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The effect of lactic acid combined with modified atmosphere packaging on the quality of fresh goat meat during storage

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Summary

To extend the shelf life of fresh goat meat, the modified atmosphere packaging (MAP) combined with lactic acid treatment was extensively studied. Quality parameters of goat meat during storage (4 °C) have been evaluated, including pH, drip loss, shear force, colour, sensory properties, fat and protein, lipid oxidation and microbial criteria. These indicators were determined after slaughter and at 3, 6, 9, 12, 15, 18, and 21 days of storage. From the findings, goat meat quality can be preserved for up to 21 days by treating it with 2% lactic acid and using the MAP setting (40% O_2 + 30% CO_2 + 30% N_2), extending the storage time up to 21 days.

Keywords

goat meat; preservation; food packaging; physicochemical properties; sensory evaluation; shelf life

Fresh meat has a high perishability because it contains a large volume of free water and all the nutrients needed for bacteria to spoil. Hence, preserving meat after slaughter demonstrates a significant issue [1]. The main reasons for meat deterioration (reduction in colour and structure) during storage may include enzymatic autolysis, lipid and protein oxidation, and microbial development [2]. Meat quality has been impacted by the activity of pathogenic microorganisms, which is a possible risk to consumers' health [3]. Meat can be effectively preserved by using the right preservation packaging conditions to prevent deterioration from both internal and external sources [4]. Various approaches were proposed to improve the quality and extend the shelf life. The modified atmosphere packaging (MAP) containing a mixture of typical gases such as N_2, O_2, and CO_2 is recognised as one of the best methods [4].

Organic acids are frequently employed as food preservatives since they are known to be safe. Their effects depend on the kind of acid, dosage, temperature, contact time, and the type of microorganism [5]. Numerous results have mentioned the useful role of lactic acid in decreasing the number of bacteria in poultry meat [5]. The treatment of lactic acid at different concentrations reduces bacteria from 1 to 3 log units on the meat surface [6]. Lactic acid solutions at concentrations from 2 % to 5 % have been approved by the European Union since 2013 [7]. The European Food Safety Authority (EFSA) recently examined the safety and efficacy of lactic acid in reducing bacterial contamination on pork and concluded that the substance used complies with food additive specifications and effectively reduces surface microbial contamination. Lactic acid treatment for pork decontamination poses no health concerns [8]. Significantly, the application of lactic acid is very appropriate for reducing *Salmonella*, *Campylobacter*, and *Listeria* [9–13].

Several investigations have been carried out to evaluate the influences of the MAP methods on the quality of red meat and poultry products [8, 13]. When compared to aerobically packaged products, the MAP with a high oxygen concentra-

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tion gave the desired red colour, accelerated the growth of aerobic spoilage microorganisms, and also oxidised lipids and pigments [8, 13]. Low oxygen MAP atmospheres could prevent microbiological growth but cause the meat to turn purple [13]. High CO_2 concentration in the modified atmosphere packaging prevented microbiological development but was mainly responsible for oxidation-induced meat browning [13]. Goat meat is consumed as a high-quality, easily digestible source of protein with a low fat level. To date, there has been no study evaluating the combined effect of lactic acid treatment with MAP for preserving fresh goat meat. The current study aims to determine the effects of different lactic acid concentrations combined with various MAP conditions on the samples, preserved at 4 °C. From the preservation process, the meat quality parameters pH, drip loss, shear force, colour, sensory properties, fat and protein content, antioxidative thiobarbituric acid reactive substances (TBARS), and microbial activity were also evaluated.

MATERIALS AND METHODS

Material, packing method, and storage

The experimental protocol has been approved by the Institute of Biotechnology Scientific Council (No. 496/QD-VHL, 3 March 2018, Vietnam Academy of Science and Technology, Hanoi, Vietnam). The fresh goat meat, which was obtained from the leg (hind limb) of goats aged 6–8 months, has been provided by Duc Hoa Livestock Slaughterhouse in Ninh Thuan, Vietnam. Meats were sliced into blocks (each, 300 g), and then packaged using a MAP machine (TECNO, Shenzhen, Guangdong, China). The packaging employed a PE/EVOH/PA multilayer film under a modified atmosphere with a permeability of O_2 2.46 cm^3·m^{-2} per day, a tensile strength of 33.5 MPa, elongation at break of 518.3 %, and a thickness of 50 μm. For each of the seven formulation groups, three independent meat samples (n = 3) were collected and analysed at each sampling time.

Food-grade lactic acid (≥ 98% purity; Sigma-Aldrich, St. Louis, Missouri, USA) was used for meat treatment. Lactic acid solutions at concentrations of 1 % and 2 % were freshly prepared by dissolving 1 g or 2 g of lactic acid, respectively, in 100 ml of sterile distilled water and mixed thoroughly until complete dissolution. The solutions were prepared immediately before use and maintained at room temperature (25 ± 2 °C).

Seven formulas were used in the experiments, where setting for MAP1 were 80% O_2 + 20% CO_2 and for MAP2 40% O_2 + 30% CO_2 + 30% N_2:

- formula 1 – vacuum packaging (control);
- formula 2 – packaging with MAP1;
- formula 3 – packaging with MAP1 combined with 1% lactic acid (pH 2.8–3.0);
- formula 4 – packaging with MAP1 combined with 2% lactic acid (pH 2.4–2.6);
- formula 5 – packaging with MAP2;
- formula 6 – packaging with MAP2 combined with 1% lactic acid (pH 2.8–3.0);
- formula 7 – packaging with MAP2 combined with 1% lactic acid (pH 2.4–2.6).

Each experimental formulation was established in triplicate. The samples were then placed in a refrigeration chamber at 4 °C and stored for 21 days, with sample collection occurring every 3 days.

The pH analysis

The pH was determined using a digital pH meter QHI 99163 (Hanna Instruments, Woonsocket, Rhode Island, USA) equipped with a penetrating electrode by the international standard ISO 2917:1999 [14]. In brief, 10 g of minced meat was homogenised with 100 ml of redistilled water for 60 s using a laboratory homogeniser, and the pH of the homogenate was subsequently recorded.

Drip loss

The exudative level of meat was assessed using filter papers in the capillary suction method [15]. The greater the capillary force of the filter paper, the more water molecules are drawn from the meat sample to the exterior. As can be seen, the structure of the meat sample is compromised, and the release of unretained free water becomes progressively easier. Based on this, the drip loss (DL) percentage is calculated as follows:

$$DL = 100 \times \frac{(P_2 - P_0)}{(P_1 - P_0)} \quad (1)$$

where P_0 represents the initial weight of the filter paper, P_1 denotes the combined weight of the filter paper and meat sample, and P_2 signifies the weight of the filter paper after enclosing the meat sample at 10 °C for 24 h.

Shear force

The samples were cooked in a water bath at 80 °C until the internal core temperature reached 70 °C and cut into cylindrical forms with a diameter of 1.27 cm. The shear force (SF) value was then determined using a Texturometer TAXT2i (Stable Micro Systems, Godalming, United Kingdom). The SF measurements were conducted perpendicular to the orientation of muscle fibres, employing a test speed of 1.5 $mm \cdot s^{-1}$ and a distance of 30 mm from the base.

Instrumental colour analysis

Colour parameters L^*, a^*, and b^* were measured on the surface of the meat using the CHN CS-410 colourimeter (Hangzhou CHNSpec Technology, Hangzhou, China) with the optical system D/8 specular component included (SCI) and specular component excluded (SCE). The L^* value represents the luminance or lightness component (ranging from 0 to 100), along with two chromatic components: a^* (green to red) and b^* (blue to yellow), which range from –120 to 120.

Sensory analysis

Sensory assessment was conducted by nine evaluators, based on two primary criteria: smell and taste. The samples were cooked on an electric stove until their core temperature reached 70 °C. The obtained meat was then cut into pieces (2 cm × 2 cm × 2 cm) and presented to the panel members for scoring. Experiments were performed individually by the panel members under monitored conditions of light, temperature, and humidity. To cleanse their palates and eliminate any lingering flavours or scents from the prior sample, the panel members engaged in palate cleansing between the assessments of different samples. Before the sensory evaluation, a 2-hour orientation session was held to acquaint the panel with the chosen intensity scale for odours, including off-scale attributes. A 0–9 point intensity scale was used to estimate smell and taste, including 9 (excellent), 8 (very good), 7 (acceptable), 6 (poor), and less than 6 (first occurrence of strange smell or taste); with an intensity level of 6 being the lowest acceptable limit. A product was considered unacceptable with the first occurrence of off-odour or off-taste [16]. The panel assessors did not evaluate goat meat samples exceeding the aerobic plate counts (*APC*) limit of 7.0 log $CFU \cdot cm^{-2}$. A total of 10 evaluation sessions were conducted, with each member assessing six samples in each session.

Fat and protein content

The total fat content was determined using the acidic hydrolysis method [17]. In brief, the sample (1.5 g) was treated with 5 ml of dilute hydrochloric acid and digested for approximately 45 min in a water bath. The resulting mixture was then extracted using a solvent mixture consisting of methanol (2.5 ml), diethyl ether (7.5 ml), and petroleum ether (7.5 ml). Subsequently, the mixture was centrifuged, the ether-fat layer was separated and evaporated, and the fat content was quantified.

The lyophilised sample was utilised to determine the total protein content. Protein content was assessed by measuring nitrogen content, which was determined using the Gerhardt semi-micro Kjeldahl method [18], and the LECO CHNS 932 apparatus (LECO, St Joseph, Michigan, USA), which used the combustion method.

Lipid oxidative assay

The TBARS index, expressed as milligrams of malondialdehyde (MDA) per kilogram, was determined following the previous method with minor modifications [19]. About 5.0 g of the minced meat sample was homogenised with 97.5 ml of water. Subsequently, 2.5 ml of 4 $mol \cdot l^{-1}$ HCl and 3–4 drops of anti-foaming silicone were added. The resulting mixture was distilled to obtain a 50 ml distillate. Next, 5 ml of the distillate reacted with 5 ml of 0.02 $mol \cdot l^{-1}$ thiobarbituric acid (TBA) in a water bath at 98 °C for 35 min. After being cooled, the absorbance of the mixture was measured using the UV-Vis spectrometer 912 A0959 (Thermo Fisher Scientific, Waltham, Massachusetts, USA) at a wavelength of 532 nm.

Microbial assay

To evaluate the microbial content, samples were analysed at intervals of 0, 3, 6, 9, 12, 15, 18, and 21 days during refrigerated storage. A meat sample (10 g) was aseptically weighed and placed into a stomacher bag containing 90 ml of 0.1% NaCl solution, then stirred for 1 min at 25 °C. After homogenising the diluted solutions at various concentrations in the 0.1% saline solution, 1 ml of the sample was taken each time and inoculated onto a Petri dish. Microbial counting was performed on dishes with microbial counts ranging from 30 to 300 after incubation for a specified period. Aseptic Petri dishes were inoculated with uniformly diluted samples, followed by the addition of 15 to 20 ml of plate count agar (Merck, Darmstadt, Germany) to determine total viable count (*TVC*). The incubation was performed for 48 h at 37 °C [5]. Lactic acid bacteria (LAB) were determined on the Man-Rogosa-Sharpe agar medium (Merck) after incubation for 72 h at 37 °C [20]. For *Enterobacteriaceae* counts, subsequent dilutions were performed on meat samples and inoculated onto Petri dish surfaces and the violet red bile glucose agar medium (Merck). The Petri dishes containing samples and agar were then incubated for 24 h at 37 °C [21]. *Pseudomonas* bacteria counts were conducted by further diluting the meat samples. Meat samples were inoculated onto the surface of Petri dishes, and 15–20 ml of the selective medium base for *Pseudomonas* CFC (Merck) was applied. The Petri dishes containing samples were then solidified and incubated at 30 °C for 72 h.

Statistical analysis

Data were analysed using one-way and two-way analysis of variance (ANOVA) to evaluate the effects of lactic acid concentration (1% and 2%), packaging method (vacuum, MAP1, and MAP2), storage time, and their interactions. Differences were considered statistically significant at $p < 0.05$.

RESULTS AND DISCUSSION

pH effect

The pH results during storage are presented in Tab. 1. They demonstrate the effectiveness of combining lactic acid and MAP on the quality of goat meat. In the lactic acid-treated samples, pH values decreased after 3 days of storage compared to non-treated samples (formulas 1, 2, and 5) but tended to increase in the subsequent days. During the storage period, samples treated with higher concentrations of lactic acid had lower pH values. The results also indicated that the pH values of MAP-packaged samples were higher compared to other samples after 21 days of storage. This increase in pH may be attributed to the decomposition of protein molecules, leading to the formation of small molecules and ammonia. These compounds have the potential to promote the growth of pathogenic microorganisms [22].

Drip loss effect

The conditions of the MAP packaging, acid concentration, and storage time showed a significant effect. In Fig. 1, the *DL* values of all tested samples gradually increased during storage time. The *DL* rate in the control formula (formula 1) was higher than in the formulations treated with acid combined with MAP packaging during cold storage at 4 °C for 21 days, due to the formation of cross-links from myosin oxidative reactions in the presence of oxygen. With longer storage time, the increased water loss is due to the decreasing water-holding capacity of the goat meat proteins. The results also showed that formulas 5–7 reduced the percentages of water loss in the goat meat samples compared to those of formulas 1–4, which can be explained by the role of the nitrogenous agent. These findings are consistent with several previously published studies.

Shear force effect

After 21 days of storage, there was no discernible change in the *SF* values across the various MAP packaging techniques or acid treatments. However, the length of storage had a visible effect on these values (Tab. 2). When comparing the formulas treated with lactic acid and the MAP conditions, the *SF* values of the control formula were the lowest. During the storage period, fresh goat meat treated with 2% lactic acid in combination with the MAP2 (40% O_2 + 30% CO_2 + 30% N_2) had the highest *SF* values. One possible explanation for the substantial decline in the *SF* values during storage is the oxidation of proteins in an aerobic environment [23]. The higher *DL* values of the meat may also be connected to the

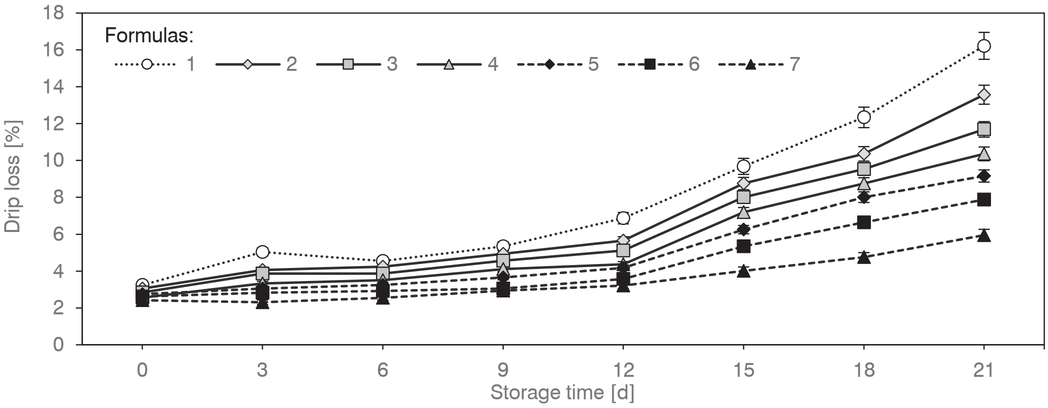

Fig. 1. Drip loss of goat meat packaged at various conditions during storage.

Formula 1 – vacuum packaging (control), formula 2 – MAP1 (80% O_2 + 20% CO_2), formula 3 – MAP1 combined with 1% lactic acid, formula 4 – MAP1 combined with 2% lactic acid, formula 5 – MAP2 (40% O_2 + 30% CO_2 + 30% N_2), formula 6 – MAP2 combined with 1% lactic acid, formula 7 – MAP2 combined with 2% lactic acid.

Tab. 1. Effect of storage time on the pH of goat meat packaged at various conditions.

Formulas			Storage time [d]							
	Packaging	Lactic acid [%]	0	3	6	9	12	15	18	21
pH										
1	Vacuum	0	5.62 ± 0.15	5.92 ± 0.14	6.65 ± 0.12	6.25 ± 0.13	6.39 ± 0.12	6.50 ± 0.17	6.69 ± 0.13	6.74 ± 0.18
2	MAP1	0	5.70 ± 0.12	5.87 ± 0.15	6.02 ± 0.13	6.20 ± 0.15	6.25 ± 0.14	6.35 ± 0.14	6.52 ± 0.12	6.62 ± 0.17
3		1	5.71 ± 0.16	5.73 ± 0.12	5.92 ± 0.16	6.04 ± 0.12	6.12 ± 0.16	6.28 ± 0.16	6.35 ± 0.14	6.58 ± 0.13
4		2	5.70 ± 0.15	5.72 ± 0.15	5.80 ± 0.16	5.92 ± 0.15	6.17 ± 0.15	6.25 ± 0.12	6.31 ± 0.16	6.51 ± 0.14
5	MAP2	0	5.71 ± 0.13	5.81 ± 0.16	6.00 ± 0.16	6.12 ± 0.16	6.20 ± 0.16	6.30 ± 0.17	6.48 ± 0.15	6.60 ± 0.15
6		1	5.72 ± 0.17	5.75 ± 0.15	5.86 ± 0.14	5.93 ± 0.12	6.06 ± 0.17	6.14 ± 0.13	6.21 ± 0.14	6.35 ± 0.16
7		2	5.68 ± 0.12	5.70 ± 0.17	5.75 ± 0.13	5.81 ± 0.17	5.86 ± 0.13	5.95 ± 0.14	6.07 ± 0.18	6.21 ± 0.14

MAP – modified atmosphere packaging. MAP1 – 80% O_2 + 20% CO_2, MAP2 – 40% O_2 + 30% CO_2 + 30% N_2.

Tab. 2. Effect of storage time on the shear force of goat meat packaged at various conditions.

Formulas			Storage time [d]							
	Packaging	Lactic acid [%]	0	3	6	9	12	15	18	21
Shear force [N]										
1	Vacuum	0	4.16 ± 0.11	3.84 ± 0.13	3.54 ± 0.11	3.28 ± 0.12	3.05 ± 0.12	2.88 ± 0.13	2.69 ± 0.12	2.30 ± 0.12
2	MAP1	0	4.15 ± 0.13	3.87 ± 0.13	3.54 ± 0.12	3.32 ± 0.11	3.11 ± 0.11	2.95 ± 0.11	2.71 ± 0.11	2.35 ± 0.11
3		1	4.15 ± 0.14	3.98 ± 0.14	3.78 ± 0.12	3.54 ± 0.13	3.32 ± 0.11	3.17 ± 0.12	2.82 ± 0.14	2.42 ± 0.13
4		2	4.17 ± 0.15	4.05 ± 0.13	3.92 ± 0.14	3.78 ± 0.13	3.55 ± 0.13	3.34 ± 0.14	2.95 ± 0.13	2.64 ± 0.14
5	MAP2	0	4.14 ± 0.12	3.95 ± 0.14	3.71 ± 0.11	3.48 ± 0.15	3.25 ± 0.11	3.09 ± 0.12	2.78 ± 0.12	2.39 ± 0.14
6		1	4.15 ± 0.14	4.01 ± 0.12	3.86 ± 0.15	3.61 ± 0.11	3.46 ± 0.12	3.29 ± 0.14	2.91 ± 0.11	2.55 ± 0.12
7		2	4.15 ± 0.13	4.09 ± 0.16	4.02 ± 0.14	3.95 ± 0.16	3.76 ± 0.13	3.45 ± 0.11	3.09 ± 0.15	2.73 ± 0.14

MAP – modified atmosphere packaging. MAP1 – 80% O_2 + 20% CO_2, MAP2 – 40% O_2 + 30% CO_2 + 30% N_2.

Tab. 3. Effect of storage time on the colour of goat meat packaged at various conditions.

	Formulas		Storage time [d]							
	Packaging	Lactic acid [%]	0	3	6	9	12	15	18	21
						L*				
1	Vacuum	0	55.30 ± 0.22	56.52 ± 0.25	57.20 ± 0.26	57.85 ± 0.21	58.20 ± 0.24	58.95 ± 0.31	59.21 ± 0.24	59.31 ± 0.21
2	MAP1	0	55.29 ± 0.28	56.59 ± 0.21	57.27 ± 0.21	57.92 ± 0.26	58.27 ± 0.25	59.02 ± 0.28	59.28 ± 0.29	59.39 ± 0.24
3		1	55.26 ± 0.24	58.29 ± 0.17	59.16 ± 0.23	60.02 ± 0.27	59.92 ± 0.27	60.59 ± 0.23	60.97 ± 0.27	60.28 ± 0.28
4		2	55.25 ± 0.18	59.45 ± 0.22	62.59 ± 0.26	62.96 ± 0.20	62.16 ± 0.30	62.59 ± 0.26	62.97 ± 0.23	63.18 ± 0.26
5	MAP2	0	55.38 ± 0.35	56.68 ± 0.24	57.35 ± 0.21	58.01 ± 0.22	58.36 ± 0.25	59.13 ± 0.25	59.37 ± 0.25	59.48 ± 0.25
6		1	55.26 ± 0.24	57.48 ± 0.23	59.95 ± 0.25	59.85 ± 0.28	60.91 ± 0.24	61.26 ± 0.25	61.57 ± 0.26	61.59 ± 0.24
7		2	55.25 ± 0.28	59.12 ± 0.21	62.58 ± 0.23	62.95 ± 0.25	63.15 ± 0.28	63.58 ± 0.28	63.98 ± 0.22	64.18 ± 0.24
						a*				
1	Vacuum	0	10.62 ± 0.15	10.45 ± 0 .15	10.21 ± 0.12	10.05 ± 0.12	9.98 ± 0.15	9.92 ± 0.14	9.85 ± 0.15	9.51 ± 0.13
2	MAP1	0	10.62 ± 0.16	10.50 ± 1.14	10.12 ± 0.11	10.65 ± 0.13	10.98 ± 0.13	11.23 ± 0.12	11.65 ± 0.12	12.90 ± 0.15
3		1	10.62 ± 0.19	10.79 ± 0.12	10.65 ± 0.13	11.31 ± 0.15	11.45 ± 0.15	12.18 ± 0.15	12.41 ± 0.11	13.02 ± 0.14
4		2	10.62 ± 0.18	10.81 ± 0.13	10.72 ± 0.15	12.31 ± 0.14	12.65 ± 0.17	12.98 ± 0.16	13.21 ± 0.13	13.85 ± 0.15
5	MAP2	0	10.62 ± 0.17	10.53 ± 0.18	10.15 ± 0.16	10.68 ± 0.16	11.02 ± 0.13	11.25 ± 0.14	11.68 ± 0.17	12.95 ± 0.18
6		1	10.62 ± 0.19	10.80 ± 0.17	10.69 ± 0.17	11.35 ± 0.17	11.49 ± 0.13	12.22 ± 0.13	12.45 ± 0.14	13.07 ± 0.17
7		2	10.65 ± 0.16	10.85 ± 0.16	11.70 ± 0.12	12.36 ± 0.15	12.71 ± 0.16	13.02 ± 0.17	13.26 ± 0.12	13.87 ± 0.14
						b*				
1	Vacuum	0	10.75 ± 0.18	12.95 ± 0.13	14.34 ± 0.13	14.71 ± 0.13	15.35 ± 0.12	15.62 ± 0.12	15.91 ± 0.13	16.26 ± 0.13
2	MAP1	0	10.96 ± 0.14	12.21 ± 0.14	12.02 ± 0.16	13.11 ± 0.15	14.44 ± 0.16	14.95 ± 0.13	15.25 ± 0.16	15.57 ± 0.16
3		1	10.93 ± 0.18	11.54 ± 0.16	13.15 ± 0.14	13.82 ± 0.14	12.91 ± 0.13	13.24 ± 0.15	13.56 ± 0.11	13.82 ± 0.13
4		2	10.12 ± 0.15	12.66 ± 0.13	11.84 ± 0.13	12.61 ± 0.13	13.72 ± 0.15	13.95 ± 0.14	14.24 ± 0.12	14.58 ± 0.12
5	MAP2	0	10.84 ± 0.16	13.37 ± 0.15	14.96 ± 0.12	13.97 ± 0.15	16.75 ± 0.17	16.94 ± 0.17	17.18 ± 0.17	17.37 ± 0.15
6		1	10.27 ± 0.14	11.38 ± 0.14	13.24 ± 0.17	14.15 ± 0.13	15.57 ± 0.12	15.76 ± 0.13	15.97 ± 0.12	16.14 ± 0.18
7		2	10.76 ± 0.12	14.64 ± 0.18	14.73 ± 0.13	15.28 ± 0.12	14.64 ± 0.16	15.86 ± 0.14	16.07 ± 0.13	16.26 ± 0.16

MAP – modified atmosphere packaging. MAP1 – 80% O_2 + 20% CO_2, MAP2 – 40% O_2 + 30% CO_2 + 30% N_2.

SF values in preservation formulas. The action of protein-degrading enzymes on the muscle fibres during storage may be responsible for decreases in the *SF* values [23]. Furthermore, it is also related to butchered ages; the meat becomes less tender, probably as a result of increased collagen content and collagen cross-linking [24].

Meat colour

These alternations in colour characteristics are linked to the quality indicators of the meat, as well as the level of consumer preference. In terms of customer acceptance, the colour threshold for fresh goat meat should be higher than 44 for the L^* value [25]. In this study, the L^*, a^*, and b^* colour values of goat meat were found to change during the preservation period (Tab. 3). The longer the preservation time, the duller the colour of the meat. The L^* values of samples treated with lactic acid at concentrations of 1% and 2% and preserved in MAP1 and MAP2 were significantly higher after day 3 compared to other preservation samples, exceeding the threshold of 44 during the preservation process. Additionally, it is generally observed that the L^* value of each formula rose during storage time. The same results were also found in previous reports [26]. For instance, the L^* values of the meat increased over time for samples preserved in MAP packaging conditions (20% CO_2 + 10% O_2 + 70% N_2) or (80% CO_2 + 20% O_2), ranging from 45.32 to 48.92 [26]. The increase in the L^* value is due to increased light scattering, protein degradation, and pH changes in the meat samples [25].

Similar to the trends in the L^* values, the a^* and b^* values of formulas that used lactic acid at concentrations of 1% and 2% and were preserved in MAP1 and MAP2 are higher than those of the remaining formulas. Furthermore, the a^* value of lactic acid samples preserved in the MAP is close to the threshold value of 14.5, which is suggested for consumer acceptance [27]. The brilliant red hue on the meat surface is a result of higher oxygen levels in the MAP packaging. In comparison to vacuum-packaged pork, higher oxygen concentrations in MAP packaging improve the red colour of the meat (higher a^* values). In addition, higher oxygen concentrations in packaging may promote and prolong the synthesis of metmyoglobin, which is the main cause of meat decay. The presence of metmyoglobin on the sample surface during preservation in packaging with decreased oxygen concentration could be the cause of the increased b^* value. Analysing various myoglobin types is crucial to understanding how meat colour deteriorates [28].

Sensory evaluation

Based on the data in Tab. 4, the sensory scores for the smell and taste of the goat meat samples displayed a consistent decline over time across all preservation methods. This trend suggested that the shelf life of fresh goat meat can be prolonged to 21 days by employing lactic acid in conjunction with the MAP. Furthermore, the smell and taste of samples treated with lactic acid consistently maintained satisfactory levels throughout the storage period.

Likewise, Smaoui et al. [29] documented that using lactic acid at a concentration of 1% immediately post-slaughter can effectively prolong the shelf life of poultry meat while preserving its aroma and taste characteristics. Lactic acid exhibited antioxidative properties that aid in sustaining the colour and taste of meat during storage. This acid served as a protective measure against the rancidity caused by oxidation and promoted colour consistency in fresh and processed meat products. Lactic acid acts as a reducing agent to hinder myoglobin oxidation and the formation of browning reactions in meat [29].

Moreover, the sensory assessments aligned closely with the microbiological parameters of various preservation techniques. The fresh goat meat treated with lactic acid (2%) in combination with the MAP2 (40% O_2 + 30% CO_2 + 30% N_2) consistently exhibited superior sensory ratings for smell and taste throughout the storage duration.

Fat and protein content

In general, the contents of fat and protein were found to be reduced, especially in the last period of preservation (Tab. 5). The protein level was drastically reduced, which could be because the meat samples had lessened oxidation. According to previous research findings, there is a connection between lipid oxidation and protein, which would affect the protein concentration throughout storage [30]. It is also recognised that enzymatic or microbiological lipid breakdowns produce free fatty acids when meat samples are stored.

In another aspect, the fat and protein contents in the control (formula 1) and untreated groups (formulas 2 and 5) have the lowest values compared to the groups of lactic acid combined with the MAP packaging. It reflected the significant role of lactic acid, and the fresh goat meat treated with lactic acid (2%) in combination with the MAP2 (40% O_2 + 30% CO_2 + 30% N_2) has the highest protein and fat contents throughout the storage period.

Tab. 4. Effect of storage time on the sensory quality of goat meat packaged at various conditions.

	Formulas		Storage time [d]							
	Packaging	Lactic acid [%]	0	3	6	9	12	15	18	21
Smell										
1	Vacuum	0	8.90 ± 0.09	8.15 ± 0.07	7.86 ± 0.08	5.18 ± 0.09	4.42 ± 0.05	–	–	–
2	MAP1	0	8.92 ± 0.11	8.42 ± 0.08	8.04 ± 0.12	7.98 ± 0.10	7.52 ± 0.09	6.46 ± 0.07	5.65 ± 0.05	4.25 ± 0.05
3		1	8.90 ± 0.08	8.65 ± 0.11	8.34 ± 0.11	8.05 ± 0.12	7.85 ± 0.08	7.46 ± 0.08	7.16 ± 0.06	6.78 ± 0.06
4		2	8.91 ± 0.10	8.79 ± 0.10	8.76 ± 0.10	8.65 ± 0.14	8.54 ± 0.11	8.21 ± 0.08	8.06 ± 0.06	7.42 ± 0.07
5	MAP2	0	8.91 ± 0.09	8.36 ± 0.12	8.01 ± 0.09	7.15 ± 0.13	6.24 ± 0.05	6.05 ± 0.07	5.12 ± 0.05	4.45 ± 0.05
6		1	8.90 ± 0.08	8.54 ± 0.09	8.25 ± 0.07	7.45 ± 0.08	7.98 ± 0.08	8.21 ± 0.07	7.89 ± 0.08	7.65 ± 0.06
7		2	8.92 ± 0.12	8.83 ± 0.11	8.86 ± 0.08	8.72 ± 0.09	8.65 ± 0.07	8.46 ± 0.09	8.35 ± 0.11	8.17 ± 0.09
Taste										
1	Vacuum	0	8.91 ± 0.13	8.16 ± 0.10	7.87 ± 0.12	5.65 ± 0.10	4.56 ± 0.04	–	–	–
2	MAP1	0	8.95 ± 0.08	8.20 ± 0.09	7.72 ± 0.10	7.40 ± 0.11	6.85 ± 0.05	6.18 ± 0.05	5.50 ± 0.04	4.50 ± 0.06
3		1	8.95 ± 0.07	8.87 ± 0.08	8.82 ± 0.07	8.72 ± 0.11	8.68 ± 0.09	8.30 ± 0.08	7.55 ± 0.07	7.02 ± 0.06
4		2	8.96 ± 0.12	8.90 ± 0.12	8.86 ± 0.09	8.82 ± 0.12	8.82 ± 0.08	8.48 ± 0.09	8.02 ± 0.07	7.92 ± 0.05
5	MAP2	0	8.93 ± 0.11	8.21 ± 0.10	7.75 ± 0.11	7.45 ± 0.10	6.92 ± 0.08	6.24 ± 0.07	5.56 ± 0.04	4.52 ± 0.04
6		1	8.94 ± 0.09	8.89 ± 0.13	8.86 ± 0.13	8.76 ± 0.11	8.71 ± 0.08	8.32 ± 0.08	8.14 ± 0.07	7.28 ± 0.06
7		2	8.95 ± 0.09	8.91 ± 0.12	8.89 ± 0.12	8.87 ± 0.13	8.85 ± 0.07	8.51 ± 0.09	8.33 ± 0.09	8.21 ± 0.09

MAP – modified atmosphere packaging. MAP1 – 80% O_2 + 20% CO_2, MAP2 – 40% O_2 + 30% CO_2 + 30% N_2.

Tab. 5. Protein and fat content of goat meat samples packaged at various conditions during storage period.

	Formulas		Storage time [d]							
	Packaging	Lactic acid [%]	0	3	6	9	12	15	18	21
						Fat [g.kg-1]				
1	Vacuum	0	25.2 ± 0.2	25.0 ± 0.3	23.5 ± 0.3	22.0 ± 0.4	19.0 ± 0.4	15.1 ± 0.3	10.1 ± 0.5	08.5 ± 0.4
2	MAP1	0	25.3 ± 0.3	24.9 ± 0.4	24.7 ± 0.3	22.8 ± 0.3	21.5 ± 0.4	19.0 ± 0.3	15.3 ± 0.4	10.2 ± 0.4
3		1	25.3 ± 0.4	25.2 ± 0.5	24.8 ± 0.5	23.2 ± 0.5	22.1 ± 0.3	19.8 ± 0.4	15.3 ± 0.4	13.1 ± 0.5
4		2	25.6 ± 0.4	24.3 ± 0.3	22.2 ± 0.5	18.8 ± 0.4	14.6 ± 0.5	19.9 ± 0.5	15.4 ± 0.5	13.4 ± 0.4
5	MAP2	0	25.5 ± 0.2	25.0 ± 0.2	23.0 ± 0.4	21.5 ± 0.3	19.2 ± 0.5	15.1 ± 0.4	12.0 ± 0.3	10.5 ± 0.3
6		1	25.3 ± 0.3	24.9 ± 0.5	24.4 ± 0.3	23.0 ± 0.3	21.1 ± 0.4	19.0 ± 0.3	14.7 ± 0.3	13.2 ± 0.4
7		2	25.7 ± 0.3	25.1 ± 0.3	24.3 ± 0.4	23.0 ± 0.4	21.5 ± 0.3	19.3 ± 0.4	14.9 ± 0.4	14.0 ± 0.5
						Protein [g.kg-1]				
1	Vacuum	0	206.5 ± 1.5	188.5 ± 1.4	160.5 ± 1.5	137.3 ± 1.4	101.6 ± 1.6	98.5 ± 1.7	72.5 ± 1.5	62.1 ± 1.8
2	MAP1	0	204.6 ± 1.6	198.4 ± 2.7	190.1 ± 1.5	187.5 ± 1.3	172.3 ± 1.5	162.0 ± 1.6	142.5 ± 1.3	122.4 ± 1.5
3		1	205.8 ± 1.6	199.5 ± 1.4	191.4 ± 1.3	188.8 ± 1.5	176.0 ± 1.6	164.5 ± 1.7	152.2 ± 1.5	101.2 ± 1.4
4		2	206.0 ± 1.7	198.5 ± 1.5	190.9 ± 1.5	188.4 ± 1.7	175.6 ± 1.8	164.4 ± 1.5	151.5 ± 1.6	140.5 ± 1.6
5	MAP2	0	203.8 ± 1.8	199.0 ± 1.4	190.7 ± 1.6	188.9 ± 2.6	173.4 ± 1.5	162.9 ± 1.4	144.2 ± 1.5	123.5 ± 1.8
6		1	204.4 ± 1.6	195.4 ± 1.5	190.8 ± 1.5	188.6 ± 1.5	175.5 ± 1.4	163.2 ± 1.6	150.5 ± 1.3	132.8 ± 1.3
7		2	206.0 ± 1.5	199.0 ± 1.3	191.2 ± 1.4	188.5 ± 1.4	175.4 ± 1.3	164.3 ± 1.3	150.2 ± 1.6	144.5 ± 1.2

MAP – modified atmosphere packaging. MAP1 – 80% O_2 + 20% CO_2, MAP2 – 40% O_2 + 30% CO_2 + 30% N_2.

Tab. 6. The oxidative process of goat meat packaged at various conditions during storage.

	Formulas		Storage time [d]							
	Packaging	Lactic acid [%]	0	3	6	9	12	15	18	21
			TBARS [mg·kg-1]							
1	Vacuum	0	0.42 ± 0.02	0.52 ± 0.04	1.03 ± 0.03	1.76 ± 0.04	2.35 ± 0.02	2.46 ± 0.03	2.75 ± 0.03	2.98 ± 0.02
2	MAP1	0	0.45 ± 0.03	0.65 ± 0.03	0.85 ± 0.02	0.89 ± 0.03	1.26 ± 0.03	1.37 ± 0.04	1.68 ± 0.04	1.85 ± 0.02
3		1	0.43 ± 0.02	0.59 ± 0.02	0.78 ± 0.05	0.96 ± 0.02	1.12 ± 0.04	1.15 ± 0.02	1.36 ± 0.02	1.57 ± 0.04
4		2	0.44 ± 0.01	0.52 ± 0.04	0.68 ± 0.04	0.85 ± 0.02	0.98 ± 0.03	1.12 ± 0.02	1.21 ± 0.03	1.52 ± 0.06
5	MAP2	0	0.46 ± 0.04	0.48 ± 0.05	0.64 ± 0.03	0.73 ± 0.04	0.95 ± 0.03	1.09 ± 0.03	1.18 ± 0.03	1.45 ± 0.04
6		1	0.43 ± 0.03	0.45 ± 0.04	0.56 ± 0.02	0.64 ± 0.03	0.81 ± 0.05	0.95 ± 0.04	1.04 ± 0.04	1.32 ± 0.03
7		2	0.45 ± 0.02	0.49 ± 0.03	0.59 ± 0.03	0.67 ± 0.03	0.85 ± 0.01	0.94 ± 0.03	1.02 ± 0.03	1.37 ± 0.05

TBARS – thiobarbituric acid reactive substances (expressed as milligrams of malonaldehyde).
MAP – modified atmosphere packaging. MAP1 – 80% O_2 + 20% CO_2, MAP2 – 40% O_2 + 30% CO_2 + 30% N_2.

Lipid oxidative activity

It should be noted that the TBARS content of 2.0 mg·kg-1 is considered a sensory and acceptable limitation for fresh meat [31]. As shown in Tab. 6, the TBARS values of goat meat in all formulations increased gradually during the storage period and reached the highest level in the control group (formula 1). The TBARS values of formula 1 significantly increased, especially after 9 days, reaching the highest level of 2.98 mg·kg-1. Importantly, the treatment with lactic acid-combined MAP could reduce the TBARS values, with content not exceeding 1.57 mg·kg-1 in both MAP1 and MAP2 packaging conditions after 21 days of storage. On the other hand, the goat meat samples treated with 1% and 2% lactic acid and preserved in MAP2 packaging showed lower TBARS values than those of MAP1 after 3 days of storage. This can be explained by the fact that the length of storage and highly oxygenated media (MAP1 with 80% O_2) have great effects on the meat's lipid oxidative process, with the enhanced oxygenated environment leading to a greater degree of oxidation.

Linares et al. [32] noted that the O_2 concentration at 70% could create conducive conditions for lipid oxidation. They also observed that the addition of the low CO concentration (0.7 %) was responsible for an oxidative reduction of lamb meats by forming stable pigments and carboxymyoglobin. The enhanced stability of myoglobin colouration is associated with reduced lipid oxidation in meat. Using a 75% O_2 and 25% CO_2 mixture in the MAP can lead to an increase in lipid oxidative levels in beef. When astaxanthin was added at a level of 20–80 mg·kg-1, it successfully prevented the onset of illness and lipid oxidation during cold storage, increasing the meat's shelf life [33]. Similarly, the meat's shelf life can be extended by using 0.1% tarragon oil in conjunction with MAP packaging (80% CO_2 + 20% N_2) [34]. Furthermore, dietary supplements like citroflavan-3-ol and resveratrol function as antioxidants, delaying lipid oxidation in fresh meat. These substances are thought to be safe and advantageous for the health of consumers and the preservation sector [20].

Microbial activity

The microbial activity was found to be increased in all formulas during the preservation period. Changes in the *TVC* values in goat meat samples during storage at 4 °C are presented in Fig. 2. On the initial days, the *TVC* values in all the samples ranged from 3.42 log CFU·g-1 to 3.56 log CFU·g-1. In comparison to samples kept

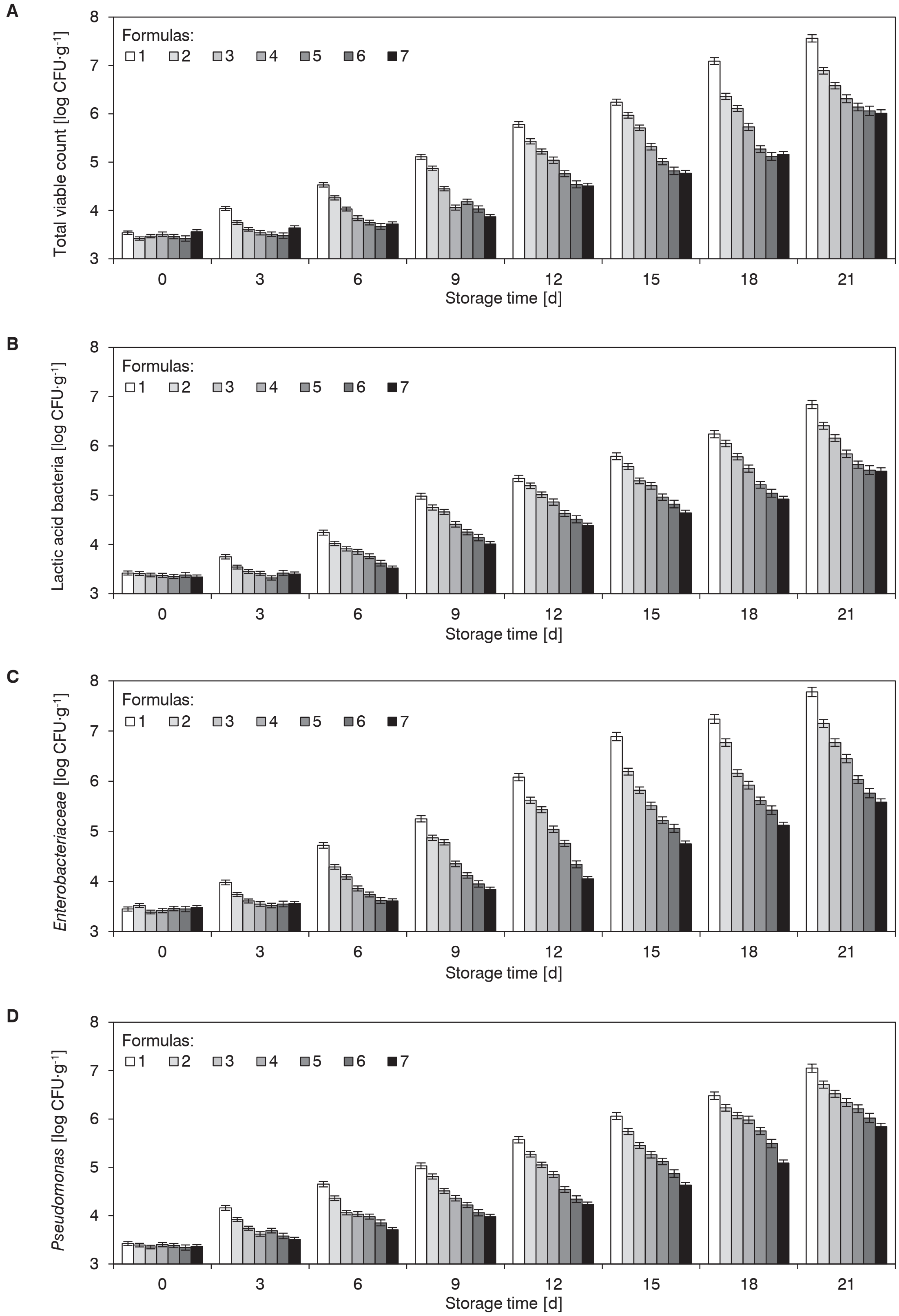

Fig. 2. The effect of storage time on total viable count, lactic acid bacteria, *Enterobacteriaceae*, and *Pseudomonas* counts in goat meat packaged at various conditions.

A – total viable count, B – lactic acid bacteria, C – *Enterobacteriaceae*, D – *Pseudomonas*.
Formula 1 – vacuum packaging (control), formula 2 – MAP1 (80% O_2 + 20% CO_2), formula 3 – MAP1 combined with 1% lactic acid, formula 4 – MAP1 combined with 2% lactic acid, formula 5 – MAP2 (40% O_2 + 30% CO_2 + 30% N_2), formula 6 – MAP2 combined with 1% lactic acid, formula 7 – MAP2 combined with 2% lactic acid.

in the MAP without lactic acid, the development of microorganisms was reduced when combining lactic acid treatment in both the MAP1 and MAP2 settings. The *TVC* values in the samples (without lactic acid and MAP packaging) were significantly higher on days 15, 18, and 21 of storage compared to all other samples, exceeding 7 log CFU·g^{-1}, surpassing the *TVC* threshold in meat set by the International Commission on Microbiological Specifications for Foods (ICMSF) [35]. For this criterion, it might lead to off-odours, sour taste, and the formation of slimy characteristics in the meat [35]. The goat meat samples treated with 1% and 2% lactic acid combined with MAP2 packaging conditions after 21 days of storage showed the lowest *TVC* values of 6.01 log CFU·g^{-1} and 6.06 log CFU·g^{-1}, respectively.

Considering the LAB counts (Fig. 2), these values in all formulas were also observed to increase gradually during the storage period, with the highest increase observed in the control formula, ranging from 3.34 log CFU·g^{-1} to 6.41 log CFU·g^{-1}. In contrast, samples treated with lactic acid combined with the MAP1 and MAP2 conditions significantly decreased the growth of lactic acid bacteria. The LAB values in the control samples were higher on days 9 and 12 compared to other preservation formulas. There was no remarkable difference in samples preserved in both MAP conditions. After 21 days of storage, the LAB counts in the control samples (untreated with lactic acid and not packaged with MAP) had the highest value. Using lactic acid at concentrations of 1% and 2% in the MAP2 condition resulted in counts of 5.49–5.51 log CFU·g^{-1} after 21 days, the lowest among the remaining preservation formulas.

The variations in *Enterobacteriaceae* counts during the storage duration are also presented in Fig. 2. In the first stage, there was no significant difference among the preservation formulas, with values of 3.39–3.52 log CFU·g^{-1}. *Enterobacteriaceae* counts in the control formulas increased quickly compared to other studied formulas, reaching 7.78 log CFU·g^{-1} after 21 days of storage. Conversely, this value in samples treated with lactic acid combined with the MAP1 and MAP2 conditions increased significantly from day 9 to day 21. *Enterobacteriaceae* quantity decreased in goat meat samples treated with 1% and 2% lactic acid combined with the MAP2, with the counts after 21 days of storage being 5.76 log CFU·g^{-1} and 5.58 log CFU·g^{-1}, respectively.

The quantity of *Pseudomonas* bacteria tends to increase during the storage period, in which the control formula exhibited the highest rate of increase (Fig. 2). Initially, there was no significant distinction in the *Pseudomonas* bacterial count among the formulas, ranging from 3.34 log CFU·g^{-1} to 3.40 log CFU·g^{-1}. However, after 18 and 21 days of storage, the *Pseudomonas* bacterial count in the control samples was the highest (5.09–6.71 log CFU·g^{-1}), compared to all other formulas. Both the MAP1 and MAP2 conditions, with or without lactic acid, exhibited an increasing trend from day 12 to day 21 during the storage period.

CONCLUSIONS

Lactic acid supplementation successfully inhibited the growth of microorganisms in both MAP settings. During the preservation process, the samples maintained in the MAP2 with 2% lactic acid showed better resistance to *TVC*, LAB, *Enterobacteriaceae*, and *Pseudomonas* bacteria. By combining with the MAP, lactic acid can be used as a highly effective preservative to improve the colour stability and oxidative stability of fresh goat meat. Overall, the quality of the product was maintained, with freshness-related parameters assessed using internationally recognised methods, including ISO 2917:1999 [14]. This establishes the groundwork for expanding the Vietnamese fresh goat meat preservation technology, boosting shelf life, preserving quality for storage, and meeting local and international demands.

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