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Lactic Acid Production: A Context For Sustainability And Trends

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Abstract:

Background*: Lactic acid is a significant industrial bioproduct with diverse applications in the food, pharmaceutical, and cosmetic industries. It is also a key raw material for biodegradable plastics such as polylactic acid (PLA), offering a sustainable alternative to petrochemical products. This study explores the production of lactic acid through fermentation, with a specific focus on batch processes, which provide flexibility and enhanced quality control compared to continuous and semi-continuous methods.*

Materials and Methods*: The paper examines various fermentation methodologies, comparing batch, continuous, and semi-continuous variants. Batch fermentation is highlighted for its robustness and suitability in managing by-product formation, such as acetic acid, formic acid, and succinic acid, which require additional purification steps. The study also discusses metabolic engineering as a strategy to enhance production efficiency and reduce unwanted by-products.*

Results*: The findings emphasize that batch fermentation remains a key industrial technology, providing advantages in quality control and process adaptability. The role of lactic acid in supporting a circular economy is underscored, particularly through the use of renewable raw materials. Applications of lactic acid in producing biodegradable plastics, such as PLA, align with global sustainability goals and demonstrate its potential for replacing petrochemical-based products.*

Conclusion: *Batch fermentation is reaffirmed as a crucial industrial process for producing lactic acid. Its capacity for flexibility, quality control, and alignment with sustainability principles highlights its relevance in industrial applications. The integration of metabolic engineering further enhances its potential, solidifying its role in advancing sustainable industrial practices.*

Keywords*: Lactic Acid; PLA; Sustainability; Biotechnology.*

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I. Introduction

Lactic acid (LA) has a wide range of applications in the food, chemical, pharmaceutical, and cosmetics industries. Recently, there has been growing interest in lactate as a raw material for the production of biodegradable polymers and bioplastics, notably polylactic acid (PLA), a biodegradable thermoplastic derived from natural and renewable sources (Payot et al., 1999; Paulova et al., 2020; Zhao et al., 2021; Ojo and Olga, 2023).

In line with the increasing focus on more sustainable practices, lactic acid production via biochemical batch processes has emerged as a strategic approach, despite facing challenges when compared to continuous processes, which generally offer greater scalability and higher efficiency. Batch processes, however, remain versatile, with advantages such as precise control over process parameters, allowing for optimal environmental conditions for the reactions involved. Additionally, batch operations are more adaptable to diverse raw materials, expanding the range of carbon sources that can be used—an important factor for industrial flexibility and sustainable, ecologically responsible practices. Common operational challenges in batch processes include production time and the need for equipment cleaning between cycles, both of which can lead to increased operational costs (Saez-Lara et al., 2015; Gullón et al., 2008; López-Gómez et al., 2019; Zang and Bao, 2024; Arrieta et al., 2017; Komesu et al., 2017; Bikram et al., 2014).

From the perspective of process advantages and challenges, including batch, continuous, and fed-batch models, Paulova et al. (2020) highlight that key parameters such as productivity, yield, and final L-lactic acid concentration are critical for optimizing fermentation processes. Surprisingly, a comparison of batch, fed-batch, and continuous cultivation shows almost identical productivities under all tested conditions, challenging the conventional belief that continuous processes always result in higher productivity. At the beginning of lactic acid production processes, specific microorganisms are inoculated into controlled or supplemented media to facilitate the conversion of substrates and carbon sources into the final product. Various mesophilic lactic acid bacteria strains, such as *Lactobacillus helveticus, Lactobacillus delbrueckii, and Lactobacillus plantarum*, are commonly used for lactic acid production. However, these mesophilic strains are less suitable for industrial-scale lactate production due to the high contamination risks they pose. Thermophilic strains, such as Bacillus coagulans, are ideal for this production because they do not require sterile conditions, making them more suitable for large-scale operations. Several studies have explored the use of thermophilic strains as lactic acid producers (Timmer and Kfromkamp, 1994; Aksu and Kutsal, 1986; Di Giori et al., 1985; Barreto et al., 1990; Ohara and Yahata, 1996; Heriban et al., 1993; Payot et al., 1999).

In the pursuit of process efficiency and considering that the vast majority of lactic acid production processes involve fermentation pathways, the ideal microorganism for industrial application is one that not only promotes high yields but is also capable of utilizing low-cost substrates. In this context, genetic and metabolic engineering has enabled the development of microorganisms with desired commercial and industrial characteristics. These engineered strains can reduce costs, minimize environmental impacts, and increase the value-added products obtained through the modification, deletion, or addition of metabolic pathways (De Lima, 2017; Bikram et al., 2014; Arrieta et al., 2017; Choi et al., 2024).

Given the growing demand for more efficient and sustainable processes, this study aims to explore the primary objectives related to lactic acid production through batch fermentation, evaluating its advantages and limitations. It will also discuss technological advancements that can help mitigate the challenges faced by this method. Furthermore, the study seeks to promote reflection on the importance of sustainable bioproduction and the role of metabolic engineering in optimizing fermentation processes. Throughout the development of the study, elements that enhance the understanding of the environmental and economic impacts of lactic acid production will be identified, particularly in relation to its applications in bioplastics and the food industry. By adopting the proposed approach, the study intends to move beyond theoretical information, using the “Concluding Remarks” section to provide insights that foster an integrated perspective on greener, innovative industrial practices. The approach aims to highlight opportunities for implementing more sustainable solutions, essential for advancing industrial processes aligned with the principles of the circular economy.

II. Material And Methods

This study is conducted through a bibliographic survey aimed at reflecting on batch fermentation for lactic acid production and its implications within the context of sustainability and industrial innovation. Key concepts related to fermentation, metabolic engineering, and the circular economy are organized and analyzed, considering their implications for the efficiency and economic viability of the lactic acid production process. The goal is to contextualize batch fermentation in today's industry, examining its advantages, limitations, and challenges and exploring technological innovations that contribute to more efficient and sustainable production methods. To achieve this, an exploratory research approach is employed, gathering insights on the different methodologies for lactic acid production, the raw materials used, and technological advancements impacting the process. The data analysis is performed systematically, aiming to identify patterns, technological innovations, limitations, and potential areas for improvement. The research is further complemented by a discursive analysis of the ideas and reflections presented, providing a conceptual foundation for the final considerations. These include insights into the evolution of the production process and future perspectives.

III. Development

Lactic Acid Production by Biochemical Processes

Context and Process Description

Lactic acid has been utilized for many years across various industries, including food and beverages, personal care, cosmetics, pharmaceuticals, chemicals, leather, and textiles. Recently, its use as a precursor for biodegradable polylactic acid (PLA) polymers, gaining recognition as sustainable packaging materials, has led to a surge in demand. Compared to chemical synthesis, lactic acid production via fermentation offers significant advantages, such as reliance on renewable resources and the ability to produce specific isomers of lactic acid, like L-lactic acid, using microorganisms such as *Lactobacillus casei*. Through this process, concentrations of L-lactic acid as high as 180 g/L have been achieved. Lactic acid can be produced through two primary methods: chemical synthesis and microbial fermentation. The chemical synthesis method is associated with environmental pollution and high costs (Komesu et al., 2017; Ding and Tan, 2006; Paulova et al., 2020; Kacaribu and Darwin, 2024).

Currently, the majority of industrial lactic acid fermentations are carried out in batch mode. The batch fermentation process for lactic acid (LA) is widely adopted in industry due to its versatility and the ability to meticulously control process parameters. However, a significant disadvantage of batch fermentation is the decrease in L-lactic acid concentration and productivity due to inhibition by high substrate concentrations, a common issue in batch processes. In addition to these challenges, reduced productivity and inefficiencies during inter-batch periods are also typical. These limitations can be mitigated using fed-batch processing, which prevents substrate inhibition, shortens the lag phase, and allows for the targeted feeding of concentrated nutrients to enhance product concentration and overall productivity. Despite the increasing demand for lactic acid, there has been limited interest in developing continuous lactic acid fermentation processes compared to batch fermentation (Paulova et al., 2020; Strack, 2021; López-Gómez et al., 2019; Ding and Tan, 2006).

From a microbiological standpoint, intrinsic factors associated with extrinsic and environmental conditions impact substrate conversion rates into products, thereby influencing process efficiency. Rigorous control of fermentation conditions, such as pH, temperature, nutrient concentration, and cell density, is essential for process optimization. Automated control systems, along with the use of substrates from renewable sources such as agro-industrial waste biomass, have been proposed to enhance operational efficiency and align with sustainability goals. These systems often involve hydrolytic enzymes, which contribute to the overall sustainability of the process.

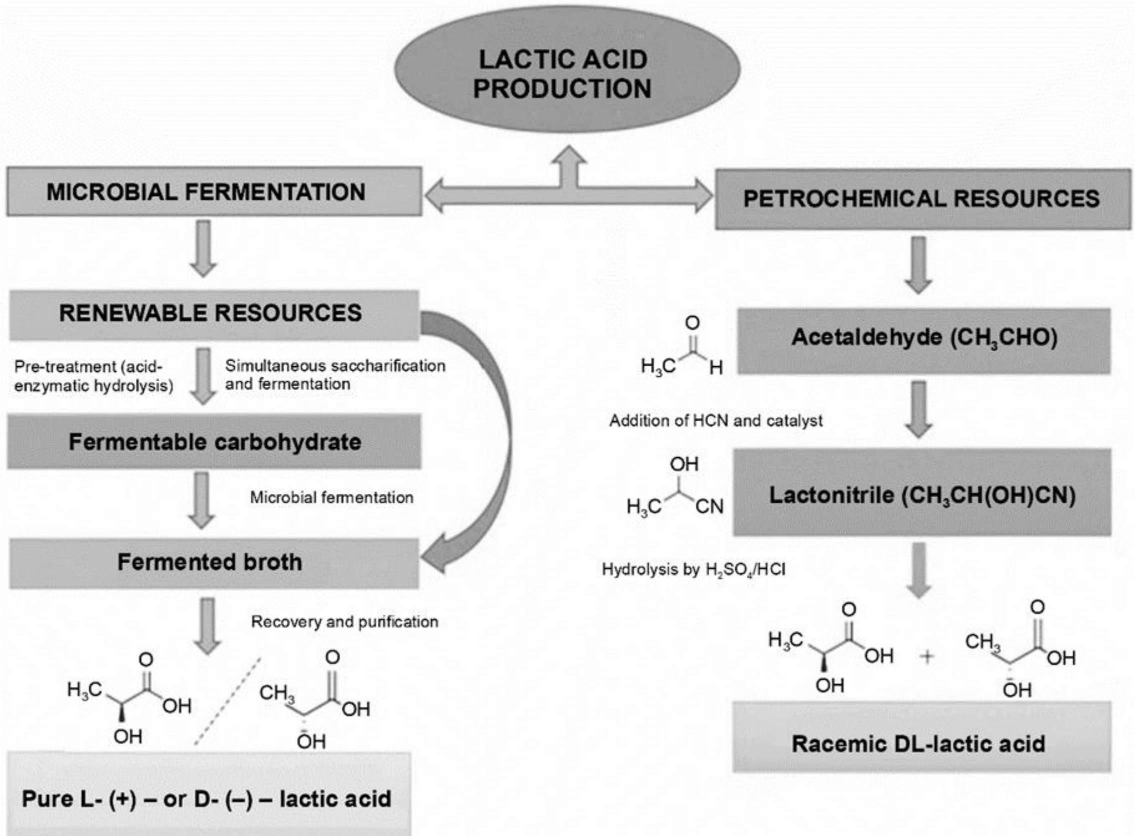

Figure 1. Comparisson of chemical synthesis and microbial fermentation to obtaining LA
Source: Kacaribu and Darwin (2024)

In a simplified form, the lactic acid obtained from non-petrochemical sources via batch fermentation involves bioreactors for the conversion of carbon substrates into lactic acid. This process includes media preparation, enzymatic actions, microbial inoculation, optimized fermentation conditions, cell filtration, and final product concentration. Figure 1 compares chemical synthesis with microbial fermentation for lactic acid production (Strack, 2021; López-Gómez et al., 2019; Ding and Tan, 2006; Gullón et al., 2008).

Process design is a critical factor in determining key bioengineering parameters, including yield, productivity, and final product concentration, making it a crucial aspect of industrial biotechnology. Achieving yields close to the theoretical maximum (100% in the case of lactic acid during homofermentative fermentation) helps minimize raw material costs. Additionally, improving productivity and reducing non-productive downtime enhances the efficient use of manufacturing equipment. High product concentrations further reduce downstream processing costs (Paulova, 2024; Gullón et al., 2008; Saez-Lara et al., 2015; Komesu et al., 2017).

Sustainability and the Use of Non-Food Sources

Fermentation using renewable substrates offers several advantages, including lower costs, reduced economic losses, and an abundant supply of high-sugar content materials that do not compete with the food sector. An important factor to consider is the global issue of food waste, with approximately 95% of food scraps being discarded and ending up in landfills. However, when managed properly, food waste can be a valuable resource. The use of alternative raw materials not only enhances the sustainability of the process but also reduces dependence on fossil resources (Paulova et al., 2020; Kuznetsov et al., 2017; Ajala et al., 2020).

To summarize the key points regarding each carbon source used in lactic acid production, including their characteristics, challenges, and relevant references, Table 1 has been created, based on the information initially presented in the study by Kacaribu and Darwin (2024). The table aims to visually present essential details related to this topic.

Table 1. Different types of carbon sources for lactic acid (LA) production.

Material	Sources	Characteristics	Associated Challenges
Lignocellulosic Biomass*[1]	Agricultural and industrial waste (e.g., bagasse, grass, straw, corn cob, wood waste, molasses, sugar beet pulp, coconut pulp)	High availability, renewable, and abundant; requires pretreatment to break down lignocellulose into fermentable sugars (glucose and sucrose).	Pretreatment complexity; low yield without pretreatment; inhibitors like lignin affect fermentation.
Sugar / Starch*[2]	Molasses, sugarcane by-products	High sugar content (glucose, sucrose, and fructose); contains vitamins and proteins; economic.	Presence of inhibitors (e.g., phenolic compounds, metal ions); pretreatment needed to remove inhibitors and improve fermentation.
Macroalgae*[3]	Seaweed (macroalgae), microalgae	High carbohydrate content, fast growth, low lignin content, no need for fertile land or freshwater, rich in nutrients.	Requires pretreatment with thermal acid hydrolysis; variability in carbohydrate content and growth conditions.
Glycerol*[4]	By-product of biodiesel, bioethanol, and oleochemical industries	Glycerol is produced in large quantities in biodiesel and bioethanol production. It can be used by lactic acid bacteria (LAB) to produce LA.	Glycerol utilization efficiency; possible need for chemical or enzymatic methods to enhance production.

**References:* [1]*AbdelRahman et al. (2011), Velvizhi et al. (2022), Ghaffar et al. (2014), Darwin et al. (2018), Alexandri et al. (2022);* [2]*Vignesh et al. (2022);* [3]*Cesário et al. (2018), Chung et al. (2021), Filote et al. (2021), Chen et al. (2013), Garofalo et al. (2022), Talukder et al. (2012), Tong et al. (2021),* [4]*Murakami et al. (2016), Doi (2018), Tao et al. (2016), Ma et al. (2022)*

It is important to emphasize that recent studies demonstrating the application of various substrates, such as alternative carbon sources for lactic acid production, incorporate incremental strategies to improve efficiency and reduce costs. These approaches are often driven by sustainability goals, sometimes integrating metabolic engineering as a key element of technological innovation.

The manipulation of microorganisms to optimize metabolic pathways, in order to improve lactic acid production and reduce unwanted by-products, represents a promising approach that is transforming traditional biochemical production processes. This can be achieved by modifying, deleting, or adding metabolic pathways, even in batch fermentation. Increasing the tolerance of microorganisms to lactic acid, as well as improving substrate conversion efficiency, are key trends associated with this scientific practice (De Lima, 2017; Bikram et al., 2014; Arrieta et al., 2017; Choi et al., 2024).

Production Methodologies

Lactic acid production involves a variety of methodologies, each with its own advantages and limitations. While chemical synthesis of lactic acid offers some process control, it is often considered economically unfeasible due to the formation of a racemic mixture, consisting of both L-lactic acid (used in food and cosmetics) and D-lactic acid (less desirable for industrial applications). Recent advancements in chemical synthesis, however, have improved selectivity, allowing for higher yields of L-lactic acid. Additionally, chemical synthesis is generally more energy-intensive and requires catalysts, such as calcium oxide, to drive the reaction. As a result, biological methodologies are often preferred for their cost-effectiveness and Sustainability (Zhao et al., 2021; Smith & Jones, 2010; Kim et al., 2020; Strack, 2021).

On the other hand, fermentation, whether batch or continuous, is widely utilized in the production of lactic acid. Batch fermentation offers simplicity and easier control of operational parameters such as pH, temperature, and substrate concentration. In this method, microorganisms and substrates are added to a closed system, and fermentation occurs without further addition of nutrients. This helps minimize fluctuations in conditions, which contributes to a more stable process and lowers the risk of contamination. However, batch fermentation is less efficient in terms of continuous production compared to continuous fermentation, which maintains consistent growth rates and acid production. Continuous fermentation is particularly advantageous for large-scale operations due to its higher productivity per unit of time and less frequent interruption (Johnson et al., 2019; Kim et al., 2020; Cordeiro et al., 2021; Strack, 2021; Souza et al., 2021).

Although batch fermentation remains practical for smaller-scale operations or when high purity is essential, continuous fermentation can be more efficient in maximizing production output. With proper monitoring, continuous systems can be operated with minimal contamination risks, especially in larger, well-controlled industrial settings (Johnson et al., 2019; Kim et al., 2020; Cordeiro et al., 2021).

Additionally, alternative methodologies such as solid-state fermentation (SSF) and simultaneous saccharification and fermentation (SSF) are explored to enhance process efficiency and reduce production costs. SSF is particularly effective for utilizing agricultural residues, turning them into valuable products such as lactic acid. However, it is not always superior to liquid fermentation, which remains the dominant method due to faster fermentation times and higher yields (Chen et al., 2018).

In contrast, simultaneous saccharification and fermentation (SSF) is more commonly applied to lignocellulosic materials like crop residues. This method combines enzymatic hydrolysis and fermentation into a single process step, thus reducing energy consumption and simplifying operations. Table 2 organizes information related to the key characteristics, advantages, and disadvantages of different methodologies (Cordeiro et al, 2021; Srtack, 2021; Wang et al., 2018).

Among the methods, batch fermentation stands out due to its operational simplicity and ability to achieve high product concentrations with a reduced risk of contamination. However, it is less ideal for large-scale, continuous production compared to continuous fermentation, which can optimize productivity over time (Strack, 2021; Souza et al., 2021).

In terms of sustainability, the shift toward using waste materials in fermentation processes offers significant environmental benefits. Utilizing agro-industrial by-products for lactic acid production reduces the competition for food-grade resources and lowers the overall environmental footprint of the process. By leveraging these waste streams, industries can not only achieve higher yields but also contribute to circular economy initiatives (Johnson et al., 2019; Kim et al., 2020; Cordeiro et al., 2021; Strack, 2021; Souza et al., 2021).

Table 2. Key characteristics of different methodologies for LA production

Methodology	Key Characteristics	Advantages	Disadvantages
Chemical Synthesis	Involves chemical reactions to produce lactic acid, resulting in a racemic mixture of D(-) and L(+) lactic acid	Precise control over the process; Pure lactic acid production	Economically unfeasible: High reagent and energy costs; Racemic mixture with undesirable isomers
Batch Fermentation	Addition of microorganisms and substrates (closed system). High product concentration with low contamination risk.	Operational simplicity; Lower contamination risk; High lactic acid concentration production	Process inhibition due to accumulation of substrates or byproducts
Continuous Fermentation	Maintains constant cell growth rates, preventing product accumulation.	Avoids product accumulation inhibition; Increased process efficiency	Requires microorganism recycling; Greater operational complexity
Semi-Continuous Fermentation	Combines continuous and batch fermentation. High cell density, high productivity.	High productivity; Easy implementation and scalability	Requires more than one reactor to complete the process
Submerged Liquid Fermentation	Microbial culture in a liquid medium with soluble substrates. Easy temperature and pH control.	Easy control of temperature and pH; Good heat transfer	Difficulty in measuring pH, dissolved O_2, substrate concentration in solid state, and water content
Solid-State Fermentation	Microbial growth on the surface of solid substrates. Higher productivity and yield.	Higher productivity per substrate unit; Lower substrate costs	Difficulty in measuring pH, dissolved O_2, substrate concentration, water content
Simultaneous Saccharification and Fermentation	Enzymatic hydrolysis and fermentation (simultaneously), reducing costs.	Reduction in production costs; Improves process efficiency	Difference in optimal temperatures for enzymes and fermentative cells
Cell Immobilization	Microbial cells or enzymes immobilized on a specific support. Higher efficiency.	Increased process efficiency - Can occur in stressful environments	High cost of immobilization materials
Biomass Recycling	Reuse of microbial cells. Increases cell density and productivity.	- Increased cell density - Higher productivity	- Need for separation or addition of cells after each cycle

Source: *References: AbdelRahman et al. (2011), Velvizhi et al. (2022), Ghaffar et al. (2014), Darwin et al. (2018), Alexandri et al. (2022); Vignesh et al. (2022); Cesário et al. (2018), Chung et al. (2021), Filote et al. (2021), Chen et al. (2013), Garofalo et al. (2022), Talukder et al. (2012), Tong et al. (2021), Murakami et al. (2016), Doi (2018), Tao et al. (2016), Ma et al. (2022), Amaral et al. (2022).*

Microorganisms and Enzymes Involved in the process

Bacteria and fungi are the most widely groups applied for LA production. The selection of microbial strains plays a critical role in the efficiency and productivity of lactic acid process. *Rhizopus* species such as *R. oryzae* and *R. arrhizus,* among the fungal families, have been exploited for direct aerobic fermentation of starchy substrates into LA. LAB are among the most prominent microorganisms involved in lactic acid production, with numerous studies emphasizing their importance in this field. These bacteria are typically Gram-positive, non-motile, non-sporulating, catalase-negative, and cytochrome-negative. LAB can exist in either rod-shaped (bacilli) or spherical (cocci) forms. They belong to various genera, including *Lactobacillus*, *Lactococcus*, *Enterococcus*, *Streptococcus*, *Bifidobacterium*, *Leuconostoc*, *Weissella*, *Oenococcus*, *Pediococcus*, *Tetragenococcus*, and *Carnobacterium* (Oliveira et al., 2021; Stiles and Holzapfel, 1997; Mora-Villalobos et al., 2020; Hatti-Kau et al., 2018; Saez-Lara et al., 2015).

LAB are basically classified into two main categories: homofermentative and heterofermentative strains. Homofermentative LAB converts glucose, with higher efficiency, exclusively into lactic acid (LA) as their sole metabolic product. During homolactic fermentation, the theoretical yield is two moles of LA for every mole of glucose consumed. These bacteria typically utilize the Embden–Meyerhof pathway (glycolysis) to metabolize glucose. Examples of homofermentative LAB include *L. acidophilus*, *L. acidophilus*, *L. bulgaricus*, *L. helveticus*, and *L. salivarius*. In contrast, heterofermentative LAB breaks down glucose into a mixture of ethanol, carbon dioxide, and/or acetic acid along with LA, resulting in a theoretical LA yield of only 0.50 g per gram of substrate. Representative heterofermentative LAB species include *L. brevis*, and *L. fermentum*, *among others*. The selection of microorganisms mainly depends on the type of substrate used in fermentation, as it directly influences the metabolism of microorganisms. Figure 2 allows to compare metabolic pathways of homofermentative and heterofermentative LAB (Kim et al, 2022)

During fermentation, LAB undergoes a series of metabolic reactions that start with glycolysis. In this process, LAB converts one mole of glucose into pyruvate, producing two moles of lactic acid and generating two moles of energy (ATP). A key enzyme in this pathway is lactate dehydrogenase (LDH), which catalyzes the conversion of pyruvate into lactic acid. LDH utilizes NADH while simultaneously regenerating the NAD+ cofactor, which is essential for the continuation of fermentation. The activity of lactate dehydrogenase is crucial, as its rate directly affects both the efficiency of the process and the final concentration of lactic acid in the product (Oliveira et al., 2021; Stiles and Holzapfel, 1997; Mora-Villalobos et al., 2020; Hatti-Kau et al., 2018; Saez-Lara et al., 2015).

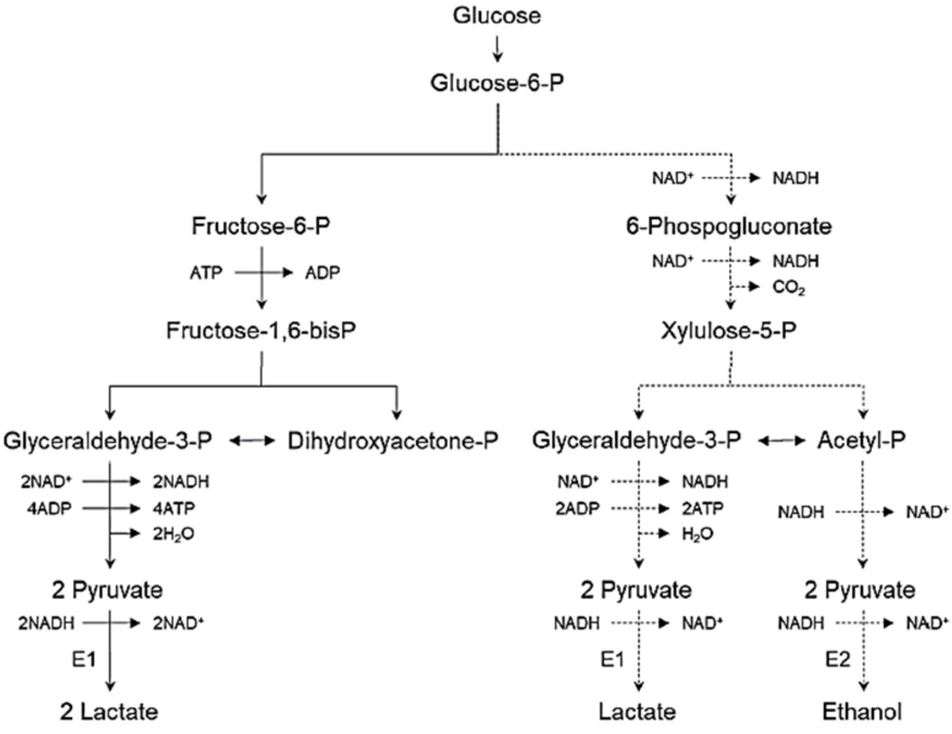

Fig. 2. Metabolic pathways of homofermentative (solid line) and heterofermentative (dotted line) lactic acid bacteria. P, phosphate; ADP, adenosine 5′-diphosphate; ATP, adenosine 5′-triphosphate; NAD+, nicotinamide adenine dinucleotide (oxidized form); NADH, nicotinamide adenine dinucleotide (reduced form); E1, lactate dehydrogenase; E2, alcohol dehydrogenase.

Source: Kim et al., (2022)

Enzyme activity is essential throughout the fermentation process. If LDH activity is limited, it can create a bottleneck in lactic acid production, making it a critical target for process optimization. Additionally, enzymes involved in energy metabolism, such as ATP synthase, are essential for ATP generation, which supports the metabolic activities of bacteria during fermentation. ATP synthase utilizes the proton gradient across the cell membrane to synthesize ATP, while also maintaining intracellular pH balance. This pH control is particularly important, as excessively acidic environments can inhibit bacterial activity and reduce fermentation efficiency. Thus, maintaining a proper enzymatic balance and pH control are key factors for successful fermentation (Oliveira et al., 2021; Saez-Lara et al., 2015; Arrieta et al., 2017).

Furthermore, enzymes in the glycolytic pathway, such as hexokinase and phosphofructokinase, are integral to lactic acid production. Hexokinase initiates glycolysis by phosphorylating glucose, while phosphofructokinase regulates the rate of flow through the glycolytic pathway, acting as a critical control point for energy production and metabolic intermediates. The efficiency of these conversions is crucial, as the pyruvate generated is ultimately converted into lactic acid by LAB (Saez-Lara et al., 2015; Arrieta et al., 2017; Souza et al., 2021).

Environmental factors, such as temperature, significantly influence lactic acid production. Temperature affects enzyme activity and overall metabolic processes, thereby impacting the rate of lactic acid synthesis. pH control is equally important, with the optimal range typically falling between 4 and 6, and should be carefully managed throughout fermentation.

The composition of the growth medium is also vital, as it must provide essential nutrients, including nitrogen sources, oligosaccharides, lipids, minerals, and buffering agents. These factors, along with adjustments to environmental conditions, can optimize the biochemical activities involved in lactic acid production. Ultimately, the success of the fermentation process depends on the ability to control and optimize enzymatic activity at every stage, ensuring more efficient production and a high-quality final product (Saez-Lara et al., 2015; Arrieta et al., 2017; Strack, 2021; Souza et al., 2021).

Composites in LA obtaining

In industrial processes, the term "composites" typically refers to materials made from two or more distinct substances, engineered to combine the best properties of each component. This results in materials that exhibit characteristics different from those of the individual components. Similarly, this concept can be applied to lactic acid production through batch fermentation, where the process involves not only the primary components (substrates and microorganisms) but also secondary products formed during fermentation, such as acetic acid, formic acid, and succinic acid. These byproducts can significantly impact both the efficiency and purity of the final lactic acid product (Souza et al., 2021).

For instance, acetic acid can be generated through the oxidation of ethanol produced during fermentation. At high concentrations, acetic acid can degrade the quality of lactic acid, necessitating additional purification steps and thus increasing production costs. Similarly, formic acid and succinic acid may form under suboptimal fermentation conditions, such as inappropriate pH levels or high substrate concentrations. The presence of these byproducts can reduce lactic acid yield and compromise the overall process efficiency.

To maximize the yield and purity of lactic acid, it is essential to optimize fermentation conditions. This requires stringent control over parameters such as nutrient concentration, temperature, pH, and aeration. By minimizing the formation of unwanted byproducts, the process can achieve higher lactic acid yields and reduced operational costs (Cordeiro et al., 2021; Saez-Lara et al., 2015; Arrieta et al., 2017; Souza et al., 2021).

Advanced purification techniques, such as chromatography and adsorption, can be employed to remove these byproducts, ensuring a cleaner final product. These measures not only improve process efficiency but also contribute to the economic sustainability of industrial-scale lactic acid production (Cordeiro et al., 2021; Saez-Lara et al., 2015; Arrieta et al., 2017; Souza et al., 2021).

Revisiting the critical importance of controlling process parameters, it is essential to emphasize that lactic acid production through batch fermentation requires stringent monitoring of operational conditions, particularly to minimize the formation of byproducts that can adversely affect both product quality and process efficiency. Continuous monitoring, combined with the implementation of effective purification strategies, can optimize the fermentation process, enhance lactic acid purity, and reduce production costs, thereby fostering the economic sustainability of the process (Souza et al., 2021; Cordeiro et al., 2021; Strack, 2021).

IV. Conclusion

Lactic acid production has firmly established itself as a pivotal technology in the industrial landscape. Its broad applicability across diverse sectors and potential for integration within a circular economy underscore its growing significance. The flexibility of production methods—such as batch, fed-batch, and continuous fermentation—enables industries to adapt to market fluctuations and scalability challenges. As a vital biochemical intermediate, lactic acid is essential in producing bioactive compounds, including preservatives and food additives, and in manufacturing bioplastics like polylactic acid (PLA), which offers a sustainable alternative to conventional plastics. The shift toward renewable feedstocks, such as agricultural residues and regional biomass, not only reduces the environmental impact of lactic acid production but also strengthens the circular economy by lowering logistical costs and supporting local economies. Tropical countries, with abundant untapped biomass, present a strategic opportunity to adopt alternative feedstocks, further enhancing the sustainability of the supply chain. Adapting lactic acid production to these models fosters a growing demand for responsible industrial practices, aligning with global sustainability and carbon-neutral goals. Biotechnological advances, particularly in metabolic engineering, are optimizing microbial strains, improving fermentation efficiency, lowering operational costs, and enhancing the quality and purity of lactic acid. Additionally, emerging technologies like automation and artificial intelligence are revolutionizing industrial processes, enabling real-time adjustments to optimize both efficiency and sustainability. This technological integration is not only transforming the food industry but also holds promise in fields such as regenerative medicine and biomaterials, reinforcing the versatility and relevance of lactic acid. However, global competitiveness and evolving regulatory frameworks require close attention to food safety standards and sustainability. Aligning with international standards, such as carbon-neutral targets, ensures compliance with regulatory demands and facilitates the global expansion of markets for bioplastics and food additives. This harmonization also opens doors for exporting sustainable solutions to developing countries, fostering synergy between research, innovation, and global markets. Furthermore, investing in the education and training of professionals specialized in biotechnology, particularly in emerging economies, is crucial for the effective and sustainable implementation of technological advancements. The development of a skilled workforce will drive innovation, generate green jobs, and promote sustainable practices, thereby aligning scientific progress with broader societal values. In conclusion, lactic acid production exemplifies how emerging technologies can meet the growing demand for sustainability and industrial innovation while contributing to social and economic advancement. The continuous development and integration of these technologies ensure that lactic acid, as a biochemical intermediate and strategic raw material, will play a pivotal role in the future of industry and society—fostering greener, more efficient, and inclusive solutions. Future research offers numerous exciting possibilities to further explore the sustainability and diverse applications of lactic acid production. Key areas for investigation include optimizing microbial strains to enhance fermentation efficiency and reduce operational costs, especially at larger production scales. Researchers could also explore alternative metabolic pathways and identify new feedstocks that improve lactic acid yields. The integration of advanced technologies such as automation, artificial intelligence, and the Internet of Things (IoT) provides significant opportunities to enhance real-time monitoring and process optimization, further improving efficiency and sustainability. Additionally, exploring the use of tropical biomass and agricultural residues—such as rice straw and coconut shells—offers promising prospects for reducing production costs and supporting local economies with sustainable alternatives. Another critical area of future research lies in integrating circular economy principles within lactic acid production processes. Investigating methods for recycling or reusing by-products, particularly in bioplastics production, and exploring the combination of carbon capture technologies with renewable carbon sources could significantly reduce the carbon footprint of lactic acid production. Beyond the food industry, lactic acid's potential in pharmaceuticals, cosmetics, and biomedical sectors warrants further exploration. Interdisciplinary research, combining biotechnology, materials science, and nanotechnology, could unlock new applications for lactic acid in the development of biodegradable implants and tissue engineering scaffolds. As the regulatory landscape evolves, research into how global sustainability standards and carbon-neutral goals will affect the viability of lactic acid-based products in international markets is essential. Such investigations will ensure that lactic acid production remains competitive and aligned with the demands of sustainable global markets. Lastly, prioritizing the education and training of the next generation of professionals in biotechnological and sustainable practices, particularly in emerging economies, will be key to equipping the workforce with the skills needed to address both technological and sustainability challenges.

In summary, the multifaceted nature of lactic acid production offers ample opportunities for future research. By addressing technological, regulatory, and social dimensions, these studies will play a crucial role in enhancing the sustainability and scalability of lactic acid production, positioning it as a cornerstone of environmentally responsible industrial practices.

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