Fermented sour wort enriched with *Pediococcus acidilactici* PA-2 as a natural marinade to reduce *Listeria monocytogenes* and *Salmonella Typhimurium* in raw chicken

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Abstract

Raw chicken, valued for its affordability and nutritional benefits, remains vulnerable to contamination by meat-borne pathogens despite advances in food safety systems. Biopreservation using lactic acid bacteria, particularly pediocin-producing *Pediococcus acidilactici*, offers a natural strategy to inhibit foodborne pathogens through the production of lactic acid and bacteriocin. This study aimed to evaluate the antimicrobial effect of sour wort fermented with *P. acidilactici* PA-2 as a natural marinade against *Listeria monocytogenes* and *Salmonella typhimurium* in raw chicken. Sour wort was prepared and fermented with *P. acidilactici* PA-2 at 30°C for 24 h and 48 h, reaching final cell counts of 8.0 and 8.5 $\log_{10}$ CFU/g, respectively, and pH values between 3.8 and 4.5. Raw chicken samples were inoculated with approximately 6.9 $\log_{10}$ CFU/mL of *L. monocytogenes* and 6.4 $\log_{10}$ CFU/mL of *S. typhimurium*, marinated with 24-h and 48-h fermented wort (Ringer's solution as control), and stored at 4°C for 16 h. On selective media, pathogen populations were enumerated. Both 24-h and 48-h fermented wort marinades significantly reduced *L. monocytogenes* and *S. typhimurium* counts compared with the control ($p < 0.05$). The 48-h fermented wort reduced *L. monocytogenes* and *S. typhimurium* counts by 1.9 and 1.8 $\log_{10}$ CFU/g, respectively, while the 24-h wort produced similar reductions of 1.7 and 1.8 $\log_{10}$ CFU/g. No significant differences were observed between the two fermentation times ($p > 0.05$). These findings suggest that *P. acidilactici* PA-2 fermented sour wort can serve as an effective clean-label marinade that enhances the microbiological safety of raw chicken during short-term refrigerated storage, contributing to reduced foodborne risk without relying on chemical preservatives.

Keywords: biopreservation; sour wort; chicken meat; *Pediococcus acidilactici*; *Listeria monocytogenes*; marinade; *Salmonella typhimurium*

Introduction

Biopreservation is the use of naturally occurring microorganisms or their metabolites to inhibit the growth of spoilage microorganisms and pathogens in food products (Kaveh *et al.*, 2023). In the recent decade, the application of bio-preservatives in the food industry has increased gradually due to consumer demand

(Amiri *et al.*, 2022). Lactic acid bacteria (LAB) are the most commonly used biopreservatives owing to their ability to produce antimicrobial compounds such as organic acids, hydrogen peroxide, and bacteriocins, which can drastically reduce pathogen loads in various food matrices, including chicken (Amiri *et al.*, 2022). Chicken is a popular protein source across the world, known for its affordability and nutritional potential. According to reports, the most consumed meat worldwide is poultry meat, with approximately 140 million tons consumed in 2023 (Statista, 2024). Poultry meat provides a suitable environment for microbial growth, which poses significant challenges for food safety. Long-term storage at refrigeration temperatures (4°C) is not possible (Göçmez and İlhak, 2025; Serter *et al.*, 2024).

The presence of foodborne pathogens in poultry products is a major public health concern. In particular, listeriosis and salmonellosis are notorious foodborne diseases that continue to pose significant challenges to national economies and public health across the globe. Presently, the primary source of human infection is the consumption of contaminated raw or undercooked poultry meat and their products (Abatcha, 2017). *L. monocytogenes* is particularly dangerous since it is ubiquitous, halophile, capable of forming biofilms, and can thrive at refrigeration temperatures, while *Salmonella enterica* subsp. *enterica* and its numerous serotypes cause severe gastrointestinal illness (Seo and Kang, 2020).

Natural preservatives are becoming more popular than chemical alternatives as consumers' awareness of healthy eating has grown (Gargi and Sengun, 2021; Göçmez and İlhak, 2025; Karatepe *et al.*, 2025). Marinades, which are commonly made with acidic substances, herbs, and spices, not only improve flavor but also have antibacterial characteristics that help limit the growth of foodborne pathogens. The use of marinades based on natural ingredients is increasingly being investigated as a means of improving the shelf-life and safety of meat products, in line with customer aspirations of clean label options (Latoch *et al.*, 2023; Rahman *et al.*, 2023). Nowdays, marinades are widely used in both households and the food industry because of the beneficial properties they provide to meat.

Researchers are focusing on the use of natural antimicrobial compounds such as bacteriocins due to concerns about chemical preservatives. Bacteriocins are ribosomally synthesized peptides or proteins produced by gram-positive and gram-negative bacteria (Khorshidian *et al.*, 2021). The most studied bacteriocins that could be utilized commercially as natural preservatives are nisin and pediocin (Khorshidian *et al.*, 2021). Currently, nisin is the only bacteriocin that can be used as an authorized additive (Khorshidian *et al.*, 2021). Some *Pediococcus* bacteria produce pediocins, which are small unmodified peptides with a low molecular weight (2.7–17 kDa) and belong to subclass IIa of bacteriocins (Khorshidian *et al.*, 2021). Pediocin and pediocin-like bacteriocins exert antimicrobial activity, especially against *L. monocytogenes* through formation of pores in the cytoplasmic membrane, causing cell membrane dysfunction, inhibition of protein synthesis, and gene expression (Khorshidian *et al.*, 2021). The current application of Pediocin PA-1 in the food industry highlights the biopreservative potential of pediococci, leading to further studies to characterize novel strains and pediocin variants that can be used in food systems to ensure quality and safety (Todorov *et al.*, 2022). Accordingly, *P. acidilactici* has emerged as a viable option among the different microbial agents investigated for their potential in food preservation (Barbosa *et al.*, 2015; Todorov *et al.*, 2022). The bacteriocins of *P. acidilactici* are effective anti-biofilm agents to control *S. typhimurium* contamination in chicken and food-processing facilities (Seo and Kang, 2020). Incorporating *P. acidilactici* into marinades may increase their bactericidal activities against pathogens such as *L. monocytogenes* and *S. typhimurium*, enhancing the microbiological safety of raw chicken (Barbosa *et al.*, 2015; Latoch *et al.*, 2023; Rahman *et al.*, 2023).

Several studies have demonstrated that marinades containing organic acids and bacteriocins can effectively reduce populations of *Salmonella* and *Listeria* in raw chicken (Göçmez and İlhak, 2025; İncili *et al.*, 2020; Meneses and Teixeira, 2022). The bactericidal effect is due to the ability of these acids and bacteriocins such as pediocins to permeate bacterial membranes, dissipate proton motive force, prevent energy production, inhibit glucose uptake, inhibit the synthesis of nucleic acids, disrupt cellular functions, and eventually lead to cell death (Latoch *et al.*, 2023; Lopes *et al.*, 2022).

Although the antimicrobial effects of LAB and their bacteriocins, including pediocin produced by *P. acidilactici*, have been demonstrated in various food systems, there is limited research on the use of sour wort fermented specifically with *P. acidilactici* PA-2 as a natural marinade for raw poultry meat. Our study aims to fill this gap by evaluating the antimicrobial effect of sour wort fermented with *P. acidilactici* PA-2 as a natural marinade for raw chicken. Specifically, we assessed the ability of 24-h and 48-h fermented wort marinades to reduce populations of *L. monocytogenes* and *S. typhimurium* on inoculated chicken meat during 16 h of refrigerated storage at 4°C, in order to determine their potential to enhance the microbiological safety of marinated chicken.

Table 1. Selected studies on antimicrobial marinades in chicken and their effects.

Study	Matrix	Target pathogens	Marinade	Storage conditions	Main antimicrobial effect (log_{10} CFU/g)
Fouladkhah *et al*., 2013	Chicken	*L. monocytogenes*	Lemon juice–based marinades	Up to 7 days at 4°C	About 2.0 log_{10} CFU/g reduction
İncili *et al*., 2020	Chicken	*S. typhimurium*	Marinade sauce	24 h at refrigeration temperature	About 4.0 log_{10} CFU/g reduction
Sengun *et al*., 2019	Chicken	*S. typhimurium*	Koruk (*Vitis vinifera* L.) juice marinade	18 h at refrigeration temperature	About 3.5 log_{10} CFU/g reduction
Eldin *et al*., 2020	Chicken	*Salmonella* spp.	Lemon juice (50–100%)	Up to 6 days at 4°C	About 3.0 log_{10} CFU/g reduction depending on lemon juice concentration
Li *et al*., 2023	Chicken	*L. monocytogenes*	Beer with leucocin C	Short-term marination under refrigeration	About 1.6 log_{10} CFU/g reduction using bacteriocin-secreting yeast
Göçmez and İlhak, 2025	Chicken	*Salmonella* spp.	Bioprotective culture marinades	Up to 14 days at 4°C	About 2.3 log_{10} CFU/g reduction
Present study	Chicken	*L. monocytogenes*, *S. typhimurium*	*Pediococcus acidilactici* PA-2 fermented sour wort	16 h at 4°C	1.7–1.9 log_{10} CFU/g reduction of both pathogens

Materials and Methods

Bacterial cultures

Experiments were performed using *P. acidilactici* PA-2 SAA 262 (Chr. Hansen, Hørsholm, Denmark), *L. monocytogenes* WSLC 1018, and *S. typhimurium* ATCC 23852 (American Type Culture Collection). Cultures were stored at −80°C and resuscitated by inoculating *P. acidilactici* in de Man, Rogosa, Sharpe (MRS; Oxoid, Basingstok, Hampshire, UK) broth, *L. monocytogenes* in Brain Heart Infusion (BHI; LabM, Lancashire, UK) broth, and *S. typhimurium* in Luria-Bertani (LB; Merck) broth; inoculated cultures were then incubated at 30°C or 37°C overnight. For the *L. monocytogenes* and *S. typhimurium* strain, a loopful of culture broth was inoculated into 10 mL of fresh BHI and LB broth, respectively, and incubated at 37°C overnight to obtain fresh culture.

Raw chicken

Fresh raw chicken was purchased from the local market on the day of the experiment, which was the same source throughout the study. Chicken meat samples were transported under good hygienic conditions to the laboratory within 30 min of purchase. Using a sterilized knife, the chicken was manually cut into approximately 25 g cubes.

Wort preparation

Malt, 2.5 kg of pilsner malt, 2 kg of pale ale malt, and 0.5 kg of wheat malt (Viking malt, Lahden Polttimo Ltd., Lahti, Finland) were ground and added to a boiler (30 L, Brewferm®) containing 20 L of preheated 70°C water. Mashing was done for 1 h at 66°C, followed by separation of the liquid and washing of the mash with 8 L of 70°C water. Thereafter, the wort was boiled for 1 h (no addition of hops), cooled to 28°C, and used as the growth medium for the chosen bacteria to yield sour wort (Figure 1).

Preparation of the marinade

The enumeration of *P. acidilactici* was carried out in 10 mL of de MRS broth and incubating at 37°C for 48 h. After incubation, *P. acidilactici* PA-2 grown in MRS broth was transferred to a centrifuge tube and centrifuged at 1,789*g* for 10 min. The supernatant was discarded, and the pellet was resuspended in 7.5 mL Ringer's solution, which was then poured into 150 mL wort, thoroughly mixed, and incubated at 30°C overnight for 24 h and 48 h (Figure 1). The initial concentration of *P. acidilactici* PA-2 in the wort before incubation was 5.0 log_{10} CFU/mL. After 24 and 48 h of fermentation at 30°C, the PA-2 count was 8.0 log_{10} CFU/mL and 8.5 log_{10} CFU/mL, respectively.

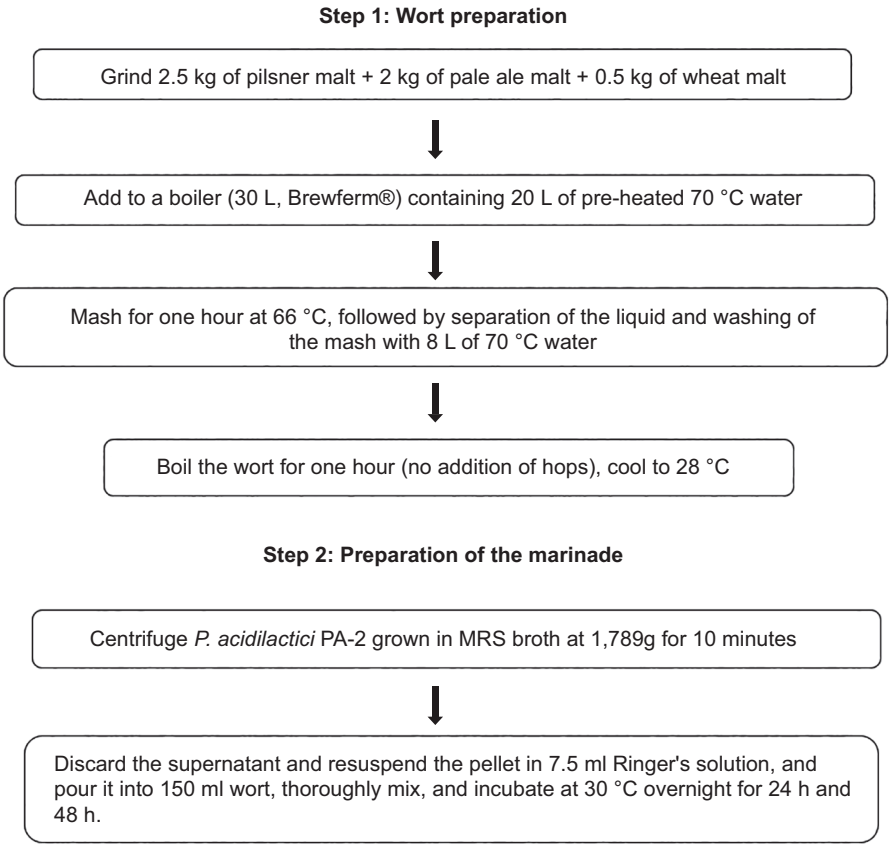

Figure 1. Illustration of the experimental procedure.

Table 2. Experimental groups stored at 4ºC for 16 h.

Groups	Treatment
Group 1	Control group marinated with Ringer's solution.
Group 2	Chicken meat marinated with 24-h fermented sour wort.
Group 3	Chicken meat marinated with 48-h fermented sour wort.

pH determination

The pH of the fermented wort was measured using a pH meter, specifically the Thermo Orion Model-420A'. An electrode was inserted directly, and measurements were taken in triplicate; averages over the triplicates were used in subsequent analyses.

Experimental groups

Chicken samples were assigned to three groups (Table 2):

Group 1: Control group marinated with Ringer's solution.

Group 2: Chicken meat marinated with 24-h fermented sour wort containing *P. acidilactici* PA-2.

Group 3: Chicken meat marinated with 48-h fermented sour wort containing *P. acidilactici* PA-2.

Microbiological analysis

A total of 25 g of raw chicken meat was placed in stomacher bags with integrated filters. Subsequent decimal dilutions of BHI broth containing *L. monocytogenes* and LB broth containing *S. typhimurium* were performed in Ringer's solution as required, and 10 mL of the sixth dilution of each broth was added to separate stomacher bags. The initial inoculation levels of *L. monocytogenes* and *S. typhimurium* at time zero was 6.9 $\log_{10}$ CFU/mL and 6.4 $\log_{10}$ CFU/mL, respectively. The spiked samples were placed in a stomacher lab-blender 400 and blended at 230 rpm for 2 min, then incubated for 30 min at room temperature. Next, wort with *P. acidilactici* PA-2 was added to each stomacher bag of *L. monocytogenes* and *S. typhimurium* and blended again in the laboratory blender. Ringer's solution (150 mL) was used instead of wort as a negative control. All samples were stored at 4ºC for 16 h. Following incubation, the samples were mixed again using the stomacher lab-blender. Decimal dilutions were performed and spread plated (100 µl) onto xylose lysine deoxycholate (XLD) (for *Salmonella*) and Oxford agar

(for *Listeria*). Plates were incubated at 37°C for 18–24 h (XLD) or 40–48 h (Oxford) before typical colonies were enumerated. The resulting data were transformed to $\log_{10}$ CFU/g. All the above treatments were performed in triplicate. The single storage scenario of 4°C for 16 h was chosen to simulate common consumer refrigeration duration for marinated poultry that may be consumed within 1 day after preparation.

Statistical analysis

Microbial counts were analyzed in triplicate. The data collected for evaluating microbial content was subjected to analysis of variance (ANOVA) using the general linear model procedure. The results are presented as mean values with their respective standard deviations. Tukey's test was used to identify significant differences between means, with a predetermined level of statistical significance set at $p \leq 0.05$. All statistical analyses were performed using Minitab 21.4 software (Minitab Inc., State College, PA, USA).

Results

pH determination

The pH values of the wort after 24 h and 48 h of fermentation were 4.5 and 3.8, , respectively, and without *P. acidilactici* PA-2, the wort pH was 5.3 (Figure 2).

L. monocytogenes

The viable count of *L. monocytogenes* declined in chicken meat marinated with fermented wort compared to the unmarinated meat sample. The initial inoculation level of *L. monocytogenes* in chicken meat prior to marination was approximately 6.9 $\log_{10}$ CFU/mL. After 16 h of refrigerated storage, *L. monocytogenes* count in untreated meat was 6.6 $\log_{10}$ CFU/g ($p < 0.05$) for 24 h and 5.8 $\log_{10}$ CFU/g ($p < 0.05$) for 48 h. In contrast, marination with wort fermented by *P. acidilactici* PA-2 for 24 h was 4.9 $\log_{10}$ CFU/g, resulting in a significant reduction of 1.7 $\log_{10}$ CFU/g in *L. monocytogenes* counts compared to the control group marinated with Ringer's solution ($p < 0.05$). Similarly, 48-h fermented wort marinade was 3.9 $\log_{10}$ CFU/g, showing a significant reduction of 1.9 $\log_{10}$ CFU/g in *L. monocytogenes* counts compared to the control group marinated with Ringer's solution ($p < 0.05$). Statistical analysis (ANOVA) showed no significant difference between reductions achieved by 24-h and 48-h fermentation treatments ($p > 0.05$) (Figure 3).

S. typhimurium

The viable count of *S. typhimurium* declined in chicken meat marinated with fermented wort compared to the unmarinated meat sample. The initial inoculation level of *S. typhimurium* in chicken meat prior to marination was approximately 6.4 $\log_{10}$ CFU/mL. After 16 h of refrigerated storage, *S. typhimurium* count in untreated meat was 6.0 $\log_{10}$ CFU/g ($p < 0.05$) for 24 h and 5.8 $\log_{10}$ CFU/g ($p < 0.05$) for 48 h. In contrast, marination with wort fermented by *P. acidilactici* PA-2 for 24 h was 4.2 $\log_{10}$ CFU/g., resulting in a significant reduction of 1.8 $\log_{10}$ CFU/g in *S. typhimurium* counts compared to the control group marinated with Ringer's solution ($p < 0.05$). Similarly, 48 h fermented wort marinade was 4.0 $\log_{10}$ CFU/g, showing a significant reduction of 1.8 $\log_{10}$ CFU/g in *S. typhimurium* counts compared to the control group marinated with Ringer's solution ($p < 0.05$). Statistical analysis (ANOVA) showed no significant difference between reductions achieved by 24 h and 48 h fermentation treatments ($p > 0.05$) (Figure 4).

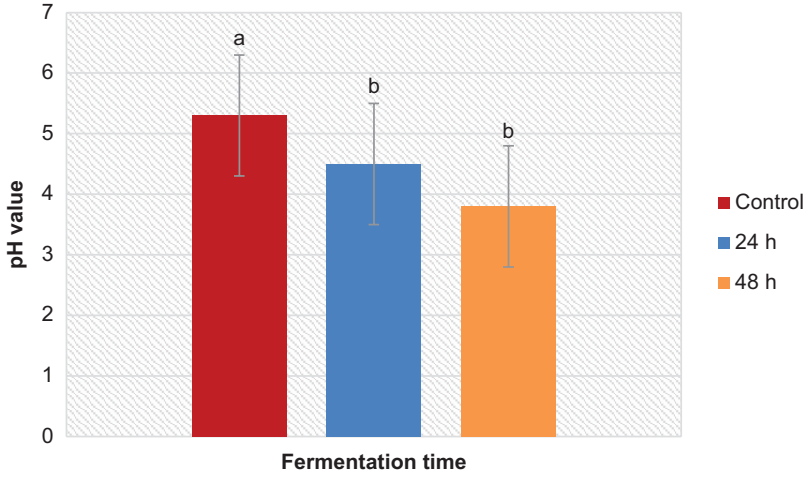

Figure 2. pH values of marinade groups with *P. acidilactici* PA-2 (24 h and 48 h fermentation) and control. Lowercase letters denote significant differences ($p < 0.05$) between samples at the same storage timepoint.

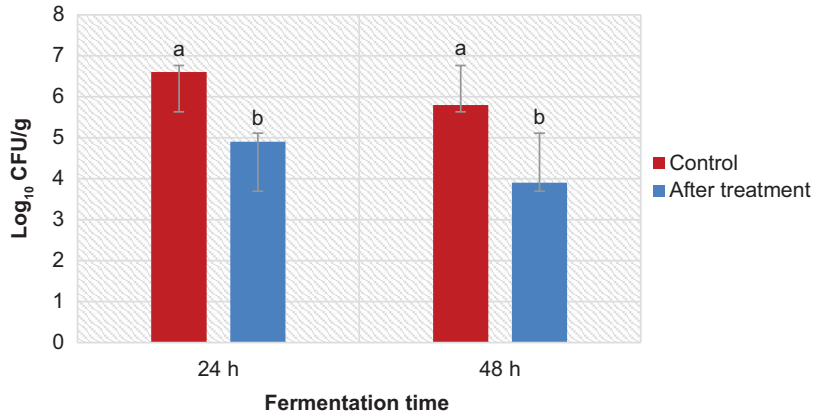

Figure 3. Log reduction in *Listeria monocytogenes* counts in raw chicken meat marinated with wort fermented for 24 h or 48 h and subsequently stored for 16 h at 4 ºC, relative to the control group marinated with Ringer's solution. Lowercase letters denote significant differences ($p < 0.05$) between samples at the same storage timepoint.

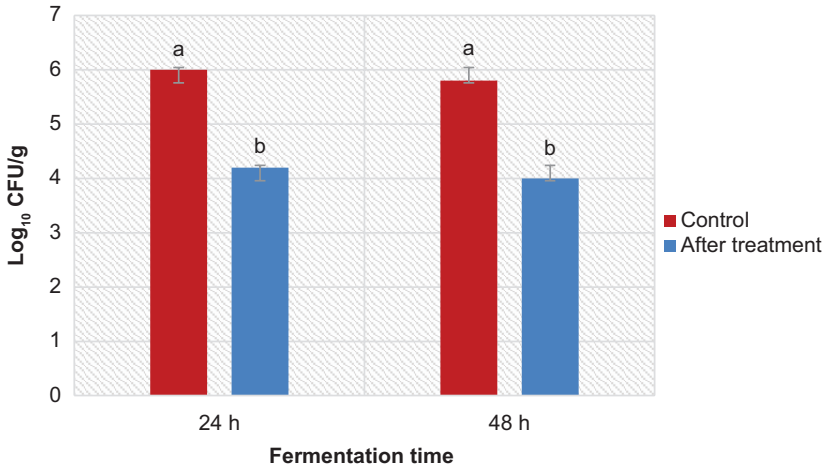

Figure 4. Log reduction in *Salmonella Typhimurium* counts in raw chicken meat marinated with wort fermented for 24 h or 48 h and subsequently stored for 16 ºC at 4 ºC, relative to the control group marinated with Ringer's solution. Lowercase letters denote significant differences ($p < 0.05$) between samples at the same storage timepoint.

Discussion

The antimicrobial efficacy of marinades is influenced by several factors, including low pH, organic acids, and other metabolites produced during fermentation by LAB such as *P. acidilactici*. This species is known to produce the bacteriocin pediocin with strong antilisterial activity, although pediocin production and activity are not always directly quantified in fermentation studies. Low pH is generally considered a major contributor to microbial inhibition in marinades (Göçmez and İlhak, 2025). The observed decrease in pH of the wort from 5.3 to 4.5 after 24 h and 3.8 after 48 h fermentation confirms strong acidification by *P. acidilactici* PA-2 in this matrix, consistent with reports that LAB, including *P. acidilactici*, reduce pH during fermentative growth in food systems (Kaveh *et al.*, 2023; Othman *et al.*, 2018). In general, larger reductions were observed when marinades with a pH of < 4.5 were used, regardless of the other ingredients present in the marinade and the food matrix (Lopes *et al.*, 2022 Fisher *et al.*, 2016). The low pH was identified as the most pronounced parameter, affecting the inactivation of pathogens in marinades; however, some effects of the ingredients and storage temperature cannot be completely ruled out (Lopes *et al.*, 2022). A lower pH does not necessarily positively affect meat tenderness and moisture content (Rahman *et al.*, 2023).

In our study, the use of pediocin-producing *P. acidilactici* strain in marinades was highly effective in reducing

L. monocytogenes and *S. typhimurium* on chicken meat under refrigerated conditions. Marinade made with *P. acidilactici* PA-2 grown in the wort for 48 h was most effective at inhibiting growth of *L. monocytogenes* on chicken meat. According to Kho *et al*. (2024), antimicrobial activity of cell-free supernatants from *P. acidilactici* was detected early at 12 h of incubation and gradually increased, peaking around the late stationary phase at 48 h. In a related study, Fouladkhah *et al*. (2013) concluded that the number of *L. monocytogenes* increased significantly in the control group while the lemon juice marinated groups decreased by 2 $\log_{10}$ CFU/g after 7 days, analogous to that of the present study. According to Nyhan *et al*. (2018), *L. monocytogenes* has strong resistance to low temperature, pH, and water activity. However, the findings of Rhoades *et al*. (2013) suggested that bacteria cannot be inactivated by pH alone—the dissociation rate of acid-producing substances also plays a role. Citric acid in lemon juice has a low undissociated acid rate and has been shown to inhibit the growth of *L. monocytogenes* (Wemmenhove *et al*., 2016). These results are in accordance with those of the present study. In addition, our findings are consistent with previous research on the inhibition of *L. monocytogenes* by pediocin PA-1 on chicken meat, which found a reduction close to 3.8 $\log_{10}$ CFU/g (Kiran and Osmanagaoglu, 2014; Xia *et al*., 2023; Zawiasa and Olejnik-Schmidt, 2025). Nieto-Lozano *et al*. 2010 revealed the importance of storage temperature in the use of bacteriocins. These findings highlighted that the inhibition of *L. monocytogenes* was more effective at 4°C. Therefore, the strain producing pediocin PA-1, *P. acidilactici* MCH14, can be used in refrigerated products, as was also seen from in study.

S. typhimurium is a major serotype responsible for distressing public health concerns worldwide. Our study showed that marinades prepared with *P. acidilactici* PA2 fermented wort (24 h and 48 h) were equally effective in inhibiting *S. Typhimurium*. Similar to this finding, İncili *et al*. (2020) found that the marinade sauce reduced the quantity of *S. typhimurium* by 4.0 $\log_{10}$ CFU/g after 24 h. Similarly, Sengun *et al*. (2019) observed that *S. typhimurium* count dropped 3.47 $\log_{10}$ CFU/g in marination sauce derived from koruk (*Vitis vinifera L.*) juice after 18 h. Pathania *et al*. (2010) also reported a drop in *S. typhimurium* count by 0.9 $\log_{10}$ CFU/g in a teriyaki marinade after 24 h. In another study by Eldin *et al*. (2020), it was mentioned that marinating chicken fillets with 50% and 100% lemon juice reduced *Salmonella* levels by 2.0 and 3.0 $\log_{10}$ CFU/g, respectively, when kept at 4°C for 6 days. These findings are consistent with the current investigation. Seo and Kang (2020) disclosed that bacteriocin derived from *P. acidilactici* can inhibit the biofilm formation of *S. typhimurium* in chicken meat, suggesting that it is a promising anti-biofilm agent to prevent issues with contamination into the food chain environments.

The statistical analysis (ANOVA) indicated no significant difference ($p < 0.05$) between the reductions achieved by 24-h and 48-h fermentation treatments for both *L. monocytogenes* and *S. typhimurium*. This finding suggests that the shorter fermentation duration of 24 h is sufficient to reach effective microbial reduction, with no additional benefit observed by extending fermentation to 48 h. Such results highlight the efficiency of the fermentation process within a relatively short timeframe, which could be advantageous for industrial applications by reducing processing time and cost.

The magnitude of *L. monocytogenes* reduction observed in our study (approximately 1.7–1.9 $\log_{10}$ CFU/g) is comparable to or greater than reductions reported for other marinades applied to chicken meat, where decreases of about 1.6–2.0 $\log_{10}$ CFU/g were achieved (Fouladkhah *et al*., 2013; İncili *et al*., 2020; Meneses and Teixeira, 2022). Specifically, the viable cells of *L. monocytogenes* decreased by approximately 1.6 $\log_{10}$ CFU/g after being marinated in beer containing leucocin C. Our study demonstrated more effective results; after treating chicken with the marinade containing *P. acidilactici* PA-2, the *L. monocytogenes* counts were reduced by approximately 1.9 $\log_{10}$ CFU/g. However, it is necessary to select pediocin-producing strains based on the food matrix to ensure adequate bacteriocin production, as highlighted in previous studies (Khorshidian *et al*., 2021). Furthermore, it has been noted that marinades containing different ingredients have different antimicrobial effects on the meat's microbiota, and gram-negative bacteria are more sensitive to acidic conditions than gram-positive bacteria. In contrast, our study showed similar magnitude of reductions in *L. monocytogenes* and *S. typhimurium* (1.8–1.9 $\log_{10}$ CFU/g) relative to the control group marinated with Ringer's solution, indicating comparable sensitivity of both pathogens to acidic conditions provided by the fermented wort marinade.

The sour wort produced by the *P. acidilactici* strain used in this study was able to exert an inhibitory effect against *L. monocytogenes* and *S. typhimurium* after 16 h storage at 4°C on raw chicken meat. The sour wort matrix not only provides a nutrient-rich environment that facilitates the growth of *P. acidilactici* but also promotes the production of its metabolites, enhancing antimicrobial activity (Othman *et al*., 2018). Our results indicate that using sour wort as a marinade offers a promising alternative to traditional LAB-based marinades, with additional benefits in flavor and preservation (Kho *et al*., 2024). This highlights the potential of sour wort to improve both antimicrobial efficacy and sensory qualities in marinated products. Regarding the influence of marinades' temperatures on the bacterial effect, the studies that evaluated the same scenario at different marinade

temperatures showed different results (Lopes *et al*., 2022). Considering that these reductions may not be sufficient to eliminate all pathogens present in meats, the use of high-quality meats coming from industries with good hygiene practices is very important. Furthermore, it is also recommended to use effective heat treatment before the consumption of marinated meats in order to ensure food safety (Lopes *et al*., 2022).

These findings support the efficacy of fermented marinades in inhibiting foodborne pathogens and align with previous research showing similar reductions (1.0–2.0 $\log_{10}$ CFU/g) in marinated meats (Meneses and Teixeira, 2022; Rahman *et al*., 2023). Fermentation-based marinades, particularly those maintaining low pH and low temperature, consistently achieve an average of 1.0–2.0 $\log_{10}$ CFU/g reduction in foodborne pathogens, but the effect is rarely absolute and should not be relied upon solely for food safety (Meneses and Teixeira, 2022).

Although our study demonstrates the promising antimicrobial effects of fermented wort marinade enriched with *P. acidilactici* against *L. monocytogenes* and *S. typhimurium*, some limitations should be acknowledged. The antimicrobial activity of *P. acidilactici* and its bacteriocin pediocin can vary depending on various factors such as bacteriocin concentration, strain variation, and environmental conditions including temperature and pH (Khorshidian *et al*., 2021). Furthermore, the stability and activity of bacteriocins in complex food matrices like chicken meat may be affected by proteolytic enzymes and interactions with food components (Khorshidian *et al*., 2021). Our study did not measure pH of the chicken–wort mixture after marination, though the buffering capacity of chicken meat can influence antimicrobial effectiveness (Göçmez and İlhak, 2025). In addition, while fermented wort marinades reduced pathogen counts significantly, reductions were incomplete, highlighting the importance of using good-quality meat and proper cooking for safety (Lopes *et al*., 2022). Lastly, the long-term stability and sensory impact of fermented wort marinades during extended storage were not assessed but should be examined in future studies. Addressing these limitations with further research will better define the practical application and optimization of *P. acidilactici*–enriched fermented marinades for enhancing the safety and quality of poultry meat.

Conclusions

This study found that using fermented wort marinade enriched with *P. acidilactici* leads to an inhibitory effect against *L. monocytogenes* and *S. typhimurium*, thereby improving the quality and safety of chicken meat. This marinade could serve as a potential cost-effective alternative to chemical preservatives. Marinating chicken with fermented wort substantially suppresses the growth of *L. monocytogenes* and *S. typhimurium* during storage and can therefore be used as an effective technique that minimizes the risk of foodborne illness in refrigerated products. However, the efficacy of fermented wort marinades is influenced by factors such as the composition of the wort and fermentation conditions, as variable fermentation can lead to varied antimicrobial effects. While marinades can inhibit certain pathogens, improper fermentation conditions may allow the survival and growth of spoilage organisms, or even pathogens, especially if pH and temperature are not strictly maintained.

Further studies should focus on investigating the impact of fermented wort marinade on other foodborne pathogens, such as *Campylobacter* spp., *Escherichia coli* (EHEC), and *Staphylococcus aureus* to establish broader food safety benefits. The effect of this marinade on the shelf-life and spoilage microbiota of chicken meat should be evaluated in future studies. In addition, future research should assess the feasibility of scaling up the use of fermented wort marinades in commercial meat processing.

Mandatory Disclosure on Use of Artificial Intelligence

The authors declare that no AI-assisted tools were used in the preparation of this manuscript.

Authors Contribution

Basobi Mukherjee was involved in writing—review and editing, writing—original draft, visualization, validation, methodology, investigation, formal analysis, and conceptualization. Farzana Nishat was responsible for writing—review and editing, methodology, investigation, and conceptualization. Saber Amiri looked into writing—review and editing, investigation, and conceptualization. Amin Yousefv was responsible for writing—review and editing, supervision, project administration, methodology, and conceptualization. Per E.J. Saris was in charge of writing—review and editing, supervision, project administration, funding acquisition, and conceptualization.

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Conflicts of Interest

The authors declare no conflict of interest that could have appeared to influence the work reported in this paper.

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