

## Biopreservation of red meats by lactic acid bacteria *Lactobacillus plantarum* and *Leuconostoc mesenteroides* isolated from camel milk

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### Article history

Received:

9 June 2024

Received in revised form:

13 August 2025

Accepted:

29 September 2025

### Keywords

meat,  
lactic acid bacteria,  
biopreservation,  
camel,  
milk

### Abstract

Lactic acid bacteria (LAB) have been used in food fermentation since ancient times due to their natural antimicrobial properties. The present work aimed to evaluate the biopreservative potential of LAB strains isolated from camel milk for application in red meat preservation. Two strains (*Lactobacillus plantarum* and *Leuconostoc mesenteroides*) were phenotypically identified and confirmed using API 50CHL biochemical profiling. Bacterial suspensions of *L. plantarum* and *L. mesenteroides* were prepared at a concentration of  $10^9$  CFU/mL and applied to camel (CM), cow (BM), and sheep (SM) meat samples by immersion. Four treatment groups were established, namely meat treated with (i) *L. plantarum*, (ii) *L. mesenteroides*, (iii) a 1:1 mixture of both strains, and (iv) an untreated control. All samples were stored at 4°C for nine days. Bacteriological analyses were performed every three days to monitor mesophilic aerobic bacteria, Enterobacteriaceae, psychrotrophs, coliforms, and staphylococci using PCA, VRBG, VRBL, and Baird-Parker agars, respectively. One-way ANOVA revealed that all LAB treatments significantly reduced bacterial loads compared to the control ( $p < 0.001$ ). However, Tukey's *post hoc* test showed no statistically significant differences ( $p > 0.05$ ) between the three LAB-treated groups, indicating similar levels of efficacy. Overall, the application of *L. plantarum* and *L. mesenteroides* extended the microbiological shelf life of red meat up to nine days under refrigerated conditions. This effect is attributed to the production of natural antimicrobial compounds, including hydrogen peroxide, organic acids (notably lactic acid), and bacteriocins which inhibit spoilage microorganisms and certain pathogens. These findings suggest that these LAB strains hold promise as natural biopreservatives for the meat industry.

### DOI

<https://doi.org/10.47836/ifrj.32.4.10>

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### Introduction

Despite significant progress in handling and hygiene practices, the risk of meat contamination during slaughter, cutting, and processing remains high. Ensuring meat safety continues to be a major challenge in the food industry due to microbial contamination risks throughout slaughter and storage processes. To extend meat shelf life, various preservation methods have been developed, including freezing, refrigeration, smoking, and salting. More recently, biopreservation has attracted growing interest as a natural and effective alternative to chemical preservatives and heat treatments (Muthuvelu *et al.*, 2023; Cocolin, 2025). Biopreservation, extensively studied over the past decade, represents a promising approach that relies on

beneficial microorganisms such as lactic acid bacteria (LAB) and their metabolites (organic acids, hydrogen peroxide, and bacteriocins) to inhibit pathogenic bacteria (Marcelli *et al.*, 2024). Unlike chemical agents and thermal treatments which may alter the organoleptic and nutritional qualities of food, biopreservation helps maintain these properties while enhancing food safety (Nath *et al.*, 2014; Jhandai *et al.*, 2019).

Several studies (El Agamy, 2000; Drici *et al.*, 2009; Khay *et al.*, 2011; Hawaz *et al.*, 2016; Chethouna, 2021) have highlighted the unique characteristics of LAB isolated from camel milk. These strains exhibit remarkable thermostability, and retain their antagonistic effect across a wide pH range (2 - 10), making them particularly suitable for biopreservation applications. In addition, LAB

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derived from camel milk have demonstrated superior physicochemical properties, including enhanced thermotolerance and halotolerance, potentially increasing their effectiveness compared to LAB from other sources. However, their specific role in meat preservation remains underexplored, creating a research gap that the present work aimed to address.

Therefore, the objective of the present work was to contribute to the advancement of meat biopreservation, by evaluating the potential of *Lactobacillus plantarum* and *Leuconostoc mesenteroides* isolated from camel milk, to extend the shelf life of camel, cow, and sheep meats. By exploring their antibacterial effects, the present work sought to propose a natural alternative preservation method that enhances both food safety and quality.

## Materials and methods

### Lactic acid bacteria

Lactic acid bacteria, specifically *Lactobacillus plantarum* and *Leuconostoc mesenteroides*, were isolated from camel milk using selective MRS and MSE media, respectively. The identification of these strains was initially performed through phenotypic and biochemical tests, and subsequently confirmed using API 50 CHL galleries.

### Meats

Red meat samples were collected 24 h post-mortem at a slaughterhouse in Algeria using the excision method. Samples were taken from the internal posterior part of the thigh, a site particularly susceptible to contamination by intestinal flora such as coliforms, Enterobacteriaceae, and *Clostridium* spp. (Guiraud, 2012).

Portions of 30 g were divided into four treatment groups as follows: (i) Batch 1 (Control): camel (CM), cow (BM), and sheep (SM) meats samples with no prior treatment; (ii) Batch 2: CM, BM, and SM samples treated with a culture of *Lactobacillus plantarum* at a concentration of  $10^9$  CFU/mL; (iii) Batch 3: CM, BM, and SM samples

treated with a culture of *Leuconostoc mesenteroides* at a concentration of  $10^9$  CFU/mL; and (iv) Batch 4: CM, BM, and SM samples treated with a 1:1 mixture of *Lactobacillus plantarum* and *Leuconostoc mesenteroides* at a final concentration of  $10^9$  CFU/mL.

Each sample was individually packaged in sterile, food-grade plastic bags, and stored at 4°C. Bacterial concentrations were standardised to  $10^9$  CFU/mL by measuring turbidity at 600 nm (DO<sub>600</sub>) using a spectrophotometer, following the method described by Koch (1994) and Stevenson *et al.* (2016) for estimating microbial populations in the exponential growth phase.

### Bacteriological analysis

#### Preparation of stock suspension and decimal dilutions

A 30-g portion of camel, cow, or sheep meats was placed in a sterile bag containing 90 mL of sterile peptone water, following ISO 6887-1:2017. The mixture was homogenised for 1 - 2 min using an electric grinder. The resulting homogenate constituted the stock suspension ( $10^0$  dilution), which was left to stand for 4 h to allow for bacterial revival. Subsequent decimal dilutions were prepared from this stock solution in accordance with ISO 6887-2:2004 to facilitate accurate microbial enumeration.

#### Bacterial enumeration

Bacteriological analyses included the enumeration of total mesophilic aerobic bacteria, psychrotrophic bacteria, coliforms, Enterobacteriaceae, and *Staphylococcus* spp. For each bacterial group, 1 mL of the appropriate dilution was plated using the pour plate method on selective or differential media specific to each bacterial group (Table 1). Results were expressed as the decimal logarithm of colony-forming units per gram ( $\log_{10}$  CFU/g). For each bacterial group, mean values and standard deviations were calculated based on logarithmic data.

**Table 1.** Isolation media and culture conditions of spoilage and pathogenic microorganisms.

Microorganism	Medium	Condition	Incubation	Standard
Total aerobic mesophilic	PCA	Anaerobic	72 h/30°C	ISO 4833-1:2013
Coliform	VRBL	Anaerobic	24 h/44°C	NF V 08-017
Enterobacteriaceae	VRBG	Anaerobic	24 h/37°C	ISO 21528-2
<i>Staphylococcus</i>	Baird Parker	Aerobic	24 h/37°C	ISO 6888-2 :2021
Psychrotrophic	PCA	Aerobic	24 h/6.5°C	NF ISO 17410

Biopreservative effects were assessed by monitoring the evolution of bacterial loads on days 0, 3, 5, 7, and 9. All experiments were independently repeated three times, each performed in triplicate to ensure the reproducibility and statistical reliability of the results.

#### Statistical analysis

Statistical analyses were performed using Python software to evaluate differences between meat samples treated with LAB strains and the corresponding untreated controls. One-way analysis of variance (ANOVA) was applied to assess the effect of treatments on bacterial counts. When significant differences were observed ( $p < 0.05$ ), Tukey's Honest Significant Difference (HSD) *post-hoc* test was used

to identify specific group differences. This approach also allowed for the assessment of biopreservation efficacy over time. Statistical procedures followed the methodology described by Montgomery (2020).

## Results and discussion

#### Bacteriological analysis

##### Initial bacterial loads of meats

Bacterial counts were performed on camel (CM), cow (BM), and sheep (SM) meat samples to assess initial contamination by total mesophilic aerobic flora (FAMT), psychrotrophic bacteria, thermotolerant coliforms, Enterobacteriaceae, and *Staphylococcus* spp. (Table 2).

**Table 2.** Initial contamination rate of red meats.

Microorganism	Meat	Load (log <sub>10</sub> CFU/mL)
Total aerobic mesophile	Camel	1.72 ± 0.03
	Cow	3.67 ± 0.02
	Sheep	2.24 ± 0.01
Psychrotroph	Camel	2.62 ± 0.54
	Cow	2.85 ± 0.31
	Sheep	2.30 ± 0.16
Coliform	Camel	1.57 ± 0.20
	Cow	2.45 ± 0.32
	Sheep	2.12 ± 0.06
Enterobacteriaceae	Camel	2.49 ± 0.37
	Cow	2.38 ± 0.25
	Sheep	1.42 ± 0.10
<i>Staphylococcus</i>	Camel	2.18 ± 0.10
	Cow	1.52 ± 0.16
	Sheep	1.45 ± 0.11

#### Total aerobic mesophiles

On day 0, the initial contamination levels by total aerobic mesophiles were  $1.72 \pm 0.03$  log<sub>10</sub> CFU/g for camel meat,  $3.67 \pm 0.02$  log<sub>10</sub> CFU/g for cow meat, and  $2.24 \pm 0.01$  log<sub>10</sub> CFU/g for sheep meat. These values complied with the acceptable limit of  $5 \times 10^5$  CFU/g established by Algerian regulations (Journal Officiel Algérien), confirming proper hygienic handling regardless of meat type. These results were lower than those reported by Oumokhtar *et al.* (2008) for cow meat ( $9.3 \times 10^6$  CFU/g) and Benaissa *et al.* (2015) for camel meat ( $2.14$  log<sub>10</sub> CFU/g); but comparable to those of

Hamad (2009) for camel meat ( $1.79 \pm 0.19$  log<sub>10</sub> CFU/g), and Benaissa (2011) for sheep meat ( $2.45$  log<sub>10</sub> CFU/g).

#### Psychrotrophic bacteria

The average psychrotrophic load was  $2.62 \pm 0.54$  log<sub>10</sub> CFU/g for camel meat,  $2.85 \pm 0.31$  log<sub>10</sub> CFU/g for cow meat, and  $2.30 \pm 0.16$  log<sub>10</sub> CFU/g for sheep meat. These values were considerably lower than those reported by Salifou *et al.* (2013) for *Pseudomonas* spp. ( $4.93$  log<sub>10</sub> CFU/cm<sup>2</sup>), a common psychrotrophic genus.

### Coliforms

Coliform counts were  $1.57 \pm 0.20 \log_{10}$  CFU/g (camel meat),  $2.45 \pm 0.32 \log_{10}$  CFU/g (cow meat), and  $2.12 \pm 0.06 \log_{10}$  CFU/g (sheep meat). Camel meat exhibited the lowest coliform load. These values were slightly higher than those reported by Hammoudi *et al.* (2013), who found  $1.83 \log_{10}$  CFU/cm<sup>2</sup>.

### Enterobacteriaceae

Mean loads of Enterobacteriaceae were  $2.49 \pm 0.37 \log_{10}$  CFU/g (camel meat),  $2.38 \pm 0.25 \log_{10}$  CFU/g (cow meat), and  $1.42 \pm 0.10 \log_{10}$  CFU/g (sheep meat). Lower levels have been reported by Colloberf *et al.* (2007) for cow meat ( $1.42 \log_{10}$  CFU/cm<sup>2</sup>), and Vallontton (2004) noted that 70% of bovine carcasses showed levels below  $1.5 \log_{10}$  CFU/cm<sup>2</sup>. In contrast, Salifou *et al.* (2013) reported higher contamination levels ( $6.05 \log_{10}$  CFU/cm<sup>2</sup>). Hamad (2009) also reported lower counts in camel meat ( $0.96 \log_{10}$  CFU/cm<sup>2</sup>).

### Staphylococcus spp.

Average *Staphylococcus* counts were  $2.18 \pm 0.10 \log_{10}$  CFU/g (camel meat),  $1.52 \pm 0.16 \log_{10}$  CFU/g (cow meat), and  $1.45 \pm 0.11 \log_{10}$  CFU/g (sheep meat). These values are lower than those found by Ingham *et al.* (2005) ( $5.9 \log_{10}$  CFU/g), but comparable to Sagoo *et al.* (2007) and Vidova *et al.* (2012), who reported mean loads of 1.3 and  $1.4 \log_{10}$  CFU/g, respectively, in vacuum-packed meat. One-way ANOVA followed by Tukey's HSD test revealed highly significant differences ( $p < 0.001$ ) between the different red meat types for all bacterial groups. These differences in contamination levels are influenced by various factors, including animal species, production methods, processing conditions, and post-slaughter handling (Guiraud, 2012).

### Effect of lactic acid bacteria on bacterial loads of red meats

Bacteriological analyses were conducted on camel (CM), cow (BM), and sheep (SM) meat samples to assess the effect of LAB treatments compared to untreated controls. The primary bacterial groups monitored were total mesophilic aerobic flora, psychrotrophs, coliforms, Enterobacteriaceae, and *Staphylococcus* spp. Figure 1 presents the results obtained on day 5 of refrigerated storage at 4°C.

One-way analysis of variance (ANOVA) revealed a highly significant effect ( $p < 0.001$ ) of

LAB treatments (*Lactobacillus plantarum* (Lb), *Leuconostoc mesenteroides* (Ln), and their combination (Lb+Ln)) on the reduction of bacterial loads across all meat types.

These results highlighted the effectiveness of LAB as natural biopreservatives, capable of inhibiting the growth of spoilage and pathogenic bacteria in red meats. Their antibacterial activity is primarily attributed to the production of organic acids (e.g., lactic acid), bacteriocins, hydrogen peroxide, and other bioactive metabolites (Stiles, 1996; Gálvez *et al.*, 2007).

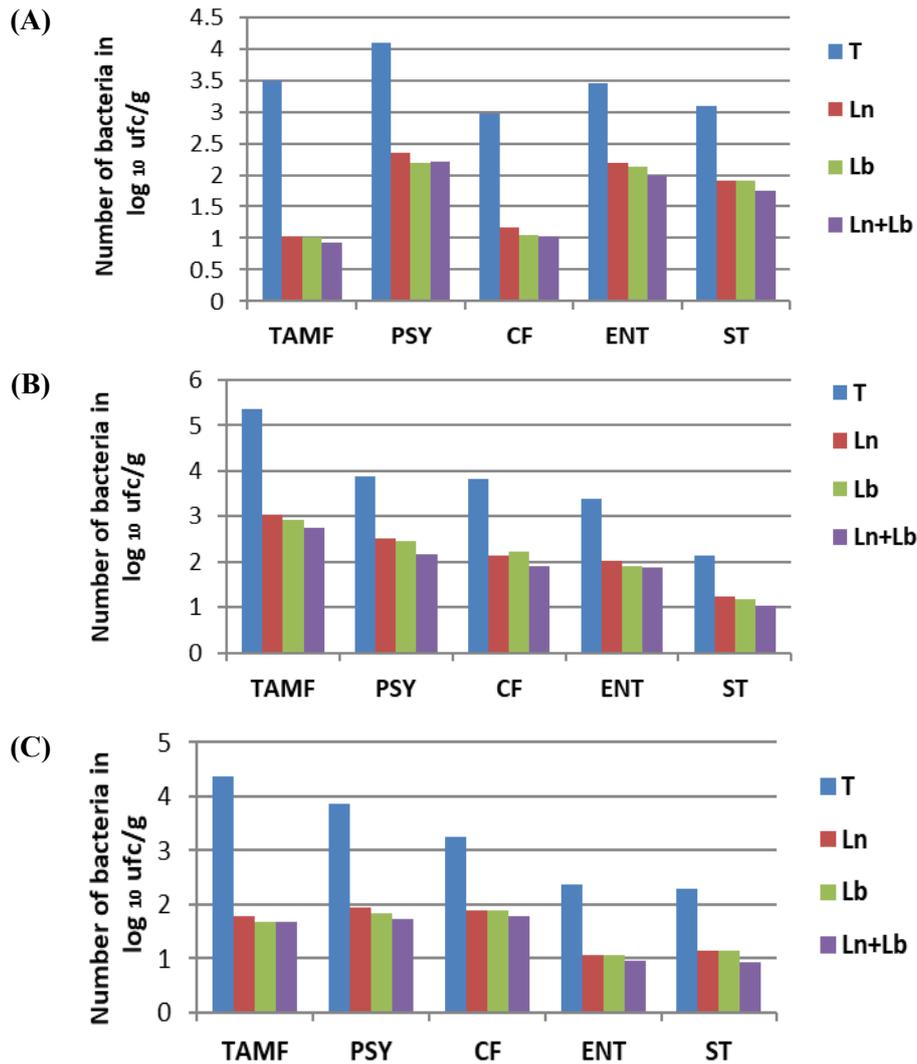
However, Tukey's HSD *post-hoc* test indicated no statistically significant differences ( $p > 0.05$ ) among the individual LAB treatments. Although all treatments significantly reduced bacterial loads relative to controls, none exhibited a clearly superior effect. This suggested that *L. plantarum*, *L. mesenteroides*, and their combination possessed comparable antibacterial efficacy under the tested conditions. The absence of synergism may be due to overlapping mechanisms of action or a plateau effect in antibacterial activity.

These findings were consistent with those of Hugas and Tsigarida (2008), who reported similar antimicrobial performance among LAB strains applied to meat products. Likewise, Leroy and De Vuyst (2004) emphasised the value of LAB as functional starter cultures in food fermentation, while noting that efficacy differences between strains or combinations are not always significant.

Previous research has confirmed the inhibitory effect of *L. plantarum* against spoilage organisms and pathogens such as *Listeria monocytogenes* and *Salmonella* spp. (Gálvez *et al.*, 2007). Similarly, *L. mesenteroides* has demonstrated the capacity to produce antimicrobial metabolites and to modify environmental conditions (such as pH and nutrient availability) that limit microbial growth (Talon and Leroy, 2006). The absence of an additive effect in the combined treatment may result from functional redundancy or metabolic competition between the two strains.

### Evolution of bacterial flora during meat storage at 4°C

We followed the evolution of the spoilage and pathogenic flora on red meats treated with LAB strains in comparison with untreated meats (controls), with the aim of estimating their shelf life.



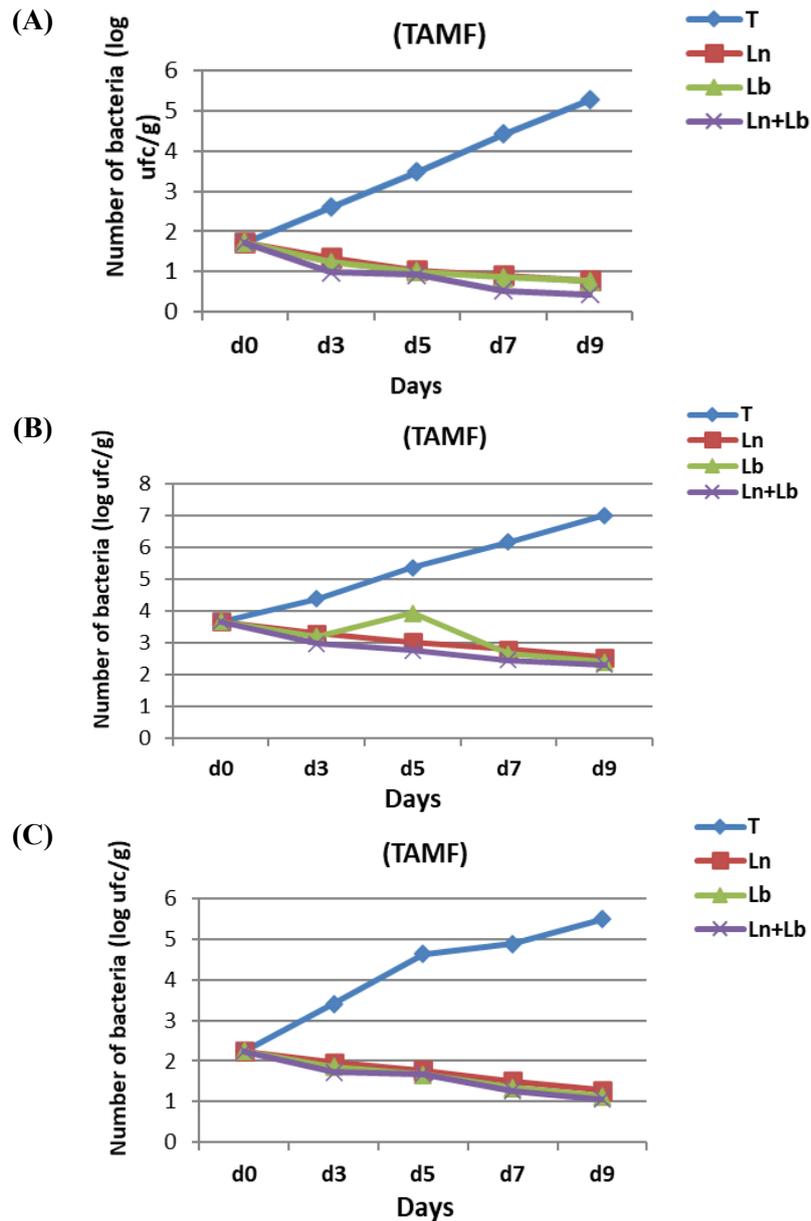
**Figure 1.** Effect of lactic acid bacteria on bacterial loads of red meats. **(A):** camel meat; **(B):** cow meat; and **(C):** sheep meat. T: untreated meat, control; Ln: meat treated with *Leuconostoc mesenteroides*; Lb: meat treated with *Lactobacillus plantarum*; and Ln+Lb: meat treated with *Lactobacillus plantarum* and *Leuconostoc mesenteroides*. TAMF: total aerobic mesophile; PSY: psychrotroph; CF: coliform; and ST: *Staphylococcus*.

#### Evolution of total aerobic mesophiles

The evolution of total aerobic mesophiles during the storage of CM, BM, and SM at 4°C showed a steady increase in bacterial counts in untreated control samples, from initial levels of 1.72, 3.67, and 2.24 log<sub>10</sub> CFU/g on day 1 to 5.28, 7.01, and 5.5 log<sub>10</sub> CFU/g by day 9, respectively (Figure 2). These findings were consistent with previous observations by Benaissa *et al.* (2015), who reported significant microbial proliferation in camel and sheep meats under similar refrigerated conditions. Conversely, a substantial decrease in bacterial load was observed in samples treated with *Lactobacillus plantarum* (Lb), *Leuconostoc mesenteroides* (Ln),

and their mixed cultures (Lb+Ln). This inhibitory effect can be attributed to two synergistic mechanisms: (i) the impact of refrigeration in slowing microbial metabolism, and (ii) the antimicrobial action exerted by LAB, notably through the production of organic acids and bacteriocins.

The effectiveness of LAB strains in controlling spoilage microorganisms in refrigerated meats have been supported by several recent studies. Djenane *et al.* (2020) demonstrated that the application of nisin and *Olea europaea* subsp. *laperrinei* leaf extract significantly extended the shelf life of camel meat stored under modified atmosphere packaging. Similarly, Zhao *et al.* (2022) found that microbial



**Figure 2.** Evolution of total aerobic mesophiles during meat storage at 4°C. (A): camel meat; (B): cow meat; and (C): sheep meat. T: untreated meat, control; Ln: meat treated with *Leuconostoc mesenteroides*; Lb: meat treated with *Lactobacillus plantarum*; and Ln+Lb: meat treated with *Lactobacillus plantarum* and *Leuconostoc mesenteroides*.

loads in pork meat stored at 4°C increased from approximately 4.0 to 6.2 log<sub>10</sub> CFU/g over 15 days, highlighting the need for additional biopreservative strategies during chilled storage.

Moreover, the use of bacteriocin-producing LAB, particularly *L. plantarum*, has been recognised for its strong antimicrobial activity against spoilage organisms in chilled meat products. According to Putri *et al.* (2024), bacteriocins offer a natural, efficient means of enhancing food safety by inhibiting a wide range of spoilage and pathogenic bacteria.

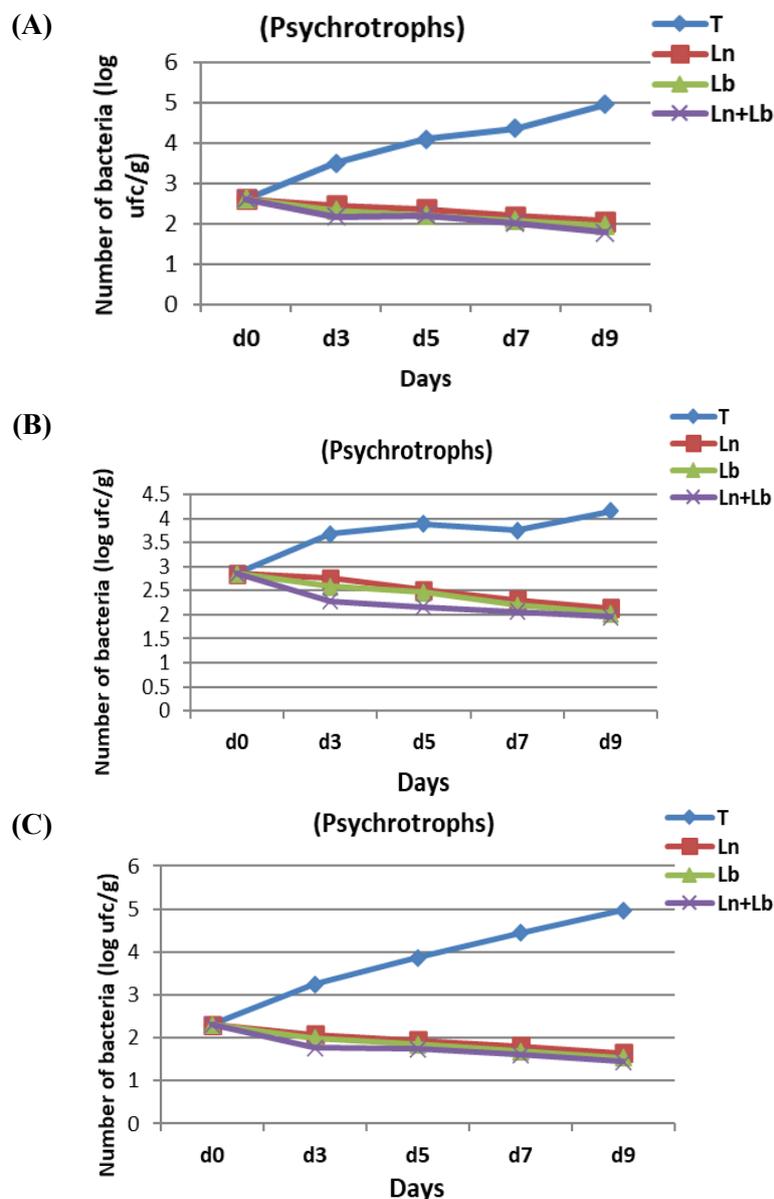
Behera *et al.* (2018) further emphasised that *L. plantarum* strains with functional properties can not only enhance the microbial safety, but also prolong the shelf life of fermented and non-fermented food products.

Overall, our results confirmed that the inoculation of meat with selected LAB strains could serve as an effective biopreservation approach, reducing spoilage and pathogenic bacteria, thus improving the quality and shelf life of refrigerated meat products.

### Evolution of psychrotrophs

Psychrotrophs are agents of food poisoning (such as *Clostridium perfringens*, *Escherichia coli*, and *Salmonella*) or spoilage (such as *Pseudomonas* spp., *Acinetobacter* spp., and *Staphylococcus* spp.). These microorganisms significantly impact the marketable quality and safety of meat products, and represent a major limiting factor in the preservation of refrigerated foods (Jay *et al.*, 2005; Nychas *et al.*, 2008; Rouger *et al.*, 2017). The evolution of psychrotrophic bacteria observed in the present work highlighted their major role in the spoilage of refrigerated meats. Untreated samples showed a significant increase in bacterial loads over time

(Figure 3), confirming their ability to proliferate even at low temperatures. These results were consistent with the findings of Jay *et al.* (2005) and Nychas *et al.* (2008), who emphasised the importance of psychrotrophs as key spoilage agents in chilled meat products. Among these bacteria, *Pseudomonas* spp. are frequently identified as the dominant flora under refrigerated and modified atmosphere conditions. Casaburi *et al.* (2015) demonstrated the rapid proliferation of *Pseudomonas* in meat stored at 4°C, leading to sensory degradation within just a few days. Our results confirmed this observation, as psychrotrophic counts in the control samples increased rapidly throughout storage.



**Figure 3.** Evolution of psychrotrophs during meat storage at 4°C. (A): camel meat; (B): cow meat; and (C): sheep meat. T: untreated meat, control; Ln: meat treated with *Leuconostoc mesenteroides*; Lb: meat treated with *Lactobacillus plantarum*; and Ln+Lb: meat treated with *Lactobacillus plantarum* and *Leuconostoc mesenteroides*.

In contrast, meat samples treated with *Lactobacillus plantarum*, *Leuconostoc mesenteroides*, or their combination (Lb+Ln) exhibited a clear reduction in psychrotrophic levels. This inhibition can be attributed to the well-known antimicrobial activity of LAB, mainly through the production of organic acids, bacteriocins, and other inhibitory metabolites (Behera *et al.*, 2018; Putri *et al.*, 2024). LAB also lower the pH of the medium, creating an unfavourable environment for spoilage organisms (Djenane *et al.*, 2020).

The use of LAB strains such as *L. plantarum* represents a natural biopreservation approach, offering an effective alternative to chemical preservatives. Several recent studies support this strategy. For example, Zhao *et al.* (2022) showed that the combined use of LAB and modified atmosphere packaging significantly extended the shelf life of refrigerated pork by limiting the growth of psychrotrophic flora.

Overall, our findings confirmed that inoculating meat with selected LAB strains could be a promising strategy to slow microbial spoilage, enhance hygienic quality, and extend the shelf life of chilled meat products. This approach is particularly relevant in the current context, where consumers seek preservative-free yet microbiologically safe food products.

#### *Evolution of enterobacteria and coliforms*

Enterobacteriaceae forms a large family of Gram-negative bacteria that include many genera of clinical and food safety significance. These bacteria are responsible for diseases of varying severity, ranging from mild gastroenteritis to severe systemic infections, depending on their pathogenic mechanisms (Eng *et al.*, 2015). Their preferred habitat is the intestinal tract of humans and animals, although many members can also be found in soil, water, and food environments. While some species are part of the normal gut microbiota, others can become opportunistic or primary pathogens, posing a threat to food hygiene and public health (Rasko and Sperandio, 2010; Tenaillon *et al.*, 2010).

Coliforms include various bacterial species within the Enterobacteriaceae family. While most of these microorganisms are non-pathogenic and form part of the normal intestinal microbiota, some strains can become pathogenic under certain conditions.

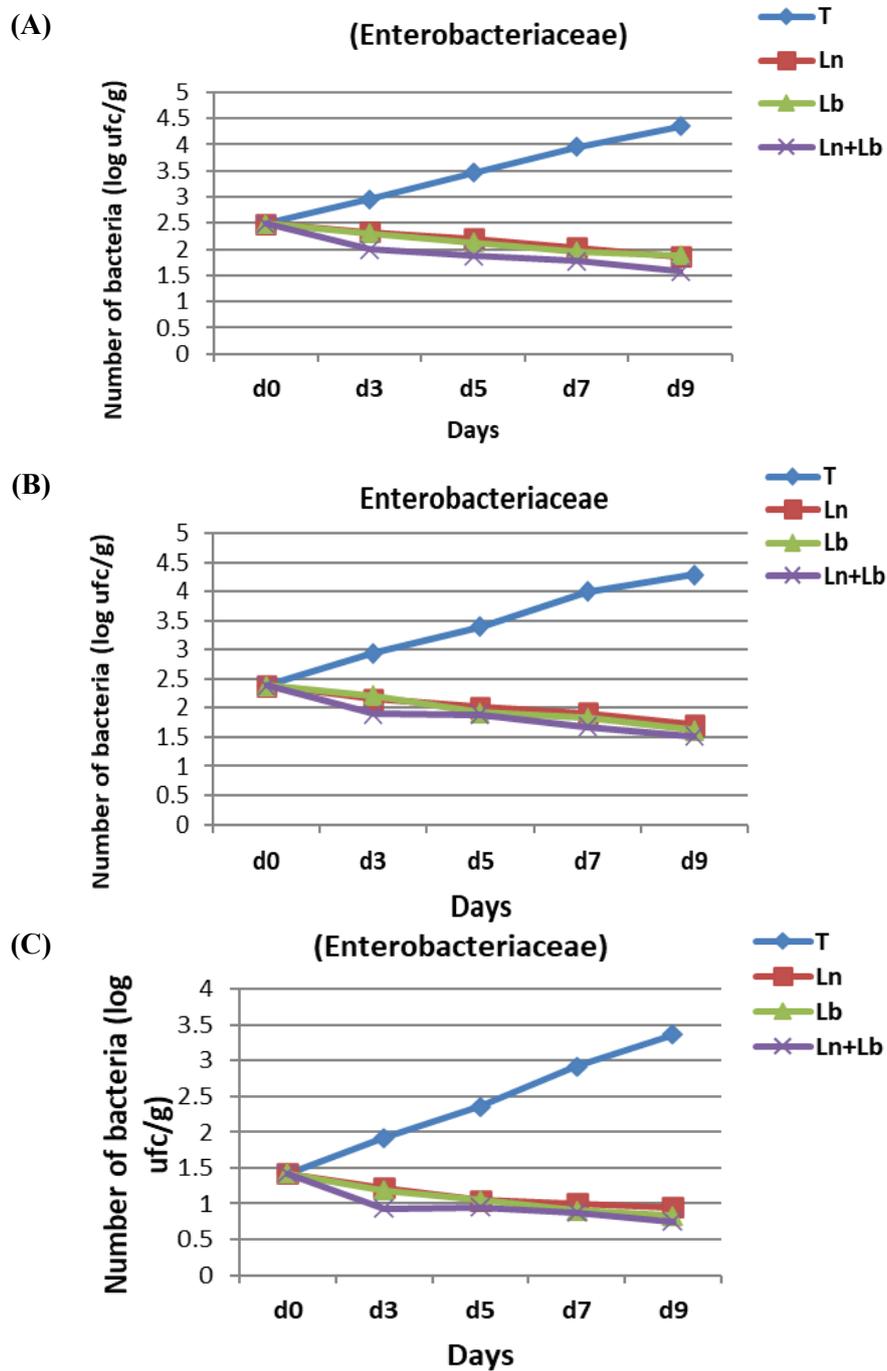
A well-known example is *Escherichia coli* O157:H7, an enterohemorrhagic strain associated with severe gastroenteritis in humans, which can lead to complications such as haemolytic uremic syndrome (Karmali, 2004; Gyles, 2007; Pennington, 2010).

The evolution of enterobacteria and coliforms during the storage of red meats at 4°C revealed a gradual increase in bacterial load in untreated meat samples. Initial levels of enterobacteria on day 1 were 2.49 log<sub>10</sub> CFU/g (camel), 2.38 log<sub>10</sub> CFU/g (cow), and 1.42 log<sub>10</sub> CFU/g (sheep), which increased to 4.35, 4.29, and 3.36 log<sub>10</sub> CFU/g, respectively, by day 9 (Figure 4). A similar trend was observed for coliforms, with initial counts of 1.57, 2.45, and 2.12 log<sub>10</sub> CFU/g, increasing to 3.95, 4.77, and 4.97 log<sub>10</sub> CFU/g, respectively, by the end of the storage period (Figure 5).

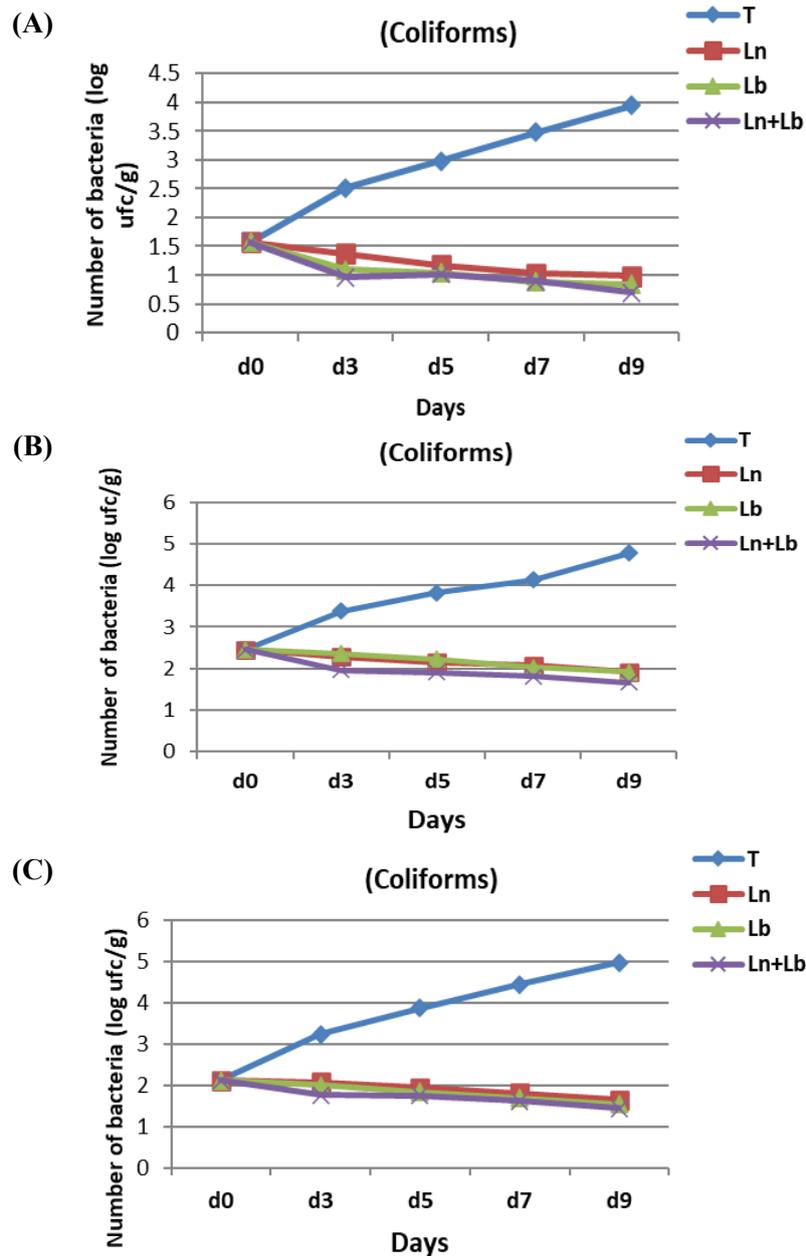
The application of LAB on camel, cow, and sheep meats appeared to slow the proliferation of both enterobacteria and coliforms, as evidenced by reduced growth rates in treated samples (Figures 4 and 5). Several studies have reported the antagonistic effects of LAB on spoilage and pathogenic flora in meat. Djenane *et al.* (2005) inoculated beef steaks with two LAB strains: *Lactobacillus sakei* CTC 372 (bacteriocinogenic: sakacin T) and *Lactobacillus curvatus* CTC 711 (non-characterised). When stored in modified atmosphere packaging, both strains delayed the growth of spoilage flora by up to 10 d. Sparo *et al.* (2013) demonstrated the bactericidal activity of *Enterococcus faecalis* CECT7121 against major pathogens including *Escherichia coli* O157:H7, *Staphylococcus aureus*, *Clostridium perfringens*, and *Listeria monocytogenes* when inoculated into ground beef. Zhang *et al.* (2018) studied *L. sakei* and *L. curvatus* as bioprotective cultures applied to vacuum-packed raw beef. Both strains significantly reduced the levels of Enterobacteriaceae, *Pseudomonas* spp., and *Brochothrix thermosphacta*, with *L. sakei* exhibiting the strongest inhibitory effect. Wambui *et al.* (2017) used seven LAB isolates from fermented camel milk to protect camel meat against ten strains of Enterobacteriaceae. Their results showed effective inhibition of *Shigella* spp., *Citrobacter* spp., and three of seven *E. coli* isolates.

#### *Evolution of Staphylococcus spp.*

Staphylococci, saprophytic flora commonly



**Figure 4.** Evolution of Enterobacteriaceae during meat storage at 4°C. **(A):** camel meat; **(B):** cow meat; and **(C):** sheep meat. T: untreated meat, control; Ln: meat treated with *Leuconostoc mesenteroides*; Lb: meat treated with *Lactobacillus plantarum*; and Ln+Lb: meat treated with *Lactobacillus plantarum* and *Leuconostoc mesenteroides*.



**Figure 5.** Evolution of coliforms during meat storage at 4°C. (A): camel meat; (B): cow meat; and (C): sheep meat. T: untreated meat, control; Ln: meat treated with *Leuconostoc mesenteroides*; Lb: meat treated with *Lactobacillus plantarum*; and Ln+Lb: meat treated with *Lactobacillus plantarum* and *Leuconostoc mesenteroides*.

found on the skin and mucous membranes of humans and animals, include strains (primarily of the species *Staphylococcus aureus*) that are capable of producing enterotoxins. These enterotoxins are thermostable, meaning they can withstand standard cooking temperatures, which makes them particularly problematic in the context of food safety. For this reason, *S. aureus* is of major hygienic concern due to its toxigenicity and its frequent involvement in foodborne outbreaks (Hennekinne *et al.*, 2012; Claeys *et al.*, 2013; CDC, 2024; ScienceDirect, 2024)

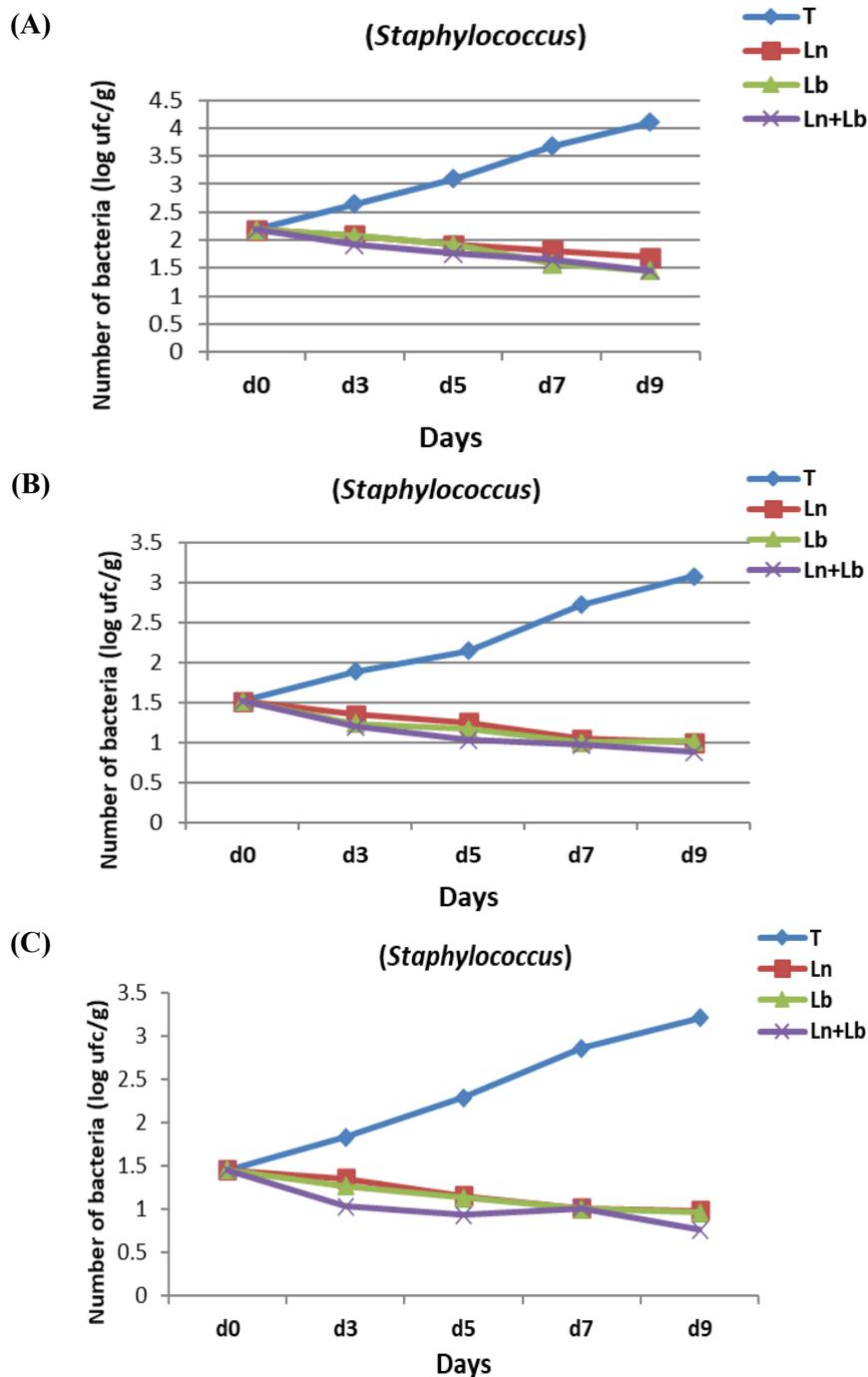
According to the Centers for Disease Control and Prevention (CDC), *S. aureus* food poisoning typically occurs after the ingestion of pre-formed enterotoxins in contaminated foods. Symptoms often appear rapidly (within - 6 h) and include nausea, vomiting, abdominal cramps, and diarrhoea. Though the illness is usually self-limiting, resolving within 24 - 48 h, its impact on public health and food safety systems remains significant (CDC, 2024).

Moreover, the heat resistance of these toxins poses a unique risk: even if the bacteria are destroyed

by heat during cooking, the toxins remain biologically active, necessitating strict preventive measures during handling and storage.

Monitoring the evolution of the microbial flora revealed a progressive growth of *Staphylococcus* species in untreated meat samples. Initial counts were 2.18, 1.52, and 1.45 log<sub>10</sub> CFU/g for camel, cow, and sheep meats, respectively. By the ninth day of storage at 4°C, these levels had increased to 4.10, 3.08, and

3.21 log<sub>10</sub> CFU/g, indicating a significant proliferation of staphylococcal flora. In contrast, the application of LAB treatments, including *Lactobacillus* (Lb.), *Lactococcus* (Ln.), and their combination (Lb+Ln), effectively slowed down or even inhibited the growth of *Staphylococcus* spp. in all three meat types (Figure 6). In support of these findings, another researcher isolated strains of *Lactococcus lactis* subsp. *lactis* from camel and goat



**Figure 6.** Evolution of *Staphylococcus* spp. during meat storage at 4°C. **(A)**: camel meat; **(B)**: cow meat; and **(C)**: sheep meat. T: untreated meat, control; Ln: meat treated with *Leuconostoc mesenteroides*; Lb: meat treated with *Lactobacillus plantarum*; and Ln+Lb: meat treated with *Lactobacillus plantarum* and *Leuconostoc mesenteroides*.

milk, and demonstrated their biopreservative potentials. When applied to chicken and camel meats, both the bacterial cells and their culture supernatant significantly inhibited the growth of *Staphylococcus aureus* ATCC 25923 previously inoculated into the samples. In the present work, the incorporation of LAB (*Lactobacillus plantarum* and *Leuconostoc mesenteroides*) allowed for the extension of meat shelf life up to 9 d under refrigerated conditions. This improvement in microbiological stability can be attributed to the production of natural antimicrobial metabolites such as bacteriocins, organic acids (notably lactic acid), and secondary inhibitory compounds (like hydrogen peroxide), which act against spoilage flora and certain pathogens. These findings were consistent with observations from several studies that have used organic acids such as acetic, propionic, or lactic acids. For example: Ogden *et al.* (1997) applied a combination of propionic and ascorbic acids to pork meat. This treatment extended the shelf life up to eight days, with a significant reduction in microbial loads while maintaining good sensory quality. Hajipour *et al.* (2015) treated chicken drumsticks with 1% citric, acetic, or propionic acid. Propionic acid proved to be the most effective, extending shelf life to seven days compared to four days in the control. El Asuoty *et al.* (2023) demonstrated that a 2% acetic acid solution applied to beef extended its shelf life up to 15 days, although there was a risk of sensory alteration, including pronounced acidity and colour changes. Their study highlighted the trade-off between microbiological safety and sensory quality, with acetic acid effectively reducing microbial load but impacting the sensory attributes of the meat.

However, these treatments may sometimes alter the meat's colour or flavour due to their direct acidity. In contrast, the use of LAB, as in the present work, offers the advantage of a more natural and gradual effect. In addition to their antimicrobial properties, these microorganisms may enhance the meat's sensory profile (mild tangy flavour, improved colour stability), which is a key asset in biopreservation strategies. Compared to the use of chemical preservatives or acid solutions, biopreservation using LAB thus appears to be a more sustainable and acceptable alternative, particularly in response to consumer demand for less processed foods free from chemical additives.

## Conclusion

The present work highlighted the promising role of lactic acid bacteria (LAB), specifically *Lactobacillus plantarum* and *Leuconostoc mesenteroides*, isolated from camel milk, in the biopreservation of red meats. The application of these strains significantly inhibited the growth of spoilage and pathogenic bacteria, and extended the shelf life of camel, cow, and sheep meats from 3 d (control) to more than 9 d under refrigerated conditions. These results confirmed the antibacterial potential of LAB, attributed to their production of bacteriocins, organic acids, and other inhibitory compounds. Beyond confirming the efficacy of these strains in laboratory conditions, the present work also provided valuable insights for the meat industry, which is increasingly seeking natural and consumer-friendly alternatives to chemical preservatives. The use of LAB could be integrated into existing meat processing and storage workflows to enhance product safety, and extend shelf life, while also responding to growing consumer demand for minimally processed foods. Future research should aim to evaluate the sensory impact of these treatments, explore their effectiveness under commercial storage and packaging conditions (*e.g.*, vacuum or modified atmosphere), and assess the scalability of LAB applications in industrial settings. Furthermore, molecular studies on the specific antimicrobial compounds produced by these strains could open new avenues for targeted biopreservation strategies.

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