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Review Article

Functional Use of Lactic Acid in Food Fermentation: Overview, Current Trends and Future Perspectives

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ABSTRACT

The functional use of lactic acid in food fermentation has gained considerable attention in recent years due to its role in enhancing the safety, shelf life, and nutritional properties of various food products. Fermented foods are the first processed staple human diet that has been produced and consumed since the development of human civilizations. The production and consumption of a significant portion of fermented foods involve controlled microbial growth and enzymatic conversions of both major and minor food components. These processes elevate the value of fermented foods due to the enhancement of their organoleptic properties. This review begins with an introduction that underscores the historical significance and enduring relevance of lactic acid fermentation in the food industry. It then delves into the various types of lactic acid, namely L-(+)-lactic acid and D-(-)-lactic acid, elucidating their distinct chemical properties and roles in different fermentation processes. Current trends in the use of lactic acid in food fermentation are addressed, reflecting the growing consumer demand for natural, health-oriented, and plant-based fermented products. This review provides a comprehensive overview of the functional aspects of lactic acid in food fermentation. It further exhibited the resultant effects of ethnic and cultural diversity in the use of lactic acid for food processing in Africa, explores current trends in its application, and outlines future perspectives emphasizing advancements in biotechnology, exploration of novel substrates, and the potential for more sustainable fermentation processes.

Keywords: Food Fermentation, Food Preservation, Traditional Food, Lactic Acid Bacteria, Organic Acid, Probiotics.

Introduction

In Africa, the functional use of lactic acid in food fermentation is deeply rooted in traditional food processing methods.[1] These practices are integral to the culinary heritage of diverse African communities, playing a crucial role in food preservation, enhancing nutritional value, and imparting unique flavors to various food products. Lactic acid fermentation serves as a natural and effective method of preserving food, particularly in regions where access to refrigeration is limited.[2] Fermented foods have an extended shelf life, allowing communities to store and consume perishable ingredients over longer periods.[2] Lactic acid is a naturally occurring organic acid produced during the fermentation of carbohydrates by lactic acid bacteria (LAB).[3] It plays a crucial role in food fermentation processes, contributing to the flavor, texture, and shelf life of many fermented products.[4] LAB are a diverse group of Gram-positive, non-spore-forming bacteria that are widely used in food and industrial fermentation processes Their primary function is to produce lactic acid as the major metabolic byproduct of carbohydrate fermentation, and they are generally regarded as safe for consumption. Lactic acid fermentation is commonly used in the production of foods such as yogurt, sauerkraut, pickles, and sourdough bread.[4] Lactic acid fermentation is commonly used in the production of foods such as yogurt, sauerkraut, pickles, and sourdough bread. Lactic acid itself is a potent organic acid that acts as a pH regulator and preservative in food products. Its sour taste and low pH make it effective at inhibiting the growth of bacteria and fungi, which extends the shelf life of food products.[3] Lactic acid's flavor profile, similar to vinegar or lemon juice, is also frequently used as a flavoring agent in beverages, dairy products, and baked goods. Its high-water solubility allows it to be easily incorporated into various food products. There are two optical isomers of lactic acid: L-lactic acid and D-lactic acid. Humans can metabolize L-lactic acid, but D-lactic acid can be toxic and is not metabolized efficiently.[11] Most research and applications involving lactic acid, especially in the food, beverage, and pharmaceutical industries, focus on L-lactic acid. The precise uses of L- and D-lactic acid, along with their differences in characteristics and functions, depend on their intended applications. Lactic acid can be produced either chemically or biologically.[5] The most common method of chemical synthesis involves the hydrolysis of lactonitrile using strong acids, while biosynthesis is achieved through microbial fermentation. Recently, microbial fermentation has gained more attention due to its numerous advantages, including lower cost, higher efficiency, environmental sustainability, and high optical purity.[6] Common microorganisms used for lactic acid fermentation include *Lactobacillus acidophilus, Lactobacillus plantarum, Lactobacillus casei, Leuconostoc mesenteroides, Streptococcus thermophilus, Saccharomyces cerevisiae,* and *Lactobacillus bulgaricus*.[3]

In warmer climates, lactic acid plays a critical role in preserving fermented foods by inhibiting spoilage microorganisms. Warmer temperatures can promote the rapid growth of spoilage organisms such as bacteria, molds, and yeasts, which degrade food quality and pose health risks.[7] The acidic environment created by LAB suppresses the growth of these spoilage organisms, which prefer neutral or slightly

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acidic conditions.[8] Additionally, lactic acid helps to inhibit pathogenic bacteria that cause foodborne illnesses, as these pathogens generally thrive in neutral pH environments.[9] The acidic conditions also help preserve the texture, structure, and flavor of fermented products by inhibiting enzymatic activity that could degrade proteins and other macromolecules in food.[4] In some cases, warmer climates may encourage spontaneous fermentation, where naturally occurring microorganisms in the environment initiate fermentation, producing lactic acid and other organic acids. Lactic acid serves several functions, including acting as an antioxidant, preservative, flavor enhancer, flavoring agent, leavening agent, and pH control agent. Due to its diverse functional properties, lactic acid is a key ingredient in various food and beverage products.[10] The widespread utilization of lactic acid in the food and beverage industry, coupled with the multifaceted benefits provided by food acidulants, plays a pivotal role in driving the food acidulants market. The growing demand for lactic acid in the food and beverage industry, along with the multifunctional benefits it provides as a food acidulant, continues to drive the global food acidulant market. As consumer preferences and economic development in Africa evolve, the region is expected to become an increasingly promising market for food acidulants, contributing to the expansion of the food and beverage industry. Furthermore, lactic acid is extensively used in the preservative market, and Figure 1 illustrates the revenue of the African food acidulant market.

Figure 1: Africa Food Acidulant Market Revenue[59]

Types of Lactic acid

Lactic acid, both L-lactic acid and D-lactic acid, plays a vital role in food fermentation due to its preservative properties, ability to regulate pH, and flavor enhancement. The two forms differ structurally as stereoisomers, with L-lactic acid being the most common in nature and essential in human metabolic processes.[11] D-lactic acid, on the other hand, is produced primarily by certain bacteria and can accumulate in the body under specific conditions, leading to D-lactic acidosis in individuals with medical conditions like short bowel syndrome.[12] The orientation of the hydroxyl group (-OH) on the carbon atom of the lactic acid molecule is what distinguishes L-lactic acid from D-lactic acid.[13] The hydroxyl group in D-lactic acid is orientated to the right, whereas it is directed left in L-lactic acid. In some medical disorders, such as short bowel syndrome, when there is an interruption in the regular absorption and metabolism of carbohydrates in the gut, D-lactic acid synthesis can take place. This can lead to an overgrowth of bacteria that produce D-lactic acid, leading to an accumulation of this form of lactic acid in the body. This can cause a condition known as D-lactic acidosis, which can result in symptoms such as confusion, lethargy, and neurological dysfunction.[14] In general, L-lactic acid is the form of lactic acid that is most commonly studied and used in various applications, such as in the production of foods, beverages, and pharmaceuticals. The properties and functions of L-lactic acid and D-lactic acid can differ, and their specific applications depend on the intended use. Lactic acid production process of L- lactic acid and D- lactic acid is illustrated in Figure 2.

Lactic Acid fermentation

Lactic acid bacteria (LAB) convert carbohydrates (like glucose) into lactic acid as part of the fermentation process in lactic acid. Homolactic fermentation and heterolactic fermentation are the two primary categories of lactic acid fermentation processes.

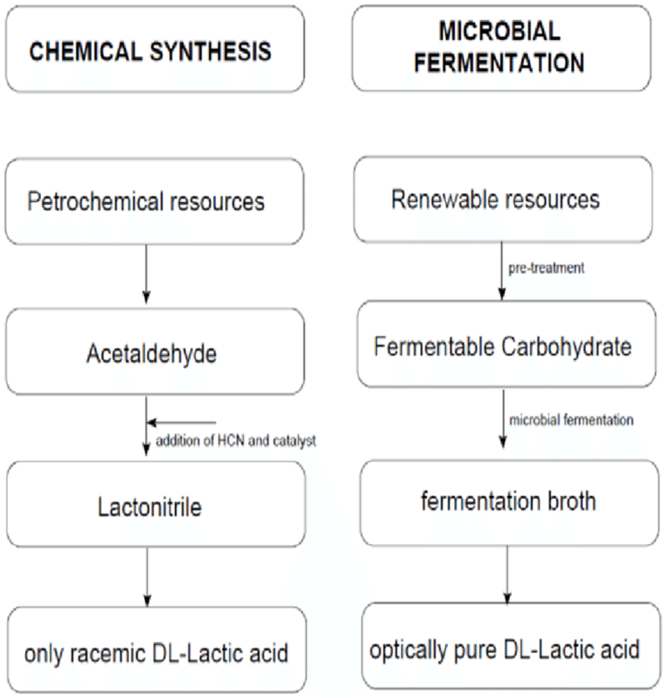

Figure 2: Lactic acid production process of L- lactic acid and D- lactic acid[60]

Homolactic fermentation

In this process, lactic acid bacteria convert the sugars in the substrate (usually glucose) into lactic acid as the main end-product. This process occurs when a microorganism, such as some species of *Lactobacillus* and *Streptococcus* bacteria, converts glucose into lactic acid as the sole product. [3] During this process, glucose is metabolized via glycolysis to produce two molecules of pyruvate, which are then converted into two molecules of lactic acid by the enzyme lactate dehydrogenase. Homofermentative Lactic Acid Bacteria include *Streptococcus lactis, Streptococcus faeclis, Streptococcus thermophiles, Lactobacillus delbrueckii, Lactobacillus plantarum, Lactobacillus bulgaricus, Lactobacillus helveticus, Lactobacillus casei,* and *Lactobacillus delbrueckii*. This process produces two ATP molecules per glucose molecule. The reaction is as follows: Glucose → 2 lactate + 2 ATP. Homolactic fermentation produces only lactic acid as the end-product, and no other byproducts are formed. This type of fermentation is used to produce foods such as yogurt, sour cream, and some types of cheese.

Heterolactic fermentation

In this process, lactic acid bacteria convert the sugars in the substrate (usually glucose) into lactic acid, ethanol, and carbon dioxide as the end-products. This process occurs when a microorganism, such as some species of *Leuconostoc* and *Lactobacillus* bacteria, produces both lactic acid and other compounds, such as ethanol, acetic acid, and carbon dioxide, as end products.[3] During this process, glucose is metabolized via the pentose phosphate pathway, producing pentose sugars and NADPH. The pentose sugars can then be metabolized to produce additional products, such as acetic acid and ethanol. *Leuconostoc mesenteroides, Lactobacillus cremoris, Lactobacillus brevis,* and *Lactobacillus fermentum* are the heterofermentative Lactic Acid Bacteria. One ATP molecule is produced here for every glucose molecule. Glucose = 1 lactate + 1 ethanol + 1 carbon dioxide + 1 ATP. Lactic acids, as well as other byproducts including ethanol and carbon dioxide, are produced during heterolactic fermentation. Foods like sauerkraut, pickles, and various varieties of cheese are made using this form of fermentation. Both homolactic and heterolactic fermentation processes are used in the food industry to produce a wide range of fermented products with different flavors, textures, and nutritional properties.[16] The specific fermentation process used depends on the desired end-product and the type of lactic acid bacteria used. These processes are also important in the human body, where they can occur in muscles during intense exercise, leading to the production of lactic acid and subsequent muscle fatigue.

Lactic acid fermentation pathway

The pathway for lactic acid production is known as lactic acid fermentation. It is a metabolic pathway that converts glucose or other sugars into lactic acid. [4] A group of microorganisms known as lactic acid bacteria (LAB) are responsible for producing lactic acid and are typically found in a variety of habitats, including the human body, soil, plants, and food products.[17] The pathway involves several steps:

Glycolysis

The first step in lactic acid fermentation is glycolysis, in which glucose is converted into two molecules of pyruvate. This process yields a small amount of ATP.

Pyruvate to lactate conversion

The enzyme lactate dehydrogenase catalyzes this process, converting pyruvate to lactate. NAD+ (nicotinamide adenine dinucleotide), which is required for glycolysis to continue, is also produced by this reaction.

Regeneration of NAD+

Lactic acid fermentation requires a constant supply of NAD+ for glycolysis to continue. Since NAD+ is used up during the conversion of pyruvate to lactate, it must be replenished in order for glycolysis to continue. This is achieved through the oxidation of NADH (the reduced form of NAD+) back to NAD+. Lactic Acid Fermentation is as shown in Figure 3. Glucose 2 lactate + 2 ATP is the general chemical equation for lactic acid fermentation. Two molecules of lactate and two molecules of ATP (adenosine triphosphate) are produced in this process from two molecules of glucose. The organism can utilise the lactate produced during lactic acid fermentation as a source of energy, and it also gives some fermented foods, like yogurt, their tart flavor. The manufacture of many different foods, such as cheese, yogurt, and sauerkraut, involves the fermentation of lactic acid.[18] Temperature, pH, and the type of microorganisms used all have an impact on the lactic acid fermentation process. Variable LAB strains may have variable lactic acid production rates and environmental requirements for optimum development and fermentation.

Temperature

According to Abedi, (2020) temperature has a considerable impact on the rate of metabolic responses as well as the growth of the lactic acid bacteria (LAB) that produce lactic acid. In general, temperatures between 30 and 40°C (86 and 104°F) are favorable for the synthesis of lactic acid. At these temperatures, LAB can grow and metabolize sugars efficiently, leading to a higher production of lactic acid. However, different strains of LAB may have different optimal temperature ranges for lactic acid production. At temperatures outside of the optimal range, the rate of lactic acid production may decrease, or the LAB may become stressed or inhibited.[19] For example, at temperatures below the optimal range, the metabolic reactions may slow down, and the growth of LAB may be inhibited. The LAB may get stressed and produce less lactic acid at temperatures over the optimal range. The final characteristics of the fermented product, such as the texture, flavor, and aroma, are also influenced by temperature. Temperature can be classified into the following:

Thermophilic

For optimum growth and lactic acid generation, they prefer warmer temperatures, often in the range of 40–45°C (104–113°F). For instance, some LAB strains such as *Streptococcus thermophiles* and *Lactobacillus delbrueckii subsp. Bulgaricus*.[19]

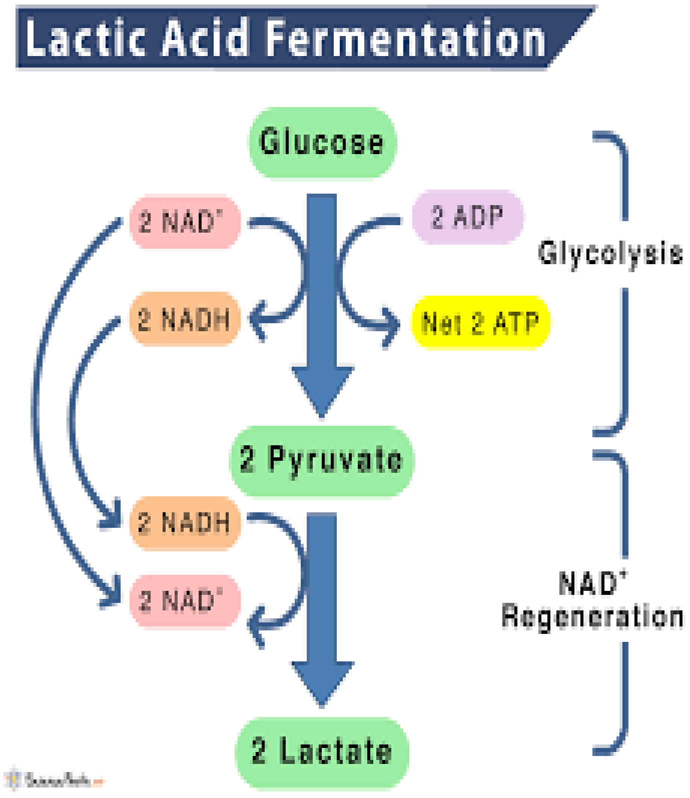

Figure 3: Lactic Acid Fermentation Pathway[61]

These strains are frequently used together while making yogurt because they reduce the pH and cause the milk proteins to coagulate converting lactose into lactic acid. Thermophilic LAB are also used to make various fermented dairy products, including kefir, koumiss, and some kinds of cheese, in addition to yogurt. By producing lactic acid and other metabolites in these applications, the LAB strains improve the flavor, texture, and shelf life of the finished product.

Mesophilic

For optimum growth and lactic acid production, they need lower temperatures, which are often in the range of 25–35°C (77–95°F). For instance, *Lactobacillus fermentum* and *Lactobacillus plantarum*.

Psychrotrophic: Lactic acid bacteria that can survive and grow in cold environments during lactic acid production are also called psychrotrophic lactic acid bacteria. These LAB strains can tolerate and thrive in low temperatures, typically in the range of 0-7°C (32-45°F), which makes them well suited for lactic acid fermentation in refrigerated environments. Some common psychrotrophic LAB strains used in lactic acid production include *Lactococcus lactis, Lactobacillus curvatus*, and *Leuconostoc mesenteroides*. Psychrotrophic LAB are particularly useful in the production of refrigerated foods such as yogurt, cheese, and sour cream, as they can grow and ferment at low temperatures, helping to preserve the product and extend its shelf life.

Oxygen

Anaerobic processes, like lactic acid fermentation, occur in the absence of oxygen. The presence of oxygen can hinder the growth of LAB and the production of lactic acid. Hence, fermentation requires oxygen-free conditions. The impact of oxygen during lactic acid fermentation varies depending on the specific circumstances and the type of lactic acid bacteria (LAB) involved. Generally, exposure to oxygen can impede the growth and metabolism of LAB, resulting in decreased lactic acid production. This is because LAB strains are facultative anaerobes, capable of switching between anaerobic and aerobic respiration based on oxygen availability. However, aerobic respiration yields less ATP (energy) compared to anaerobic respiration, which can limit the growth and metabolic activity of LAB. Additionally, oxygen exposure can facilitate the growth of undesirable microorganisms like yeast and molds, which compete with LAB for nutrients and reduce lactic acid production. Some examples of lactic acid anaerobes include *Lactobacillus acidophilus*, *Lactococcus lactis*, and *Streptococcus salivarius*.

pH

The production of lactic acid in lactic acid bacteria (LAB) is greatly affected by the pH level. LAB are microorganisms that can tolerate acidic conditions and utilize sugars for growth and metabolism. The optimal pH range for lactic acid production is typically between pH 5.0 and 6.5.[3] The impact of pH on lactic acid production can be attributed to its influence on the growth and metabolic activity of LAB. In environments with low pH values, the concentration of hydrogen ions (H^+) is high, which can hinder the growth and metabolic activity of LAB. However, as LAB produce lactic acid, the pH of the fermentation medium decreases, creating a more acidic environment that promotes their growth and metabolic activity.[20] However, as the pH decreases further, the growth of LAB may be hindered due to the formation of harmful lactate ions (L-) resulting from the accumulation of lactic acid. Moreover, at extremely low pH levels, the activity of enzymes produced by lactic acid bacteria may be compromised, leading to a decrease in lactic acid production.[3] Conversely, at high pH levels, the activity of these enzymes may also be suppressed, resulting in reduced lactic acid production. This is because the alkaline environment can cause denaturation or alteration of enzyme structure, thereby reducing their effectiveness in catalyzing metabolic reactions. Therefore, maintaining an optimal pH range is crucial for maximizing lactic acid production in LAB. This can be achieved by adjusting the initial pH of the fermentation medium and monitoring and adjusting the pH throughout the fermentation process as necessary.[10] Additionally, different strains of LAB may have varying optimal pH ranges for lactic acid production, depending on their specific metabolic pathways and acid tolerance capabilities.[21] pH can be categorized as follows: -

Acidophilic LAB (lactic acid bacteria) are a type of LAB that can thrive in environments with a pH of 4.5 or below.[22] These bacteria are well-suited for fermenting acidic foods such as pickles, sauerkraut, and kimchi, as they require a low pH to inhibit the growth of harmful bacteria. Examples of acidophilic LAB *include Lactobacillus acidophilus, Lactobacillus delbrueckii subsp. bulgaricus,* and *Lactobacillus plantarum*.

Neutrophilic LAB (lactic acid bacteria) are a type of LAB that can grow and thrive in a relatively neutral pH environment, typically ranging from 5.5 to 8.0.[19] For instance, *Lactococcus lactis, Streptococcus thermophilus,* and *Lactobacillus casei* are examples of neutrophilic LAB.

Alkaliphilic LAB, also known as lactic acid bacteria, are a specific group of bacteria that can thrive and flourish in highly alkaline environments, typically with a pH range of 8.0 to 10.0.[19] These bacteria possess a unique ability to tolerate extreme alkaline conditions, setting them apart from other types of LAB. This characteristic makes them well-suited for fermenting certain types of food that require an alkaline environment. However, due to their relatively lower prevalence compared to other LAB, they are not as extensively utilized in food fermentation processes. Examples of alkaliphilic LAB include *Enterococcus faecalis* and *Bacillus coagulans.*

Availability of nutrients

The production of lactic acid by lactic acid bacteria (LAB) can be significantly influenced by the availability of nutrients. The growth rate and metabolic activity of LAB, which ultimately determine the rate and quantity of lactic acid produced, are affected by the availability of different nutrients. There are specific ways in which nutrient availability can impact lactic acid production:

Carbon source: Lactic acid fermentation necessitates a source of fermentable carbohydrates, such as glucose, lactose, or sucrose. The availability and type of carbohydrate can influence the growth and activity of LAB, thereby affecting the rate and quantity of lactic acid produced.[4]

Nitrogen source: The development and metabolic activity of LAB rely on the synthesis of amino acids and other cellular components, both of which require nitrogen. The amount and rate of lactic acid produced depend on the growth rate and metabolic activity of LAB, which, in turn, are influenced by the type and availability of nitrogen source.[3]

Substrate: The term "substrate" describes the material that lactic acid bacteria are fermenting to produce lactic acid. This substrate can be diverse, including milk, cereals, vegetables, or fruits, and the specific substrate used can have a significant impact on lactic acid generation. In order to produce lactic acid, lactic acid bacteria require a suitable substrate, such as carbohydrates. The type and concentration of the substrate can greatly influence the yield and rate of lactic acid production. While glucose, lactose, and sucrose are commonly used substrates for lactic acid bacteria, different strains may have specific preferences for certain substrates. The substrate affects lactic acid production in various ways:

Carbohydrates: The availability and type of sugar are crucial for LAB fermentation and lactic acid production. The quantity and type of sugar in the substrate, such as molasses or glucose, can influence fermentation rates and lactic acid yields. Different LAB strains may have preferences for specific substrates.[3]

Nutrient content: Lactic acid bacteria require other nutrients besides sugar to grow and produce lactic acid. Substrates with higher levels of nitrogen, phosphorus, and other nutrients can support better growth and higher lactic acid yields.[23]

Food waste: Food waste, encompassing residues from food production and consumer-generated waste, is rich in carbohydrates, making it an ideal substrate for lactic acid production. Various studies have indicated that food waste, including kitchen residues, municipal solid wastes, potato peels and a variety of organic materials, can serve as suitable substrates for lactic acid production.[10]

Functional Use of Lactic Acid in Food Fermentation

Food Preservation

The proliferation of spoilage microorganisms and pathogens in food is hindered by the presence of lactic acid, which creates an acidic environment. This natural preservation effect effectively extends the shelf life of fermented products. Lactic acid is derived from the fermentation of lactose, a sugar found in milk, and serves as a naturally occurring organic acid. To further enhance the preservation and prolong the shelf life of fermented foods, lactic acid bacteria (LAB) are commonly employed as starter cultures. It is frequently utilized as a natural preservative and acidifier in food preservation processes. By reducing the pH of food, lactic acid creates an acidic environment that is unfavorable for the growth of spoilage and pathogenic bacteria and fungi.[24] Lactic acid finds extensive use in the preservation of dairy products such as cheese and yogurt, as well as in fermented foods like sauerkraut, kimchi, and pickles. Moreover, it is employed in the preservation of meat, poultry, and fish products.[2] Apart from its preservative properties, lactic acid also enhances the flavor and texture of various foods. For example, it contributes to the acidic taste of sourdough bread and the crisp texture of pickled vegetables.[25]

pH regulation

Lactic acid is frequently employed as a pH modulator in various food items.[7] Its characteristic sour taste and low pH contribute to the creation of an acidic environment that effectively hampers the proliferation of bacteria and fungi, thereby prolonging the shelf life of food products. It is commonly incorporated into acidic food items, such as fruit juices, soft drinks, and salad dressings, to precisely adjust their pH levels and enhance their stability. Moreover, the addition of lactic acid in these products also serves to enhance their flavor and mouth feel. By aiding in the regulation of the pH levels in food products, lactic acid plays a crucial role in ensuring their safety and overall quality.[26] The coagulation of casein proteins in dairy products such as yogurts and certain types of cheese is affected by the acidity level. The addition of lactic acid, which reduces the pH, can assist in attaining the desired texture and consistency in these particular products. Furthermore, the pH of a food item can impact its visual appearance. By utilizing lactic acid, the pH level can be adjusted to stabilize the color of the product, thereby ensuring its attractiveness to consumers.

Flavoring agent

Lactic acid is responsible for the distinctive tangy flavor commonly associated with fermented foods. Its presence during fermentation enhances the sensory characteristics of the final product, making it more enjoyable to consume. Lactic acid is used as a flavor enhancer in various food items, including dairy products, beverages, and baked goods.[27] Similar to other organic acids like citric acid and acetic acid, lactic acid imparts a sour taste. Lactic acid is frequently added to foods such as bread, cheese, and yogurt to enhance their flavor and texture.[28] It occurs naturally in many food items like yogurt, cheese, and sourdough bread, and is also produced during the fermentation process of certain foods and beverages, such as sauerkraut and beer. [18] Lactic acid possesses the ability to augment and harmonize flavors in diverse food items, thereby intensifying the taste of other constituents. It is frequently incorporated in salad dressings, marinades, and sauces to impart a delicate tanginess that elevates the overall flavor composition without overshadowing the presence of other flavors. Lactic acid plays a significant role in concealing undesirable tastes in certain food items. For instance, within processed foods, it effectively masks the lingering flavors of various preservatives or synthetic additives, thereby enhancing the overall palatability of the products. Lactic acid finds its application in confectionery products, including hard or gummy candies, to introduce a delightful tangy flavor that complements the sweetness of sugar. This combination of tastes creates a harmonious and pleasurable flavor profile, enhancing the overall sensory experience.

Texture and structure (meat tenderizer)

Lactic acid plays a significant role in influencing the texture and structure of fermented foods, particularly meat. Its ability to modify proteins and other components contributes to the overall texture, consistency, and mouth feel of the final product. One notable application of lactic acid is its use as a meat tenderizer. This is due to its capacity to break down and denature proteins present in meat.[29] When lactic acid is added to meat, it effectively penetrates the muscle tissue and interacts with the proteins, causing them to unravel and break apart. This process, known as protein hydrolysis, aids in breaking down the tough connective tissue in meat, resulting in improved tenderness and ease of chewing. The use of lactic acid as a meat tenderizer is particularly advantageous for tougher cuts of meat, such as beef brisket, chuck roast, and pork shoulder. These cuts typically contain higher amounts of connective tissue, which requires longer cooking times to break down and become tender. However, by incorporating lactic acid as a meat tenderizer, the cooking time can be reduced, leading to a more tender and flavorful end product. In addition to its tenderizing properties, lactic acid also possesses antimicrobial properties that help prevent the growth of bacteria on meat.[30] This is especially crucial for meat products that are stored for extended periods or cooked at low temperatures. By utilizing lactic acid as a meat tenderizer, the quality and texture of meat products can be enhanced safely and effectively. It serves as a natural alternative to chemical tenderizers in the meat processing sector, improving the overall quality and consistency of meat products.

Ethnic diversity and cultural representation of the use of lactic acid in food fermentation in Africa

In Africa, the functional use of lactic acid in food fermentation is deeply rooted in traditional food processing methods. These methods are not only essential to the rich culinary traditions of many African communities, but they also improve food quality, preserve food, and give different foods their own distinct flavors.[1] Particularly across the many ethnic landscapes of Africa, the application of lactic acid in food fermentation represents an intriguing junction of science, culture, and tradition. Food fermentation techniques have a great deal of cultural and social significance in communities, forging social relationships and fostering a sense of shared identity.[1] Fermented foods are prepared and consumed during festivals, rituals, and social gatherings, which emphasizes their importance in fostering social cohesiveness and cultural expression among many ethnic groups. Foods with lactic acid fermentation have a higher nutritional profile since they have more probiotics, vitamins, and minerals available.[7] Given that various ethnic groups have evolved fermentation methods to suit their unique dietary requirements and environmental circumstances, this area of food science is especially pertinent when considering ethnic diversity. The advantages of these fermented foods for health make it crucial to protect and advance traditional fermentation techniques. African cuisine has a long history of using lactic acid in food fermentation, which has its roots in the diverse ethnic and cultural representation of the continent.[16] This ancient method of food preservation not only demonstrates how adaptable different African cultures are, but it also demonstrates the complex ways in which these communities have learned to recognize and utilize the available natural processes to improve the flavor, safety, and nutritional value of their traditional foods. Every ethnic group in Africa, from the arid Saharan landscapes to the lush Congo Basin rainforests, has its own set of fermented foods that are a reflection of their cultural heritage, adaptations to their environment, and historical interactions with neighboring communities and the natural world. Lactic acid fermentation is a cornerstone of food preservation in Africa. It is a method that has been passed down through the years and is frequently intertwined with social customs, rituals, and traditional knowledge that goes beyond simple nutrition. Showcasing a variety of fermented items made from locally obtained resources such grains, tubers, milk, and vegetables, it is a monument to the richness of the continent. Lactic acid bacteria aid in the fermentation process, which contributes significantly to the nutritional requirements of different populations by improving the bioavailability of nutrients and imparting unique flavors and textures.[10] The variety of fermented foods on the continent is massive, ranging from the thick, sour milk known as amasi in South Africa to the teff-based flatbread known as injera in Ethiopia. A history of cultural identity, environmental adaptability, and communal resilience can be found in each of these dishes. The Yoruba and Igbo in West Africa, for instance, ferment cassava to make garri, and the Hausa make pito, a traditional beer, demonstrating the multifaceted social and economic functions these foods play in society. Similar to this, the Luos' preparation of fermented fish and the Maasai's intake of fermented milk in East Africa highlight the ways in which fermentation practices are woven into these groups' social and nutritional fabric. It is impossible to overestimate the cultural significance of these fermented foods because they frequently act as hubs for celebrations, rituals, and customary rites of passage. Fermented food production and consumption are essential to the expression of cultural identity because they have cultural connotations that represent affluence, hospitality, or social standing.[2] Globalization, urbanization, and changes in living patterns pose threats to the cultural and biological variety that sustains these traditional fermenting processes, making their maintenance difficult in the current period. In spite of these obstacles, traditional fermented foods are becoming more and more valued for their contributions to food security and health, as well as for serving as archives of cultural diversity and sources of sustainable innovation.

Traditional Fermented Foods and Ethnic Practices across Africa, lactic acid fermentation is integral to the production of a wide array of traditional foods. These fermented products are not only crucial for nutritional security but also carry deep cultural and ethnic significances. For example:

Injera in Ethiopia: This sourdough flatbread, a staple in Ethiopian cuisine, is made from teff flour and undergoes lactic acid fermentation. The practice is a cornerstone of Ethiopian culture, reflecting the country's agricultural traditions and communal eating practices.

Uji in East Africa: A fermented porridge commonly consumed in Kenya, Tanzania, and Uganda, uji is made from various grains and undergoes lactic acid fermentation. This process enhances its nutritional profile and is deeply embedded in the weaning practices and daily diets of several ethnic groups in the region.

Garri in West Africa: Particularly in Nigeria, garri (fermented cassava) is a key food product resulting from lactic acid fermentation. It showcases the ingenuity of West African cultures in food preservation techniques, contributing to food security and serving as a dietary staple across ethnic lines.

The use of lactic acid in food fermentation is a widespread practice across Nigeria, reflecting the country's rich ethnic diversity and cultural heritage. Nigeria, with its multitude of ethnic groups, including but not limited to the Hausa, Yoruba, Igbo, Fulani, and Ijaw, showcases a variety of fermented foods that are integral to the diet, culture, and traditions of its people. Each ethnic group brings its own unique methods and cultural significances to these fermentation practices, contributing to a rich gastronomic tapestry.[4]

Fermented Foods across Ethnic Groups in Nigeria

In Nigeria, the rich diversity of ethnic groups is vividly reflected in the wide variety of fermented foods across the country. Each ethnic group brings its own unique cultural significance and traditional practices to the fermentation process, enriching the culinary landscape while demonstrating the ingenious ways these communities have harnessed lactic acid fermentation to preserve food, enhance its nutritional value, and infuse it with distinctive flavors deeply embedded in Nigerian food culture.[1] From the north to the south, east to west, the practice of fermenting foods spans across Nigeria's many ethnic groups, showcasing a shared tradition that is uniquely adapted and celebrated by each community.

Among the Igbo in the southeast, for instance, the fermentation of cassava roots to produce garri underscores the importance of this staple food in their diet. The fermented cassava flour can be made into a doughy paste known as eba or soaked in water to create a refreshing meal, often accompanied by various soups and stews. This highlights the versatility of fermented foods in catering to different culinary preferences.[18] Similarly, the Yoruba people in the southwest have a strong tradition of fermenting maize, sorghum, or millet to produce ogi, a sour porridge commonly eaten for breakfast and essential for weaning infants. This process enhances the cereal's digestibility and introduces beneficial probiotics, reflecting the integral role fermented foods play in nutrition and child care within Yoruba culture.[27] In the northern regions, the Hausa and Fulani people have their own distinctive fermented products, such as nono, a fermented milk beverage that resembles yogurt and serves as a crucial source of protein and probiotics, reflecting the pastoral lifestyle of the Fulani and their deep connection with cattle herding. This practice of milk fermentation is a testament to the ingenuity of these ethnic groups in preserving perishable milk in the hot climate, showcasing the adaptability of fermentation techniques to environmental conditions and lifestyle needs Additionally, palm wine fermentation is a practice that transcends ethnic boundaries. The tapping and fermenting of palm sap is common among many groups, including the Igbo, Yoruba, and Ijaw. This alcoholic beverage plays a significant role in social gatherings and traditional ceremonies while also connecting people to their environment by utilizing natural resources to produce a drink cherished across ethnic lines.[28] The diversity of fermented foods in Nigeria reflects not only the country's rich ethnic mosaic but also the cultural interconnectivity fostered by food. Fermentation techniques, passed down through generations, preserve food, enhance its flavors, and carry the stories, traditions, and identities of the Nigerian people. These fermented foods serve as cultural artifacts, embodying ancestral wisdom, the diversity of the Nigerian landscape, and the shared heritage that binds people together despite their varied ethnic backgrounds. For example;

Garri (Cassava): Garri, a granulated flour made from fermented cassava tubers, is a staple food across Nigeria, transcending ethnic boundaries. The fermentation process, which involves lactic acid bacteria, reduces the cyanide content of cassava, making it safe for consumption. Garri serves as a base for various dishes and is consumed in different forms – soaked in cold water, cooked into a hot paste, or used as flour for baking. The production and consumption of garri highlight the ingenuity of Nigerian ethnic groups in utilizing fermentation to enhance food safety and security.[1]

Fufu: Fufu is another staple food made from different starchy foods like cassava, yams, or plantains. These foods are boiled, fermented, and then pounded into a dough-like consistency. The fermentation process, which also involves lactic acid bacteria, enhances the digestibility and flavor of the fufu. Different ethnic groups have their unique versions and methods of preparation, making fufu a versatile dish that reflects the culinary diversity of Nigeria.[1]

Ogi (Pap): Ogi is a fermented cereal pudding usually made from maize, sorghum, or millet. It is a popular breakfast dish and weaning food across many Nigerian ethnic groups. The fermentation process not only improves the nutritional value of the cereal by increasing its vitamin content but also imparts a sour taste that is appreciated in many Nigerian communities. Ogi is often served with sugar, milk, or honey to enhance its flavor.[1]

Nono (Fermented milk): Nono is a fermented milk product similar to yogurt, traditionally made by the Fulani, a predominantly pastoralist ethnic group. The milk, usually from cows, is fermented in calabashes using natural lactic acid bacteria from the environment. Nono is a significant part of the Fulani diet and culture, consumed on its own or used as a base for other dishes.[16]

Ugba (Fermented Oil Bean Seeds): Primarily associated with the Igbo ethnic group, ugba is made from oil bean seeds that have been fermented. It is commonly used as a condiment or a salad ingredient in Igbo cuisine.[16]

Palm Wine: Fermented from the sap of palm trees, palm wine holds cultural significance among many Nigerian ethnic groups, including the Igbo, Yoruba, and Ibibio. It is not only consumed as a beverage but also used in traditional ceremonies and rituals.[16]

Current trends in the use of lactic acid

In developing economies like China, India, and Indonesia, the food and beverage industry have a significant demand for lactic acid. This organic acid is widely used in various sectors, including cosmetics and industrial applications. Its probiotic properties—beneficial bacteria for human health—are gaining recognition, contributing to its rising demand across multiple industries in both developed and developing regions.[22] Lactic acid has seen a surge in demand within the pharmaceutical industry, in addition to its established use in the food and beverage sector.[31] The dairy industry, for example, relies on lactic acid for fermentation processes. Moreover, lactic acid plays a crucial role in curing meats, sausages, and fish. Its versatility extends beyond food processing; it is also used as a disinfectant in the cosmetics industry, where it is applied topically. Furthermore, lactic acid is an essential component in the production of biodegradable polymers. In the United States, lactic acid produced through fermentation is extensively used, especially in the food industry.[33] The COVID-19 pandemic drove a substantial increase in the demand for polylactic acid (PLA), particularly for manufacturing disposable cutlery and food storage containers that are microwave-safe. This surge was partly due to PLA's ability to enhance the aesthetic appeal of containers while providing resistance to food oils, which became critical in meeting health and safety needs during the pandemic. PLA also played a key role in promoting better sanitation and reducing virus transmission.[34] The growing demand for lactic acid across various industries is due to the many benefits it offers. Its skin-friendly properties make it valuable in cosmetics production, while the chemical and pharmaceutical industries use it in the manufacturing of medicines.[31] In the food industry, lactic acid is used to cure meats and sausages and is integral to the dairy industry's fermentation processes. The high demand for lactic acid extends to the canning industry, where it is used for pickling olives and other vegetables.[7] Poly lactic acid, produced using lactic acid through fermentation, is particularly notable for its biodegradable properties. Lactic acid also plays a critical role in the fermentation process of yogurt.[35] As the popularity of probiotic drinks increases, there is an expected rise in demand for lactic acid in the coming years due to its rich content of beneficial bacteria.[36] The applications of and demand for lactic acid in different industries is shown in Figure 4.

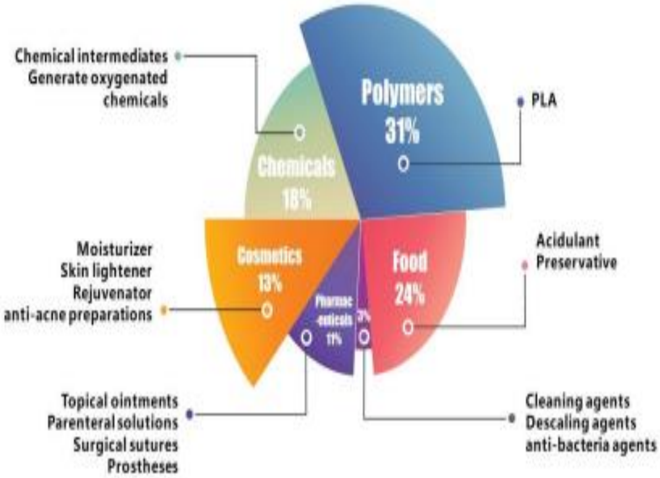

Figure 4: The applications of and demand for lactic acid in different industries[6]

Strain development
Strain development has been a major advance in lactic acid production and fermentation processes in the food industry in recent years. Researchers have developed new strains of lactic acid bacteria (LAB) that have improved fermentation efficiency and tolerance to harsh environmental conditions, leading to increase in yields and quality of lactic acid.[10] The development includes Genetic engineering and metabolic engineering;

Genetic engineering
Advances in strain development have allowed for the creation of bacterial strains that are more efficient at producing lactic acid. For example, some strains (*Lactococcus lactis* N8-1, *Lactococcus lactis* F44, *Pediococcus acidilactici* ZY271 and *Saccharomyces cerevisiae* BTCC3) have been developed that are able to tolerate higher temperatures or lower pH levels, allowing for the production of lactic acid under more challenging conditions. In addition, advances in genetic engineering have allowed for the creation of bacterial strains that are better adapted to specific fermentation processes or have enhanced metabolic pathways that result in higher yields of lactic acid.[37] The genetically engineered microorganisms are shown in Table 1.

Metabolic engineering
Metabolic engineering involves modification of the metabolic pathways of organisms to enhance production of the specific compounds of interest. In the case of lactic acid production, this approach focuses on altering the metabolic pathways of microorganisms to increase their ability to produce lactic acid efficiently. A novel strategy for developing robust microbial strains capable of producing pure lactic acid (LA) with high yield and productivity is through metabolic engineering.[39] Traditionally, methods of metabolic engineering have concentrated on modifying metabolic pathways or using heterologous gene expression. For example, the d-lactate dehydrogenase (GlyDH) gene from *Bacillus coagulans* was transferred into *Synechocystis* 6803 using a heterologous gene expression method. The genetically modified strain demonstrated a significantly high rate of lactic acid production.[40] Researchers have also engineered Escherichia coli strains to produce lactic acid by introducing genes encoding the lactate dehydrogenase (LDH) enzyme, which catalyzes the conversion of pyruvate to lactic acid. This process involves modifying E. coli's central metabolic pathways, such as glycolysis and the pentose phosphate pathway, to redirect carbon flow towards lactic acid production.[41] Similarly, *Saccharomyces cerevisiae*, a yeast species, has been metabolically engineered to produce lactic acid. This is achieved by introducing lactate dehydrogenase genes from lactic acid bacteria into the yeast genome. Additionally, modifications are made to enhance the production of pyruvate, the precursor of lactic acid, by manipulating the yeast's glycolytic and fermentative pathways.[4]

Mixed-culture fermentation
Traditionally, lactic acid production has been carried out using pure cultures of lactic acid bacteria, such as *Lactobacillus* spp. and *Streptococcus* spp. as well as fungal species.[3] In mixed-culture fermentation, a combination of different microorganisms, often bacteria and/or yeast, is used in lactic acid production. This approach can lead to a more stable and efficient fermentation process, as well as increased productivity and yield. Hence, mixed-culture fermentation involves the use of a complex microbial community to produce lactic acid, rather than using a pure culture of a single species.[42]

Use of new substrates
The fermentation of byproducts and food waste is gaining attention as a sustainable practice. For instance, using fruit peels, vegetable scraps, or spent grains from the brewing process in fermentation reduces food waste and adds value to underutilized resources. The use of new substrates in food fermentation reflects a dynamic and innovative approach to culinary practices.[42] This trend is driven by a combination of consumer preferences, sustainability goals, and the desire to create diverse and unique fermented products with enhanced nutritional profiles and flavors.[43]

Bioreactor design
The design of bioreactors represents a significant advancement in recent years for lactic acid production and fermentation processes within the food industry.[44] A bioreactor serves as a vessel where living cells or organisms conduct biological processes. In the specific context of lactic acid production, bioreactors are instrumental in cultivating and regulating the growth of lactic acid bacteria, optimizing the fermentation process. Innovations in bioreactor design offer enhanced control over fermentation conditions such as temperature, pH, and oxygen levels, all of which profoundly influence lactic acid production.[42] Notably, some bioreactors are equipped with sensors and controllers capable of real-time monitoring and adjustment of these conditions, ensuring greater precision and consistency throughout the fermentation process. The meticulous design and optimization of bioreactors play a pivotal role in enhancing the efficiency, scalability, and precision of food fermentation processes. Advance bioreactors with biosensors are illustrated in Figure 5.

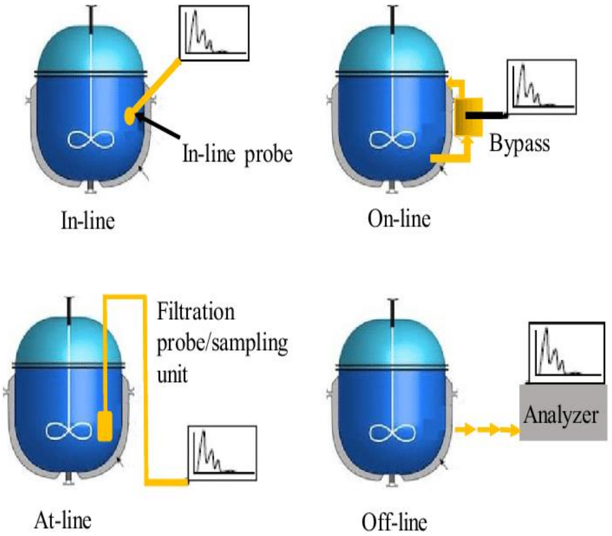

Figure 5: Advance Bioreactors with Biosensors[45]

Production of polylactic acid (pla) from lactic acid

The production of polylactic acid (PLA) from lactic acid is an important trend in food fermentation and biotechnology. PLA is a biodegradable, bio-based polymer with numerous applications, including food packaging, disposable tableware, and textiles.[46] Sourced from renewable materials like corn, starch, or sugarcane, PLA is a type of polyester synthesized through the fermentation of lactic acid.[47] PLA has a wide range of uses, such as in packaging materials, food and beverage containers, trays, cups, bags, food wrap, and textile fibers. In the food industry, PLA is particularly valuable for packaging, food storage, and transportation, offering a sustainable alternative to traditional petroleum-based plastics.[48] However, it is essential to recognize that while PLA is more eco-friendly, proper waste management and disposal are still necessary to avoid negative environmental impacts..[49] During its production, specific bacterial strains, such as Lactobacillus and Streptococcus, can ferment glucose or other sugars to produce lactic acid, which serves as the starting material for PLA synthesis.[50] Once produced, PLA can be molded or extruded into various shapes and forms for use in food packaging, utensils, and other applications.[51] Examples of synthesized PLA, lactic acid market share, global lactic acid applications in the food sector, and current uses of lactic acid are illustrated in Figures 6, 7, 8, and 9, respectively.

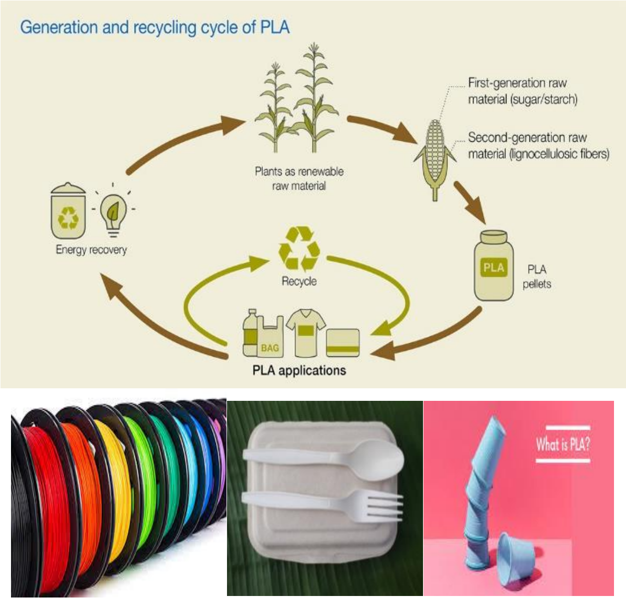

Figure 6: Synthesized PLA and its products[62]

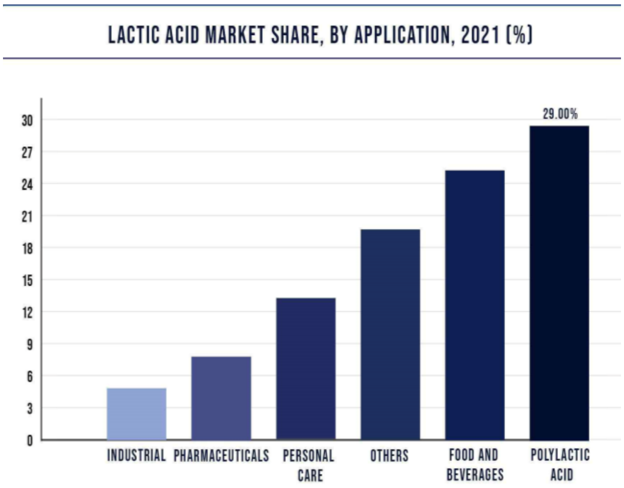

Figure 7: Lactic acid market share[63]

Future Trends in the Use of Lactic Acid

Alternative protein sources

The exploration of alternative protein sources is emerging as a significant trend in the application of lactic acid in food fermentation. Although lactic acid itself is not a protein, it plays a critical role in various fermentation processes and is gaining attention in the context of alternative protein production. Lactic acid, produced by lactic acid bacteria (LAB) during fermentation, is increasingly being used in the production of plant-based protein sources, such as mycoprotein and cultured meat.[52] Fermentation processes involving LAB can also contribute to the production of microbial proteins from microorganisms like fungi, algae, or bacteria, providing alternative protein sources. Fermented foods that are naturally high in protein, such as tempeh and certain soy-based products, rely on lactic acid fermentation. These protein-rich fermented foods serve as viable alternatives to traditional animal protein sources.[53] The flexibility of lactic acid fermentation allows for the use of a diverse range of substrates, which helps in the development of innovative and eco-friendly protein-rich foods.

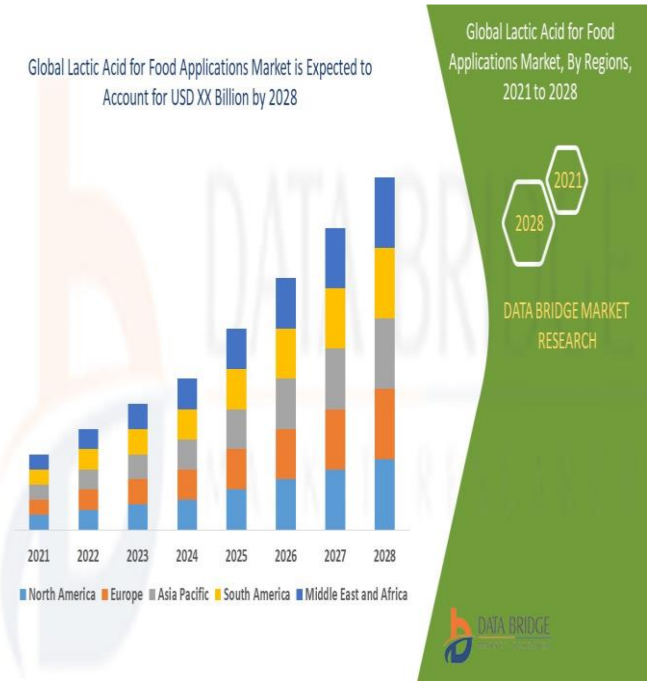

Figure 8: Global Lactic Acid for Food Application Market[64]

Genome editing

Genome editing is another promising trend in the production of lactic acid for the food industry. By using genome editing techniques like CRISPR-Cas9, scientists can make precise modifications to the DNA of LAB to enhance their ability to produce lactic acid.[54] For example, CRISPR-Cas9 has been used to delete genes in LAB that are responsible for producing other compounds, thereby optimizing their metabolic pathways for increased lactic acid production.[55] Genome editing can also be applied to modify the flavor and texture of fermented foods. Researchers have used CRISPR-Cas9 to alter the genomes of LAB used in cheese production, leading to the creation of new cheese varieties with unique flavor profiles and textures. This approach offers a promising avenue for developing LAB strains that can produce lactic acid with improved properties tailored for specific food industry applications.[57] Although genome editing has been widely used in model organisms like *Saccharomyces cerevisiae* and *E. coli,* its application to probiotic LAB remains limited due to regulatory constraints and market acceptance issues.[58] The use of genome editing in food production continues to be a topic of debate, requiring careful evaluation of safety and ethical concerns before broader adoption.

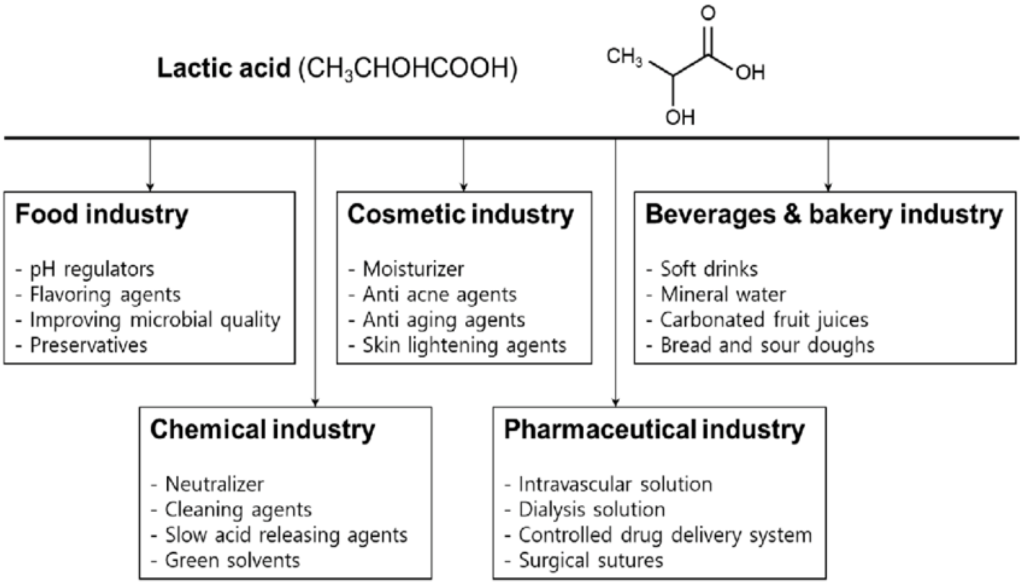

Figure 9: Current Uses and Applications of Lactic Acid in various industries[65]

Table 1: Genetically engineered microorganisms

Microorganism	Genetic Modification	Process Description	Application	References
Escherichia coli	Modified to express lactate dehydrogenase	The process of converting sugars into lactic acid through fermentation has been optimized to enhance the efficiency of lactic acid production.	Industrial production of lactic acid	66
Lactobacillus plantarum	Genetically enhanced for increased metabolic flux to lactate	Enhanced for increased production of lactic acid from diverse substrates.	Food industry, bioplastics	67
Saccharomyces cerevisiae (Yeast)	Altered to overproduce pyruvate and redirect it to lactic acid synthesis	Glycolysis and engineered pathways are employed to generate lactic acid from glucose.	Biofuel and biochemical production	68
Bacillus coagulans	Engineered for thermotolerance and improved lactic acid production	Achieving optimal lactic acid fermentation at elevated temperatures.	Industrial scale lactic acid production	69, 70
Lactococcus lactis	Metabolically engineered to alter glycolytic pathway to improve lactate yield	Enhancing lactic acid production through the optimization of sugar fermentation.	Dairy and food industry, bioplastic production	71
Corynebacterium glutamicum	Metabolically engineered to overexpress lactate dehydrogenase and disable competing pathways	Reduced formation of byproducts during the fermentation process leads to the production of lactic acid from sugars.	Biotechnological applications, bio-based materials	72

Conclusion

Lactic acid has a long history of use in the food industry due to its natural origin and beneficial properties. Its functional versatility makes it economically significant. Current trends, such as its role in alternative protein production and the use of genome editing to enhance LAB strains, show great potential for advancing lactic acid applications in the food industry. Collaboration among researchers, food manufacturers, and regulatory bodies to share knowledge, exchange best practices, and facilitate the responsible use of lactic acid in the food industry should be encouraged. Furthermore, there should be research and development in the field of lactic acid utilization, focusing on improving production processes, identifying novel applications, and optimizing its functionality in food products. Lastly, awareness among consumers about the benefits and safety of lactic acid usage in food products through informative labeling, educational campaigns, and transparent communication should be developed.

Conflict of interests

The authors declare no conflict of interest.

Authors' Declarations

The authors hereby declare that the work presented in this article are original and that any liability for claims relating to the content of this article will be borne by them.

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