Optimization of the *Arapaima gigas* Meat Product Manufacturing Process Using Probiotic Lactic Acid Bacteria

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Abstract

Compounds derived from microorganisms have considerable potential in fish preservation. Among them, lactic acid bacteria (LAB) are widely studied because they dominate the natural microflora of many foods and produce antimicrobial metabolites. Accordingly, this research aimed to optimize the processing of *Arapaima gigas* meat products through the application of probiotic LAB. Significant differences ($p < 0.05$) were observed among treatments. Higher pH values were recorded in canned products treated with *Lactobacillus plantarum* (6.90), while lower values occurred in fresh/raw products with *Leuconostoc mesenteroides* (6.45). Titratable acidity was higher in mojama (salted/dried) processed with *Lactobacillus reuteri* (0.60%) and lower in canned products with the same strain (0.39%). Moisture content was greater in fresh/raw samples (69.20% with *L. plantarum*) and lower in mojama (20.41% with *L. reuteri*). Ash content was concentrated in salted/dried products (28%), fat was higher in canned samples (>28%), and protein predominated in fresh/raw products, reaching 19.89% with *L. reuteri*. Microbiologically, treatment T1 (fresh/raw + *L. plantarum*) showed 65 CFU/g of total cocci and low enterobacteria counts (10 CFU/g), with no detection of *Escherichia coli*, *Salmonella* spp., molds, or yeasts. In treatments T6 (mojama + *L. reuteri*) and T8 (canned + *L. mesenteroides*) no microbial growth was detected. Overall, probiotic LAB combined with appropriate processing improved microbial safety and contributed to the nutritional stability of *A. gigas* products.

Keywords: bioconservation, microorganisms, native fish, *Lactobacillus plantarum*, *Lactobacillus reuteri*, *Leuconostoc mesenteroides*

Optimización del proceso de elaboración de productos cárnicos de *Arapaima gigas* mediante bacterias lácticas probióticas

Resumen

Los compuestos derivados de microorganismos presentan un alto potencial para la conservación de pescado. Entre ellos, las bacterias ácido-lácticas (BAL) han sido ampliamente estudiadas debido a su capacidad para dominar la microflora natural y producir metabolitos antimicrobianos. En este contexto, el objetivo de esta investigación fue optimizar el procesamiento de productos cárnicos de *Arapaima gigas* mediante la aplicación de BAL con propiedades probióticas. Se observaron diferencias significativas (p<0,05) entre tratamientos. Los valores más altos de pH se registraron en productos enlatados tratados con *Lactobacillus plantarum* (6,90) y los más bajos en productos frescos/crudos con *Leuconostoc mesenteroides* (6,45). La acidez titulable fue mayor en la mojama procesada con *Lactobacillus reuteri* (0,60%) y menor en productos enlatados con la misma cepa (0,39%). La humedad fue superior en muestras frescas/crudas (69,20% con *L. plantarum*) y menor en la mojama (20,41% con *L. reuteri*). El contenido de cenizas se concentró en los productos salados/secos (28%), la grasa fue mayor en los enlatados (>28%) y la proteína predominó en los frescos/crudos, alcanzando 19,89% con *L. reuteri*. Microbiológicamente, el tratamiento T1 presentó bajos recuentos de enterobacterias (10 UFC/g) y ausencia de patógenos. En T6 y T8 no se detectó crecimiento microbiano. En conclusión, el uso de BAL probióticas, combinado con un procesamiento adecuado, mejoró la seguridad microbiológica y contribuyó a la estabilidad nutricional de los productos de *A. gigas*.

Palabras clave: bioconservación, microorganismos, peces nativos, *Lactobacillus plantarum*, *Lactobacillus reuteri*, *Leuconostoc mesenteroides*

Otimização do processo de fabricação de produtos cárneos de *Arapaima gigas* utilizando bactérias láticas probióticas

Resumo

Os compostos derivados de microrganismos apresentam alto potencial para a conservação de peixes. Entre eles, as bactérias ácido-lácticas (BAL) têm sido amplamente estudadas devido à sua capacidade de dominar a microflora natural e produzir metabólitos antimicrobianos. Nesse contexto, o objetivo desta pesquisa foi otimizar o processamento de produtos cárneos de *Arapaima gigas* por meio da aplicação de BAL com propriedades probióticas. Foram observadas diferenças significativas (p < 0,05) entre os tratamentos. Os maiores valores de pH foram registrados em produtos enlatados tratados com *Lactobacillus plantarum* (6,90) e os menores em produtos frescos/crus com *Leuconostoc mesenteroides* (6,45). A acidez titulável foi maior na mojama processada com *Lactobacillus reuteri* (0,60%) e menor em produtos enlatados com a mesma cepa (0,39%). A umidade foi superior nas amostras frescas/cruas (69,20% com *L. plantarum*) e menor na mojama (20,41% com *L. reuteri*). O teor de cinzas concentrou-se nos produtos salgados–secos (28%), a gordura foi maior nos enlatados (>28%) e a proteína predominou nos frescos/crus, atingindo 19,89% com *L. reuteri*. Microbiologicamente, o tratamento T1 apresentou baixos valores de enterobactérias (10 UFC/g) e ausência de patógenos. Nos tratamentos T6 e T8 não foi detectado crescimento microbiano. Em conclusão, o uso de BAL probióticas, combinado com processamento adequado, melhorou a segurança microbiológica e contribuiu para a estabilidade nutricional dos produtos de *A. gigas*.

Palavras-chave: bioconservação, microrganismos, peixes nativos, *Lactobacillus plantarum*, *Lactobacillus reuteri*, *Leuconostoc mesenteroides*

1. Introduction

Native fish species have historically played a fundamental role in the food security of Amazonian Indigenous communities and, more recently, of settler populations established in this region (Aberoumand & Baesi, 2023). However, population growth and the consequent increase in food demand have led to a significant decline in fish populations within natural ecosystems. In response to this situation, aquaculture has emerged as a key

productive alternative to meet the growing needs of local, regional, and international markets (Alahmad et al., 2021).

In this context, the *paiche* (*Arapaima gigas*), one of the most emblematic species of the Amazon basin, represents a strategic option for sustainable aquaculture development. This fish is notable for its rapid growth and high-quality meat –traits that have generated increasing interest in its cultivation. Commonly known as "paiche" in Peru and Ecuador, and "pirarucú" in Brazil (An et al., 2022), *A. gigas* is considered the largest freshwater fish in the world, reaching up to 250 kg in weight and over 3 meters in length in its adult stage (Association of Official Analytical Chemists, 2005). Its geographical distribution includes the Amazon, Tocantins-Araguaia, and Essequibo river basins, extending across Brazil, Ecuador, Guyana, and Peru (Burgos-Morán & Altamirano-Cantos, 2023).

The aquaculture potential of this species is supported by various productive traits, such as the large size of its scales, rapid growth, ease of handling, and the organoleptic quality of its flesh. These characteristics make *A. gigas* a viable and profitable alternative for the economic development of Amazonian communities (Cabanillas-Bojórquez et al., 2025). In Ecuador, its distribution is limited to the eastern provinces of Sucumbíos, Orellana, and Pastaza. In particular, in the Sucumbíos province, within the Cuyabeno area, its use has traditionally been restricted to self-consumption by native communities (Casado-Del Castillo et al., 2020).

The utilization of *A. gigas* has resulted in a variety of meat products, such as raw fillets, canned goods, and *mojama* (cured and dried fish), all of which hold a prominent place in Amazonian gastronomy. However, the preparation and preservation of these products pose significant challenges regarding food safety and shelf life (Castillo-Jiménez et al., 2017). This underscores the need to apply technologies that enhance both microbiological stability and the sensory quality of derived products.

A promising biotechnological alternative is the use of lactic acid bacteria (LAB) with probiotic properties, which contribute to microbiological preservation while also enhancing the sensory and functional qualities of food products (Braitenbach Cavali et al., 2024). Among LAB, *Lactobacillus plantarum* has demonstrated efficacy in the fermentation of fish products, improving their organoleptic profile and reducing the presence of pathogenic microorganisms (Contreras Tirado & Cardiles Guerrero, 2013). Similarly, *Lactobacillus reuteri* produces reuterin, a broad-spectrum antimicrobial compound effective against bacteria such as *Listeria monocytogenes*, without affecting beneficial microbiota, making it an ideal agent for the preservation of meat products (Diez-Echave et al., 2021). Additionally, *Leuconostoc mesenteroides* plays a crucial role in the initial stages of fermentation, producing lactic acid and other compounds that inhibit undesirable microorganisms and create optimal conditions for other LAB, while also contributing to the development of characteristic flavors and textures (Duarte et al., 2020).

The incorporation of LAB as starter cultures enables controlled and reproducible fermentation, which is essential for standardizing production processes at an industrial scale. Such standardization is key to ensuring final product quality, promoting consumer acceptance, and complying with current food safety regulations. Within this framework, the present study aimed to optimize the production process of meat products derived from *Arapaima gigas* through the application of lactic acid bacteria with probiotic properties, with the objective of enhancing the microbiological safety of these products in their various forms: raw, canned, and mojama.

2. Materials and Methods

2.1 Location

This research was conducted at the Universidad de las Fuerzas Armadas ESPE, Santo Domingo extension, located at the Zoila Luz estate, at kilometer 24 along the Quevedo highway (Ecuador). The experimental practices were carried out in the laboratories of Industrial Biotechnology, Industrial Processes, Bromatology, and Cellular Microbiology.

2.2 Sample Preparation

2.2.1 Fresh Paiche (Raw) Sample

A total of 500 g of paiche (*Arapaima gigas*) loin meat, provided by the company ASOARAPAIMA, was weighed for physicochemical, bromatological (pH, acidity, moisture, fat, ash, and protein), and microbiological analyses. This sample was divided into four fractions of 125 g each. One fraction was used as a control, while the other three were inoculated with specific lactic acid bacteria (*Lactobacillus plantarum*, *Lactobacillus reuteri*, and *Leuconostoc mesenteroides*). Each inoculated fraction received 1 ml of bacterial suspension adjusted to 10^8 CFU/ml, resulting in an approximate final concentration of 10^6 CFU/g of meat.

2.2.2 Canned Paiche Sample

A total of 720 g of paiche meat was weighed and cut into rectangular blocks. Then, 60 g of meat was placed into glass jars with a tare weight of 90 g. For the preservation solution, a sauté (*refrito*) was prepared with garlic, pearl onion, and salt, to which sunflower oil was added. This mixture was heated to 100 °C for 10 minutes to enhance flavor, then allowed to cool. Each jar received 25 ml of the solution. The jars were autoclaved for 20 minutes at 121 °C. Afterward, they were hermetically sealed and subjected to a second autoclaving process under the same temperature conditions, at a pressure of 0.9 atm for 1 hour. Finally, the jars were carefully removed, labeled, and stored for further analysis (Castillo-Jiménez et al., 2017).

2.2.3 Dried Paiche (Mojama) Sample

A total of 500 g of paiche meat was selected, thoroughly washed, and completely covered with 3 kg of coarse salt. The sample was wrapped in aluminum foil and left to rest for 8 days for initial dehydration. After this period, the excess salt was removed, and the dehydrated meat was divided into three portions (one per experimental replicate). The portions were then hung in a refrigerated chamber at −5 °C for 3 days (ElShehawy & Farag, 2019).

2.2.4 Preparation of the Bacterial Solution

MRS broth was prepared by dissolving 78.375 g in 1.5 L of distilled water. The mixture was heated and stirred in a flask, then sterilized in an autoclave for 25 minutes at 121 °C and 15 psi. Once cooled in a laminar flow cabinet (previously sterilized with UV light for 15 minutes), selected bacterial strains were inoculated using a bacteriological loop. The flask was sealed with cotton and parafilm and incubated for 24 hours at 37 °C. After incubation, several washing steps were performed using a sodium citrate-citric acid buffer (pH 3.8). Five ml of buffer were mixed with 5 ml of bacterial culture, then centrifuged at 10,000 rpm for 15 minutes. The supernatant was discarded, and the sediment was retained. This process was repeated until a whitish sediment was obtained. Finally, the sediment was resuspended in 5 ml of the same buffer to obtain a bacterial solution with antimicrobial activity, adjusting the absorbance to the desired level (Braitenbach Cavali et al., 2024).

2.3 Evaluated Variables

2.3.1 Determination of pH

Ten grams of fish sample were weighed and placed into a beaker, to which 100 ml of distilled water were added. The mixture was then homogenized and filtered using a cloth to remove connective tissue. The pH was measured by carefully inserting the electrode of the potentiometer into the beaker, avoiding contact with the container walls. Once the reading stabilized, the corresponding pH value was recorded (Food and Agriculture Organization of the United Nations [FAO] & World Health Organization, 2020).

2.3.2 Determination of Titratable Acidity

Ten grams of fish sample were weighed and placed in a blender jar, where they were mixed with 200 ml of distilled water. The resulting mixture was filtered using a cloth to eliminate connective tissue. The filtrate was transferred to a 250 ml volumetric flask and brought to volume with distilled water. From this solution, 25 ml were taken and poured into a 150 ml flask, followed by the addition of 75 ml of distilled water and five drops of phenolphthalein as an indicator. The solution was titrated with 0.01 N sodium hydroxide (NaOH). This procedure was repeated three times to ensure reproducibility. A blank sample was prepared using 100 ml of distilled water with five drops of phenolphthalein and titrated under the same conditions (FAO, 2020). The following formula was then used to calculate the percentage of titratable acidity:

$$\text{Acidity (\%)} = \frac{V1 * N1 * M}{V2}$$

Where:

V1 = ml of NaOH used in the titration.

N1 = Normality of the NaOH solution.

M = Molar weight of the reference acid. (Lactic acid = 0.090).

V2 = Volume in ml or mass in grams of the sample taken for analysis.

2.3.3 Moisture Determination

To determine the moisture content, the crucible was preheated in an oven at 100 °C for 40 minutes. It was then allowed to cool in a desiccator and weighed. Two grams of the fish sample were then weighed and placed in the crucible. The samples were then placed in an oven at 131 °C for 24 hours for drying (Martins & da Silva Pena, 2017). The moisture content was determined using the following equation:

$$\text{Humidity (\%)} = \frac{W2 - W1}{Wo} * 100$$

Where:

W2 = Weight of the crucible plus the sample before drying.

W1 = Weight of the crucible plus the sample after drying.

W0 = Weight of the sample in grams.

2.3.4 Ash Determination

To determine the ash content, the crucible was heated in an oven at 100 °C for 40 minutes. Two grams of fish were then weighed and placed in the crucible along with a few drops of olive oil. The crucible was placed in a furnace, where the sample was completely calcined. Once the sample was burned, the crucible was placed in a muffle furnace at 600 °C for 4 hours, until the sample was completely converted to ash. Finally, it was allowed to cool again in the desiccator and weighed (Martins & da Silva Pena, 2017). The percentage of ash is obtained by weight difference using the following formula:

$$Ash\ (\%) = \frac{W2 - W1}{Wo} * 100$$

Where:

C = Moisture percentage.

W2 = Weight of the crucible plus the calcined sample.

W1 = Weight of the empty crucible.

W0 = Weight of the sample in grams.

2.3.5 Fat Determination

Fat content was determined using the Soxhlet extraction method, following the procedure described by Gálvez-Escudero and Mendoza De La Vega (2024). Beakers were previously dried in an oven at 100 °C for 1 h, cooled in a desiccator to room temperature, and weighed. Two grams of each dried sample were placed on filter paper, inserted into an extraction thimble covered with freeze-dried cotton, and assembled in the thimble holder. Subsequently, 50 mL of petroleum ether was added to each beaker as the extraction solvent. The thimbles were placed in the corresponding beakers and mounted on the metal rings of a Goldfisch fat extractor. The extraction process was carried out for approximately 4 h. After completion, the beakers were carefully removed, the thimbles separated, and the beakers were placed in an oven at 40 °C for 30 min or until complete solvent evaporation. Finally, the beakers were cooled in a desiccator and weighed to calculate the fat content using the following formula:

$$Fat\ (\%) = \frac{W2 - W1}{Wo} * 100$$

Where:

G = Moisture percentage.

W2 = Weight of the glass plus fat.

W1 = Weight of the empty glass.

W0 = Weight of the sample in grams.

2.3.6 Protein Determination

To determine protein content, approximately 2 grams of fish samples were weighed and placed in crucibles. The crucibles were then placed in an oven at 131 °C for 24 hours to dry. From the dried sample, 0.3 grams were taken and placed in microtubes along with a catalyst tablet and 5 ml of concentrated sulfuric acid. Digestion was performed in a Kjeldahl apparatus, raising the temperature to 400 °C for 30 minutes. Upon completion, the samples were allowed to cool to room temperature, yielding a blue liquid. Ten ml of distilled water was then added to each microtube, and distillation was carried out in a system connected to a flask containing 50 ml of boric acid. Upon completion of the distillation, a volume of approximately 150 ml was obtained, which was used for titration. For this step, 4 drops of an indicator mixture (methyl red and bromocresol green solution) were added, and titrated with 0.1 N hydrochloric acid using a magnetic stirrer (Martins & da Silva Pena, 2017).

$$\text{Protein (\%)} \frac{(\text{VHCL} - \text{VB}) * 1.401 * \text{NHCL} * \text{F}}{\text{g}} (100)$$

Where:

1.401 = Atomic weight of Nitrogen.

NHCl = Normality of hydrochloric acid (0.1 N).

VHCl = Volume of hydrochloric acid.

F = Conversion factor (6.25).

Vb = Blank volume (0.3).

2.3.7 Microbial Enumeration on Petrifilm™ Plates

To determine the microbial count, 3 grams of each fish sample were ground. Under sterile conditions in a laminar flow chamber, serial dilutions were made up to 10^{-5} using autoclaved peptone water. The stock solution was prepared by mixing 3 grams of the ground sample with 27 ml of peptone water. The remaining test tubes contained 9 ml of sterile peptone water. From the stock solution, 1 ml was transferred to the second tube to make the first dilution, and so on until the fifth dilution was obtained. From the fifth dilution, 1 ml was inoculated onto a Petrifilm™ plate for aerobes and another 1 ml onto a Petrifilm™ plate for molds and yeasts. Aerobic plates were incubated at 37 °C for 48 hours, while mold and yeast plates were incubated at 21 °C for 72 hours (Heilpern et al., 2021). The bacterial count was determined using the following formula:

$$\frac{\text{UFC}}{ml} = \frac{N * F}{V}$$

Where:

N = Number of colonies per plate.

F = Dilution factor.

V = Volume inoculated on the plate.

2.4 Experimental Design

To evaluate the optimal process for obtaining different types of meat products from paiche (*Arapaima gigas*) through the incorporation of various lactic acid bacteria as probiotic cultures, several factors and levels were considered under a completely randomized design with a factorial arrangement A*B (*Type of paiche meat product × Lactic acid bacteria*). A completely randomized block ANOVA design was applied with three replicates per treatment, resulting in a total of 27 experimental units. For the functional analysis of the results, Tukey's significance test (p<0.05) was used to determine statistically significant differences between treatments (Table 1).

Table 1. Experimental treatments according to the type of *Arapaima gigas* meat product and bacterial strain used

Treatment	Description
T1	Raw + *Lactobacillus plantarum*
T2	Canned + *Lactobacillus plantarum*
T3	*Mojama + Lactobacillus plantarum*
T4	Raw + *Lactobacillus reuteri*
T5	Canned + *Lactobacillus reuteri*
T6	*Mojama + Lactobacillus reuteri*
T7	Raw + *Leuconostoc mesenteroides*
T8	Canned + *Leuconostoc mesenteroides*
T9	*Mojama + Leuconostoc mesenteroides*

3. Results

3.1 Results of Bromatological Analysis of the A*B Interaction (Paiche Meat Product Type * Lactic Acid Bacteria)

The pH values (Figure 1A) showed significant differences (p<0.05) depending on the type of processing and the Lactobacillus strain used as a biopreservative. Canned samples exhibited the highest pH values, with the treatment using *L. plantarum* reaching the maximum (6.90), followed by *L. reuteri* (6.83) and *L. mesenteroides* (6.77). In contrast, raw and dried (mojama) samples showed lower pH values, with the lowest observed in the "Raw + *L. mesenteroides*" treatment (6.45). These results suggest that the food matrix significantly influences the acidifying capacity of lactic acid bacteria, likely due to differences in nutrient availability, water content, and the inherent buffering capacity of each product.

Regarding titratable acidity, expressed as percentage of lactic acid (Figure 1B), significant differences were also observed among treatments (p<0.05). Dried samples (mojama) exhibited the highest acidity values, reaching up to 0.60% when combined with *L. reuteri*. Conversely, canned samples showed the lowest acidity, with a minimum of 0.39%, also with *L. reuteri*. Raw samples displayed intermediate values, ranging from 0.41% to 0.51%. These findings indicate that the low moisture and high solids content of mojama promote the accumulation of organic acids, while in canned products, the higher water content and potential dilution of fermentative metabolites contribute to lower final acidity.

Moisture content (Figure 1C) was primarily determined by the processing method, regardless of the inoculated strain. Raw samples showed the highest moisture levels, with a maximum of 69% in the *L. plantarum* treatment. Canned samples had intermediate moisture content (55%), while dried samples presented the lowest values, with a minimum of 20.41% observed in the *L. reuteri* treatment. These data reflect the impact of thermal and dehydration processes on water retention, which directly affect product texture and the viability of the inoculated microbiota.
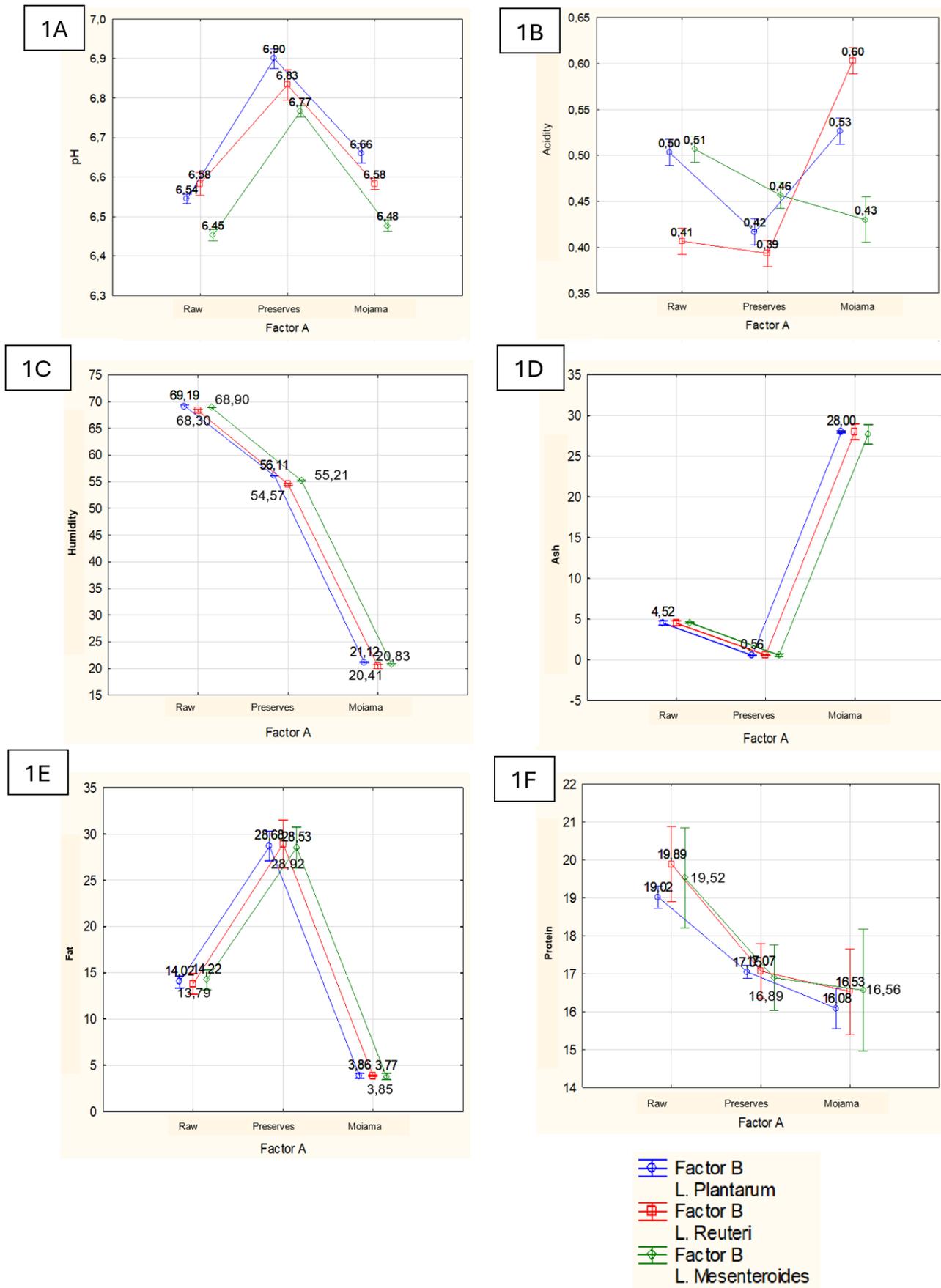
Figure 1. Tukey significance test (p<0.05) for the results of bromatological analysis of the A*B Interaction (Type of paiche meat product * Lactic acid bacteria)

Ash content (Figure 1D) also varied significantly among treatments (p<0.05). Dried samples recorded the highest ash content (28%), attributed to mineral concentration due to water loss during drying. In contrast, canned products showed the lowest ash levels (0.6%), likely resulting from mineral dilution in the covering liquid. Raw samples exhibited intermediate values, around 4.5%. These results suggest that drying not only reduces water activity but also concentrates solid components such as mineral salts.

In terms of fat content (Figure 1E), canned products had the highest levels, exceeding 28%, with no significant differences among bacterial strains. Raw samples showed moderate fat levels, ranging from 13.79% to 14.25%, while dried samples recorded the lowest fat content (3.8%). This distribution suggests that the thermal processing in canned products may enhance lipid retention, whereas intensive drying in mojama may cause fat loss or relative redistribution of solids, reducing the lipid proportion.

Finally, protein content (Figure 1F) was significantly higher (p<0.05) in raw samples, with *L. reuteri* treatment showing the highest value (19.89%), followed by *L. mesenteroides* (19.52%) and *L. plantarum* (19.08%). Both canned and dried products showed lower protein levels, ranging from 16.08% to 17.07%, with no significant differences among strains. These results may be related to thermal protein degradation in canned products and the loss of soluble nitrogen during drying in mojama, both of which can affect the quantification of total protein.

3.2 Microbiological Analysis of the Treatments

Significant differences in microbial load were observed among the evaluated treatments, depending on the type of meat product and the applied microorganism (Table 2). Treatment T1 (raw + *Lactobacillus plantarum*) showed total cocci count of 65 CFU/g and a low level of enterobacteria (10 CFU/g), while *Escherichia coli*, *Salmonella* spp., molds, and yeasts were not detected. In contrast, treatments T6 (mojama + *Lactobacillus reuteri*) and T8 (canned + *Leuconostoc mesenteroides*) showed no growth of total cocci, nor the presence of *E. coli*, *Salmonella* spp., molds, or yeasts. Only in T6 was a minimal enterobacterial count detected (0.5 CFU/g). These results indicate that the applied treatments, particularly in processed products such as mojama and canned preparations combined with lactic acid bacteria, are effective in inhibiting the growth of spoilage and pathogenic microorganisms.

Table 2. Microbiological analysis of the treatments

Variables	Treatments		
	T1 Raw + *Lactobacillus plantarum*	T6 Mojama + *Lactobacillus reuteri*	T8 Preserved + *Leuconostoc mesenteroides*
Total cocci	65	0	0
Enterobacteria	10	0.5	0
Escherichia coli	0	0	0
Salmonella spp.	0	0	0
Mold and yeast count	0	0	0

4. Discussion

4.1 Proximate Analysis of the A*B Interaction (Type of Paiche Meat Product * Lactic Acid Bacteria)

The pH values observed in this study (6.45–6.90) for fermented fish preserves prepared with different *Lactobacillus* strains are consistent with previous findings that emphasize the role of both the food matrix and bacterial strain in modulating acidification during fermentation. Research involving *Lactobacillus plantarum* and *L. reuteri* in traditional fermented fish products such as Thai *plaa-som* has demonstrated marked pH reductions,

confirming the active acidifying role of lactic acid bacteria (LAB). It is also essential to consider the natural pH range of muscle tissue in species like *Arapaima gigas*, whose fillets typically exhibit values between 6.26 and 6.49 (Jiang et al., 2023). Similarly, the inoculation of LAB strains such as *Streptococcus thermophilus* and *Lactobacillus acidophilus* in red tilapia (*Oreochromis niloticus*) has yielded stable pH values between 6.20 and 6.54 without compromising freshness (López-Salas et al., 2021), underscoring the importance of anatomical region and processing conditions in determining pH evolution during fermentation.

The application of LAB as biopreservative agents in paiche-based products proved effective in enhancing microbiological safety and physicochemical stability. This is supported by the titratable acidity results, which showed statistically significant differences between treatments ($p<0.05$). The acidity levels recorded are consistent with prior studies, such as the 0.41% lactic acid content reported in marinated tilapia fillets, a benchmark value for preserved fresh fish products (Medina Bracamonte et al., 2014). In a similar vein, preserved paiche cuts (loin and belly) have demonstrated acidity ranges from 0.35% to 0.56%, reflecting the influence of tissue type and processing techniques on the acid profile of the final product (Castillo-Jiménez et al., 2017). These findings reinforce the potential of LAB as valuable technological tools for maintaining the quality and shelf life of paiche-based meat products.

Moisture content in fish products treated with biopreservatives varies considerably depending on the preservation method. Traditional techniques like salting and drying –as used in products such as mojama– induce significant water loss, thereby limiting microbial growth. Scientific evidence supports this effect, demonstrating that salting denatures muscle proteins and reduces their water-holding capacity, contributing to greater moisture loss (Neira Mosquera et al., 2021). In contrast, fish products not subjected to intense dehydration, such as fillets from *Rastrelliger kanagurta* (Indian mackerel) and *Cyprinus carpio* (carp), exhibit higher moisture levels, typically ranging from 60.40% to 71.80% (Neira-Mosquera et al., 2025).

Ash content in fish products is also highly influenced by processing methods. In mojama, elevated ash values are primarily due to mineral concentration resulting from dehydration. Additionally, the use of salt and LAB during curing enhances mineral retention. A recent study reported ash content in salted dried fish reaching up to 18.72%, compared to 5.22% in unsalted counterparts, clearly illustrating the impact of salting on mineral concentration (Reinoso Ocaña, 2021). By contrast, unprocessed seafood such as skinless paiche fillets typically contain around 1% ash, while fresh *Thunnus* spp. loin slices show similar values, averaging 1.58% (Roldán-Acero et al., 2020; Saithong et al., 2010).

The marked reduction in fat content observed in mojama is attributable to lipid loss during intensive drying, which, by drastically lowering moisture content, increases the relative proportion of proteins and minerals and reduces lipid concentration in the final product. These results align with previous studies reporting fat loss in cured fish subjected to extended drying (Neira Mosquera et al., 2021). Conversely, thermal processing such as canning may retain or even concentrate lipids, while fermentation with LAB has been associated with lipid reduction due to the lipolytic activity of these bacteria (Salazar et al., 2020). For instance, in a traditional Chinese fermented fish product, LAB strains such as *L. plantarum* and *Pediococcus acidilactici* reduced fat content to 10-12%, compared to approximately 13% in uninoculated controls (Simpson et al., 2022).

The decline in protein content in processed samples may be attributed to heat-induced denaturation in canned products and protein cross-linking during drying in mojama, both of which impair solubility and reduce detectability via conventional analytical methods (Reinoso Ocaña, 2021). Conversely, the higher protein concentration observed in raw samples inoculated with *L. reuteri* may reflect this strain's capacity to preserve proteins during early fermentation. However, subsequent processes such as cooking or drying may degrade or modify protein structures, ultimately leading to comparable protein levels across treatments. Notably, the protein values

reported in this study align with those found in red tuna (*Thunnus* spp.) loin fillets, which average approximately 22.51% protein (Saithong et al., 2010).

4.2 Microbiological Analysis of the Treatments

The microbiological load results obtained in this study for fish meat products treated with LAB demonstrate remarkable effectiveness in inhibiting pathogenic and spoilage microorganisms, aligning with international food safety standards. These findings meet the microbiological limits set by the World Health Organization (WHO) and the FAO, which recommend a total microbial count not exceeding 10^5 CFU/g for fish meat products (Alahmad et al., 2021). Thus, the evaluated treatments effectively reduce microbial loads, complying with global food safety regulations.

Among the treatments, the use of *Lactobacillus plantarum* showed particularly promising results. Previous studies with tilapia fillets revealed that immersion in *L. plantarum* solutions significantly reduced spoilage microbial growth and the formation of volatile nitrogenous compounds, maintaining microbiological and chemical quality during refrigerated storage (Sun et al., 2022). Similarly, research on antimicrobial extracts derived from LAB cultures in vacuum-packed fresh tilapia fillets demonstrated notable effectiveness. According to Salazar et al. (2020), extracts from both pure and combined cultures of *L. plantarum* produced the largest inhibition zones against pathogenic and spoilage bacteria. After 10 days of storage at 8 °C, reductions of 2.8 and 1.6 log cycles in mesophilic aerobes and total coliforms, respectively, were observed (Talledo Solórzano et al., 2020; Vialle et al., 2018).

5. Conclusions

In conclusion, the incorporation of probiotic lactic acid bacteria in meat products derived from *Arapaima gigas* showed significant effects on their physicochemical and microbiological properties, mainly influenced by the type of processing. The strains used, particularly *L. reuteri* and *L. plantarum*, demonstrated variable interactions with the food matrix, affecting key parameters such as pH, titratable acidity, and nutrient retention. The preserved products exhibited higher fat content, while the mojama concentrated minerals and acids showed reductions in moisture and fat. On the other hand, the raw samples maintained higher protein content. Regarding microbiological quality, treatments T6 and T8 stood out for their effectiveness in reducing pathogenic microorganisms, ensuring greater safety of the final product. These findings highlight the technological and sanitary potential of lactic acid bacteria treatments in optimizing meat products based on *Arapaima gigas*. They support the use of lactic acid bacteria as bioprotective agents in the meat industry, improving food safety and complying with microbiological standards.

Transparency of Data

Available data: The entire data set that supports the results of this study was published in the article itself.

Author Contribution Statement

	JA Neira Mosquera	CP Falconi Intriago	SN Sánchez Llaguno	KY Revilla Escobar	JP Aldas Morejon
Conceptualization					X
Data curation					X
Formal analysis		X			
Funding acquisition			X		
Investigation				X	
Methodology				X	
Project administration	X				
Resources	X				
Software				X	
Supervision			X		
Validation			X		
Visualization		X			
Writing – original draft				X	
Writing – review and editing					X

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