all attributes, and overall acceptance did not reach the limit (score 4), whereas control samples did reach the limit on day 8. On day 0 of storage, the samples stored under MAP-2 indicated significantly higher overall acceptability scores than VP, MAP-1, and control. There was a moderate decline in overall acceptability scores along with the storage duration. On days 6 and 8 of storage, both MAP samples had considerably higher overall acceptability scores than the vacuum-packed and control samples. However, MAP-1 had shown higher overall acceptability scores than MAP-2 and VP when the storage duration was completed. The order of overall acceptability for poultry breast fillets was MAP-1 & MAP-2>VP>Control.

Sensory properties including color, flavor, tenderness, juiciness and overall acceptability of cooked samples are given in Table 7. The results have shown a significant ($p<0.05$) declining pattern among all the sensory scores at the end of the storage time. It is observed that the extended storage time resulted in the compromised sensory quality of meat samples; color, flavor, juiciness, and overall acceptability illustrated a similar decreasing trend in each of the packaging regimes. Both MAP-1 and MAP-2 displayed a matching effect on the sensory properties of poultry breast meat samples. Throughout storage, MAP samples indicated significant ($p<0.05$) scores for all attributes, whereas the overall acceptability figures never reached the maximal limit (score 5). Flavor and juiciness scores declined rapidly among other variables for all three treatment groups. Evaluated by the taste and overall acceptability, the control samples attained the sensory acceptability limit on day 6. Samples stored as control group become unacceptable at day 8 and thus excluded from sensory analysis at day 10. Balamatsia et al. (2007) reported that during 15 days of storage, the VP, in contrast to the low-O_2 MAP sample, had the least acceptable sensory results at the end of storage.

Contrary to this trial, Rajkumar et al. (2007) found better odor results in VP than in high-O_2 MAP stored turkey meat. As evaluated by sensory scores documented in Table 7, the sensory scores for poultry breast meat are equally affected by the storage time and environment and other quality attributes. Based on sensory scores, it was observed that VP exhibited approximately a similar effect as that of MAP on the shelf-life extension of chicken fillets, provided that the storage time and

Table 7. Effect of aerobic, vacuum and different modified atmosphere packagings on sensory properties of poultry breast fillets

Packaging methods		Storage time (D)						p-value		
		0	2	4	6	8	10	d	trt	d×trt
Color	Control	7.00^{a}±0.13	6.19^{fg}±0.17	5.58^{h}±0.16	6.03^{g}±0.12	5.58^{h}±0.16	0	<0.0001	<0.0001	<0.0001
	VP	6.78^{abcde}±0.13	6.06^{fg}±0.16	6.50^{bcdefg}±0.11	4.81^{i}±0.24	4.72^{i}±0.19	6.08^{fg}±0.12			
	MAP-1	6.86^{abc}±0.14	6.83^{abcd}±0.13	6.31^{efg}±0.19	6.56^{abcdef}±0.15	6.06^{fg}±0.13	6.53^{abcdef}±0.15			
	MAP-2	6.89^{ab}±0.13	6.36^{defg}±0.11	6.39^{cdefg}±0.14	6.39^{cdefg}±0.15	6.11^{fg}±0.16	6.56^{abcdef}±0.16			
Flavor	Control	6.94^{ab}±0.17	6.36^{cde}±0.19	5.53^{g}±0.22	4.75^{h}±0.21	3.00^{i}±0.12	0	<0.0001	<0.0001	<0.0001
	VP	6.86^{abc}±0.16	6.47^{abcde}±0.22	6.67^{abcd}±0.22	5.81^{fg}±0.24	6.75^{abc}±0.16	6.08^{ef}±0.16			
	MAP-1	6.42^{bcde}±0.20	6.06^{ef}±0.22	6.14^{def}±0.23	6.17^{def}±0.17	6.92^{abc}±0.15	5.50^{g}±0.17			
	MAP-2	7.03^{a}±0.14	6.86^{abc}±0.11	6.47^{abcde}±0.12	6.58^{abcde}±0.16	6.47^{abcde}±0.13	5.78^{fg}±0.14			
Tenderness	Control	5.83^{c}±0.15	6.19^{abc}±0.23	6.39^{abc}±0.26	6.39^{abc}±0.27	2.06^{d}±0.17	0	<0.0001	<0.0001	<0.0001
	VP	6.44^{abc}±0.18	6.50^{ab}±0.24	6.64^{ab}±0.20	7.03^{a}±0.19	6.86^{ab}±0.19	7.06^{a}±0.17			
	MAP-1	6.39^{abc}±0.18	6.69^{ab}±0.27	6.64^{ab}±0.20	7.03^{a}±0.19	6.86^{ab}±0.19	6.81^{ab}±0.20			
	MAP-2	6.89^{a}±0.19	6.47^{abc}±0.24	6.64^{ab}±0.20	7.03^{a}±0.19	6.67^{ab}±0.18	6.42^{abc}±0.19			
Juiciness	Control	6.28^{bcd}±0.25	5.75^{def}±0.33	5.28^{efg}±0.30	4.78^{g}±0.26	1.19^{h}±0.07	0	<0.0001	<0.0001	<0.0001
	VP	7.28^{a}±0.15	6.50^{bc}±0.24	6.08^{cde}±0.26	5.53^{defg}±0.28	5.39^{efg}±0.27	5.33^{efg}±0.21			
	MAP-1	6.83^{ab}±0.19	6.06^{cde}±0.25	5.56^{defg}±0.30	5.39^{efg}±0.26	5.33^{efg}±0.26	5.33^{efg}±0.26			
	MAP-2	6.89^{ab}±0.19	6.03^{cde}±0.25	5.61^{def}±0.31	5.67^{def}±0.28	5.25^{efg}±0.25	5.11^{fg}±0.23			
Overall acceptability	Control	7.22^{ab}±0.13	6.81^{bcd}±0.14	6.28^{def}±0.18	4.39^{i}±0.29	1.19^{j}±0.07	0	<0.0001	<0.0001	<0.0001
	VP	7.17^{ab}±0.16	6.75^{bcde}±0.29	6.00^{fg}±0.27	5.31^{h}±0.26	5.31^{h}±0.26	5.31^{h}±0.26			
	MAP-1	7.17^{ab}±0.12	6.94^{bc}±0.13	6.50^{cdef}±0.16	6.28^{def}±0.25	6.22^{def}±0.25	6.14^{efg}±0.25			
	MAP-2	7.58^{a}±0.10	7.22^{ab}±0.13	6.94^{bc}±0.17	6.50^{cdef}±0.28	6.47^{cdef}±0.17	5.89^{fg}±0.19			

Control, aerobic packaging; VP, vacuum packaging; MAP-1, modified atmosphere packaging 1 (0% O_2, 40% CO_2, 60% N_2); MAP-2, modified atmosphere packaging 2 (20% O_2, 40% CO_2, 40% N_2).

$^{a–j}$ Superscripts indicate a statistical significant difference between days and treatment ($p<0.05$).

environment should not be fluctuating. Based on the readings obtained from sensory evaluation, the storage life of aerobically packaged fresh poultry meat ranged around 5 days, whereas the combination of both VP and MAP lengthened the product shelf life by 4–5 days. This extension is ranged approximately a 100% extension in the shelf-life of the samples.

Conclusion

It could be concluded that the type of packaging comparatively may affect significantly on different studied microbiologically and physicochemical parameters like TVC, coliform count, *Pseudomonas*, *Salmonella* count, TVB-N, pH, cooking loss, color, lipid oxidation, tenderness, and sensory analysis. Vacuum and modified atmosphere packaging extend poultry meat's shelf life by oxygen-permeable packaging by at least 5 days at display storage comparable to aerobic packaging. The same pattern was observed in the color scores, a significant increase in cooking loss, and poor results in the sensory analysis in the case of aerobic packaging comparison to VP and MP.

Conflicts of Interest

The authors declare no potential conflicts of interest.

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Conceptualization: Nauman K, Jaspal MH. Data curation: Nauman K, Jaspal MH, Asghar B, Manzoor A. Formal analysis: Nauman K, Jaspal MH, Ali S. Methodology: Asghar B, Akhtar KH, Ali U, Manzoor A. Software: Akhtar KH, Ali U, Nasir J. Validation: Nauman K, Jaspal MH, Ali S, Nasir J. Investigation: Nauman K, Jaspal MH, Asghar B, Manzoor A. Writing - original draft: Nauman K, Asghar B, Akhtar KH, Ali U. Writing-review & editing: Nauman K, Jaspal MH, Asghar B, Manzoor A, Akhtar KH, Ali U, Ali S, Nasir J, Sohaib M, Badar IH.

Ethics Approval

The study was conducted according to the guidelines followed in accordance with the Helsinki Declaration of 1975 on human experimentation and approved by the Institutional Ethical Review Committee, Office of Research, Innovation and Commercialization (ORIC), University of Veterinary and Animal Sciences (UVAS), Lahore, Pakistan (vide letter no. DR/74, 14 January 2020).

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