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Lactic Acid Bacteria Isolated from Sourdough Fermentation: Insights into Potential Applications

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Lactic acid bacteria (LAB) are essential microorganisms implicated in the fermentation process of dough, contributing to the development of desirable sensory attributes and ensuring dough quality. This review article aimed to provide an overview of the LAB isolated from dough fermentation, focusing on their potential applications. LAB strains have diverse applications across multiple sectors. In the food industry, they serve as probiotics, improving gut health, enhancing immune function, and acting as natural preservatives. Additionally, LAB strains from sourdough fermentation hold promise in pharmaceutical and biotechnological fields, offering potential for novel antibiotics, antimicrobial agents, and bioactive compounds with therapeutic properties. In addition,, In agriculture, these strains can be employed as biocontrol agents to suppress plant pathogens while enhancing soil health, nutrient cycling, and plant growth. Overall, This comprehensive review illuminates the significance of LAB in dough fermentation and underscores their immense potential for diverse industrial applications.

Keywords: Lactic acid bacteria, LAB, dough, probiotics, pharmaceutical, biotechnological.

INTRODUCTION

Fermentation, an age-old technique, is utilized in the production of diverse food items globally (Ibrahim *et al.* 2023). It has been employed throughout human history as one of the earliest forms of food biotechnology, playing a crucial role in the preparation of various foods and beverages. Fermented foods are consumed extensively worldwide, particularly in developing countries (Mao and Yan, 2019).

Dough fermentation is a fundamental process in the production of bakeshop products, influencing their sensory attributes, texture, and overall quality. The microbiota found in sourdough actively participates in a range of metabolic processes. These activities involve acidification, which is primarily carried out by LAB, as well as flavour formation, which is facilitated by both LAB and yeasts. Additionally, fermentation processes are conducted by yeasts and heterofermentative LAB species (De Vuyst *et al.* 2014). Among the diverse microorganisms involved in dough fermentation, lactic acid bacteria (LAB) stand out among the various microorganisms, attracting considerable interest for their crucial impact on moulding the traits of fermented dough. These strains play a vital role in crafting appealing flavours, improving dough consistency, and imbuing baked goods with nutritional and functional attributes (Alfo*et al.* 2017). Delving into the adaptation mechanisms and examining the potential uses of LAB strains isolated from dough fermentation are essential endeavours, as they promise to elevate dough quality and foster the creation of enhanced bakery offerings.

LAB are a group of gram-positive, non-spore-forming bacteria renowned for their ability to convert sugars into lactic acid through the process of homofermentation (Halima *et al.* 2020; Eji *et al.* 2023). Furthermore, to lactic acid production, LAB also synthesizes exopolysaccharides, bacteriocins, and aroma compounds, which significantly influence the shelf life and sensory attributes of fermented foods (De Souza *et al.* 2023). LAB have been extensively employed in food fermentation for over 4,000 years, encompassing approximately 20 genera. Major genera of LAB include *Lactococcus, Lactobacillus, Pediococcus, Carnobacterium, Leuconostoc, Aerococcus, Enterococcus, Oenococcus, Tetragenococcus, Vagococcus, Streptococcus*, and *Weisella* (Abiola *et al.* 2022). Additional genera such as *Lactosphaera* and *Paralactobacillus* have also been identified (Dashen, 2016).

The ability of LAB strains to adapt to the distinctive conditions of dough fermentation is shaped by various factors such as pH, temperature, and salt concentration. These microorganisms demonstrate impressive flexibility, allowing them to flourish and carry out their metabolic functions within the dough environment (Martín-Garcia *et al.* 2023). The term "lactic acid bacteria" was established in the early 20th century (Dashen, 2016). Certain strains of LAB have been recognized for their beneficial properties for human health and are referred to as probiotics (Abiola *et al.* 2022). Probiotics are beneficial microorganisms that offer advantages to the host by exhibiting traits like resilience in gastrointestinal conditions, adhesion to the intestinal surface, and performing various functions that support overall well-being (Kaya *et al.* 2022). As per the FAO/WHO definition, probiotics are live microorganisms that are safe, non-toxic, and when consumed in sufficient quantities, confer health benefits (Fekri *et al.* 2020).

Furthermore, LAB strains derived from dough fermentation present a diverse array of potential applications within the food industry. Their functional attributes, encompassing probiotic qualities, antimicrobial efficacy, and proficiency in exopolysaccharide synthesis, render them appealing for numerous industrial uses. These strains can be harnessed for the creation of functional foods, eco-friendly preservatives, and bakery items boasting enriched nutritional content. Moreover, their pivotal involvement in sourdough bread production, influencing distinct flavour nuances and texture refinement, underscores their pivotal role within the bakery domain (Abedin *et al.* 2023). While previous studies have delved into LAB strains within dough fermentation, there remains a substantial amount to uncover regarding their adaptation mechanisms and the breadth of their potential applications. Given their pivotal role in improving dough quality and their commercial promise in the food industry, further investigation is warranted.

This study aims to provide in-depth insights into the mechanisms of adaptation and potential applications of lactic acid bacteria (LAB) strains obtained from dough fermentation. Through a thorough examination of existing literature and analysis of prior studies, we aim to illuminate the genetic diversity, metabolic functions, and functional attributes of LAB strains within the context of dough fermentation. Moreover, we will delve into the technological implications, and regulatory considerations associated with employing LAB strains in bakery products. By deepening our understanding of LAB strains in dough fermentation, this study endeavours to contribute to optimizing fermentation processes, creating value-added bakery items, and fostering sustainable and innovative practices within the food industry.

Sourdough

Sourdough bread is a unique kind of bread that relies on a sourdough starter for leavening. The starter is created by combining flour and water, which then undergoes fermentation with lactic acid bacteria (LAB) and yeasts. This fermentation process can occur spontaneously or be deliberately initiated through inoculation. Spontaneous sourdough, known as the oldest-known leavening agent for bread, is formed by allowing the dough to sit at room temperature for several hours. During this time, the dough undergoes fermentation by naturally occurring microorganisms, which produce metabolites that influence the dough's characteristics (Tamang *et al.* 2010). To develop a typical sour taste in the dough, additional flour and water can be added through a process known as backslopping. This promotes the growth of a diverse ecosystem of yeasts and LAB within the dough. Yeasts primarily produce carbon dioxide (CO_2) for leavening, while LAB is responsible for producing acetic acid, lactic acid, or both, which contribute to the aroma and flavour of the bread. The metabolic activities of microorganisms present in sourdough have a significant impact on the dough's technological performance, nutritional properties, aroma profile, shelf life, and overall quality of the resulting bread. However, despite the benefits of using sourdough as a leavening agent, compressed baker's yeast is more commonly employed in bread production due to the complexities associated with managing sourdough and its associated bread-making process. Baker's yeast provides reliable and rapid leavening, meeting the requirements of both artisanal and industrial bakeries, and is readily available commercially. Nevertheless, there are notable sensory, nutritional, and physical distinctions between bread made with yeast and sourdough bread (Paterson *et al.* 2006). Sourdough bread typically possesses a more pronounced flavour, acidic taste, denser crumb, and longer shelf life compared to yeast-based bread. Furthermore, sourdough bread exhibits superior nutritional properties, including a lower glycemic index (GI) and increased mineral bioavailability, as supported by numerous scientific studies (Catzeddu *et al.* 2019).

Therefore, during dough fermentation, a complex biochemical process occurs involving microorganisms, predominantly yeast and LAB, which interact with the dough elements and produce various metabolic byproducts. This fermentation process is a critical step in bread and other baked goods production, as it significantly influences the flavor, texture, and overall quality of the final product (Alfonzo *et al.* 2017). *Saccharomyces cerevisiae* is the main microorganism responsible for dough fermentation, consuming fermentable sugars and undergoing alcoholic fermentation, converting sugars into carbon dioxide gas and ethanol (Katina *et al.* 2005). LAB, including species like *Lactobacillus* and *Pediococcus*, also contribute to dough fermentation, particularly in sourdough fermentation, by converting sugars into lactic acid through lactic acid fermentation, leading to acidification, flavour development, and preservation of the dough

(Gobbetti *et al.* 2016). Enzymatic activity, such as amylases breaking down complex carbohydrates and proteases contributing to flavour development and dough structure, also plays a critical role during dough fermentation (Gänzle, 2015). The metabolic activities of the microorganisms generate volatile compounds, including esters, alcohols, and organic acids, contributing to the characteristic aromas and flavours associated with fermented dough (Coda *et al.* 2013). Furthermore, dough fermentation affects gluten proteins, modifying their structure and improving dough extensibility and elasticity, ultimately impacting the texture and crumb structure of the final baked product (Gänzle, 2015). Overall, understanding the dynamics of dough fermentation is crucial for optimizing fermentation conditions, selecting appropriate microorganisms or starter cultures, and achieving consistent and high-quality baked goods (Gobbetti *et al.* 2016).

The rising demand for flavorful and healthier bread alternatives has sparked a growing appreciation for sourdough bread among consumers. Capitalizing on this trend, specialized companies have introduced a wide range of innovative sourdough products. Additionally, the availability of advanced equipment designed for sourdough handling has further contributed to its widespread adoption in both artisanal and industrial bakeries (Catzeddu *et al.*2019).

Classification

The stability of mature sourdough relies on various factors that arise from the spontaneous formation of mixed microbial cultures. These factors encompass (1) The microflora found in the flour, other ingredients, and environmental conditions; (2) The role of microorganisms in the dough, including their metabolic activity, production of enzymes like proteolytic and amylolytic enzymes, and extra physiological properties; (3) The enzymatic activity and chemical composition of the flour; (4) Technological process parameters such as the ratio of flour to water, fermentation, pH, storage temperature, redox potential, number of backsloppings, and the choice between using starter cultures or bread maker yeast (Petkova *et al.* 2021).

There are four primary types of sourdough starters based on their species composition. Type I starters emerge through a spontaneous succession where a mixture of flour and water becomes colonized by environmental bacteria and yeasts that ferment the carbohydrates and nutrients present. Type II starters are developed for industrial processes and serve as baking improvers or leavening agents to impart the traditional sourdough flavour to the bread. Type II sourdough is stored at low temperatures and involves careful parameter control, often employing bioreactors and the addition of baker's yeast towards the end of fermentation. Type III sourdough functions as an acidifier or bread enhancer and closely resembles Type II, but it may undergo drying or pasteurization for easier handling in industrial bakeries. Type IV sourdough combines characteristics from Types I to III, involving the inoculation of a microbial starter into a dough followed by daily back-slopping. This type, with a firm or semiliquid texture, is commonly used in artisanal bakeries (Catzeddu, 2019).

Type I sourdough starters are commonly employed in artisanal bakeries and are typically kept at room temperature. Alternatively, they can be refrigerated during periods of inactivity or at regular intervals. These starters initially have a pH that is close to neutral but gradually decreases as they mature. This decrease in pH is attributed to the production of organic acids by LAB and acetic acid bacteria, leading to a high level of acidity in the starter. The maturity of Type I sourdough starters is generally evaluated based on macroscopic observations such as volume, height, smell, flavour, and the presence of bubbles (Calvert *et al.* 2021).

Sourdough-based baked goods exhibit a longer shelf life compared to products fermented solely by yeasts. This extended shelf life is attributed to the production of antifungals, bacteriocins, and increased acidity. Furthermore, they offer improved sensory qualities such as enhanced flexibility, internal humidity, and higher concentrations of volatile compounds. Additionally, they provide significant nutritional value by reducing anti-nutritional complexes like the phytase enzyme (Siepmann *et al.* 2018).

Importance of LAB in Dough Fermentation:

LAB play a pivotal role in dough fermentation, wielding a multitude of advantages that profoundly influence the excellence of bakery products (Sha *et al.* 2023). LAB's production of lactic acid during fermentation serves as a crucial catalyst for dough acidification, creating an inhospitable environment that reduces the growth of undesirable microorganisms (Rameez *et al.* 2024). This controlled acidification not only fosters the emergence of desirable flavours but also elevates the quality and overall quality of the end product. LAB strains exhibit remarkable versatility, generating diverse metabolites that impart distinct flavour profiles to a range of baked goods. Moreover, their enzymatic prowess in breaking down complex carbohydrates contributes to enhanced dough elasticity and improved gas retention capacity, thereby refining the texture and structure of the final product (Sun *et al.* 2023). Additionally, LAB fermentation has been found to enhance the nutritional content of bakery items through increased bioavailability of essential nutrients and the synthesis of beneficial compounds. Furthermore, LAB's natural preservation abilities prolong the shelf life of bakery products by creating an acidic environment that deters the growth of spoilage microorganisms (Smaoui *et al.* 2023). Notably, certain LAB strains even possess probiotic traits, offering the potential to confer additional health benefits to consumers. By harnessing the immense potential of LAB in dough fermentation, bakers and food manufacturers can create bakery products that are enriched in flavour, texture, and nutritional content, possess extended shelf life, and potentially promote consumer well-being.

Characterization of LAB Strains

The process of isolating and characterizing Lactic Acid Bacteria (LAB) strains involves the identification and analysis of LAB strains are critical steps in understanding their diversity, functional properties, and potential applications across various industries. The process begins with the collection of samples from different sources, such as dough or fermented foods, ensuring the representation of a wide range of LAB strains. These samples are then prepared for analysis through appropriate dilution or homogenization. LAB strains are subsequently isolated using selective culture media that promote their growth while inhibiting other microorganisms. The isolated strains are purified through sub-culturing to obtain pure cultures free from contamination. Phenotypic characterization involves assessing observable traits like colony and cellular morphology, Gram staining, and metabolic capabilities. Genotypic characterization delves into the genetic analysis of LAB strains through techniques like PCR or DNA sequencing, providing insights into their genetic diversity and potential functional genes. Physiological and biochemical tests further characterize the strains by examining their metabolic activities and properties. Finally, isolated LAB strains are stored and preserved for future research and applications. These steps form the foundation for understanding the functional potential and applications of LAB strains in various fields, facilitating the development of innovative products and processes (Nami *et al.* 2024).

Diversity of LAB Species in Dough Fermentation

Spontaneous sourdough contains diverse microorganisms like lactic acid bacteria (LAB) and yeast. They come from flour, the environment, or intentional inoculation. Research has advanced our understanding of sourdough microflora since the early 1900s (De Vuyst *et al.* 2014).

Among the LAB species isolated from sourdough, the Lactobacillus genus takes the lead, boasting an impressive repertoire of over 60 identified species. However, it's worth noting that species from the *Pediococcus*, *Leuconostoc*, and *Weissella* genera are also commonly encountered. Some intriguing discoveries include newly identified Lactobacillus species, like *Lactobacillus sanfranciscensis* and *Lactobacillus alimentarius*, which exhibit a remarkable affinity for sourdough. However, to definitively ascertain their exclusivity to the sourdough ecosystem, further investigations involving other food substrates are required.

It is noteworthy that specific species found in sourdough, such as *Lactobacillus reuteri* and *Lactobacillus acidophilus*, could have originated from the intestinal environment, potentially due to unintentional cross-contamination. In contrast, species like *Lactobacillus plantarum* and *Lactobacillus brevis*, which are commonly found in different habitats and foods, also contribute to the microbial communities in sourdough (Corsetti *et al.* 2007; De Vuyst *et al.* 2014).

The intricate microcosm of sourdough microflora continues to captivate researchers, unravelling the intricate relationships between microorganisms and their unique adaptations within this fascinating culinary ecosystem.

In Italy, *Lactobacillus sanfranciscensis* is the dominant species of lactic acid bacteria found in sweet-leavened baked goods and wheat breads. It contributes to the fermentation process and imparts unique characteristics and flavours to these products (Gobbetti *et al.* 1994; Ottogalli *et al.* 1996). Similarly*, L. sanfranciscensis* is also prevalent in traditional Greek wheat sourdough (De Vuyst *et al.* 2002). In southern Italy, *Lactobacillus pentosus* and *L. plantarum* are the predominant species in sourdough breads made with durum wheat flour (Ricciardi *et al.* 2005; Catzeddu *et al.* 2006). Turkish and Portuguese sourdough breads, on the other hand, are characterized by the prevalence of L. brevis (Gül *et al.* 2005).

While various yeast species from the Ascomycetes phylum have been isolated from sourdough, only certain species belonging to the *Saccharomyces* and *Candida* genera are commonly found and considered essential for the fermentation process. *Saccharomyces cerevisiae* is frequently detected in sourdough, often due to environmental contamination, particularly in bakeries where commercial baker's yeast is used (Corsetti *et al.* 2007; Minervini *et al.* 2015; De Vuyst *et al.* 2016). Yeast plays a crucial role in leavening the dough by producing carbon dioxide in sourdough.

In sourdough, a mutually beneficial relationship exists between the yeast species *Saccharomyces exiguus* (now *Kazachstania exigua*) and the LAB *Lactobacillus sanfrancisco* (now *L. sanfranciscensis*). These microorganisms were initially discovered together in San Francisco bread and play vital roles in the fermentation and souring processes. While *L. sanfranciscensis* can effectively utilize maltose, the primary sugar in sourdough, *K. exigua* lacks this ability. During fermentation, *L. sanfranciscensis* converts maltose into glucose, utilizing one glucose molecule while excreting the other. The excreted glucose serves as a substrate for the yeast, which ferments it further. In return, the yeast releases amino acids and peptides, providing favorable conditions for the growth of *L. sanfranciscensis*. This symbiotic relationship enhances the overall fermentation process in sourdough. Similar stable associations between yeast and LAB have been observed in other sourdough instances. For example, *Candida humilis* and *L. sanfranciscensis*, as well as *S. cerevisiae* and *L. plantarum*, exhibit similar cooperative interactions, contributing to the intricate dynamics of sourdough ecosystems (Kline *et al.* 1971; Corsetti *et al.* 2007; De Vuyst L *et al.* 2014; Catzeddu *et al.* 2019).

Typically, the most commonly found LAB species in dough fermentation include *Lactobacillus sanfranciscensis*, *Lactobacillus plantarum*, *Pediococcus pentosaceus*, *Lactobacillus brevis*, *Lactobacillus fermentum* (from the *Lactobacillus reuteri* group) and *Lactobacillus paralimentarius* (from the *Lactobacillus alimentarius* group). Some sourdoughs may also contain *Weissella and Leuconostoc* species (Van *et al.* 2017). It's significant to note that the composition and abundance of LAB species can vary depending on the specific dough fermentation process and environmental factors. Additionally, different LAB species may dominate at different points of fermentation, as the conditions change throughout the process.

Factors Influencing LAB Diversity

The diversity of LAB in different environments, including dough fermentation, is affected by numerous factors. These factors play a role in determining which LAB species are present and their abundance. Several key factors that impact LAB diversity include substrate composition, fermentation conditions, microbial interactions, starter cultures, environmental factors, processing techniques, contamination and hygiene practices, and genetic factors.

The diversity of LAB in dough fermentation is influenced by the composition of the substrate, particularly the type of flour used. Different types of flour provide varying nutrients and environmental conditions that can selectively support the growth of specific LAB strains. As a result, the choice of flour can significantly impact the diversity and abundance of LAB species present during fermentation (Alfonzo *et al.* 2017). Fermentation conditions, including temperature, pH, and duration, directly influence LAB diversity as different species have different tolerances and preferences for these conditions (Sheeladevi *et al.* 2011). Microbial interactions with other microorganisms present in the environment can also shape LAB diversity (Mante *et al.* 2003). Interactions with yeasts, moulds, or other bacteria can either promote or inhibit the growth of specific LAB species(Ewuoso *et al.* 2020).

The use of starter cultures, whether natural or added, significantly influences LAB diversity. Starter cultures consist of selected LAB strains introduced to initiate fermentation, dominating the LAB population and influencing overall diversity. Environmental factors such as geographical location, climate, and seasonal variations contribute to variations in LAB diversity. Different regions and climates harbour unique microbial communities, including LAB species(Viiard *et al.* 2016).

Processing techniques employed during dough fermentation, such as mixing, kneading, or proofing, affect LAB diversity by influencing factors like oxygen availability, temperature gradients, and mechanical stress (Huma *et al.* 2016). Contamination from external sources can introduce different LAB species, altering the existing LAB diversity. Hygiene practices and cleanliness of equipment and working environments are crucial in maintaining the desired LAB diversity and preventing unwanted contamination.

Intrinsic genetic factors of LAB strains, including their genetic diversity and adaptability, contribute to the overall LAB diversity observed in dough fermentation. Different strains possess varying traits, metabolic capabilities, and responses to environmental conditions, influencing their representation in the LAB population.

Molecular Studies of LBA in Sourdough

While traditional bacterial identification methods have been widely used and established over many decades, they have limitations. They can be time-consuming, requiring several days to obtain results, and may lack the sensitivity and specificity needed for accurate identification of certain bacterial species. Moreover, these methods are often labour-intensive and require skilled personnel to perform and interpret the tests. In recent years, advancements in molecular techniques, such as polymerase chain reaction (PCR) and DNA sequencing, have revolutionized bacterial identification. These molecular methods enable the direct detection and analysis of specific DNA sequences or genetic markers, offering rapid and precise identification of bacteria. Molecular approaches have significantly enhanced our understanding of bacterial taxonomy, phylogeny, and epidemiology. As a result, a method known as genotypic trait identification has been developed to avoid potential issues with phenotypic techniques(Meroth *et al.* 2003).

Molecular studies of LAB in sourdough have provided significant insights into the bacterial composition, diversity, and dynamics during the fermentation process. Molecular studies of LAB in sourdough have been conducted to understand their genetic characteristics, diversity, and behaviour during the fermentation process. These studies utilize various molecular techniques to analyze the DNA or RNA of LAB present in sourdough samples (Çakır *et al.* 2020;

Gunduz *et al.* 2020; Sevgili *et al.*2023).

The study focused on examining the isolation and identification of lactic acid bacteria (LAB) in homemade traditional sourdoughs. The LAB was detected using the PCR method and subsequently utilized in the manufacture of sourdough bread (SDB). A total of 36 sourdough samples yielded 11 identified LAB species. The most commonly isolated LAB-specific species were *Lactobacillus brevis*, *Pediococcus acidilactici*, and *Lactobacillus plantarum* (45.0%, 20.0%,18.3%) respectively, while the remaining LAB-specific species were isolated at lower frequencies ranging from 1.7% to 3.5%. Based on these isolated LABs, twelve different types of SDB were produced by combining them (Sevgili *et al.*2023).

In the laboratory setting, a total of 32 distinct LAB strains were isolated from spontaneously fermented einkorn sourdough. Using PCR analysis targeting the 16S gene, seven different LAB species were identified: *Lactobacillus crustorum* (with 10 strains as the dominant species), *Lactobacillus brevis* (6 strains), *Pediococcus* (4 strains), *Lactobacillus fermentum* (4 strains), *Lactobacillus paraplantarum* (1 strain), *Lactobacillus plantarum* (5 strains), and *Lactobacillus curvatus* (2 strains). Among these species, *Lactobacillus paraplantarum* and *Pediococcus acidilactici* exhibited strong antibacterial activity against *Bacillus subtilis* ATCC6633, *Bacillus cereus* ATCC11778, and *Escherichia coli* ATCC25922. Additionally, *Lactobacillus crustorum* strain MN047 and *Lactobacillus brevis* strain R-1 demonstrated antifungal effects against *Aspergillus flavus*, *Penicillium carneum*, and *Aspergillus niger*. Furthermore, all strains displayed a high tolerance to acidic conditions, as they exhibited a survival rate of over 70% at pH 2.5 (Çakır *et al.* 2020).

Overall, molecular studies of LAB in sourdough, using DNA sequencing, have enhanced our understanding of their genetic diversity, functional potential, and behaviour during fermentation. These studies have implications for optimizing sourdough production processes, improving bread quality, and developing tailored starter cultures.

Adaptation of LAB in Dough Fermentation

In recent times, there has been an increased focus on the microbial metabolic characteristics of LAB, owing to their significant roles in the food industry and their probiotic functions. These bacteria possess the capability to break down complex substances found in food, including polysaccharides, and also facilitate the conversion of undesirable flavor compounds. Furthermore, they exhibit a diverse range of metabolic activities, leading to the production of various compounds such as short-chain fatty acids, amines, bacteriocins, vitamins, and exopolysaccharides. Capitalizing on these metabolic traits, lactic acid bacteria have found expanded applications in the food industry. They are employed to enhance the flavour of fermented foods, improve nutritional value, diminish harmful substances, and extend shelf life, among other benefits. Additionally, they are utilized as probiotics to promote overall health in the body (Wang *et al.* 2021).

Lactic acid bacteria (LAB) generate various metabolites that possess the ability to enhance multiple aspects associated with the general quality of fermented foods. These foods encompass a wide range of categories such as dairy products, baked goods, meat products, fruits, and vegetables. LAB produces a diverse array of important metabolites, including H2O2, organic acids, bacteriocins, amino acids, fatty acids, exopolysaccharides, acetoin, and acetaldehyde. These metabolites play significant roles in improving different characteristics and attributes of fermented foods *(*De Souza *et al.* 2023).

During dough fermentation, Lactic Acid Bacteria (LAB) undergo specific adaptations to thrive in acidic, nutrient-limited, and low-oxygen conditions. LAB strains regulate their intracellular pH, possess acid resistance genes, and employ efficient nutrient utilization pathways to withstand the acidic environment and utilize the available nutrients. They produce antimicrobial compounds, utilize niche-specific resources, and employ anaerobic respiration or fermentation pathways to outcompete other microorganisms and adapt to low-oxygen conditions. LAB strains also develop heat shock response mechanisms to tolerate the elevated temperatures

Potential Applications of LAB Strains:

Food and Beverage Industry

LABs are a diverse group of bacteria that play a crucial role in various fermentation processes. They metabolize carbohydrates in food, producing lactic acid as the primary fermentation product. Moreover, LAB's breakdown of proteins and lipids, along with the production of compounds such as alcohols, aldehydes, acids, esters, and sulfur compounds, contribute to the distinct flavors found in different fermented foods. LAB is extensively used as starter culture in a wide range of fermented dairy products, including cheese, yogurt, and fermented milks. They are also employed in meat, fish, fruit, vegetable, and cereal products. LAB enhances the flavor, texture, and nutritional value of these fermented foods and can act as adjunct cultures. For example, they accelerate cheese maturation, improve yogurt texture through exopolysaccharide production, and control secondary fermentations in wine production. Some LAB strains produce bacteriocins and antifungal compounds, making them valuable as bio-protective cultures in certain foods. Additionally, specific LAB strains have well-documented health benefits, leading to their incorporation, often in combination with bifidobacteria, as probiotic cultures with diverse applications in the food industry (Bintsism 2018; Liang *et al.* 2023).

LAB and their bacteriocins find various applications across various fields. In the food industry, LAB and their bacteriocins have diverse applications across various fields, particularly in the food industry. One notable use is in food preservation, where LAB and their bacteriocins serve as natural preservatives. They effectively inhibit the growth of pathogens and spoilage bacteria, thereby extending the shelf life of food products.

LAB and their bacteriocins are also pivotal in the biopreservation of meat, fish, and fermented foods, where they inhibit spoilage bacteria, maintain product quality, and ensure food safety. Moreover, they have applications in veterinary medicine, serving as alternatives to antibiotics in animal feed and promoting animal health. Additionally, LAB and their bacteriocins are being studied for their biomedical and therapeutic potential, as they demonstrate antimicrobial properties against drug-resistant bacteria and may have therapeutic applications in treating bacterial infections. This application provides a natural and safe alternative to traditional preservatives in the food industry. Overall, LAB and their bacteriocins offer a wide range of applications, impacting various industries and fields with their antimicrobial properties and beneficial effects (Mokoena *et al.* 2021).

Biotechnology and Enzyme Production

Biotechnology plays a significant role in enzyme production, and LABs are valuable contributors to this field. LAB strains are widely utilized in biotechnological processes for the production of enzymes with various applications.

Several studies have focused on investigating the enzymatic activities and modern or potential applications of LAB in various aspects of our lives. Glycosidases, which break down the extremely abundant food molecules and serve as carbon sources, support the existence of organisms on Earth. Additionally, LAB's ability to convert lactose, a uniquely mammalian carbohydrate, into lactic acid ensures microbial safety and innocuity. Lipases and proteases, including proteinases, play a crucial role in food fermentations and contribute to flavour development, especially in dairy products. Bacteriocins and peptidoglycan hydrolases are enzymes found in the enzymatic system of lactic acid bacteria (LAB). These enzymes have evolved to make LAB strong competitors in various microbiomes, particularly in the important environment of the human gut. Their presence and activity contribute to the ecological balance and functionality of the gut microbiota, which in turn has significant implications for human health.(García-Cano *et al.* 2020; Okoye *et al.* 2023; Liang *et al.* 2023).

Bacteriocins

Lactic acid bacteria (LAB) exhibit strong inhibitory activity against pathogenic bacteria, both in laboratory settings (*in vitro*) (Petrova *et al.* 2009) and in living organisms (*in vivo*) (Hamed *et al.* 2011)). LAB's broad-spectrum antagonistic properties are attributed to the production of germicidal substances such as bacteriocins and organic acids. These substances disrupt the growth and survival of pathogenic bacteria by targeting their cellular membranes and metabolic processes. LAB's inhibitory special effects aren't limited to the gut environment, as they are also utilized as natural preservatives in fermented foods(Vesković-Moračanin *et al.* 2014).

Scientists have recently modified various bacteriocins derived from lactic acid bacteria. These bacteria strains, commonly found in food groups, have demonstrated the ability to produce highly effective bacteriocins or antimicrobial proteins against pathogens that cause foodborne such as *Staphylococcus aureus, Pseudomonas aeruginosa, Pseudomonas fluorescens, Shigella flexneri, Salmonella typhi, Listeria monocytogenes, Escherichia coli O157:H7,* and *Clostridium botulinum* (Darbandi *et al.* 2022). Bacteria belonging to the genera Bifidobacterium and Lactobacillus, known for their health-promoting characteristics, have been extensively studied and characterized. Understanding the mechanisms of action of these antimicrobials can help identify specific probiotic lactic acid bacteria capable of producing them, which is crucial for preserving functional foods or for medicinal applications (Ren *et al.* 2019; Darbandi *et al.* 2022).

Pharmaceutical and Medical Applications

LAB have various pharmaceutical and medical applications (Gerez *et al.* 2012; Daba *et al.* 2020; Daba *et al.* 2021). Lactic acid bacteria (LAB) have established themselves as highly valuable biotechnological tools due to their probiotic properties and the production of various compounds with meaningful applications in pharmaceutical industries and food. LAB species, renowned for their probiotic characteristics, are esteemed in the field and possess the remarkable ability to synthesize a wide range of valuable compounds. Among these compounds, exopolysaccharides (EPS) (Sha *et al.* 2023) and bacteriocins hold particular importance (Abdullahi *et al.* 2021). EPS, generated by specific LAB genera, extend the shelf life of products and enhance technological functionality in the food and dairy industries, while also offering beneficial health effects. Bacteriocins, including those produced by LAB, are peptides with diverse applications in food processing, preservation, and commercial products. Their potent properties make them valued in the food industry, and their potential extends to being agents against multidrug-resistant bacteria, as well as potential anticancer, antileishmanial, and antiviral agents in the pharmaceutical and medical fields.

LAB strains are commonly used as probiotics for promoting gastrointestinal health and immune function (Mazahreh *et al.* 2009; Carvalho *et al.* 2017). They also show potential as antibiotic alternatives, producing antimicrobial substances like bacteriocins (Daba *et al.* 2020; Daba *et al.* 2021, Al-Maaqar *et al*. 2022). LAB-based therapies have been explored for managing conditions such as inflammatory bowel disease (Saez-Lara et a.. 2015; Chen *et al.* 2023), vaginal health issues (Nam *et al.* 2007), oral health problems (Comelli *et al.* 2002), skin disorders (Huang *et al.* 2020), allergies, asthma, and cancer therapy support (Jin *et al.* 2020; Liu *et al.* 2021; Garbacz, 2022).

Agriculture and Animal Feed

Lactic acid bacteria have important roles in agriculture and animal feed. In agriculture, LAB strains promote crop health and growth, improve soil health and nutrient cycling, and suppress plant diseases (Alfonzo *et al.* 2017; Raman *et al*. 2022). In animal feed, LAB-based probiotics enhance gut health, digestion, immune function, and disease prevention in livestock and poultry. They also contribute to improved feed efficiency, animal performance, and silage fermentation (Bartkiene *et al.* 2017; Deng *et al.* 2022).

CONCLUSIONS

In conclusion, the study of lactic acid bacteria (LAB) provides valuable insights into their potential applications. The various LAB strains present in sourdough contribute to its distinct flavour, texture, and extended shelf life. These LAB strains have demonstrated promising potential beyond their traditional role in bread-making, spanning multiple industries. In the food industry, LAB strains derived from sourdough fermentation can be utilized as probiotics, offering health benefits to consumers. They contribute to improved gut health, enhanced immune function, and overall well-being. Furthermore, LAB strains exhibit antimicrobial properties, making them viable natural preservatives and alternatives to synthetic additives for food preservation. Moreover, LAB strains from sourdough fermentation show potential in the pharmaceutical and biotechnological sectors. Their antimicrobial properties can be explored for the development of novel antibiotics and antimicrobial agents. LAB strains may also produce bioactive compounds with potential therapeutic applications, including antioxidants, anti-inflammatory agents, and anticancer substances. LAB strains isolated from sourdough fermentation also hold promise in agriculture. They can be employed as biocontrol agents to suppress plant pathogens, reducing the need for chemical pesticides. Additionally, LAB's ability to enhance soil health, nutrient cycling, and plant growth makes them valuable for sustainable agricultural practices. Overall, the study of LAB isolated from sourdough fermentation reveals a wide array of potential applications. Further research and exploration are necessary to fully capitalize on their benefits in food, agriculture, pharmaceuticals, and biotechnology. With their diverse capabilities and beneficial properties, LAB strains present exciting opportunities for innovation and advancement across various fields.

Supplementary materials

Not applicable.

Author contributions

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Conflict of interest

The present study was conducted without any conflicts of interest, according to the authors.

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