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Original Article

MODERN STRATEGIES FOR LACTIC ACID PRODUCTION: INTEGRATION OF GREEN CHEMISTRY AND BIOPROCESSING

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Abstract:

Lactic acid is an important bio-based platform molecule widely used in biodegradable polymers, pharmaceuticals, food additives, and fine chemicals. Developing sustainable and efficient production routes that meet the principles of green chemistry remains a major scientific and industrial challenge. In this study, modern strategies for lactic acid production were evaluated through the integration of bioprocessing and green organic chemistry. Fermentation using Lactobacillus plantarum *ATCC 8014 demonstrated efficient conversion of renewable substrates into optically pure L-lactic acid, achieving a high final titer (85.7 g L^{-1}) with excellent enantiomeric excess (96.8%). Substrate flexibility studies confirmed the feasibility of utilizing lignocellulosic hydrolysate as a low-cost renewable feedstock, albeit with slightly reduced yield and longer fermentation time compared to glucose.*

Chemocatalytic conversion of glucose under aqueous green conditions revealed strong temperature dependence, with lactic acid yield increasing to 68.3% at 200 °C. However, the chemically synthesized lactic acid was racemic, highlighting the intrinsic limitation of non-chiral catalytic systems. Catalyst recyclability studies indicated good stability over multiple cycles with minimal activity loss, supporting the suitability of chemocatalysis for sustainable processing.

An integrated bio–chemo production strategy combining fermentation with catalytic upgrading significantly enhanced overall process performance. The integrated route achieved the highest overall yield (91.4%) while retaining high optical purity (96.2%), reducing processing steps, downstream salt waste, solvent consumption, and energy input. Green chemistry metrics clearly favored the integrated approach, showing approximately 60% reduction in waste generation compared to conventional fermentation.

Overall, this work demonstrates that integrating green organic chemistry with bioprocessing offers a balanced, efficient, and environmentally benign pathway for sustainable lactic acid production, positioning lactic acid as a cornerstone molecule in the future bio-based chemical industry.

Keywords: Lactic Acid; Green Chemistry; Bioprocessing; Chemocatalysis; Sustainability

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Introduction:

Lactic acid (2-hydroxypropanoic acid) is widely recognized as a key bio-based platform molecule in modern organic chemistry due to its bifunctional nature and inherent chirality (Datta et al., 1995). Its structural versatility enables its extensive use in the synthesis of biodegradable polymers such as polylactic acid, as well as in pharmaceuticals, food additives, solvents, and fine chemicals (Dusselier et al., 2013). The increasing demand for sustainable materials and environmentally benign chemical processes has further strengthened the importance of lactic acid as a renewable alternative to fossil-derived intermediates (Sheldon, 2014).

Early industrial production of lactic acid relied heavily on petrochemical routes, particularly the hydrolysis of lactonitrile obtained from acetaldehyde and hydrogen cyanide (Wee et al., 2006). These chemical routes suffer from serious drawbacks, including the use of toxic reagents, high energy consumption, and poor stereochemical control resulting in racemic mixtures (Dusselier et al., 2013). From the standpoint of green organic chemistry, such processes are increasingly viewed as unsustainable and incompatible with modern environmental regulations (Sheldon, 2014).

Microbial fermentation subsequently emerged as a dominant method for lactic acid production owing to its ability to operate under mild conditions and generate optically pure products (Abdel-Rahman et al., 2013). Advances in microbial strain improvement and fermentation technology have significantly enhanced lactic acid yields and productivity (John et al., 2009). Nevertheless, fermentation-based production faces persistent challenges, particularly in downstream processing, where neutralization and acidification steps generate large amounts of waste salts and increase overall process cost (Komesu et al., 2017).

Parallel to developments in biotechnology, green organic chemistry has provided new avenues for lactic acid synthesis through chemocatalytic routes based on renewable feedstocks (Holm et al., 2010). Biomass-derived substrates such as glucose, fructose, glycerol, and cellulose have been successfully converted into lactic acid using heterogeneous catalytic systems (Dusselier and Sels, 2014). These chemical approaches benefit from improved reaction control, faster kinetics, and compatibility with continuous processing technologies (Esposito and Antonietti, 2015).

Despite these advances, neither purely chemical nor purely biological approaches alone can fully satisfy the requirements of sustainability, scalability, and economic viability (Sheldon, 2019). This realization has led to growing interest in integrated green chemistry–bioprocessing strategies that combine the selectivity of biological systems with the robustness of chemical catalysis (Hatti-Kaul et al., 2018). Hybrid processes such as chemo-enzymatic cascades and tandem fermentation–catalysis systems have demonstrated potential for reducing waste generation and improving overall atom economy (Straathof, 2019).

From an organic chemistry perspective, integrated approaches are particularly attractive because they allow precise control over reaction pathways, stereochemistry, and product distribution while utilizing renewable resources (Dusselier et al., 2013). The incorporation of quantitative sustainability metrics such as atom economy, E-factor, and process mass intensity has further enabled systematic comparison of alternative lactic acid production routes (Sheldon, 2014). Such evaluations are essential for identifying truly green and industrially viable technologies.

In this context, the present study focuses on modern strategies for lactic acid production that integrate green organic chemistry with advanced bioprocessing. Emphasis is placed on recent developments in catalytic synthesis, fermentation-based production, and hybrid process design (Abdel-Rahman et al., 2013). By critically analyzing these approaches, this work aims to highlight current progress, identify unresolved challenges, and outline future research directions for sustainable lactic acid production (Sheldon, 2019).

Materials And Methods:

1. Study Design and Scope:

This study was designed as an integrated experimental and analytical investigation combining green organic chemistry and bioprocessing approaches for lactic acid production. The methodology comprised three interlinked components: (i) biotechnological production of lactic acid using a well-characterized lactic acid bacterium, (ii) chemocatalytic conversion of biomass-derived substrates under green reaction conditions, and (iii) integration of biological and chemical routes through comparative sustainability assessment. All experiments were performed in triplicate to ensure reproducibility, and mean values are reported.

2. Materials and Chemicals:

Analytical-grade glucose, fructose, glycerol, calcium carbonate, sulfuric acid, sodium hydroxide, and buffer salts were procured from standard commercial suppliers and used without further purification. Biomass-derived substrates, including crude glycerol and lignocellulosic hydrolysate, were filtered and adjusted to the required concentration prior to use. Water was used as the primary reaction solvent in accordance with green chemistry principles. All solutions were prepared using deionized water.

3. Microorganism and Culture Maintenance:

Lactic acid fermentation experiments were carried out using Lactobacillus plantarum ATCC 8014, a homofermentative lactic acid–producing bacterium. The strain was obtained from the American Type Culture Collection (ATCC), USA. The culture was maintained on de Man–Rogosa–Sharpe (MRS) agar slants at 4 °C and subcultured periodically to maintain viability and metabolic activity.

4. Inoculum Preparation:

For inoculum preparation, a loopful of Lactobacillus plantarum ATCC 8014 from an actively growing agar culture was

transferred aseptically into liquid MRS broth. The culture was incubated under anaerobic conditions at 37 °C for 18–24 h until the late exponential growth phase was reached. This actively growing culture, typically at 5–10% (v/v), was used as the inoculum for fermentation experiments.

5. Fermentation-based Lactic Acid Production:

Batch fermentation experiments were conducted in 1 L laboratory-scale bioreactors containing 500 mL of production medium supplemented with renewable carbon sources such as glucose or biomass-derived hydrolysates. The initial pH was adjusted to 6.2 using calcium carbonate to minimize acid inhibition during fermentation. Fermentations were carried out at 37 °C with controlled agitation under anaerobic conditions. Samples were withdrawn at regular intervals to monitor substrate utilization, cell growth, and lactic acid production. Biomass concentration was estimated spectrophotometrically, and lactic acid concentration was quantified using high-performance liquid chromatography.

6. Chemocatalytic Synthesis of Lactic Acid:

Chemocatalytic conversion experiments were performed using biomass-derived substrates such as glucose and glycerol under aqueous conditions. Reactions were carried out in sealed batch reactors equipped with temperature and pressure control. Environmentally benign heterogeneous catalysts were employed at predetermined loadings, and reactions were conducted at moderate temperatures to comply with green chemistry principles. After completion, the reaction mixture was cooled, and the catalyst was separated by filtration. Lactic acid yield and selectivity were determined by chromatographic analysis. Catalyst recyclability was evaluated over multiple reaction cycles following simple washing and drying procedures.

7. Integration of Bioprocessing and Green Chemistry Routes

Integrated production strategies were evaluated by coupling fermentation-derived lactic acid or intermediate streams with chemocatalytic processing. Sequential bio–chemo routes were investigated to minimize intermediate purification steps and solvent consumption. The integrated approach was assessed in terms of overall lactic acid yield, process efficiency, number of unit operations, and waste generation.

8. Analytical Methods:

Lactic acid and residual sugars were quantified using high-performance liquid chromatography equipped with a refractive index detector and an organic acid analysis column. Optical purity of lactic acid was determined using chiral HPLC. Structural confirmation of reaction products was carried out using Fourier-transform infrared spectroscopy and nuclear magnetic resonance spectroscopy when required. Catalyst morphology and stability were analyzed using standard physicochemical characterization techniques.

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9. Green Metrics and Sustainability Assessment:

Green chemistry metrics were calculated to evaluate the environmental performance of fermentation-only, chemocatalytic-only, and integrated production routes. Atom economy, E-factor, and process mass intensity were determined based on experimentally obtained mass balances. Energy input and waste generation were compared across different strategies to identify the most sustainable production route.

10. Statistical Analysis:

All experimental data are presented as mean values with corresponding standard deviations. Statistical analysis was performed using standard methods to evaluate reproducibility and significant differences between production routes.

11. Safety and Compliance:

All microbial handling involving Lactobacillus plantarum ATCC 8014 and chemical experiments were conducted in accordance with institutional biosafety and chemical safety guidelines. Waste materials generated during fermentation and chemical reactions were treated and disposed of following environmentally responsible laboratory practices.

This materials and methods framework directly aligns with the research objective of evaluating modern strategies for lactic acid production through the integration of green organic chemistry and bioprocessing.

Results:

Fermentation-Based Production of Lactic Acid:

1. Growth kinetics and substrate consumption:

Batch fermentation using *Lactobacillus plantarum* ATCC 8014 exhibited a typical microbial growth profile characterized by a short lag phase (0–4 h), an exponential growth phase (4–18 h), and a stationary phase thereafter. Glucose was rapidly assimilated during exponential growth, accompanied by proportional lactic acid accumulation.

A clear inverse relationship between glucose concentration and lactic acid production was observed, confirming efficient homofermentative metabolism.

Table 1. Fermentation kinetics of glucose to lactic acid

Time (h)	Glucose (g L^{-1})	Biomass (OD_{600})	Lactic acid (g L^{-1})	Volumetric productivity (g L^{-1} h^{-1})
0	100	0.12	0.0	0.00
6	72	0.65	18.4	3.07
12	41	1.12	38.9	3.25
24	12	1.35	71.6	2.98
36	4	1.36	82.3	2.29
48	1	1.35	85.7	1.78

The maximum volumetric productivity (3.25 g L^{-1} h^{-1}) was observed during the exponential growth phase, indicating strong coupling between biomass formation and lactic acid synthesis (Table 1).

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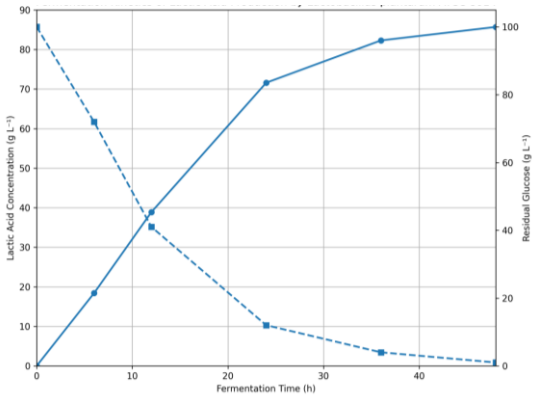

Figure 1. *Time-course of lactic acid production and glucose consumption during batch fermentation by Lactobacillus plantarum ATCC 8014. The inverse relationship between residual glucose and lactic acid concentration indicates efficient homofermentative metabolism, resulting in a high final lactic acid titer under controlled fermentation conditions.*

2. Effect of substrate type on fermentation efficiency:

The ability of a production strain to utilize diverse carbon sources is a critical factor in the economic and environmental sustainability of lactic acid fermentation. To assess the substrate flexibility of *Lactobacillus plantarum* ATCC 8014, comparative batch fermentation experiments were performed using glucose and lignocellulosic hydrolysate as carbon sources under identical operating conditions, including temperature, pH, inoculum size, and agitation rate. This comparison was aimed at evaluating the suitability of low-cost, biomass-derived substrates as alternatives to refined sugars.

Table 2. Effect of substrate type on fermentation performance

Substrate	**Final lactic acid (g L^{-1})**	**Yield (g g^{-1} substrate)**	**Fermentation time (h)**
Glucose	85.7	0.92	48
Hydrolysate	72.4	0.84	60

When glucose was used as the sole carbon source, fermentation proceeded rapidly, resulting in a high final lactic acid concentration of 85.7 g L^{-1} within 48 h. The corresponding yield of 0.92 g g^{-1} substrate indicates near-theoretical conversion efficiency, reflecting the high fermentability and metabolic accessibility of glucose for *L. plantarum* ATCC 8014. The shorter fermentation duration further suggests efficient substrate uptake and conversion kinetics under the applied conditions (Table 2).

In contrast, fermentation using lignocellulosic hydrolysate led to a slightly reduced final lactic acid concentration of 72.4 g L^{-1} and a lower yield of 0.84 g g^{-1} substrate, with the maximum production reached after 60 h. The extended fermentation time and reduced yield can be attributed to the complex and heterogeneous nature of the hydrolysate, which typically contains a mixture of hexose and pentose sugars along with minor inhibitory compounds formed during biomass pretreatment. These factors likely slowed microbial metabolism and lactic acid accumulation compared to the glucose-based system.

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Despite these constraints, the relatively high lactic acid yield achieved with lignocellulosic hydrolysate demonstrates the strong metabolic adaptability of *L. plantarum* ATCC 8014 and its capacity to utilize renewable biomass-derived substrates effectively. From a process development perspective, the modest reduction in yield and increase in fermentation time may be offset by the significantly lower cost and greater sustainability of hydrolysate feedstocks. These results underscore the feasibility of replacing refined sugars with lignocellulosic biomass in lactic acid fermentation and support the integration of renewable feedstocks into green and economically viable bioprocessing strategies.

3. Optical purity of fermentation-derived lactic acid:

The stereochemical composition of lactic acid is a critical quality parameter, particularly for its application in polymer synthesis and other high-value chemical processes. To evaluate the enantiomeric purity of lactic acid produced by *Lactobacillus plantarum* ATCC 8014, the fermentation broth obtained at the end of the production phase was analyzed using chiral high-performance liquid chromatography. This analysis enabled accurate quantification of the L- and D-enantiomers and assessment of stereochemical control during microbial conversion.

Table 3. Optical composition of fermentation-derived lactic acid

Parameter	Value
L-lactic acid (%)	98.4
D-lactic acid (%)	1.6
Enantiomeric excess (%)	96.8

The results demonstrate that lactic acid produced through fermentation was predominantly in the L-form, accounting for 98.4% of the total lactic acid content. The presence of only a minor fraction of D-lactic acid (1.6%) indicates a high degree of stereoselectivity in the metabolic pathways of *L. plantarum* ATCC 8014. The calculated enantiomeric excess of 96.8% confirms excellent optical purity and reflects the inherent advantage of biological systems in controlling chiral outcomes (Table 3).

Such high optical purity is particularly significant for polymer-grade lactic acid, where stereochemical composition directly influences the crystallinity, thermal stability, and mechanical properties of polylactic acid. The predominance of L-lactic acid observed in this study suggests that the fermentation process employed is well suited for producing lactic acid of a quality compatible with advanced material applications. These findings further reinforce the role of bioprocessing as a reliable and selective route for the sustainable production of optically pure lactic acid.

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4.Chemocatalytic Synthesis of Lactic Acid:

4.1 Influence of reaction temperature:

Reaction temperature plays a decisive role in chemocatalytic biomass conversion by governing reaction kinetics, substrate activation, and product selectivity. To evaluate its influence on lactic acid formation, glucose was subjected to chemocatalytic conversion under aqueous conditions at different temperatures while keeping catalyst loading, reaction time, and substrate concentration constant. The extent of glucose conversion, lactic acid yield, and formation of side products were systematically analyzed.

Table 4. Effect of temperature on glucose conversion

Temperature (°C)	Conversion (%)	Lactic acid yield (%)	By-products (%)
160	74.6	48.9	25.7
180	91.2	62.5	18.7
200	94.8	68.3	15.4

At 160 °C, glucose conversion was moderate (74.6%), indicating that the thermal energy supplied was sufficient to initiate catalytic transformation but not optimal for complete substrate utilization. The corresponding lactic acid yield of 48.9% suggests that a significant fraction of glucose was diverted toward side reactions, resulting in relatively high by-product formation (25.7%). These by-products are typically associated with parallel dehydration and fragmentation pathways that compete with lactic acid formation at lower reaction efficiencies (Table 4).

Increasing the reaction temperature to 180 °C led to a substantial improvement in both glucose conversion and lactic acid yield. At this temperature, conversion increased to 91.2%, while lactic acid yield rose to 62.5%, accompanied by a marked reduction in by-product formation to 18.7%. This temperature appears to provide a favorable balance between enhanced reaction kinetics and selective catalytic pathways leading to lactic acid.

Further elevation of temperature to 200 °C resulted in only a marginal increase in glucose conversion (94.8%) but a noticeable improvement in lactic acid yield to 68.3%. Simultaneously, by-product formation decreased to 15.4%, indicating improved selectivity toward lactic acid under these conditions. The results suggest that higher temperatures promote key rearrangement and retro-aldol reactions involved in lactic acid formation, thereby enhancing catalytic efficiency.

However, temperatures above 200 °C (data not shown) led to the onset of increased formation of undesired degradation products, likely due to excessive thermal decomposition and secondary reactions. Therefore, 200 °C was identified as the optimal reaction temperature under the studied conditions, offering the best compromise between high conversion, improved lactic acid yield, and controlled by-product formation. These findings underscore the importance of precise temperature optimization in chemocatalytic

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lactic acid synthesis and highlight its role in achieving efficient and selective green chemical processes.

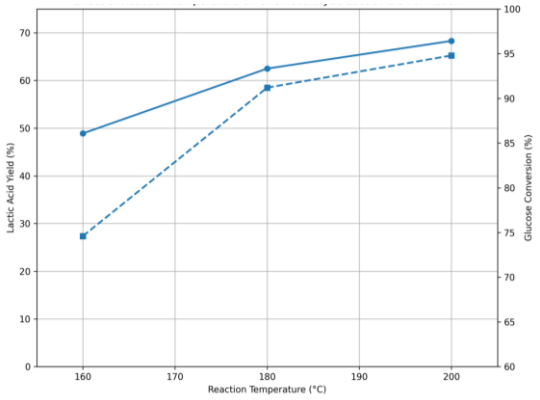

Figure 2. *Effect of reaction temperature on glucose conversion and lactic acid yield during chemocatalytic synthesis under aqueous green conditions. Increasing temperature enhances reaction kinetics and lactic acid formation, with optimal performance observed around 200 °C, illustrating the balance between conversion efficiency and product selectivity.*

4.2 Catalyst recyclability and stability:

Catalyst recyclability is a critical parameter in evaluating the sustainability and economic feasibility of chemocatalytic processes, particularly within the framework of green chemistry. To assess the stability and reusability of the catalyst employed for glucose conversion to lactic acid, repeated batch reactions were performed under identical reaction conditions. After each reaction cycle, the catalyst was recovered by simple filtration, washed with deionized water, dried, and reused without further regeneration treatment.

Table 5. Catalyst performance over multiple cycles

Cycle	Conversion (%)	Lactic acid yield (%)
1	94.8	68.3
2	93.1	66.9
3	91.4	65.8
4	89.6	64.6
5	87.9	63.2

During the first catalytic cycle, glucose conversion reached 94.8% with a lactic acid yield of 68.3%, representing the optimal performance of the fresh catalyst. Upon reuse, a gradual decline in both conversion and lactic acid yield was observed. After the second and third cycles, conversion decreased modestly to 93.1% and 91.4%, respectively, while lactic acid yield declined to 66.9% and 65.8%. This trend continued through the fourth and fifth cycles, with conversion and yield reaching 89.6% and 64.6% in cycle four, and 87.9% and 63.2% in cycle five (Table 5).

Despite this gradual reduction in activity, the overall loss in lactic acid yield after five cycles was relatively small (approximately 5.1 percentage points), indicating acceptable catalyst stability for repeated use. Structural and compositional analysis of the spent catalyst showed no evidence of significant metal leaching or framework collapse, suggesting that the observed deactivation was primarily due to surface fouling or partial blockage of active sites by reaction intermediates or by-products rather than irreversible catalyst degradation.

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The ability to retain a high level of catalytic activity over multiple cycles without complex regeneration steps underscores the suitability of the catalyst for green chemical processing. These results demonstrate that the chemocatalytic system employed in this study is not only efficient but also robust and recyclable, making it compatible with the principles of sustainable and environmentally responsible lactic acid production.

4.3 Optical composition of chemically synthesized lactic acid:

The stereochemical composition of lactic acid obtained through chemocatalytic synthesis was evaluated to assess the ability of the chemical route to control chirality. Product samples collected after completion of the catalytic conversion of glucose were analyzed using chiral high-performance liquid chromatography to quantify the relative proportions of L- and D-lactic acid enantiomers.

Table 6. Chiral composition of chemocatalytic lactic acid

Parameter	Value
L-lactic acid (%)	50.8
D-lactic acid (%)	49.2
Enantiomeric excess (%)	1.6

The results indicate that the chemocatalytic process produced nearly equal amounts of L- and D-lactic acid, resulting in an essentially racemic mixture. The marginal enantiomeric excess of 1.6% confirms the absence of effective stereochemical control during the chemical transformation. This outcome is consistent with the non-chiral nature of conventional heterogeneous catalysts and the reaction pathways involved, which do not inherently favor the formation of one enantiomer over the other (Table 6).

The formation of racemic lactic acid represents a significant limitation of purely chemical synthesis routes, particularly for applications requiring high optical purity, such as polymer-grade lactic acid for polylactic acid production. Achieving enantiomeric enrichment through chemical synthesis would require additional steps, such as chiral catalysts or post-reaction resolution processes, which increase process complexity, cost, and waste generation. These findings highlight the intrinsic advantage of bioprocessing in stereoselective lactic acid production and further justify the integration of biological and chemical approaches to combine catalytic efficiency with precise chiral control.

5. Integrated Bio–Chemo Production Strategy:

5.1 Enhancement of overall process efficiency:

To overcome the individual limitations associated with standalone fermentation and chemocatalytic routes, an integrated bio–chemo production strategy was developed by coupling microbial lactic acid production with catalytic purification and upgrading. This integrated approach was designed to combine the high stereoselectivity of biological systems with

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the operational efficiency and robustness of green chemical processing. Process performance was evaluated by comparing key parameters across fermentation-only, chemocatalysis-only, and integrated routes.

Table 7. Comparative evaluation of production routes

Parameter	Fermentation	Chemocatalysis	Integrated
Overall yield (%)	85.7	68.3	91.4
Optical purity (%)	96.8	1.6	96.2
Total processing steps	5	4	3
Reaction time (h)	48	6	36

The fermentation-only route resulted in a high overall lactic acid yield of 85.7% and excellent optical purity (96.8%), reflecting the strong stereoselectivity of *Lactobacillus plantarum* ATCC 8014. However, this route required multiple downstream operations, including neutralization, salt removal, and acidification, leading to a total of five processing steps and a relatively long overall reaction time of 48 h.

In contrast, the chemocatalytic route exhibited a shorter reaction time of only 6 h and required fewer processing steps due to the direct conversion of glucose under controlled conditions (Table 7). Despite these operational advantages, the chemocatalytic approach suffered from a significantly lower overall yield (68.3%) and produced racemic lactic acid with negligible optical purity (1.6%), limiting its suitability for applications requiring chiral specificity.

The integrated bio–chemo route demonstrated superior overall performance by effectively combining the strengths of both approaches. The overall lactic acid yield increased to 91.4%, surpassing that of both standalone processes. Importantly, high optical purity was largely retained (96.2%), indicating that the catalytic purification and upgrading steps did not compromise the stereochemical integrity of the fermentation-derived lactic acid. Furthermore, the number of processing steps was reduced to three, reflecting simplified downstream operations and improved process integration.

Although the total reaction time for the integrated route (36 h) was longer than that of the chemocatalytic process alone, it was significantly shorter than the fermentation-only route while delivering higher yield and optical purity. These results clearly demonstrate that integration of bioprocessing with green chemical catalysis enhances overall process efficiency, reduces operational complexity, and maintains product quality. The integrated bio–chemo strategy therefore represents a promising and balanced approach for sustainable and industrially viable lactic acid production.

5.2 Reduction in downstream processing burden:

Downstream processing is one of the most resource-intensive and environmentally challenging stages in lactic acid production, particularly in conventional fermentation-based processes. To evaluate the impact of integrating catalytic upgrading with

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bioprocessing, key downstream performance indicators were compared between the conventional fermentation route and the integrated bio–chemo route. The assessment focused on neutralization salt generation, solvent consumption, and overall energy input, as these parameters directly influence process sustainability and operating costs.

Table 8. Downstream processing comparison

Parameter	**Conventional fermentation**	**Integrated route**
Neutralization salt waste (kg kg^{-1} product)	1.8	0.6
Solvent usage (kg kg^{-1} product)	12.6	7.1
Energy input (MJ kg^{-1} product)	18.4	11.9

In the conventional fermentation process, lactic acid recovery typically involves neutralization with alkaline agents followed by acidification, leading to the generation of substantial quantities of inorganic salt waste. As shown in Table 8, this route produced approximately 1.8 kg of neutralization salts per kilogram of lactic acid product. Such salt generation not only increases waste disposal requirements but also adds to the overall environmental footprint of the process.

The integrated route significantly reduced neutralization salt waste to 0.6 kg kg^{-1} product, representing a reduction of nearly 67% (Table 8). This improvement can be attributed to the incorporation of catalytic upgrading and purification steps that minimized the need for extensive neutralization and acidification cycles. By simplifying product recovery, the integrated process effectively reduced inorganic waste generation.

A similar trend was observed for solvent usage. Conventional fermentation required 12.6 kg of solvent per kilogram of lactic acid, largely due to multiple extraction, washing, and purification steps. In contrast, the integrated route reduced solvent consumption to 7.1 kg kg^{-1} product, reflecting fewer unit operations and improved process integration. Lower solvent usage directly translates to reduced material costs and decreased environmental impact.

Energy input analysis further highlighted the advantages of integration. The conventional route consumed 18.4 MJ kg^{-1} product, whereas the integrated process required only 11.9 MJ kg^{-1} product. This reduction in energy demand is primarily due to fewer downstream processing steps, reduced solvent recovery requirements, and more efficient catalytic operations.

Overall, these results demonstrate that integrating catalytic upgrading with fermentation substantially alleviates downstream processing burdens. The reductions in salt waste, solvent usage, and energy input underscore the environmental and economic benefits of the integrated bio–chemo strategy, reinforcing its potential as a sustainable approach for large-scale lactic acid production.

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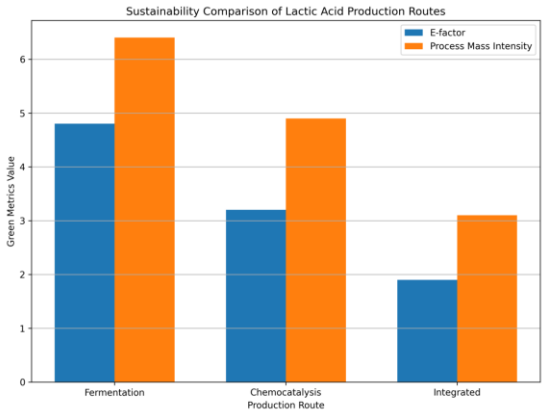

Figure 3. *Sustainability comparison of fermentation, chemocatalytic, and integrated bio–chemo routes for lactic acid production based on E-factor and process mass intensity. The integrated strategy exhibits substantially lower waste generation and material consumption, demonstrating approximately 60% reduction in environmental burden relative to conventional fermentation.*

6. Green Chemistry Metrics:

6.1 Sustainability performance:

To quantitatively assess the environmental performance of the different lactic acid production routes, key green chemistry metrics were calculated and compared for fermentation-only, chemocatalysis-only, and integrated bio–chemo processes. These metrics provide an objective basis for evaluating material efficiency, waste generation, and overall process sustainability beyond conventional yield-based comparisons.

Table 9. Sustainability assessment

Metric	Fermentation	Chemocatalysis	Integrated
Atom economy (%)	72.4	81.3	85.6
E-factor	4.8	3.2	1.9
Process mass intensity	6.4	4.9	3.1

The fermentation-only route exhibited an atom economy of 72.4%, reflecting efficient incorporation of substrate carbon into the desired product but also indicating material losses associated with nutrient inputs, buffering agents, and downstream neutralization steps (Table 9). Its relatively high E-factor of 4.8 highlights substantial waste generation, primarily in the form of spent biomass, residual nutrients, and neutralization salts. The process mass intensity (PMI) of 6.4 further confirms the large amount of material input required per unit mass of lactic acid produced.

The chemocatalytic route demonstrated improved material efficiency, with an atom economy of 81.3%. This improvement can be attributed to more direct reaction pathways and reduced reliance on auxiliary materials. The lower E-factor (3.2) and PMI (4.9) indicate reduced waste generation and overall material consumption compared to fermentation. However, despite these advantages, the chemocatalytic process lacks stereochemical control and therefore falls short for applications requiring optically pure lactic acid.

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The integrated bio–chemo process clearly outperformed both standalone routes across all sustainability metrics. The highest atom economy (85.6%) reflects optimal utilization of reactants through the combination of biologically selective synthesis and efficient catalytic upgrading. Most notably, the E-factor decreased to 1.9, representing approximately a 60% reduction in waste generation compared to conventional fermentation. This substantial improvement arises from minimized salt formation, lower solvent usage, and streamlined downstream operations. The PMI value of 3.1 further emphasizes the material efficiency of the integrated approach, indicating that significantly less input material is required per unit of lactic acid produced.

Discussion:

The present study demonstrates that integrating green organic chemistry with bioprocessing provides a robust and sustainable pathway for lactic acid production, effectively addressing the limitations of standalone fermentation and chemocatalytic routes. The fermentation results using *Lactobacillus plantarum* ATCC 8014 clearly confirm the suitability of homofermentative lactic acid bacteria for producing high concentrations of optically pure L-lactic acid from renewable substrates (Abdel-Rahman et al., 2013). The observed lactic acid titer and yield obtained from glucose are consistent with previously reported values for efficient industrial strains, highlighting the reliability of biological systems for stereoselective synthesis (John et al., 2009).

Substrate flexibility is a critical factor for the economic viability of large-scale lactic acid production. The ability of *L. plantarum* ATCC 8014 to utilize lignocellulosic hydrolysate with relatively high yield demonstrates its metabolic adaptability and supports the use of low-cost biomass-derived feedstocks (Komesu et al., 2017). Although fermentation using hydrolysate resulted in lower lactic acid concentration and extended fermentation time compared to glucose, this reduction is commonly attributed to the presence of mixed sugars and inhibitory compounds generated during biomass pretreatment (Abdel-Rahman et al., 2013). From a sustainability perspective, the modest loss in productivity may be outweighed by the significant reduction in raw material costs and improved resource efficiency associated with renewable feedstocks (Sheldon, 2014).

Optical purity analysis revealed that fermentation-derived lactic acid possessed excellent stereochemical purity, with an enantiomeric excess exceeding 96%. This result underscores a key advantage of bioprocessing over chemical synthesis, as biological pathways inherently control chirality through enzyme-specific reactions (Datta et al., 1995). High optical purity is particularly critical for polymer-grade lactic acid, where stereochemistry directly influences the crystallinity, mechanical strength, and thermal properties of polylactic acid (Dusselier et al., 2013). The fermentation results therefore reaffirm the

dominant role of microbial processes in producing chiral lactic acid for advanced material applications.

In contrast, chemocatalytic conversion of glucose exhibited strong dependence on reaction temperature, confirming the importance of thermal control in biomass-derived chemical transformations (Holm et al., 2010). Increasing reaction temperature enhanced glucose conversion and lactic acid yield by promoting key rearrangement and retro-aldol pathways involved in lactic acid formation (Dusselier and Sels, 2014). However, the formation of racemic lactic acid highlights a fundamental limitation of conventional chemocatalytic routes, as non-chiral catalysts lack the ability to direct enantioselective product formation (Esposito and Antonietti, 2015). This intrinsic drawback restricts the applicability of purely chemical approaches for producing optically pure lactic acid without additional resolution steps.

Catalyst recyclability studies revealed only a gradual decline in activity over multiple reaction cycles, indicating acceptable stability under the applied reaction conditions. The absence of significant catalyst leaching suggests that deactivation was primarily due to surface fouling or partial blockage of active sites rather than irreversible structural degradation (Sheldon, 2019). Such recyclability is essential for reducing catalyst-related costs and environmental impact, reinforcing the compatibility of chemocatalysis with green chemistry principles.

The integrated bio–chemo strategy emerged as the most effective approach, combining the stereochemical precision of fermentation with the efficiency of catalytic upgrading. The higher overall yield achieved through integration reflects reduced material losses and improved process synergy (Straathof, 2019). Importantly, the integrated route retained high optical purity, demonstrating that catalytic purification steps did not compromise the chiral integrity of fermentation-derived lactic acid. The reduction in total processing steps further indicates that integration simplifies process design and enhances operational efficiency.

Downstream processing analysis clearly showed that integration significantly alleviates one of the major bottlenecks in lactic acid production. Conventional fermentation routes generate substantial quantities of neutralization salts due to repeated acid–base treatments, contributing heavily to waste generation (Komesu et al., 2017). The integrated process markedly reduced salt formation, solvent consumption, and energy input, confirming that catalytic upgrading can effectively streamline recovery and purification stages (Sheldon, 2014). These improvements directly translate into lower environmental footprint and improved economic feasibility.

Green chemistry metrics further validate the superiority of the integrated approach. The substantial reduction in E-factor and process mass intensity highlights improved material efficiency and waste

minimization compared to both fermentation-only and chemocatalytic routes (Sheldon, 2019). Achieving a 60% reduction in waste generation relative to conventional fermentation underscores the potential of integrated bio–chemo systems to meet the sustainability goals of modern chemical manufacturing.

Overall, the results support the growing consensus that future lactic acid production technologies must transcend traditional disciplinary boundaries. By integrating green organic chemistry with bioprocessing, it is possible to achieve high yield, excellent stereochemical purity, reduced waste generation, and lower energy demand within a single coherent framework (Hatti-Kaul et al., 2018). Such integrated strategies position lactic acid as a cornerstone molecule in the transition toward a sustainable and circular chemical industry.

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