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1 The effects of *Lactiplantibacillus plantarum* 3-19 and
2 *Pediococcus pentosaceus* 18-1 on preventing the
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4 production of volatile organic compounds during sour meat
5 fermentation

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25 **Abstract**

26 Lactic acid bacteria (LAB) are frequently used in meat fermentation, and mixed starter
27 cultures are reported to perform better than single ones. *Lactiplantibacillus plantarum* 3-19 and
28 *Pediococcus pentosaceus* 18-1 were chosen from 28 sour-meat-origin strains to examine the
29 effects of single and combined inoculation on sour meat quality. Natural fermentation was used
30 as a control to investigate changes in pH, water activity (a_w), amino acid nitrogen (AN), texture,
31 microbial diversity, and volatile organic compounds (VOCs) during fermentation. The pH and
32 a_w of each inoculation group were significantly decreased, and AN content was significantly
33 increased. The inoculation of *P. pentosaceus* 18-1 significantly reduced putrescine, cadaverine,
34 and tryptamine content ($p < 0.05$), while the inoculation of *Lpb. plantarum* 3-19 significantly
35 reduced cadaverine amounts ($p < 0.05$). At the fermentation endpoint, the total biogenic amines
36 content in the C group was 992.96 ± 14.07 , which was 1.65, 2.57, and 3.07 times higher than
37 that in the Lp, Pe, and M groups, respectively. The mixed inoculation group combined the
38 advantages of both strains and decreased total biogenic amines most significantly. At the end
39 of fermentation, the VOCs in C, Lp, Pe, and M groups were 10.11, 11.56, 12.45, and 13.39
40 times higher than those at the beginning of fermentation. Inoculation promoted the production
41 of key VOCs (OAV > 2000) such as heptanal, octanal, and (E)-2-nonanal. The mixed
42 inoculation group had the highest variety and content of VOCs and the highest content of the
43 above key VOCs, significantly enhancing its fruity, floral, ester, and other aromas. Sensory
44 evaluation indicated that the M group had the best overall acceptability. Finally, it was
45 suggested that a combination of *Lpb. plantarum* 3-19 and *P. pentosaceus* 18-1 is a novel and
46 efficient starter culture for processing sour meat since they lower the amounts of biogenic

47 amines in the meat and promote the production of VOCs.

48 **Keywords:** sour meat, *Lactiplantibacillus plantarum*, *Pediococcus pentosaceus*; biogenic

49 amines; volatile organic compounds;

50 1. Introduction

51 Fermentation is a traditional meat processing method that can provide beneficial properties
52 to the product, such as microbial community succession, improved safety, and extended food
53 shelf life. This process significantly improves the texture and taste of meat products while
54 imparting unique flavor characteristics. There are two types of fermented meats: cubed meat,
55 such as sour meat, and minced meat products, such as fermented sausages.

56 Sour meat, a popular naturally fermented meat product in Southwest China, is made from
57 fresh pork mixed with rice flour, salt, and other ingredients. The mixture is thoroughly blended
58 and subjected to anaerobic fermentation for one month. However, a variety of variables,
59 including the process and surroundings, can impact fermentation, resulting in significant
60 variances in the final product's quality and an extended fermentation period. As a result, the
61 industrial production of sour meat is limited.

62 The addition of starter cultures to meat products has been shown to improve texture, flavor,
63 color, food safety, and shelf life by slowing **unwanted** bacterial growth (Lorenzo et al., 2014).
64 The most common starter culture in fermented meats, LAB contributes to the color, texture,
65 and flavor of fermented meat products (Sun et al., 2016). LAB can also improve food safety by
66 generating organic acids, primarily lactic and acetic acid, as well as other antimicrobial
67 substances that restrict the formation of **unwanted** microorganisms (Candogan et al., 2009).

68 The effect of *Lpb. plantarum* LPL-1 on the bacterial community and physicochemical
69 properties of fermented sausages was evaluated by Zhang et al. (2020), and they found *Lpb.*
70 *plantarum* LPL-1 could enhance the safety of fermented sausages by restricting the growth of
71 **unwanted** bacteria such as *Pseudomonas*, *Listeria monocytogenes*, and *Enterobacteriaceae*.

72 The production of hydrolyzing myofibrillar and sarcoplasmic protein-hydrolyzing proteases by
73 *P. pentosaceus* R1 has been shown to stimulate protein hydrolysis in meat products and improve
74 the characteristic organoleptic properties of Harbin dry sausages (Sun et al., 2019).
75 Fermentation with a single strain commonly forms a single colony dominance and has
76 limitations. Liu et al. (2023) reported that inoculation with *Lpb. plantarum* effectively increased
77 the number of LAB in fermented lamb sausage and inhibited the production of putrescine,
78 histamine, cadaverine, and tyramine but did not have significant inhibition on the production
79 of spermidine. Zhao et al. (2022) showed that the concentration of ketones, acids, and esters
80 was significantly higher in fermented sausages with *P. pentosaceus* alone, with a lower
81 concentration of aldehydes and alcohols compared to the C group, and alcohol concentrations
82 were increased by fermented sausages that solely inoculated *Staphylococcus carnosus*. Notably,
83 mixed fermentation of *P. pentosaceus* and *S. carnosus* resulted in significantly higher
84 concentrations of aldehydes, ketones, acids, esters, and alcohol. In general, mixed inoculation
85 outperforms a single inoculation. For example, Sun et al. (2016) showed that Harbin dry
86 sausages fermented with a mixed inoculum (*Staphylococcus xylosus*, *Lpb. plantarum*) inhibited
87 various biogenic amines (cadaverine, putrescine, tryptamine, 2-phenylethylamine, histamine,
88 and tyramine) significantly better than the results of a single bacterial inoculation.

89 Thus, we intend to employ mixed inoculation to improve the quality of sour meat. The pH
90 of sour meat decreases rapidly during fermentation, and eventually drop to around 4.5. We
91 concentrated on assessing strain acid tolerance in the hopes of screening strains with strong
92 acid tolerance for use in sour meat fermentation. So, 28 strains from sour meat were tested for
93 their acid tolerance ability and we selected *Lpb. plantarum* 3-19 and *P. pentosaceus* 18-1 as

94 starter culture. The effects of mixed and single inoculations on sour meat were investigated by
95 studying the physicochemical properties, bacterial diversity, biogenic amine, and VOCs during
96 sour meat fermentation, as well as the correlation analysis between the microflora structure and
97 other indexes (safety indexes and flavor indexes). This research aims to provide a starter culture
98 for sour meat fermentation and to establish the groundwork for its industrialization.

99 **2. Material and methods**

100 **2.1 Starter culture and sour meat preparation**

101 As shown in Table S1, we looked for LAB isolated from sour pork and found 28 strains in
102 the laboratory, and these two strains are included on the Chinese list of food-grade
103 microorganism. The 28 strains were subjected to acid tolerance characterization by incubating
104 them for 60 hours at medium pH of 3, 4, and 5 and their growth was determined as shown in
105 Figure S1. Among them, *Lpb. plantarum* 3-19 and *P. pentosaceus* 18-1 were found to have
106 better acid tolerance characteristics. Therefore, we selected *Lpb. plantarum* 3-19 and *P.*
107 *pentosaceus* 18-1 as starter culture for the fermentation of sour meat.

108 *Lpb. plantarum* 3-19 and *P. pentosaceus* 18-1 were incubated in MRS broth at 37 °C for
109 24 h. Then, the cell pellet was harvested by centrifuge at 10,000 g for 10 min at 4 °C. They
110 were then washed with sterile saline (0.9 % NaCl), resuspended thoroughly in 5 mL of sterile
111 saline, and adjusted to a cell concentration of 7-9 log CFU/mL.

112 The pork used in making sour meat is fresh fat and lean pork belly, purchased from Sam's
113 store on the day the sour pork is made, and rice flour and salt were purchased from a local
114 market (Dalian, China) and before using the rice flour, stir-fried them until they are golden
115 brown. Four batches of sour meat were manufactured: (1) C group, a control batch without

116 starter cultures; (2) Lp group, sour meat inoculated with *Lbp. plantarum* 3-19; (3) Pe group,
117 sour meat inoculated with *P. pentosaceus* 18-1 and (4) M group, sour meat inoculated with a
118 mixture of bacterial strains (*Lpb. plantarum* 3-19:*P. pentosaceus* 18-1 = 1:1). The preparation
119 of sour meat refers to the method of Lv et al. (2023). The pork belly was rinsed with tap water
120 and cut into pieces. The sliced meat was combined with rice flour (20 % w/w) and salt (4.5 %).
121 The bacterial inoculum for the inoculated groups (Lp, Pe, M) was 10^7 CFU/g of meat. Twelve
122 jars of samples were prepared for the C, Lp and M groups, respectively. Samples were
123 fermented at 25 °C in sealed jars and separately taken out from the center of three parallel jars
124 under sterile circumstances at 0, 7, 14 and 28 days, and they were subsequently stored at -20 °C.

125 **2.2 Determination of pH value, a_w , and amino nitrogen**

126 Samples were analyzed for physicochemical indicators in triplicate. For pH evaluation,
127 2 g samples were mixed with 20 mL of water, homogenized, and centrifuged, and the
128 supernatant was collected. The acidity of the supernatant was determined using a pH meter
129 (FE28, Mettler Toledo, Switzerland).

130 A sample of sour meat (5 g) was used to determine a_w with a water activity meter (Aqualab
131 TDL, Decagon Devices, USA).

132 The concentrations of amino nitrogen were analyzed according to Zhang's method (Zhang
133 et al., 2020) with slight modifications. First, 1 g of sour meat was homogenized with 20 mL of
134 deionized water. After centrifugation (8,000 g, 10 min, 4 °C), 10 mL of the supernatant was
135 transferred to a volumetric flask (50 mL) and adjusted to 50 mL. Then, the above solution was
136 transferred to a beaker (100 mL) and 0.1 M sodium hydroxide was used to adjust the pH to 8.2.
137 Next, 5 mL of the diluted solution was transferred to a beaker (100 mL), along with 30 mL of

138 deionized water and 10 mL of formaldehyde solution. Finally, 0.1 M sodium hydroxide was
139 used to titrate the solution until pH 9.20 was reached.

$$140 \quad \text{Amino nitrogen content (mg/100 g)} = V_a \cdot N \cdot 0.014 / [m (1/50)] \times 100$$

141 Where V_a is the consumption volume of 0.1 mol/L NaOH standard solution used to adjust
142 the solution pH from 8.2 to 9.2, mL; N is the concentration of NaOH standard solution, mol/L;
143 m is the sample weight, g; 0.014 is the milliequivalent of nitrogen.

144 **2.3 Microbiological analyses**

145 Sour meat samples were collected aseptically and stored at -80 °C for DNA collection.
146 Genomic DNA was extracted using a DNA extraction kit (MO BIO Laboratories, USA) and
147 then analyzed by agarose gel electrophoresis. DNA concentration was measured using a
148 NanoDrop2000. The V3-V4 region of the bacterial 16S rRNA gene was amplified with 343F
149 (5'-TACGGRAGGCAGCAG-3') and 798R (5'-AGGGTATCTAATCCT-3') primers.

150 The raw data was processed and analyzed according to Lv's method (Lv et al., 2019) with
151 some modifications. PCR products were purified by VAHTS™ DNA Clean Beads and
152 sequenced using the Illumina HiSeq sequencing platform (HiSeq 2500, Illumina, USA). Raw
153 reads were merged with FLASH 1.2.11, filtered with Trimmomatic 4.2, and chimeras were
154 removed with UCHIME 4.2 for valid tags. The suitable markers were then clustered using
155 USEARCH 10.0 to group those with a parameter of sequence similarity greater than or equal
156 to 97% into one OUT unit. The clustering was based on the above level of similarity, i.e., greater
157 than 97%, by using the Ribosomal Database Project (RDP) classifier (version 2.2,
158 <http://sourceforge.net/projects/rdpclassifier/>) in the Greengenes database. The raw data has
159 been uploaded to NCBI with SRP478532.

160 **2.4 Biogenic amines**

161 Biogenic amines were extracted from samples according to the method Liu et al. (2018).
162 Sample (5 g) were homogenized with 20 mL perchloric acid (0.4 mol/L) for 1 min at 4 °C in
163 an ice bath and centrifuged at 4 °C and 3,000 g for 10 min. Then, the aqueous phase was
164 collected using a volumetric flask and the residue was extracted once again using the same
165 procedure. Twice extracts were combined into the same volumetric flask and added with 0.4
166 mol/L perchloric acid to 50 mL.

167 The detection conditions of biogenic amines were performed according to Zhang et al.
168 (2019). The analysis of biogenic amine was carried out via ultrahigh-performance liquid
169 chromatography coupled (UPLC; Nexera LC-30A system, Shimaduz, Kyoto, Japan) with triple
170 quadrupole mass spectrometer (Qtrap R 5500 mass spectrometer, AB Sciex, Toronto, Canada).
171 The biogenic amines were separated using a Luna 3 µm HILIC 200A column (150 × 3.0 mm;
172 Phenomenex). Mobile phase A was 5 mmol/L ammonium acetate with a flow rate of 0.32
173 mL/min. Phase B was pure methanol flowed with a rate of 0.08 mL/min at 35 °C. The injection
174 volume was 5 µL. All experiments were performed in triplicate.

175 **2.5 Textural analysis**

176 Texture analysis was performed with TA-XT plus texture analyzer (Stable Micro Systems
177 Ltd., Surrey, UK) equipped with a P 50 probe. The following parameters were used: pre-test
178 speed 3.0 mm/s, test speed 2.0 mm/s, post-test speed 2.0 mm/s, trigger force 5 g, compression
179 of the center of the sourdough meat slices to 40 % of their previous height, and a time of 5 s
180 between contractions. All experiments were performed in six repetitions.

181 **2.6 Determination of VOCs**

182 After being steam-cooked for 20 minutes, sour meat was ground in a blender. Two grams
183 of the sample were placed in a headspace extraction vial (20 mL, 18 mm). After adding 20 μ L
184 of the internal standard, 50 mg/L cyclohexanone, each sample was left in a water bath at 60 $^{\circ}$ C
185 for 30 minutes. After that, it was extracted using solid-phase microextraction (SPME) for 40
186 minutes. The GC oven was held at an initial temperature of 35 $^{\circ}$ C for 5 min, raised to 50 $^{\circ}$ C at
187 3 $^{\circ}$ C/min and maintained for 3 min, then heated to 150 $^{\circ}$ C at 5 $^{\circ}$ C /min, and finally to 250 $^{\circ}$ C at
188 20 $^{\circ}$ C/min and kept for 5 min. The retention index (RI) was calculated using the same GC
189 conditions on 0.2 μ L of C₇-C₃₀ saturated alkane, and NIST 11 was used for VOCs' identification.
190 A semi-quantitative analysis of VOCs was performed based on the peak area of the internal
191 standard substance. Then, the odor activity value (OAV) was calculated based on $OAV = C/OT$,
192 where C is the concentration of the volatile organic compounds (VOCs) and OT is its odor
193 threshold. All experiments were performed in triplicate.

194 **2.7 Sensory evaluation**

195 The sensory evaluation panel of sour meat comprised 25 faculty members and graduate
196 students from our lab. After fermentation, the sour meat samples were cut into 5 mm thick
197 pieces and steamed for 20 minutes in a home steaming pot ($\varnothing 28 \times 19$ cm) on an induction
198 burner. The sensory examination was then completed at an ambient temperature. The evaluation
199 criteria were referenced to Lv et al. (2023) 9-point linear scale (a 9-point linear scale) in which
200 a score of 1 equals immensity dislike, a score of 5 is similar to neither like nor dislike, and a
201 score of 9 is equivalent to remarkably like. These samples were randomly coded using 1-4, and
202 the assessment members evaluated the cooked pieces. The items assessed were color, **texture**,
203 **flavor**, taste, and overall acceptability.

204 **2.8. Data analysis**

205 SPSS 23.0 (International Business Machines Corp., IL, USA) software was used for data
206 analysis. Origin 8.5 (OriginLab Corp., MA, USA) software was used to draw line plots,
207 histograms, and radar plots. Orthogonal partial least squares discriminant analysis (OPLS-DA)
208 of multivariate analysis was performed using SIMCA 14.1 (Umetrics, Sweden). Correlation
209 network plot was rendered using Cytoscape 3.9.1 software

210 **3. Results and discussion**

211 **3.1 Analysis of pH value, a_w , and amino nitrogen**

212 As shown in Fig. 1a, the pH values of the four groups of sour meat were obviously lower
213 during the early fermentation phase (0-7 days), and then the pH values tended to stabilize. The
214 pH values of the inoculated groups were lower than those of the C group at the end of
215 fermentation. This result is comparable to a study conducted by Zhang et al. (2020), which
216 discovered that the pH values of the sour meat inoculated with *Lactilactobacillus curvatus* and
217 *P. pentosaceus* were significantly lower than the control group following fermentation. The
218 growth of **unwanted** bacteria in sour meat can be inhibited by other bacteria, such as
219 *Lactiplantibacillus*, which can metabolize carbohydrates to create organic acids like lactic acid
220 (Noda et al., 2019). These bacteria multiply in an environment conducive to their growth and
221 produce organic acids, which could explain the quick pH drop at the early fermentation phase.
222 The pH value of the M group was significantly lower than that of the C group at the end of
223 fermentation. This implies that sour meat is fermented using both *Lpb. plantarum* 3-19 and *P.*
224 *pentosaceus* 18-1 significantly **increased** the acidity value of sour meat. This process effectively
225 halted the formation of **unwanted** bacteria, significantly enhancing its safety.

226 As shown in Fig.1b, a_w decreased with fermentation time. The a_w value dropped sharply
227 during the early fermentation period (0-7 d). The decrease in a_w helped maintain fermented
228 food's microbiological and quality stability (Laranjo et al., 2015). Similar trends were observed
229 in other fermented products, such as fermented sausages (Wang et al., 2013) and fermented fish
230 (Gao et al., 2016). It has been reported that a decrease in pH induces a change in protein
231 conformation, leading to a reduction in the water-holding capacity of the sample (Gómez and
232 Lorenzo, 2013), and the trend of a_w in our experiment is consistent with pH. In the end, there
233 was no significant difference in the a_w of the four samples, indicating that the a_w of the sour
234 meat would not be considerably impacted by the addition of *Lpb. plantarum* 3-19 and *P.*
235 *pentosaceus* 18-1.

236 All four groups of samples' AN tended to rise during fermentation, as seen in Fig. 1c and
237 peaked at the end of fermentation (28 d). The concentrations of AN were considerably greater
238 in the Lp, Pe, and M groups than in the C group during the middle and late stages of
239 fermentation (14–28 d). Hu et al. (2020) found that LAB in traditional dry sausages from the
240 Northeast region exhibited high protease activity. These enzymes helped break down proteins
241 into peptides, degrading them into oligopeptides. At the same time, LAB used small molecule
242 peptides such as oligopeptides to generate free amino acids or peptide derivatives, providing
243 essential precursors for the VOCs of the product (Wang et al., 2022). In our research, *Lpb.*
244 *plantarum* 3-19 and *P. pentosaceus* 18-1 may have similar effects, such as protease and
245 peptidase secretion, enhancing the release of AN from sour meat.

246 **3.2 Microbial community analysis**

247 Fig. 2 shows the bacterial succession (top 20 relative abundance) throughout the
248 fermentation of sour meat. *Acinetobacter* (11.24%) and *Brochothrix* (8.48%) were the two most
249 common bacteria in the sour meat at day 0. This is consistent with the research results reported
250 by Lv et al.(2023). *Acinetobacter* is commonly found in various environmental sources like
251 water and soil (Casaburi et al., 2014), while *Brochothrix* is typically recognized as spoilage-
252 causing microorganisms in meat products (Zhao and Eun, 2020). These microbes primarily
253 originate from the environment and raw materials before fermentation. During the fermentation
254 process, *Lactococcus garvieae*, *Lpb. plantarum*, *Latilactobacillus sakei*, and *Weissella* gradually
255 became the prevailing organisms in the C group. By the end of fermentation, their proportions
256 were 25.26%, 23.94%, 11.85%, and 5.07%, respectively, alongside minor quantities of *Serratia*,
257 *Macrococcus*, and other bacteria.

258 After fermentation, the dominant bacteria in the Lp and Pe groups were *Lpb. plantarum*
259 and *Pediococcus*, respectively. *Lpb. plantarum* and *Pediococcus* were the dominant bacteria in
260 M group, with relative abundances of 49.79% and 33.20% at the end of fermentation. It
261 demonstrated that *Lpb. plantarum* 3-19 and *P. pentosaceus* 18-1, or both, were co-inoculated,
262 they could quickly become the dominant bacterium. Furthermore, the mixed inoculation group
263 showed no discernible inhibition between the two species.

264 During the fermentation process of the Pe group, *Pediococcus* was found to be the
265 dominant bacterium, with *Enterococcus* present at a lower relative abundance (2.17-8.52%).
266 *Enterococcus* remained at a relative abundance of 5.42% at the end of fermentation. This
267 suggests that even though *Pediococcus* was the dominant bacterium, it may not have effectively
268 inhibited the growth of *Enterococcus*. *Lpb. plantarum* are the dominant bacteria in Lp and M

269 groups. During fermentation, the Lp and M groups experienced a significant decrease in
270 *Enterococcus* content (0.03-0.75%), resulting in a final relative abundance of 0.09% and 0.19%.
271 *Lpb. plantarum* may effectively prevent the growth of *Enterococcus*. Jung et al. (2019) found
272 that *Lpb. plantarum* could inhibit *Enterococcus* biofilm formation and disrupt the preformed
273 biofilm. Thus, *Lpb. plantarum* can inhibit the growth of unwanted bacteria and benefit the
274 safety of the product.

275 **3.3 Analysis of biogenic amines**

276 Biogenic amines are the product of the amination of aldehydes and ketones and the
277 decarboxylation of amino acids (Gao et al., 2023), which is commonly found in fermented food.
278 As shown in Table 1, six biogenic amines were detected in different sour meat samples. In C
279 group, the total biogenic amines content was 992.96 ± 14.07 mg/kg. The total biogenic amine
280 content in the Lp, Pe, and M groups was 1.65, 2.57, and 3.02 times lower than in the C group.
281 The results showed that the inhibition of biogenic amines had a more pronounced effect in the
282 group inoculated with the mixed starter culture compared to the other groups. Sara et al. (2000)
283 investigated the effect of single and mixed fermentation on biogenic amines in dry sausages,
284 and the results showed that mixed fermentation significantly reduced the accumulation of
285 biogenic amines. This may be due to *Lpb. plantarum* 3-19 and *P. pentosaceus* 18-1 can compete
286 with other bacteria containing amino acid decarboxylase, and mixed fermentation provides
287 advantages for both strains, further reducing the accumulation of biogenic amines (Sun et al.,
288 2016).

289 Current research and legislation do not contain precise requirements for the total amount
290 of biogenic amines in meat products. Requirements for specific biogenic amine levels vary

291 from country to country. In the United States, the histamine content in aquatic products should
292 not exceed 50 mg/kg (Hazards, 2011), while in the European Union, the histamine content in
293 food products should be kept below 100 mg/kg and tyramine content between 100-800 mg/kg
294 (Shalaby, 1996). In our country, high-histamine fish should contain less than 400 mg/kg of
295 histamine, while other marine fish should contain less than 200 mg/kg of histamine (GB 2733-
296 2015). In our study, the biogenic amine content complied with these regulations. Sun et al.
297 (2016) observed increasing levels of biogenic amines in all experimental groups during
298 fermentation, and the total biogenic amine content at the end of the fermentation was above
299 250 mg/kg. Similarly, Komprda et al. (2009) noted that the total biogenic amine content in
300 sausages at the end of fermentation was more than 550 mg/kg and putrescine more than 150
301 mg/kg.

302 Before fermentation, the samples contained 3.55 ± 0.04 mg/kg histamine; by the time
303 fermentation was finished, the histamine content in the inoculation group was significantly
304 lower than that in the control group ($p < 0.05$). It suggests that both strains can block histamine
305 more effectively. Inoculated starter could compete with other bacteria containing histamine
306 decarboxylase, decreasing the accumulation of histamine (Lee et al., 2016). On the other hand,
307 *Lpb. plantarum* and *P. pentosaceus* may contain histamine oxidase, which degrades histamine
308 formed during fermentation (Li et al., 2021). Also, the acidity of the meat matrix is another
309 factor that could hinder biogenic amine formation (Maijala and Eerola, 1993).

310 Following fermentation, the putrescine content experienced a notable elevation of 287.22
311 mg/kg within the C group. Despite increases observed in the other groups, these increments
312 were comparatively lesser than the observed rise in the C group. This implies a distinct

313 inhibitory effect of *P. pentosaceus* 18-1 on putrescine levels in sour meat. The formation of
314 putrescine is usually associated with the activity of decarboxylase-positive contaminating
315 microorganisms (*Enterobacteriaceae*). *P. pentosaceus* considerably reduced the buildup of
316 putrescine in tilapia sausages by preventing the growth of *Citrobacter*, *Streptococcus*, and
317 *Enterobacteriaceae*, according to Li et al. (2021). Therefore, *P. pentosaceus* may have a similar
318 effect in inhibiting putrescine in this experiment. However, at the end of fermentation, the Pe
319 group's tyramine content was significantly higher ($p < 0.05$) than the remaining groups. The
320 main reason for tyramine production is the presence of tyrosine decarboxylase-producing
321 microorganisms (Kim and Hur, 2018). According to the results above, *P. pentosaceus* 18-1 may
322 be selective and capable of inhibiting putrescine formation but not tyramine generation.
323 However, compared to the Pe group, the M group inhibited biogenic amines more significantly,
324 such as tyramine, cadaverine and phenethylamine. This suggests that the combined inoculation
325 may have a compound inhibitory impact on the accumulation of biogenic amines. Sun et al.
326 (2016) investigated the effects of single versus dual bacterial fermentation (*S. xylosum* and *Lpb.*
327 *plantarum*) on biogenic amines in Harbin dry sausages. This study showed that mixed bacterial
328 fermentation produced better results than single bacterial fermentation.

329 **3.4 Texture analysis**

330 Table 2 displays the textural characteristics of sour meat from several additive groups.
331 Every group's hardness trended to rise and eventually level off with time. The early
332 fermentation phase showed a considerable increase ($p < 0.05$) in the hardness of sour meat. El
333 Adab et al. (2015) suggested that the increase in hardness was mainly due to protein coagulation
334 at low pH and reduced a_w . After combining the data for pH and a_w , it was possible to see that

335 during the early fermentation phase, both indexes exhibited a sharply declining pattern before
336 stabilizing, which was in line with the rising trend of sour meat hardness values. The springiness
337 of sour meat showed a decreasing trend with the fermentation time. Zhao et al. (2022)
338 discovered that certain muscle fibers can attach to lipids through the action of bacteria and their
339 enzymes, which causes protein hydrolysis. In fermented meat, this process results in tissue
340 relaxation and a loss of elasticity. At the end of fermentation, the difference in cohesiveness
341 between each inoculated group and the C group was insignificant ($p > 0.05$), indicating that the
342 addition of bacteria did not significantly affect the hardness of sour meat. Chewiness can
343 comprehensively show the sensory quality of meat. As shown in Table 2, the chewiness tended
344 to increase and decrease with the increase in fermentation time. At the end of fermentation, the
345 Pe group had the highest chewiness, followed by the Lp group, significantly different from
346 group C ($p < 0.05$). In conclusion, fermentation can make sour meat hardness increase and
347 springiness decrease, while adding LAB can help improve the chewiness of sour meat.

348 **3.5 Analysis of VOCs**

349 A total of 45 VOCs, including 7 acids, 3 ketones, 12 esters, 6 alcohols, and 17 aldehydes
350 were detected during the fermentation process (Table S2). At the beginning of fermentation, the
351 VOCs in the sour meat were 913.32 ± 307.64 $\mu\text{g}/100$ g. All groups' total volatile compound
352 content showed an increasing trend with fermentation. At the end of fermentation, the VOCs in
353 C, Lp, Pe, and M groups were 10.11, 11.56, 12.45, and 13.39 times higher than those at the
354 beginning of fermentation. Aldehydes, produced mainly by the oxidative breakdown of lipids
355 or further reacted by creating chemicals to generate other compounds, are characterized by high
356 volatility and low threshold values (Zhao et al., 2016). Alcohols and acids are esterified, mainly

357 resulting in esters, and making food fruity (Montanari et al., 2016). Alcohols are often produced
358 in fermented meat and are involved in various metabolic pathways such as amino acid
359 metabolism, lipid oxidation, and methyl ketone reduction, so they are essential in aroma
360 formation (Sidira et al., 2015). These three compounds constitute the main components of
361 VOCs in sour meat.

362 Alcohols are one of the main components of VOCs in sour meat. Only two alcohols were
363 detected in the sample at 0 d with a total content of $25.88 \pm 1.17 \mu\text{g}/100 \text{ g}$. At the end of
364 fermentation, the total amount of alcohols in C, Lp, Pe, and M were 11.74, 16.26, 28.63, and
365 19.45 times more than that of the 0 d, respectively. Thus, it can be seen that alcohol accumulated
366 in the sour meat after fermentation, and the total amount of alcohol in the inoculated groups
367 was higher than that in the control group.

368 Aldehydes are another significant component of VOCs in sour meat. Only four aldehydes
369 were detected in the 0 d sample, including hexanal, (E)-2-decanal, (E, E)-2,4-decadienal, and
370 hexadecane were detected in the fermentation samples, suggesting that other aldehydes may
371 have been produced by fermentation. After fermentation, the Lp, Pe, and M groups had higher
372 hexanal, heptanal, and octanal content than the C group. M group had the highest hexanal,
373 heptanal, and octanal content, reaching 271.77 ± 171.45 , 223.16 ± 95.96 , and 542.83 ± 510.12
374 $\mu\text{g}/100 \text{ g}$, respectively. Hexanal can indicate oxidation level in fermented meat and imparts a
375 green grassy odor. At the same time, straight-chain aldehydes, such as heptanal and octanal,
376 with floral and fruity flavors, contribute to the flavors of the food (Latorre-Moratalla et al.,
377 2011). The higher content of aldehydes in M group samples may be due to the beneficial
378 synergistic effect of *Lpb. plantarum* 3-19 and *P. pentosaceus* 18-1 on forming aldehydes.

379 Esters were the second largest category of VOCs after sour meat fermentation. Following
380 fermentation, the samples had more than 10 esters, compared to only five in the 0 d sample.
381 This suggests that fermentation can increase the variety of esters in sour meat. Gao et al. (2016)
382 reported that sour fish samples inoculated with *Lactiplantibacillus* had a more extensive ester
383 content than the control group. This suggests that *Lactiplantibacillus* possesses esterification
384 activity, which encourages the formation of ester in fermented meat. Pe and M groups had ester
385 contents that were 1.65 and 1.12 times higher than the C group. Medium-chain fatty acid esters
386 (MCFA), such as ethyl caprylate, have been widely reported in many fermented foods due to
387 their low threshold value and essential contribution to product flavor (Hu et al., 2018). Ethyl
388 caprylate is the characteristic volatile compound of sour meat, providing a pleasant aroma
389 (fruity and floral) to the product (Giri et al., 2010). It is indicated that adding *Lpb. plantarum* 3-
390 19 and *P. pentosaceus* 18-1 will promote the production of fruity volatiles in sour meats.

391 OAV values were calculated for each compound to determine the main contributing
392 compounds in the flavor of sour meat (Table 3). The samples contained 45 VOCs, with 7, 17,
393 19, 24, and 21 VOCs in the sour meat samples of groups 0 d, C, Lp, Pe, and M, respectively.
394 These results suggested that the inoculation with *Lpb. plantarum* 3-19 and *P. pentosaceus* 18-1
395 might benefit the production of VOCs in sour meat. Among them, heptanal, octanal,
396 phenylacetaldehyde, nonanal, (E)-2-nonanal, decanal, and (E, E)-2,4-decadienal had larger
397 OAV values (>20,000), and these seven substances may contribute more to the flavor of sour
398 meat.

399 **3.6 Correlation analysis**

400 Fig. 3a shows the relationship between microorganisms and flavor under the OPLS-DA

401 mode. The R^2 and Q^2 of the model were 0.667 and 0.747, indicating that the model-fitting
402 degree was satisfied for data analysis. The top 20 microorganisms in sour meat in terms of
403 abundance and essential VOCs ($OAV > 1$) were⁹ selected for variable importance in projection
404 (VIP) analysis. Bacteria with higher VIP scores were *Lpb. plantarum*, *Enterococcus*,
405 *Latilactobacillus*, and *Pediococcus*, indicating that they are the critical bacteria that affect the
406 flavors of sour meat.

407 Correlation analysis was performed for critical bacteria (VIP scores > 1) and biogenic
408 amines affecting the VOCs of sour meat as shown in Fig. 3b. The previous study reported
409 fermented sausages inoculated with *Pediococcus* had a higher content of ketones, acids, and
410 esters (Zhao et al., 2022). *Pediococcus*, as a dominant bacterium in Pe and M groups, showed
411 a significant positive correlation with (E)-2-octen-1-ol ($r = 0.997$), oleic acid ($r = 0.739$), ethyl
412 caprylate ($r = 0.767$) and negatively correlated with tryptamine ($r = -0.822$). *Pediococcus*
413 promoted the formation of characteristic flavor substances in sour meat while inhibiting
414 tryptamine production. It has been reported that in addition to improving flavor by *P.*
415 *pentosaceus*, it could also promote the maturation of meat products and speed up the production
416 process (Corral et al., 2016). *Lpb. plantarum*, as a dominant bacterium in Lp group, showed a
417 significant negative correlation with tryptamine ($r = -0.822$) and phenylethylamine ($r = -0.771$);
418 this phenomenon was similar to that reported by Sun et al. (2016), *Lpb. plantarum* was
419 positively correlated with octanoic acid ($r = 0.969$), (E)-2-nonenal ($r = 0.873$). This indicates
420 that *Lpb. plantarum* significantly promotes the accumulation of octanoic acid and (E)-2-
421 nonenal in sour meat.

422 In conclusion, the dominant bacteria (*Lpb. plantarum* and *P. pentosaceus*) had a key

423 influence on the excellent quality features of sour meat, mainly reflected in promoting the
424 formation of VOCs and reducing the accumulation of biogenic amines.

425 **3.7 Sensory evaluation**

426 Figure 4 shows the sensory evaluation results for sour meat in terms of color, texture,
427 flavor, taste, and overall acceptability. In terms of color, the Lp group scored the highest,
428 followed by the M and Pe groups. The Lp, Pe, and M groups had higher texture scores than the
429 C group, which had lower scores ($p < 0.05$). The M group had a taste score of 7.9,
430 outperforming the others. Overall acceptability ratings for the C, Lp, Pe, and M groups were
431 7.2, 7.4, 7.4, and 7.7, with the M group receiving the highest grade. Thus, the inoculation with
432 LAB strains improved the sensory rating of sour meat, with group M having the best overall
433 acceptability.

434 **4. Conclusion**

435 This study investigates the impact of *Lpb. plantarum* 3-19 and *P. pentosaceus* 18-1,
436 isolated from traditional sour meat, on the quality of sour meat. During fermentation, the pH
437 and a_w of all four sample groups showed a decreasing trend, while the content of AN
438 significantly increased. The addition of the two strains inhibited the accumulation of biogenic
439 amines; the total amount of biogenic amines in the M group was 328.92 ± 19.43 , which was
440 lower than that of the other groups at the fermentation endpoint. GC-MS analysis revealed that
441 adding strains facilitated the generation of VOCs in sour meat, notably observing the richest
442 VOCs in the M group at the end of fermentation. Furthermore, the M group exhibited a higher
443 overall acceptance level in sensory evaluation and received the highest total score. Therefore,
444 collectively, the mixed fermentation agents containing *Lpb. plantarum* 3-19 and *P. pentosaceus*

445 18-1 could be an ideal choice to enhance the quality of sour meat.

446

447 **CRedit authorship contribution statement**

448 Hao Shang: Formal analysis, Investigation, Data curation, Writing-Original Draft,
449 Writing-Reviewing and Editing. Ying Yue: Data curation, Methodology. Bingrui Guo: Data
450 curation. Chaofan Ji: Writing-review, Methodology. Sufang Zhang: Writing-review. Liang
451 Dong: Investigation, Resources. Ilario Ferrocino: Methodology, Resources. Luca Simone
452 Cocolin: Methodology, Resources. Xinping Lin: Conceptualization, Supervision, Project
453 administration.

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1 **Table 1**

2

Biogenic amine contents of sour meat samples with or without starter culture.

Biogenic amine (mg/kg)	0 d	28 d			
		C	Lp	Pe	M
Histamine	3.55±0.04 ^b	25.40±0.73 ^a	3.62±0.05 ^b	3.51±0.01 ^b	3.54±0.02 ^b
Putrescine	36.28±0.10 ^c	323.50±11.61 ^a	295.35±39.30 ^a	54.86±7.45 ^c	120.54±17.06 ^b
Tyramine	4.61±0.23 ^c	158.13±18.58 ^b	156.47±13.90 ^b	252.91±25.41 ^a	169.65±1.31 ^b
Cadaverine	8.75±2.01 ^{cd}	391.28±5.91 ^a	58.35±7.07 ^b	22.59±1.70 ^c	5.83±0.64 ^d
Tryptamine	24.10±0.02 ^b	89.00±3.63 ^a	81.68±8.12 ^a	25.00±0.07 ^b	25.94±0.13 ^b
Phenethylamine	0.10±0.02 ^c	4.79±0.05 ^b	5.98±4.16 ^b	26.98±4.16 ^a	3.42±0.27 ^{bc}
Total	77.39±2.32 ^d	992.96±14.07 ^a	601.45±72.60 ^b	385.85±38.8 ^c	328.92±19.43 ^c

3

^{a-d} Values in a line with different lowercase letters are significantly different ($p < 0.05$). For abbreviations, see Figure 1.

4

5 **Table 2**

6

Texture parameters of sour meat with or without starter culture during the fermentation.

Fermentation days	Group	Hardness/g	Springiness	Chewiness/g	Resilience	Cohesiveness /g. s
0 d	C	544.67±57.12 ^{Ab}	0.87±0.05 ^{Aa}	271.85±63.38 ^{Ac}	0.37±0.02 ^{Aa}	0.77±0.02 ^{Aa}
	Lp	531.16±39.96 ^{Ab}	0.89±0.08 ^{Aa}	277.28±104.40 ^{Ab}	0.23±0.01 ^{Ba}	0.73±0.02 ^{Ba}
	Pe	540.02±22.89 ^{Ab}	0.78±0.04 ^{Aa}	254.43±49.47 ^{Ab}	0.30±0.06 ^{Aa}	0.74±0.01 ^{Aa}
	M	541.57±56.42 ^{Aa}	0.78±0.04 ^{Aa}	291.54±64.30 ^{Ab}	0.29±0.01 ^{Ba}	0.67±0.01 ^{Cb}
7 d	C	1084.69±54.66 ^{Aa}	0.67±0.12 ^{Ab}	565.69±58.34 ^{Aa}	0.21±0.02 ^{Abc}	0.68±0.07 ^{Aa}
	Lp	722.33±79.12 ^{Aab}	0.73±0.04 ^{Aa}	666.11±172.10 ^{Aa}	0.23±0.01 ^{Aa}	0.74±0.04 ^{Aa}
	Pe	924.54±229.64 ^{Aa}	0.75±0.04 ^{Aa}	727.87±98.53 ^{Aa}	0.27±0.09 ^{Aa}	0.73±0.02 ^{Aa}
	M	786.80±331.67 ^{Aa}	0.74±0.02 ^{Aa}	557.96±51.28 ^{Aa}	0.22±0.02 ^{Ab}	0.73±0.03 ^{Aa}
14 d	C	1163.03±48.36 ^{Aa}	0.69±0.05 ^{Ab}	621.73±42.27 ^{Aa}	0.22±0.00 ^{Ab}	0.72±0.06 ^{Aa}
	Lp	822.46±61.33 ^{Aa}	0.71±0.04 ^{Aa}	605.26±89.78 ^{Aa}	0.21±0.01 ^{Aa}	0.75±0.02 ^{Aa}
	Pe	777.57±87.86 ^{Ab}	0.70±0.06 ^{Aa}	762.02±116.56 ^{Aa}	0.22±0.04 ^{Aa}	0.71±0.04 ^{Aa}
	M	739.80±261.52 ^{Aa}	0.79±0.05 ^{Aa}	659.85±116.52 ^{Aa}	0.22±0.01 ^{Ab}	0.76±0.00 ^{Aa}
28 d	C	1070.85±83.51 ^{Aa}	0.65±0.06 ^{Ab}	443.85±35.10 ^{Cb}	0.18±0.01 ^{Bc}	0.72±0.02 ^{Aa}
	Lp	776.12±218.26 ^{Aab}	0.68±0.04 ^{Aa}	588.23±90.99 ^{Ba}	0.20±0.00 ^{ABa}	0.74±0.01 ^{Aa}
	Pe	749.00±224.78 ^{Aab}	0.69±0.03 ^{Aa}	711.58±6.26 ^{Aa}	0.22±0.02 ^{Aa}	0.70±0.05 ^{Aa}
	M	721.25±19.38 ^{Aa}	0.74±0.05 ^{Aa}	453.85±20.96 ^{Cb}	0.21±0.01 ^{ABb}	0.74±0.01 ^{Aa}

7 ^{a-c} Values in the same sample group are significantly different ($p < 0.05$). ^{A-C} Values in the different sample groups are significantly different at the same fermentation
8 period ($p < 0.05$). For abbreviations, see Figure 1.

9

10 **Table 3**
 11 The OAV value of the key volatile compounds (OAV > 1) in sour meat with and without starter
 12 culture during the fermentation.

Entry	Volatile compounds	Threshold value (µg/100 g)	OAV				
			0d	C	Lp	Pe	M
1	1-Octen-3-ol	0.03	0.00	5551.11	0.00	0.00	0.00
2	(E)-2-Octen-1-ol	0.20	0.00	0.00	185.60	1410.55	442.65
3	Phenylethyl Alcohol	1.60	4.25	51.36	60.64	67.53	69.69
4	2-Nonen-1-ol	1.30	0.00	0.00	0.00	90.82	130.20
5	Hexanal	2.50	7.83	11.51	32.43	45.22	108.71
6	Heptanal	0.01	0.00	5508.89	5828.89	7297.78	24795.56
7	(Z)-2-Heptenal	2.20	0.00	0.00	0.00	26.20	0.00
8	Benzaldehyde	0.85	0.00	142.02	356.42	167.74	28.87
9	(E)-2-Heptenal	28.00	0.00	0.00	0.00	3.25	0.00
10	Octanal	0.00	0.00	0.00	22425.00	39177.50	135707.50
11	Phenylacetaldehyde	0.02	0.00	39154.12	9427.65	12401.76	2085.29
12	(E)-2-Octenal	0.03	0.00	3380.00	4608.52	13698.15	1344.07
13	Nonanal	0.03	0.00	106013.46	11660.00	5464.62	3829.62
14	(E)-2-Nonenal	0.00	0.00	33522.22	3537011.11	35588.89	4450766.67
15	Decanal	0.03	0.00	4914.62	1821.54	10167.69	3561.15
16	(E)-2-Decenal	0.03	821.11	7170.00	717.04	3300.00	17487.78
17	(E,E)-2,4-Decadienal	0.02	4275.65	19941.30	32634.78	64013.04	15280.00
18	2,4-Decadienal	21.50	0.00	0.00	0.00	3.03	0.00
19	Butanoic acid	0.20	51.15	206.30	1003.10	1139.20	1798.15
20	Hexanoic acid	0.40	0.00	121.05	225.30	267.13	56.68
21	Octanoic acid	0.05	0.00	1825.49	5872.16	155.49	3181.96
22	Dodecanoic acid	1.00	3.49	169.98	42.07	539.68	626.39
23	Oleic Acid	440.00	0.04	0.00	0.05	0.49	0.58
24	Ethyl hexadecanoate	1.00	437.05	611.86	26.04	100.77	252.90
25	Ethyl caprylate	40.00	0.00	0.00	2.53	3.55	1.66

1 **Figure Captions**

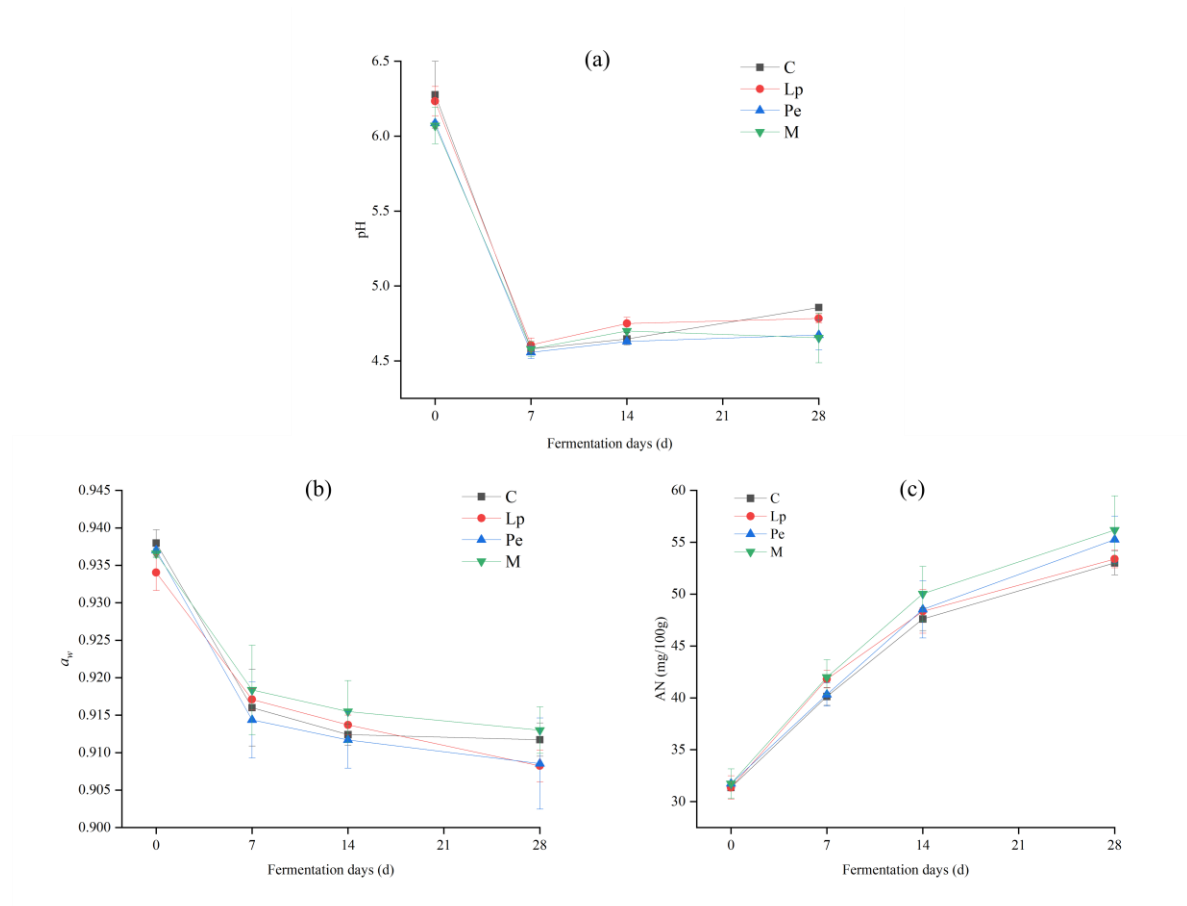
2 **Fig. 1.** Dynamic changes of pH (a), a_w (b) and amino nitrogen (AN) (c) of sour meat with or without starter culture during the fermentation process. C: control, naturally
3 fermented; Lp: sample inoculated *Lactiplantibacillus plantarum* 3-19; Pe: sample inoculated *Pediococcus pentosaceus* 18-1; M: sample inoculated both *Lpb.*
4 *plantarum* 3-19 and *P. pentosaceus* 18-1.

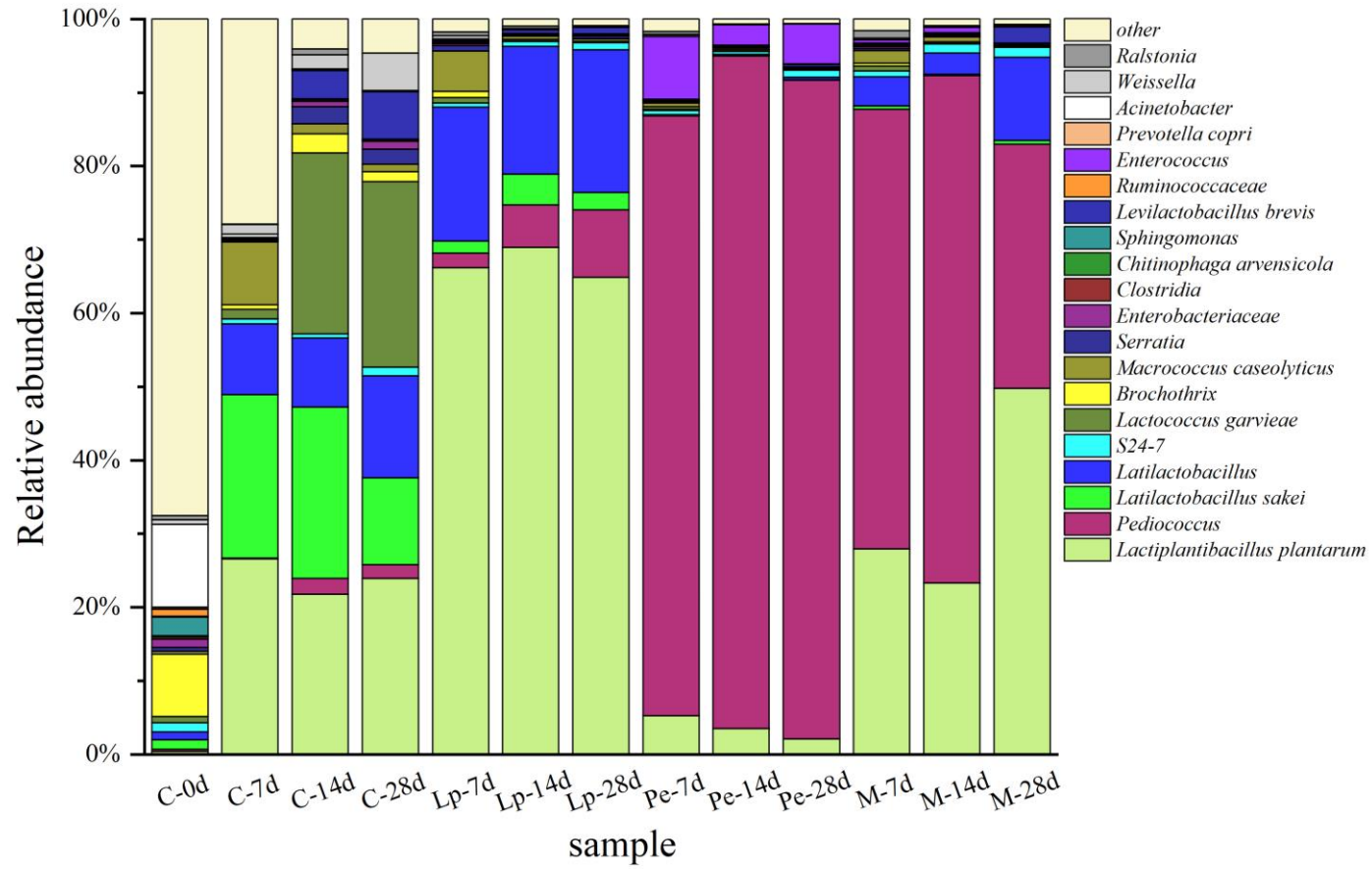
5 **Fig. 2.** The bacterial succession (relative abundance of TOP 20) in sour meats during the fermentation with or without starter culture. For abbreviations, see Figure 1.

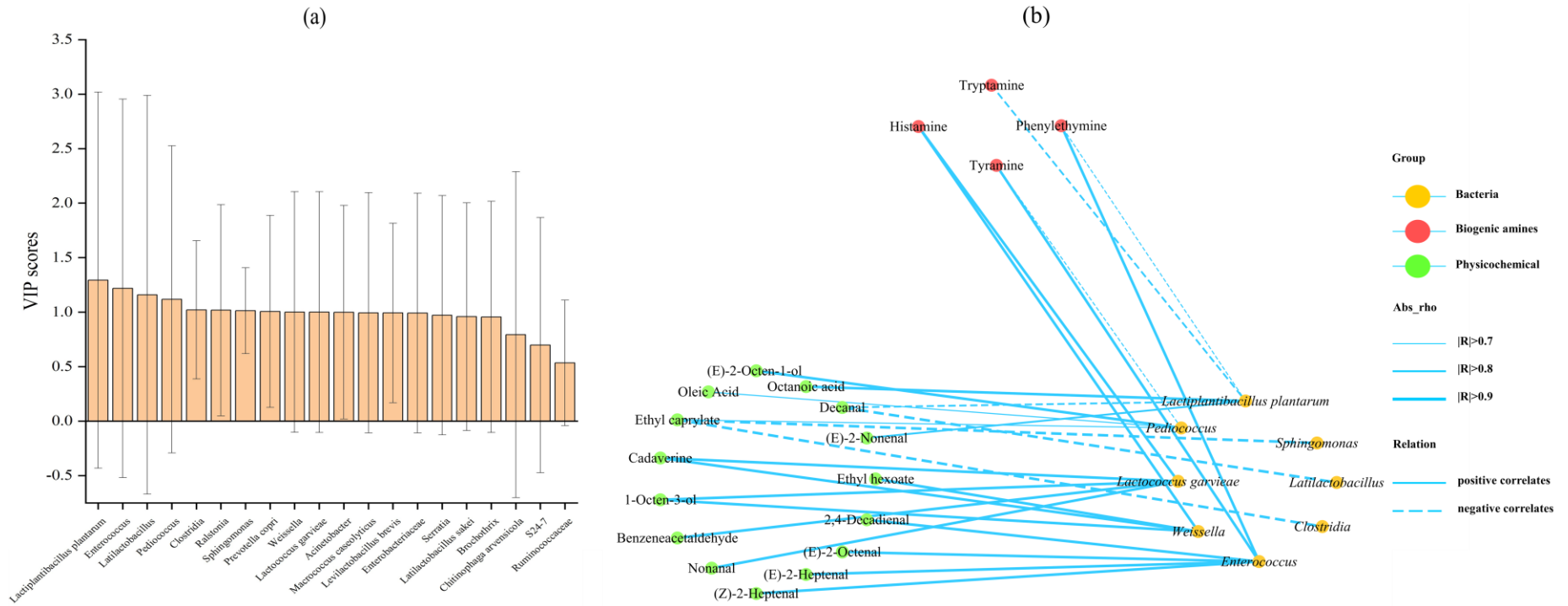
6 **Fig. 3.** (a) VIP plot of microbial community (defined as X matrix) vs. flavor (defined as Y matrix). (b) A co-occurrence network chart showing the positive correlates
7 (solid lines) and negative correlates (dotted lines).

8 **Fig. 4.** Sensory evaluation results of sour meat with or without starter culture. For abbreviations, see Figure 1.

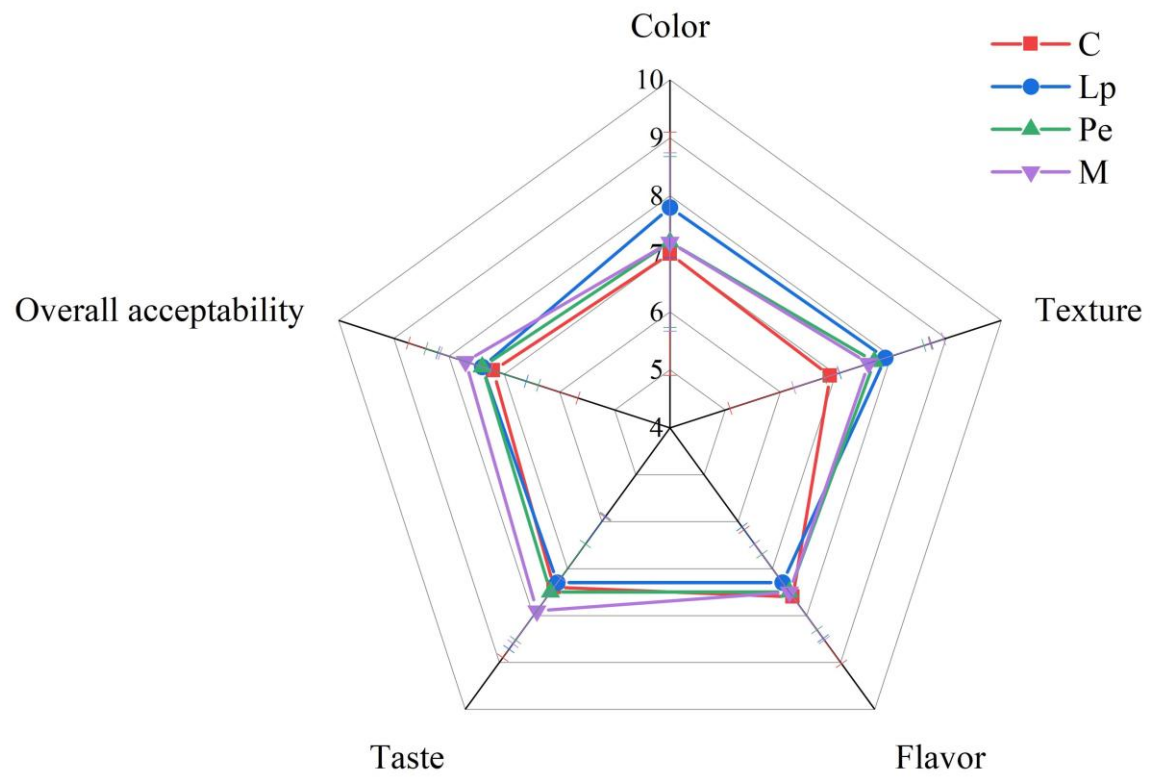
9 Fig. 1.







15 Fig. 4.



1 **Supplementary data**

2 **The effects of *Lactiplantibacillus plantarum* 3-19 and *Pediococcus pentosaceus* 18-1 on preventing the**
3 **accumulation of biogenic amines and promoting the production of volatile organic compounds during sour**
4 **meat fermentation**

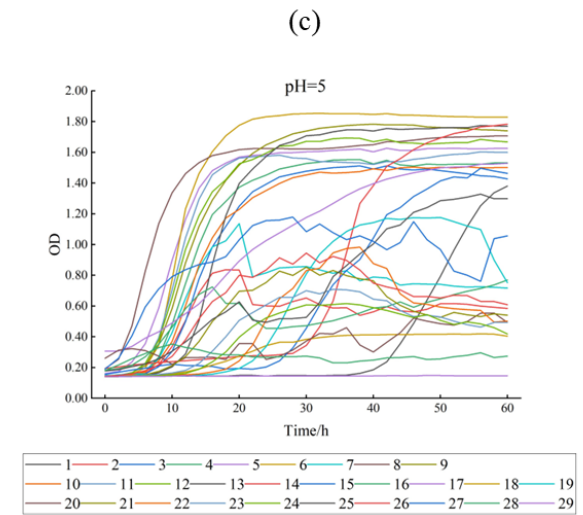
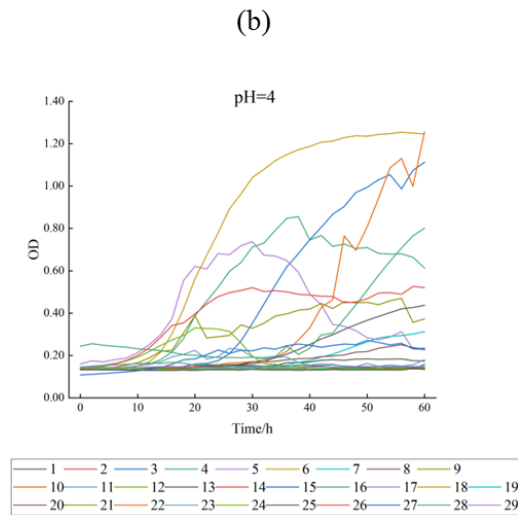
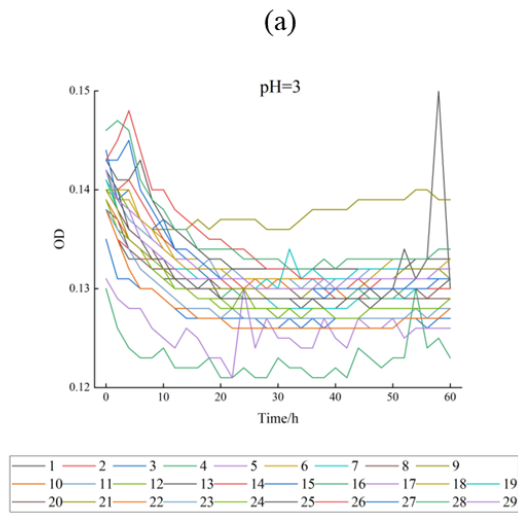
5 Hao Shang^a, Ying Yue^a, Bingrui Guo^a, Chaofan Ji^a, Sufang Zhang^a, Liang Dong^a, Ilario Ferrocino^b, Luca Simone Cocolin^b, Xinping Lin^{a,*}

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Table S1 Strain information

Serial Number	Strain	source
1	<i>Lactiplantibacillus plantarum</i> 18-1	Sour meat
2	<i>Lactiplantibacillus plantarum</i> 3-10	Sour meat
3	<i>Lactiplantibacillus plantarum</i> 2-29	Sour meat
4	<i>Lactiplantibacillus plantarum</i> 1-24	Sour meat
5	<i>Lactiplantibacillus plantarum</i> 2-7	Sour meat
6	<i>Lactiplantibacillus plantarum</i> 3-19	Sour meat
7	<i>Lactiplantibacillus plantarum</i> 3-10	Sour meat
8	<i>Pediococcus pentosaceus</i> 18-1	Sour meat
9	<i>Lactiplantibacillus plantarum</i> 2-5	Sour meat
10	<i>Lactiplantibacillus plantarum</i> 3-22	Sour meat
11	<i>Lactiplantibacillus plantarum</i> 2-22	Sour meat
12	<i>Pediococcus pentosaceus</i> 1-26	Sour meat
13	<i>Lactiplantibacillus plantarum</i> 3-14	Sour meat
14	<i>Lactiplantibacillus plantarum</i> 3-6	Sour meat
15	<i>Pediococcus pentosaceus</i> 15-1	Sour meat
16	<i>Pediococcus pentosaceus</i> 14-1	Sour meat
17	<i>Pediococcus pentosaceus</i> 13-1	Sour meat
18	<i>Pediococcus pentosaceus</i> 16-1	Sour meat
19	<i>Pediococcus pentosaceus</i> 19-1	Sour meat
20	<i>Pediococcus pentosaceus</i> 11-1	Sour meat
21	<i>Pediococcus pentosaceus</i> 5-1	Sour meat
22	<i>Pediococcus pentosaceus</i> 6-1	Sour meat
23	<i>Pediococcus pentosaceus</i> 7-1	Sour meat
24	<i>Pediococcus pentosaceus</i> 8-1	Sour meat
25	<i>Pediococcus pentosaceus</i> 12-1	Sour meat
26	<i>Pediococcus pentosaceus</i> 2-1	Sour meat
27	<i>Pediococcus pentosaceus</i> 3-1	Sour meat
28	<i>Pediococcus pentosaceus</i> 4-1	Sour meat



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Figure S1 Growth curves of 28 strains at pH 3(a), 4 (b)and 5(c). For strain number in the legend, see Table S1.

Table S2 The content of VOCs in sour meats during the fermentation.

VOCs ($\mu\text{g}/100\text{g}$)	0d	C	Lp	Pe	M
1-Octen-3-ol	N	149.88 \pm 81.35	N	N	N
2-Ethylcyclohexanol	N	N	137.97 \pm 36.68	157.64 \pm 96.70	N
(E)-2-Octen-1-ol	N	N	37.12 \pm 20.04	282.11 \pm 94.94	88.53 \pm 20.33
Phenylethyl alcohol	6.80 \pm 1.17	82.17 \pm 25.26	97.03 \pm 50.96	108.05 \pm 66.54	111.51 \pm 42.87
2-Nonen-1-ol	N	N	N	118.07 \pm 106.27	169.26 \pm 10.13
2-Heptanol	19.08 \pm 9.99	71.87 \pm 9.95	148.76 \pm 64.10	75.19 \pm 18.08	134.09 \pm 83.51
Alcohols total	175.72 \pm 87.12	4911.38 \pm 2234.08	6657.4 \pm 1294.4	3337.14 \pm 1828.94	6247.4 \pm 3121.49
Hexanal	19.57 \pm 7.77	28.77 \pm 17.78	81.07 \pm 15.94	113.04 \pm 62.08	271.77 \pm 171.45
Heptanal	N	49.58 \pm 31.2	52.46 \pm 36.08	65.68 \pm 44.32	223.16 \pm 95.96
3-Methyl-hexanal,	N	29.42 \pm 25.89	31.17 \pm 25.72	53.02 \pm 33.54	38.38 \pm 22.33
(Z)-2-Heptenal	N	N	N	57.63 \pm 30.45	N
Benzaldehyde	N	120.72 \pm 66.71	302.96 \pm 215.05	142.58 \pm 48.78	24.54 \pm 6.65
4-Methylcyclohex-3-enecarbaldehyde	N	37.27 \pm 29.18	N	N	N
(E)-2-Heptenal	N	N	N	90.97 \pm 39.95	N
Octanal	N	N	89.70 \pm 30.58	156.71 \pm 54.04	542.83 \pm 510.12
Phenylacetaldehyde	N	665.62 \pm 94.34	160.27 \pm 34.58	210.83 \pm 69.57	35.45 \pm 25.19
2-Octenal	N	91.26 \pm 46.27	124.43 \pm 68.92	369.85 \pm 242.25	36.29 \pm 19.08
Nonanal	N	2756.35 \pm 1360.65	303.16 \pm 133.81	142.08 \pm 91.28	99.57 \pm 13.77

2-Nonenal,	N	30.17±22.75	3183.31±361.25	32.03±7.82	4005.69±1427.92
Decanal	N	127.78±103.28	47.36±27.43	264.36±229.16	92.59±82.07
(E)-2-Decenal	22.17±12.36	193.59±45.12	19.36±7.66	89.10±41.35	472.17±460.14
(E,E)-2,4-Decadienal	98.34±49.39	458.65±167.03	750.60±121.79	1472.30±786.80	351.44±289.86
2,4-Decadienal	N	N	N	65.07±43.82	N
Hexadecane	35.64±17.60	322.20±223.88	1511.55±215.59	11.89±3.73	53.52±16.95
Aldehydes total	175.72±87.12	4911.38±2234.08	6657.4±1294.4	3337.14±1828.94	6247.4±3121.49
Hexanoic acid	N	48.42±32.19	90.12±31.81	106.85±12.90	22.67±5.66
Octanoic acid	N	93.10±58.30	299.48±18.31	7.93±7.93	162.28±139.54
2-Decenoic acid	N	53.55±36.74	87.88±40.75	118.74±92.80	130.41±72.69
Dodecanoic acid	3.49±1.89	169.98±42.73	42.07±18.65	539.68±276.7	626.39±562.92
Tetradecanoic acid	12.37±5.30	122.56±90.99	48.02±34.48	107.62±34.79	219.27±135.78
Hexadecanoic acid	56.77±28.40	N	109.28±18.55	75.58±45.91	128.72±67.58
Oleic Acid	17.25±2.14	N	20.21±1.25	217.30±196.85	256.48±196.64
Acids total	89.88±37.73	487.61±260.95	697.06±163.8	1173.7±667.88	1546.22±1180.81
3-Octen-2-one	N	806.69±240.77	235.92±96.96	264.67±50.97	19.73±0.29
2-Pentanone	42.27±24.26	166.42±96.16	64.75±34.94	264.47±129.61	107.80±47.98
2-Hexanone	N	N	635.45±432.25	45.75±38.46	315.12±266.24
Ketones total	42.27±24.26	806.69±336.93	936.12±564.15	574.89±219.04	442.65±314.51
Ethyl 3-methylpentanoate	N	72.49±48.79	341.81±312.07	350.22±290.87	12.49±2.86

Ethyl butanoate	437.05±34.46	611.86±381.75	26.04±18.83	100.77±7.23	252.90±216.89
Ethyl 2-methyl-2-butenolate	N	18.76±10.28	38.16±16.79	355.86±170.31	58.43±1.07
Ethyl 2-methylbutyrate	123.14±117.65	12.35±1.39	495.76±14.48	564.96±145.60	328.9±112.00
Ethyl pentanoate	N	N	101.17±19.51	142.14±36.69	66.47±29.43
Propyl octanoate	N	192.66±78.80	276.69±269.35	2788.16±1084.39	1369.61±65.95
Ethyl caprate	N	777.13±396.57	23.20±2.89	107.80±59.5	237.38±113
Ethyl octanoate	N	N	101.17 ± 19.51	142.14 ± 36.69	66.47 ± 29.43
Ethenyl decanoate	N	507.52±396.72	66.94±51.04	64.91±51.72	125.89±64.09
Pentyl decanoate	N	N	58.57±12.12	77.96±17.36	34.04±13.15
Ethyl myristate	13.67±4.47	159.62±100.95	107.4±22.4	593.96±364.88	831.64±771.81
Isobutyl acetate	11.10±0.77	209.87±90.87	89.63±8.92	245.37±181.88	89.36±34.91
Ethyl hexadecanoate	13.69±0.01	166.07±73.37	217.51±42.51	228.1±193.89	80.37±54.88
Esters total	598.65 ± 157.36	2728.33 ± 1579.49	1944.05 ± 800.42	5684.39 ± 2641.01	3553.95 ± 1489.47
Total	932.4 ± 307.64	9237.93 ± 4528.05	10655.51 ± 3004.55	11511.18 ± 5702.71	12293.51 ± 6252.99

1

Declaration of Interest Statement

2 The authors confirm that they have no conflicts of interest with respect to the work described in
3 this manuscript.