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Research Article

Dynamic Changes in Physicochemical Properties, Qualities, and Microbiota of Cooked Ma Bamboo Shoots (*Dendrocalamus latiflorus* Munro) During Natural Fermentation

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This study systematically investigated the physicochemical characteristics, quality attributes, and microbial community dynamics of Ma bamboo shoots (*Dendrocalamus latiflorus* Munro) during natural fermentation following thermal treatment. The results indicated a gradual decrease in protein, soluble sugars, vitamin C, total pectin, water-soluble pectin, total amino acids, and pH over the course of fermentation. Notably, threonine was detected on the fifth day, and the accumulation of organic acids such as lactic acid and succinic acid contributed to the development of a characteristic sour flavor in the fermented shoots. In terms of quality attributes, the fermented Ma bamboo shoots exhibited a dark yellow–green coloration. Morphological alterations and partial damage to thin-walled cells were associated with significant reductions in hardness and cohesiveness. Microbial analysis revealed that the genus *Lactobacillus* became predominant, accounting for 92% of the bacterial population by the seventh day of fermentation.

Keywords: fermentation; Ma bamboo shoots; microbial composition; microstructure; texture

1. Introduction

Ma bamboo shoots (*Dendrocalamus latiflorus* Munro) are recognized as an environmentally friendly bamboo species with low cultivation costs [1] and represent one of the most extensively cultivated edible bamboo shoot varieties in southern China [2]. In Qingyuan City, China, the cultivation area of Ma bamboo covers approximately 40,000 ha, with an annual yield of 48,000 tons of dried shoots. Remarkably, exported dried products derived from Ma bamboo shoots account for over 95% of the Japanese market for dried bamboo shoots. Fresh Ma bamboo shoots are appreciated for their crisp texture, pleasant sweetness, and distinctive aroma. However, they are highly perishable and prone to rapid lignification when stored at ambient temperature after harvest, which severely compromises their edible quality [3]. To enhance the shelf life and processing performance of Ma bamboo shoots, natural fermentation has been widely adopted as a critical step in the production of dried bamboo shoot products [4, 5]. Ma bamboo shoots that have not undergone fermentation deteriorate rapidly and have poor quality [6, 7]. In addition, fermented foods have attracted increasing global interest due to their health-promoting properties, enhanced nutritional value, and the presence of bioactive metabolites produced by probiotics. They play an increasingly vital role in the global food system [8–10]. During the fermentation of vegetables, substantial changes occur in nutritional composition, texture, and flavor, driven by complex physical, chemical, and biochemical transformations.

Natural fermentation is a biochemical process in which naturally occurring microorganisms convert sugars, proteins, and lipids in food into organic acids, gases, or alcohols without the addition of chemical agents or artificial intervention. This process significantly alters the nutritional profile, flavor, and texture of food. The duration of natural fermentation typically ranges from several weeks to several

months, or even longer, depending on factors such as the fermentation environment, the raw materials involved, and the desired final product [11]. Numerous studies have investigated the fermentation of bamboo shoots. For instance, Chen et al. [4] explored the correlations among physicochemical properties, flavor, and microbial composition during the natural fermentation of *Dendrocalamus giganteus* Munro shoots. Guan et al. [12] examined the dynamic changes in physicochemical parameters, volatile compounds, and microbial communities during the traditional preparation of suansun. Wang et al. [13] compared the flavor and texture characteristics of 16 types of suansun produced in Liuzhou and Guilin, China. However, most of these studies primarily focus on flavor formation and microbial succession, with limited attention given to the systematic evaluation of physicochemical properties, quality attributes, and microbial profiles in Ma bamboo shoots. In practice, the quality control of naturally fermented Ma bamboo shoots has long relied on empirical knowledge and traditional techniques. This reliance on experience-based methods hinders standardization and limits the sustainable development of the fermented Ma bamboo shoot industry. Although natural fermentation can enhance flavor and palatability, the involvement of complex and potentially uncontrolled microbial populations may pose certain safety risks during processing [14]. For example, Li et al. [9] and Guan et al. [12] identified up to 10 major bacterial genera in fermented bamboo shoots, highlighting the microbiological complexity of the process. Cooking Ma bamboo shoots prior to natural fermentation serves as an effective pretreatment that not only eliminates bacteria and fungi, thereby enhancing microbial safety, but also inactivates endogenous enzymes, which prevents enzymatic lignification and contributes to color stabilization. This step facilitates a more controlled fermentation process and offers significant advantages in improving the overall quality, safety, and sensory properties of fermented bamboo shoot products.

Therefore, the objective of this study was to comprehensively evaluate the physicochemical characteristics of cooked Ma bamboo shoots during natural fermentation. This included the analysis of basic nutritional components, free amino acid profiles, and organic acid composition, as well as changes in quality attributes such as color and texture parameters (hardness, chewiness, and adhesiveness). In addition, the dynamic succession of the microbial community during fermentation was also investigated. The findings of this study are expected to provide a scientific basis for improving product quality and promoting the standardized development of the fermented Ma bamboo shoot industry.

2. Materials and Methods

2.1. Materials and Chemicals. Ma bamboo shoots (*Dendrocalamus latiflorus* Munro) were obtained from a Ma bamboo shoots planting base (Qingyuan, China). Potassium dihydrogen phosphate, glutaraldehyde, hydrochloric acid, and osmic acid (analytical grade) were supplied by Tianjin Fuyu Fine Chemical Co. Ltd. (Tianjin, China). Seventeen kinds of amino acids mixed standard solution, ninhydrin, and ninhydrin buffer solution (chromatographic grade) were obtained from Guangzhou Chemical Reagent Factory (Guangzhou, China).

2.2. Preparation of Fermented Ma Bamboo Shoots. The selected material for this study was the mature Ma bamboo shoots harvested in June, characterized by a deep yellow color, high shoot height, long internodes, and tender flesh. The shoots were 70–90 cm in height and 12–18 cm in diameter. The shoots were peeled within 12 h after harvesting, cut into cylindrical segments, and then steamed at 100°C for 2 h until fully cooked. After cooling to 30–35°C, the bamboo shoots were placed in a cylindrical bamboo basket lined with two to three layers of plastic film. The shoots were then tightly compacted and sealed to undergo fermentation. The fermentation process was conducted for 1, 3, 5, 7, 14, and 21 days at 35°C, respectively. Subsequently, they were sun-dried. Fresh and cooked samples were used as control samples. A 21-day fermentation period was adopted based on established industry standards in Qingyuan, where leading export-oriented enterprises require a minimum of 21 days for fermentation. This practice originated from Taiwan's traditional processing methods and has been widely accepted, particularly for products exported to Japan. Thus, the chosen fermentation duration aligns with commercial norms and ensures relevance to real-world production.

2.3. Determination of Physicochemical Properties. The pH value of Ma bamboo shoots was assayed according to a previously reported method [15]. Protein, soluble sugar, crude fiber, total pectin, and organic acid of Ma bamboo shoots were measured according to the Chinese Standard (GB/T5009.5-2010, NY/T 1278-2007, GB/T 5009.10-2003, NY/T 2016-2011, and GB 5009.157-2016, respectively).

The quantification of free amino acids was carried out using a high-performance liquid chromatography (HPLC) system (Waters e2695, United States), following a previously established method with slight modifications [13]. Firstly, 1.20 g of ground Ma bamboo shoots sample was accurately weighed and placed into an 18 × 180 mm test tube. Then, 14 mL of 6 mol/L hydrochloric acid was added, and the mixture was shaken well. After vacuuming for 10 min, the tube was sealed and the sample was hydrolyzed in a constant temperature oven at 110°C for 22 h in a sand bath. The obtained sample was then removed from the oven and cooled to room temperature. It was shaken well and filtered. Next, 1 mL of the filtrate was taken and placed into a 50 mL beaker. The filtrate was evaporated in a 60°C constant temperature water bath and diluted with 0.02 mol/L hydrochloric acid four times. The resulting solution was filtered through a 0.22 μm filter membrane. Separation was achieved on a BEH C18 column (4.6 × 250 mm, 5 μm; Agilent, California, United States). The mobile phase consisted of 0.1 mol/L sodium acetate mixed with acetonitrile (97:3, *v*/*v*) as Solvent A and 80% acetonitrile in water as Solvent B. The gradient elution program for Solvent B was set as follows: 0 min, 0%; 13 min, 7%; 23 min, 23%; 29 min, 35%; 35 min, 40%; 40–45 min, 100%; and 47 min, 0%. The flow rate was maintained at 0.7 mL/min, and detection was

performed at a wavelength of 254 nm using a UV-Vis detector. The injection volume was 10 μL, and the column oven was maintained at 38°C. Amino acid identification and quantification were based on retention time and corresponding peak area.

2.4. Evaluation of Qualities. The color of Ma bamboo shoots was determined by a colorimeter (X-rite sp60, X-rite, Glanville, United States) at room temperature using the specular component excluded mode. The sample of dried Ma bamboo shoots was cut into pieces of 2 cm in length and 1 cm in width. The color was characterized by several parameters, including the brightness value L^*, which ranged from 0 to 100 and represents the overall brightness level (with 0 being black and 100 being white). Additionally, the red and green value a^* indicated the degree of redness or greenness of the color (with positive values indicating more red and negative values indicating greener), while the yellow and blue value b^* represented the degree of yellowness or blueness (with positive values indicating more yellow and negative values indicating bluer).

The texture of Ma bamboo shoots was measured using a texture analyzer (TA.XT Plus, Stable Micro Systems Ltd., Godalming, United Kingdom). The dried Ma bamboo shoots were boiled and left to stand for 16 h, resulting in rehydrated bamboo shoots. They were then cut into pieces approximately 2 cm in length, 1 cm in width, and 0.5 cm in thickness. Subsequently, the sample was placed under the probe of the P36R for texture analysis testing. The parameters were set as follows: pretest speed of 2 mm/s, test speed of 1 mm/s, posttest speed of 1 mm/s, compression distance of 70%, dwell time of 5 s, data acquisition rate of 400 pps, and trigger value of 5 g. Each sample was tested 12 times.

2.5. Microstructure. The Ma bamboo shoot samples were cut into dimensions of 2 mm length, 2 mm width, and 2 mm height and fixed in 4% glutaraldehyde at 25°C for 1–4 h. The samples were then vacuumed for 0.5 h and stored in a refrigerator at 4°C until further use. Next, the samples were washed three times with 0.1 mol/L phosphate buffer for 20 min each time. Afterward, the samples were fixed in 1% osmium tetroxide for 4 h and washed three times with 0.1 mol/L phosphate buffer for 20 min each time. The samples were dehydrated with a gradient of ethanol and transitioned with isoamyl acetate. Critical point drying was performed, followed by gold coating, and the microstructure of the Ma bamboo shoot cell tissue was observed using an S-3000N scanning electron microscope (SEM) (Hitachi, Tokyo, Japan).

2.6. Microbial Analysis

2.6.1. DNA Extraction, Gene Amplification, and Sequencing. PowerSoil DNA Isolation kit was used to extract total DNA from Ma bamboo shoot tissue for bacterial analysis. DNA concentration and $OD_{260/280}$ values were measured using a microspectrophotometer (NanoDrop2000, Thermo Fisher Scientific Inc., Waltham, United States), and DNA integrity was assessed by gel electrophoresis. PCR amplification of the highly variable V3–V4 regions of bacterial 16S rDNA was performed using dual-index fusion primers containing sequencing adapters and 30–50 ng of bacterial genomic DNA as template. The PCR reaction program consisted of 35 cycles of denaturation at 95°C for 45 s, annealing at 55°C for 40 s, and extension at 72°C for 1 min, with an initial denaturation step at 95°C for 3 min and a final extension step at 72°C for 5 min. The amplified products were gel-purified, and library quality was assessed using an Agilent 2100 Bioanalyzer (Agilent Technologies Co. Ltd., Palo Alto, United States), and library concentration was measured using a Qubit 2.0 fluorometer (Invitrogen, Carlsbad, United States). Qualified libraries were used for cluster preparation, and Illumina MiSeq PE250 paired-end sequencing was performed.

2.6.2. Bioinformatics Analysis. The raw data was first filtered to remove low-quality reads, and the remaining clean data was used for subsequent analysis [16]. Specifically, reads with a length less than 75% of the original read length were removed, as well as those containing adapter contamination and low-complexity reads. FLASH (Fast Length Adjustment of Short reads, v1.2.11) was used for sequence assembly [17], and reads were assembled into tags based on their overlap relationships. The assembly criteria were as follows: a minimum match length of 15 bp and an allowed mismatch rate of 0.1 in the overlap region. Qualified clean tags were then clustered into operational taxonomic units (OTUs) at 97% similarity using USEARCH (v7.0.1090), and chimeric sequences were removed from the OTU representative sequences using UCHIME (v4.2.40) [18]. The OTU representative sequences were then compared to the Greengene database using the RDP classifier (v2.2) for species annotation (confidence threshold set to 0.6) [19]. After removing low-abundance OTUs (absolute read count ≤ 5), the OTU data was used for downstream analysis.

2.7. Statistical Analysis. All data were measured at least in triplicate. The results were presented as mean ± standard deviation. The statistical significance was determined by analysis of variance (ANOVA) and Duncan's multiple range tests at a significance level of $p < 0.05$ using SPSS v.21. Downstream analysis of microbial communities was conducted using R (3.5.1). Alpha diversity indices, including richness indices (observed OTUs, ACE index, and Chao1 index) and diversity indices (Shannon's index and Simpson's index), were calculated.

3. Results and Discussion

3.1. Physicochemical Properties of Ma Bamboo Shoots

3.1.1. Basic Nutritional Composition. As shown in Table 1, the basic nutritional composition of Ma bamboo shoots underwent significant changes during natural fermentation. Among the measured parameters, only the crude fiber content remained stable ($p > 0.05$), while the levels of protein, soluble sugars, vitamin C, total pectin, and water-soluble pectin changed significantly ($p < 0.05$). The protein content showed no significant difference between fresh and cooked samples ($p > 0.05$); however, it declined progressively during

TABLE 1: Changes in basic nutritional composition of Ma bamboo shoots during natural fermentation (dry basis).

	Fresh sample	Cooked sample	Fermented samples					
			1 day	3 days	5 days	7 days	14 days	21 days
Protein (g/100 g)	3.34 ± 0.13^{a}	3.23 ± 0.11^{a}	3.11 ± 0.10^{ab}	2.96 ± 0.07^{b}	2.76 ± 0.09^{bc}	2.48 ± 0.14^{c}	2.15 ± 0.10^{cd}	1.89 ± 0.15^{d}
Soluble sugar (%)	0.15 ± 0.01^{a}	0.14 ± 0.01^{a}	0.12 ± 0.01^{b}	0.10 ± 0.01^{c}	0.08 ± 0.01^{d}	0.06 ± 0.01^{f}	0.06 ± 0.01^{f}	0.06 ± 0.01^{f}
Crude fiber (%)	0.70 ± 0.01^{a}	0.70 ± 0.01^{a}	0.60 ± 0.01^{a}	0.70 ± 0.01^{a}	0.70 ± 0.01^{a}	0.60 ± 0.01^{a}	0.70 ± 0.01^{a}	0.70 ± 0.01^{a}
Vitamin C (mg/100 g)	10.82 ± 0.16^{a}	8.45 ± 0.22^{b}	7.78 ± 0.33^{c}	6.65 ± 0.24^{d}	5.35 ± 0.28^{e}	4.67 ± 0.34^{f}	4.18 ± 0.14^{g}	4.06 ± 0.17^{g}
Total pectin (g/100 g)	0.77 ± 0.19^{a}	0.75 ± 0.13^{b}	0.63 ± 0.21^{c}	0.81 ± 0.11^{a}	0.78 ± 0.09^{a}	0.81 ± 0.26^{a}	0.80 ± 0.23^{a}	0.59 ± 0.12^{d}
Water-soluble pectin (g/100 g)	0.34 ± 0.03^{a}	0.33 ± 0.02^{a}	0.28 ± 0.02^{c}	0.31 ± 0.03^{b}	0.31 ± 0.01^{b}	0.30 ± 0.02^{ab}	0.31 ± 0.02^{ab}	0.30 ± 0.03^{b}
pH	5.82 ± 0.24^{a}	4.22 ± 0.17^{b}	4.09 ± 0.13^{b}	3.63 ± 0.13^{c}	3.63 ± 0.13^{c}	3.71 ± 0.13^{c}	3.79 ± 0.13^{c}	3.27 ± 0.13^{c}

Note: All data are expressed as mean ± standard deviation ($n = 3$). Means with different superscripts in the same row are significantly different at $p < 0.05$.

TABLE 2: Changes in amino acid composition and content of Ma bamboo shoots during natural fermentation (g/100 g) (dry basis).

	Fresh sample	Cooked sample	Fermented samples					
			1 day	3 days	5 days	7 days	14 days	21 days
Aspartic acid	0.20 ± 0.01^{a}	0.17 ± 0.01^{b}	0.14 ± 0.01^{c}	0.15 ± 0.01^{c}	0.15 ± 0.01^{c}	0.15 ± 0.01^{c}	0.15 ± 0.01^{c}	0.14 ± 0.01^{c}
Glutamic acid	0.09 ± 0.01^{a}	0.07 ± 0.01^{b}	0.07 ± 0.01^{b}	0.07 ± 0.01^{b}	0.07 ± 0.01^{b}	0.07 ± 0.01^{b}	0.07 ± 0.01^{b}	0.07 ± 0.01^{b}
Serine	0.10 ± 0.02^{a}	0.09 ± 0.02^{b}	0.08 ± 0.01^{c}	0.09 ± 0.02^{a}	0.09 ± 0.02^{b}	0.08 ± 0.01^{c}	0.09 ± 0.01^{b}	0.08 ± 0.01^{c}
Glycine	0.06 ± 0.01^{a}	0.05 ± 0.01^{a}	0.04 ± 0.01^{b}	0.04 ± 0.01^{b}	0.04 ± 0.01^{b}	0.04 ± 0.01^{b}	0.04 ± 0.01^{b}	0.04 ± 0.01^{b}
Histidine	0.03 ± 0.01^{a}	0.02 ± 0.01^{a}	0.03 ± 0.01^{a}	0.02 ± 0.01^{a}	0.02 ± 0.01^{a}	0.02 ± 0.01^{a}	0.02 ± 0.01^{a}	0.03 ± 0.01^{a}
Threonine	—	—	—	—	0.06 ± 0.01^{a}	0.03 ± 0.01^{b}	0.02 ± 0.01^{b}	0.03 ± 0.01^{b}
Phenylalanine	0.14 ± 0.01^{a}	0.08 ± 0.01^{b}	0.01 ± 0.01^{c}	—	—	—	—	—
Cystine	0.14 ± 0.01^{a}	0.08 ± 0.01^{b}	0.01 ± 0.01^{c}	—	—	—	—	—
Arginine	0.04 ± 0.01^{c}	0.05 ± 0.01^{c}	0.09 ± 0.01^{a}	0.04 ± 0.01^{c}	0.04 ± 0.01^{c}	0.07 ± 0.01^{b}	0.04 ± 0.01^{c}	0.05 ± 0.01^{c}
Tyrosine	0.02 ± 0.01^{a}	0.02 ± 0.01^{a}	0.01 ± 0.01^{a}	0.01 ± 0.01^{a}	0.01 ± 0.01^{a}	0.01 ± 0.01^{a}	0.01 ± 0.01^{a}	0.01 ± 0.01^{a}
Valine	1.00 ± 0.03^{a}	0.77 ± 0.03^{b}	0.07 ± 0.02^{c}	0.08 ± 0.02^{c}	0.08 ± 0.02^{c}	0.08 ± 0.02^{c}	0.08 ± 0.02^{c}	0.07 ± 0.02^{c}
Methionine	0.12 ± 0.02^{a}	0.11 ± 0.02^{a}	0.10 ± 0.02^{a}	0.10 ± 0.02^{a}	0.11 ± 0.02^{a}	0.10 ± 0.02^{a}	0.10 ± 0.02^{a}	0.10 ± 0.02^{a}
Isoleucine	0.07 ± 0.01^{a}	0.05 ± 0.01^{b}	0.02 ± 0.01^{c}	0.03 ± 0.01^{c}	0.03 ± 0.01^{c}	0.02 ± 0.01^{c}	0.02 ± 0.01^{c}	0.03 ± 0.01^{c}
Aminocaproic acid	0.08 ± 0.01^{a}	0.07 ± 0.01^{a}	0.07 ± 0.01^{a}	0.07 ± 0.01^{a}	0.07 ± 0.01^{a}	0.07 ± 0.01^{a}	0.07 ± 0.01^{a}	0.07 ± 0.01^{a}
Tryptophan	0.09 ± 0.01^{a}	0.08 ± 0.01^{a}	0.08 ± 0.01^{a}	0.08 ± 0.01^{a}	0.08 ± 0.01^{a}	0.10 ± 0.01^{a}	0.08 ± 0.01^{a}	0.08 ± 0.01^{a}
Iysine	0.14 ± 0.02^{c}	0.22 ± 0.02^{a}	0.21 ± 0.02^{a}	0.21 ± 0.02^{a}	0.21 ± 0.02^{a}	0.20 ± 0.02^{a}	0.21 ± 0.02^{a}	0.19 ± 0.02^{b}
Total	2.32 ± 0.06^{a}	1.93 ± 0.06^{b}	1.03 ± 0.05^{c}	0.99 ± 0.05^{c}	1.06 ± 0.05^{c}	1.04 ± 0.05^{c}	1.00 ± 0.05^{c}	0.99 ± 0.05^{c}

Note: All data are expressed as mean ± standard deviation ($n = 3$). Means with different superscripts in the same row are significantly different at $p < 0.05$. "—", not detected.

fermentation ($p < 0.05$), with a 43% reduction observed by Day 21. This decrease is likely due to the dissolution of soluble proteins and their subsequent utilization by fermentative microorganisms as nitrogen sources. Similar protein degradation patterns have been reported in rice fermented with lactic acid bacteria [20]. In addition, the soluble sugar content remained unchanged after cooking ($p > 0.05$) but decreased significantly during fermentation ($p < 0.05$). This decline can be attributed to the microbial metabolism of sugars into organic acids, alcohols, and other fermentation products. Additionally, fermentation may enhance the activity of endogenous enzymes such as amylases, which promote sugar breakdown and further contribute to the reduction in soluble sugar content. Vitamin C content also declined significantly as fermentation progressed ($p < 0.05$), likely due to its susceptibility to oxidation and degradation under acidic conditions. Furthermore, both total pectin and water-soluble pectin contents decreased throughout the fermentation period. According to Bhatt et al. [21], the textural properties of fruits and vegetables are largely determined by the composition and concentration of pectin in the cell wall. Therefore, the reduction in pectin content during fermentation may adversely affect the textural integrity of Ma bamboo shoots. In terms of acidity, the pH value decreased markedly over time ($p < 0.05$), consistent with previous studies on the fermentation and pickling of vegetables [4, 12, 22, 23]. This acidification reflects the accumulation of organic acids produced by microbial metabolism, primarily by lactic acid bacteria ($p < 0.05$).

3.1.2. The Amino Acid Content and Composition. Amino acids are essential contributors to the flavor profile of fermented foods, as they not only impart specific taste characteristics but also function as precursors for the formation of various flavor compounds [4]. Table 2 shows the composition and content changes of amino acids during the natural

TABLE 3: Changes in organic acid composition and content of Ma bamboo shoots during natural fermentation (grams per kilogram) (dry basis).

	Fresh sample	Cooked sample	Fermented samples					
			1 day	3 days	5 days	7 days	14 days	21 days
Tartaric acid	1.5 ± 0.3^{d}	1.6 ± 0.2^{d}	10.0 ± 1.3^{c}	12.0 ± 1.2^{b}	17.0 ± 2.2^{a}	13.0 ± 0.2^{b}	13.0 ± 0.3^{b}	12.0 ± 0.5^{b}
Malic acid	5.0 ± 0.4^{d}	12.0 ± 1.2^{c}	34.0 ± 2.4^{a}	4.3 ± 0.4^{d}	3.7 ± 0.5^{de}	2.9 ± 0.5^{e}	15.0 ± 1.7^{b}	15.0 ± 1.9^{b}
Lactic acid	—	—	1.9 ± 0.4^{d}	10.0 ± 1.3^{a}	9.2 ± 1.2^{a}	9.3 ± 1.7^{a}	7.4 ± 0.9^{c}	8.3 ± 0.8^{b}
Succinic acid	—	—	4.0 ± 1.5^{c}	54.0 ± 2.7^{a}	—	—	—	11.0 ± 1.8^{b}
Total	6.5 ± 0.4^{f}	13.6 ± 1.2^{e}	49.9 ± 3.1^{b}	80.3 ± 3.3^{a}	29.9 ± 2.6^{d}	25.2 ± 1.8^{d}	35.4 ± 2.0^{c}	46.3 ± 2.8^{b}

Note: All data are expressed as mean ± standard deviation ($n = 3$). Means with different superscripts in the same row are significantly different at $p < 0.05$. "—", not detected.

fermentation process of Ma bamboo shoots. The total amount of amino acids decreased significantly ($p < 0.05$) on the first day of fermentation, with a decrease of 53%, and then remained unchanged ($p > 0.05$). The content of histidine, tyrosine, methionine, aminocaproic acid, and tryptophan did not change significantly during the fermentation process ($p > 0.05$). However, the content of aspartic acid, glutamic acid, serine, glycine, valine, and isoleucine decreased. Threonine, an essential amino acid for the human body, appeared on the fifth day during fermentation of Ma bamboo shoots, and its content decreased slightly on the seventh day, and then remained unchanged ($p > 0.05$). Phenylalanine and cysteine disappeared after 1 day of fermentation. These changes may be due to a combination of factors such as microbial metabolism, acid–base regulation, and enzymatic activity. Therefore, it could be seen that the main types of amino acids in Ma bamboo shoots during fermentation did not change significantly, but the amino acids content changed.

3.1.3. The Organic Acid Content and Composition. The changes in the composition and content of organic acids during the natural fermentation of Ma bamboo shoots are presented in Table 3. The total organic acid content increased significantly during the first 3 days of fermentation, followed by a slight decline, though the levels remained significantly higher than those in fresh samples. In fresh and cooked Ma bamboo shoots, only two organic acids—tartaric acid and malic acid—were detected. Tartaric acid content initially increased and then decreased during fermentation, likely due to the breakdown of sugars by microorganisms, which initially promoted tartaric acid accumulation. As fermentation progressed, tartaric acid was further metabolized, leading to a reduction in its concentration. A similar trend was reported in the natural fermentation of mixed fruits [11]. Malic acid content showed a distinct pattern: it increased significantly on the first day, decreased thereafter, and then increased again significantly by Day 14. These fluctuations may be attributed to microbial metabolism. Initially, microorganisms metabolized sugars to produce malic acid, accounting for the initial rise. As fermentation continued, malic acid was consumed as a carbon source, resulting in a decline. The subsequent increase may be due to the microbial degradation of other components in Ma bamboo shoots, leading to renewed malic acid production. As a nonvolatile organic acid, malic acid contributes significantly to the characteristic sourness of fermented Ma bamboo shoots [13]. Notably, lactic acid and succinic acid were detected exclusively in fermented samples. Like malic acid, these are nonvolatile organic acids that play key roles in the sour taste profile of fermented bamboo shoots [13]. Lactic acid was consistently present throughout the fermentation period. While the succinic acid content significantly increased on Day 3, it disappeared from Day 5 to Day 14 and reappeared by Day 21. This dynamic trend may be attributed to shifts in microbial metabolism over time. Early in fermentation, succinic acid may accumulate as a product of partial tricarboxylic acid cycle activity or reductive pathways under anaerobic conditions. As fermentation progresses, certain microorganisms may utilize succinic acid as a carbon source or electron acceptor, leading to its depletion. The reappearance at Day 21 could be related to microbial succession or the release of intracellular contents during cell lysis, as similarly reported in other vegetable fermentations [24]. Overall, natural fermentation significantly altered the organic acid profile of Ma bamboo shoots, contributing to a more complex and distinctive flavor.

3.2. Qualities of Ma Bamboo Shoots

3.2.1. Color Measurement. The color changes of Ma bamboo shoots during natural fermentation are presented in Table 4. The trends in L^*, a^*, and b^* values after cooking and fermentation were consistent. The L^* value of cooked bamboo shoots decreased significantly ($p < 0.05$), which may be attributed to pigment degradation or transformation caused by high temperatures during cooking, resulting in a darker appearance. Similarly, the L^* value continued to decrease during fermentation, likely due to increased acidity and enzymatic activity, both of which can promote pigment degradation. In addition, both the a^* value (indicating a shift toward green) and the b^* value (indicating a shift toward yellow) increased significantly ($p < 0.05$), suggesting that fermentation altered the color of Ma bamboo shoots toward a darker yellow–green hue. This may be related to the degradation of carotenoids during fermentation [25]. Furthermore, some biochemical reactions during fermentation, such as protein degradation, pH value reduction (as shown in Table 1), and nonenzymatic browning, might also contribute to the color changes [26]. The color changes of Ma bamboo shoots could be more intuitively observed from the appearance in Figure 1. Fresh sample (Figure 1a)

TABLE 4: Changes in color parameter of Ma bamboo shoots during natural fermentation.

	Fresh sample	Cooked sample	Fermented sample					
			1 day	3 days	5 days	7 days	14 days	21 days
L^*	87.14 ± 1.43^{a}	68.12 ± 1.13^{b}	63.12 ± 0.89^{c}	65.41 ± 1.24^{bc}	69.37 ± 0.98^{b}	63.80 ± 0.67^{c}	63.19 ± 0.65^{c}	66.32 ± 0.48^{bc}
a^*	-0.41 ± 0.03^{d}	-2.82 ± 0.41^{c}	-3.52 ± 0.36^{b}	-4.14 ± 0.42^{a}	-3.38 ± 0.35^{b}	-2.84 ± 0.24^{c}	-2.87 ± 0.26^{c}	-3.01 ± 0.23^{bc}
b^*	14.49 ± 1.98^{d}	26.76 ± 1.54^{c}	28.65 ± 1.24^{c}	26.53 ± 1.28^{c}	32.51 ± 1.12^{a}	32.86 ± 0.89^{a}	30.01 ± 0.96^{b}	33.62 ± 0.87^{a}
ΔE	—	22.76^{a}	5.39^{c}	3.18^{cd}	7.21^{b}	5.61^{c}	2.91^{d}	4.78^{c}

Note: All data are expressed as mean ± standard deviation ($n = 3$). Means with different superscripts in the same row are significantly different at $p < 0.05$.



(a) (b) (c)

FIGURE 1: Visual images of the appearance of Ma bamboo shoots. (a) Fresh Ma bamboo shoots, (b) cooked Ma bamboo shoots, and (c) Ma bamboo shoot fermented for 7 days.

exhibited bright green, while samples that have been cooked (Figure 1b) and fermented (Figure 1c) appeared a darker yellow–green hue. However, Chi et al. [6] reported a notable increase in a^* values (toward red) and a slight decrease in b^* values (toward blue) during the pickling of bamboo shoots in a 10% sodium chloride solution. This discrepancy may be explained by the differences in chemical reaction mechanisms between natural fermentation and salting, which lead to distinct color development pathways in bamboo shoots.

The parameter ΔE is widely used to describe the changes in food color during processing [27]. As shown in Table 4, ΔE values represent the degree of color difference between samples, with higher values indicating more pronounced changes. A threshold of $\Delta E = 2$ is commonly used as the minimum value for visual discrimination; changes below this threshold ($\Delta E < 2$) are generally imperceptible to the human eye, while those exceeding it ($\Delta E > 2$) can be easily perceived [22, 28]. According to Table 4, all Ma bamboo shoot samples exhibited ΔE values greater than 2, indicating noticeable color differences not only before and after fermentation but also throughout the fermentation process. These differences are visually distinguishable.

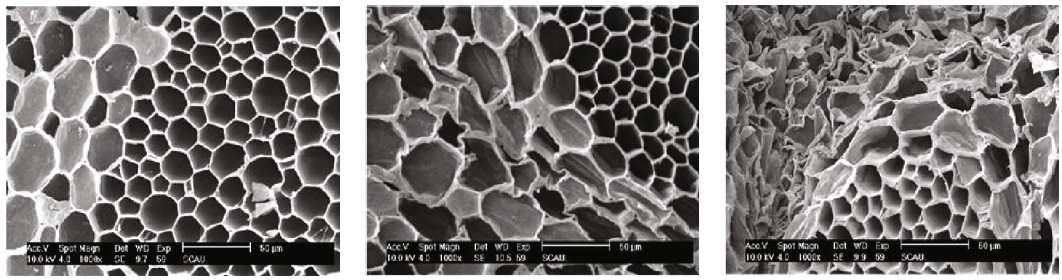
3.2.2. Textural Properties. Texture is a crucial quality indicator for vegetables and fruits [29]. Table 5 shows the changes in the textural properties of Ma bamboo shoots during natural fermentation. The hardness, chewiness, and cohesiveness of the cooked and fermented samples were significantly reduced compared to the fresh samples ($p < 0.05$). As the fermentation time increased, the hardness of the Ma bamboo shoots gradually declined. This reduction may be attributed to the metabolic activity of microorganisms and the enzymatic degradation of cellular structures. For example, pectinase breaks down the pectic substances in the middle lamella, and cellulase hydrolyzes cellulose in the cell wall. The action of these enzymes compromises cell integrity, resulting in softer tissue [6]. In addition, a decrease in pH during fermentation may reduce cell membrane permeability, further deteriorating texture properties [23]. Similar softening effects have been reported in Sichuan pickles, pickled bamboo shoots, and pickled chayote [6, 30, 31]. Although the chewiness of cooked Ma bamboo shoots initially decreased, it slightly increased with prolonged fermentation. This may be due to the breakdown of complex macromolecules such as proteins by microbial enzymes, as well as the accumulation of organic acids and other metabolites (Tables 1, 2, and 3), which may modify the structural properties of the tissue and thus influence chewiness. Cohesiveness also decreased as fermentation progressed. This parameter reflects the degree of intercellular adhesion and tissue integrity. During fermentation, enzymatic activity from microorganisms may disrupt cell structures, leading to a loosening of the tissue and a decline in intercellular binding force [6].

3.3. Microstructure of Ma Bamboo Shoots. The textural qualities of fermented products are often influenced by microstructural changes, such as shrinkage or rupture of cell membranes, cell walls, and middle lamellae [32]. Figure 2 presents the cross-sectional SEM images of Ma bamboo shoot tissue. In the fresh sample (Figure 2a), thin-walled cells exhibited a regular arrangement, with intact structures and no visible rupture or damage. Additionally, cell boundaries were distinct, and the cell walls appeared uniformly structured. However, after cooking (Figure 2b), the morphology of the thin-walled cells changed noticeably. Wrinkling of the cell walls was observed, some cells were damaged, and the intercellular spaces enlarged, resulting in

TABLE 5: Changes in textural properties of Ma bamboo shoots during natural fermentation.

	Fresh sample	Cooked sample	Fermented samples					
			1 day	3 days	5 days	7 days	14 days	21 days
Hardness (g)	$13{,}900 \pm 257^{a}$	7980 ± 153^{b}	7390 ± 174^{bc}	7210 ± 138^{c}	7097 ± 178^{d}	6890 ± 142^{e}	6610 ± 106^{ef}	6447 ± 156^{f}
Chewiness	18.50 ± 0.26^{a}	12.61 ± 0.34^{g}	13.12 ± 0.28^{f}	14.15 ± 0.19^{e}	14.17 ± 0.18^{e}	14.32 ± 0.14^{d}	14.98 ± 0.16^{c}	15.09 ± 0.16^{b}
Cohesiveness	0.26 ± 0.01^{a}	0.18 ± 0.01^{b}	0.16 ± 0.01^{c}	0.15 ± 0.01^{d}	0.15 ± 0.01^{d}	0.14 ± 0.01^{e}	0.13 ± 0.01^{f}	0.12 ± 0.01^{g}

Note: All data are expressed as mean ± standard deviation ($n = 3$). Means with different superscripts in the same row are significantly different at $p < 0.05$.



(a) (b) (c)

FIGURE 2: SEM images of Ma bamboo shoots. (a) Fresh Ma bamboo shoots, (b) cooked Ma bamboo shoots, and (c) Ma bamboo shoot fermented for 7 days.

irregularly shaped cells. Despite these changes, cell boundaries remained relatively clear. Following 7 days of fermentation (Figure 2c), further microstructural alterations were evident. Irregular wrinkles formed on the cell walls, and some cells collapsed or even disintegrated, indicating substantial structural degradation. During fermentation, microorganisms degrade complex polysaccharides such as cellulose and hemicellulose in the cell walls, leading to the breakdown of cell wall integrity. Chi et al. [6] reported similar microstructural changes in bamboo shoots during pickling with a 10% sodium chloride solution. They indicated that some folds and wrinkles observed on the cell membranes of fermented bamboo shoots were caused by cell collapse and the complex bilayer membrane structure. The trend of cell wall changes was consistent with the texture of the bamboo shoots. Compared with fresh bamboo shoots, the hardness of the samples significantly decreased. Therefore, in this study, the disintegration of cell walls and the expansion of intercellular spaces during fermentation weaken cell-to-cell adhesion, resulting in a looser and less compact tissue structure. This structural breakdown contributes to the observed decreases in the hardness and cohesiveness of Ma bamboo shoots.

3.4. Microbial Composition in Ma Bamboo Shoots. The community abundance and diversity of fermented Ma bamboo shoots are presented in Table 6. The actual number of OTUs reflected the microbial diversity in the samples, indicating that Ma bamboo shoots fermented for 3 days had the highest microbial richness. According to the ACE and Chao1 indices, which measure community richness, microbial abundance peaked on Day 3 of fermentation and gradually declined with prolonged fermentation. In terms of community diversity, the Shannon and Simpson indices revealed that microbial diversity was also highest on Day 3 and decreased as fermentation progressed. Figure 3 illustrates the bacterial composition at the genus level in fermented Ma bamboo shoots. The results revealed the presence of *Lactobacillus*, *Weissella*, *Pediococcus*, and some unidentified genera. *Weissella* was detected only on Days 3 and 21, while *Pediococcus* was primarily found on Day 3. *Lactobacillus* dominated throughout the fermentation process, with its relative abundance initially increasing and then slightly declining over time; however, it consistently accounted for more than 50% of the OTUs. The peak relative abundance of *Lactobacillus* was observed on Day 7, reaching 92%, which played a crucial role in shaping the texture and flavor of Ma bamboo shoots. The texture and flavor characteristics of fermented vegetables are largely influenced by the fermentation conditions and the resident microbial community. Both *Lactobacillus* and *Weissella*, members of the order *Lactobacillales*, are key microorganisms in food fermentation and significantly contribute to the development of unique flavors. *Weissella* initiates heterolactic fermentation, producing flavor compounds such as acetaldehyde, ethanol, mannitol, and organic acids. These metabolites not only create a favorable environment for the growth of lactic acid bacteria but also help preserve the color of vegetables [33, 34]. Furthermore, the increased production of volatile flavor compounds such as aldehydes after vegetable fermentation is closely associated with the metabolic activity of *Lactobacillus* [35].

4. Limitations of the Study

This study has several limitations that should be acknowledged. First, the analysis did not include volatile compounds, which limits a comprehensive understanding of the flavor changes during fermentation. Second, the absence of an unsteamed control group restricts the ability to fully evaluate

TABLE 6: Alpha diversity index of 16S rRNA gene libraries of Ma bamboo shoots during natural fermentation.

Sample	OTU	Chao1	ACE	Shannon	Simpson
F3	192 ± 8^{a}	308.02 ± 24.62^{a}	307.92 ± 22.63^{a}	1.49 ± 0.18^{b}	0.50 ± 0.07^{b}
F7	147 ± 10^{b}	222.78 ± 24.51^{b}	211.68 ± 18.56^{b}	1.85 ± 0.08^{a}	0.72 ± 0.03^{a}
F21	137 ± 6^{b}	185.72 ± 9.82^{b}	195.16 ± 15.70^{b}	1.56 ± 0.02^{b}	0.60 ± 0.02^{ab}

Note: All data are expressed as mean ± standard deviation ($n = 5$). Means with different superscripts in the same column are significantly different at $p < 0.05$. F3, F7, and F21 represent the fermentation of Ma bamboo shoots for 3, 7, and 21 days, respectively.
Abbreviations: ACE, the ACE estimator; Chao1, the Chao1 estimator; OTU, operational taxonomic units; Shannon, the Shannon index; Simpson, the Simpson index.

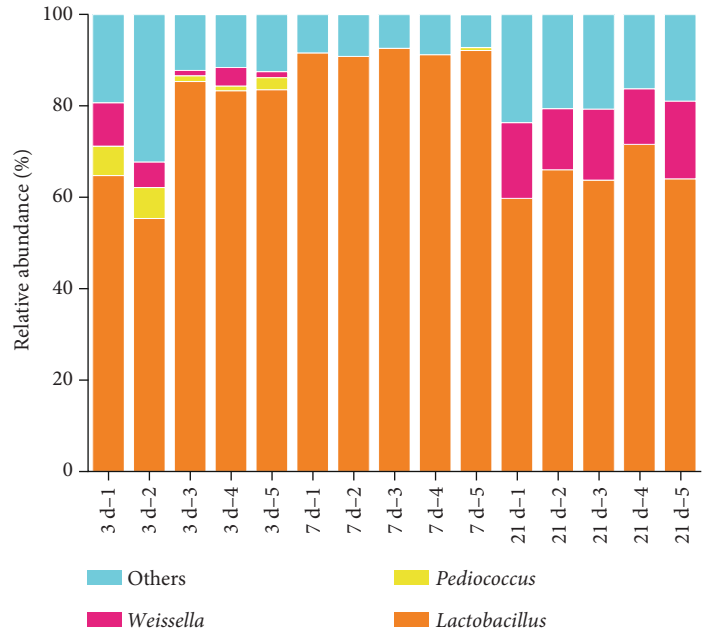


FIGURE 3: Microbial community composition in fermented Ma bamboo shoots at the genus level. Note: Others refer to genera with an average relative abundance of less than 0.5%. 3, 7, and 21 days represent the fermentation of Ma bamboo shoots for 3, 7, and 21 days, respectively.

the effects of steaming on fermentation outcomes. Third, microstructural observations by SEM were conducted at only a single time point, preventing insight into the dynamic changes over the entire fermentation period. Lastly, acidity assessment relied solely on pH measurement, which may not fully capture the complexity of acid profiles in the fermented products. Future studies should address these limitations to provide a more detailed and holistic evaluation.

5. Conclusion

In summary, this study investigated the physicochemical properties, quality attributes, and microbial composition of Ma bamboo shoots during the fermentation process following cooking. Throughout the dynamic fermentation process, the contents of protein, soluble sugars, vitamin C, total pectin, water-soluble pectin, and pH values all declined significantly. Although the types of amino acids remained relatively stable, their contents changed markedly during fermentation. In fresh and cooked Ma bamboo shoots, only tartaric acid and malic acid were detected, whereas lactic acid and succinic acid emerged in the fermented samples, contributing to their distinctive sour flavor. Furthermore, fermentation resulted in a dark yellow–green appearance and a softer, more easily chewable texture. The observed microstructural changes supported these texture alterations, indicating that cell wall disruption and increased intercellular spaces contributed to tissue softening. Microbial analysis revealed that the genus *Lactobacillus* was dominant throughout the fermentation process, maintaining a relative abundance of over 50% and playing a key role in shaping the final characteristics of the fermented Ma bamboo shoots.

Data Availability Statement

Data will be made available on request.

Conflicts of Interest

The authors declare no conflicts of interest.

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