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Holistic Optimization of Polylactic Acid Production: Reducing Environmental Footprint via Catalytic Synthesis, Biomass Utilization, and Supercritical CO_2 Processing

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Abstract. Polylactic acid (PLA) is widely applied in biomedical and industrial fields due to its biocompatibility and degradability, but its production still faces challenges such as high energy consumption, solvent use, and waste generation. This study systematically evaluated PLA's full value chain, from polymerization methods and raw material selection to processing techniques, with an emphasis on green manufacturing strategies. Comparative analysis shows that advanced catalysts enable efficient low-temperature synthesis, careful raw material selection such as sugar- and waste-based materials reduces environmental burdens, and sustainable processing routes including additive manufacturing and supercritical CO_2 foaming enhance product performance with lower emissions, while computational modeling predicted optimal foaming parameters that reduced unit energy consumption to ~1643 kWh/t. These results underline the combined role of catalysis, material management, processing and predictive analysis in achieving high-performance yet environmentally sustainable PLA production.

Keywords: Polylactic acid (PLA), Green manufacturing, Supercritical carbon dioxide foaming, Life cycle assessment (LCA), Renewable biomass raw materials

1. Introduction

Biodegradable biomedical polymer materials, particularly polylactic acid (PLA), play a key role in meeting the modern medical demands for diversified and personalized diagnostic and therapeutic approaches due to their excellent biocompatibility and in vivo metabolization. PLA, as a high-performance aliphatic polyester with excellent mechanical strength, stability and controllable degradation, and renewable sources (e.g., corn, sugarcane), has expanded its applications from medical sutures to multiple fields. Its mainstream preparation methods—ring-opening polymerization (ROP [1])and direct polycondensation (SPD)—along with subsequent processing techniques (such as melt blending, hot-melt extrusion, 3D printing, supercritical CO_2 foaming, etc.) collectively determine the final performance and application potential of the material. However, throughout the entire PLA manufacturing process, from raw material to finished product—both involving polymerization reactions and post-processing—there are significant environmental

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impacts. High energy consumption (especially in high-temperature processes), organic solvent use and potential contamination, insufficient raw material conversion rates, and the generation of multiple wastes (e.g., gaseous CO_2,VOCs(Volatile Organic Compounds); liquid wastes containing catalysts, monomer residues; solid scraps) not only increase production costs but also contradict the core concept of sustainable development [2].

Therefore, systematically evaluating and optimizing green PLA preparation processes to minimize environmental impacts while maintaining essential biomedical properties is a key challenge to enabling its safe, environmentally friendly, and efficient application. Given the environmental issues arising from PLA production, research focusing on optimizing manufacturing processes, improving energy efficiency and reducing pollutant emissions. This paper systematically analyzed the environmental impacts of different preparation methods starting from the green selection of raw materials and explored feasible improvement measures, including clean energy utilization, solvent recovery technologies, low-energy polymerization pathways and waste management strategies. In addition, real-world case studies were combined to evaluate the environmental footprint of typical processes, aiming to provide theoretical basis and practical guidance for the green preparation of PLA in the medical field, promoting its safe, environmentally friendly and efficient application under the context of sustainable development.

2. Theoretical research

PLA synthesis is mainly achieved through lactide ROP and direct SPD of lactic acid. In ROP, lactic acid is first dehydrated to form cyclic dimers (lactide), which then polymerize under catalyst action to form high-molecular-weight PLA. This pathway offers good control over molecular weight distribution and mechanical properties [3]. In SPD, lactic acid undergoes stepwise condensation reactions in a molten, solvent-free state above its melting point to gradually form polymer chains (Figure1). Although this method is simpler and potentially lower-cost, it suffers from side reactions, limited achievable molecular weight and long reaction times. Hybrid processes combining prepolymerization with ROP have been developed to balance molecular weight control with economic feasibility.

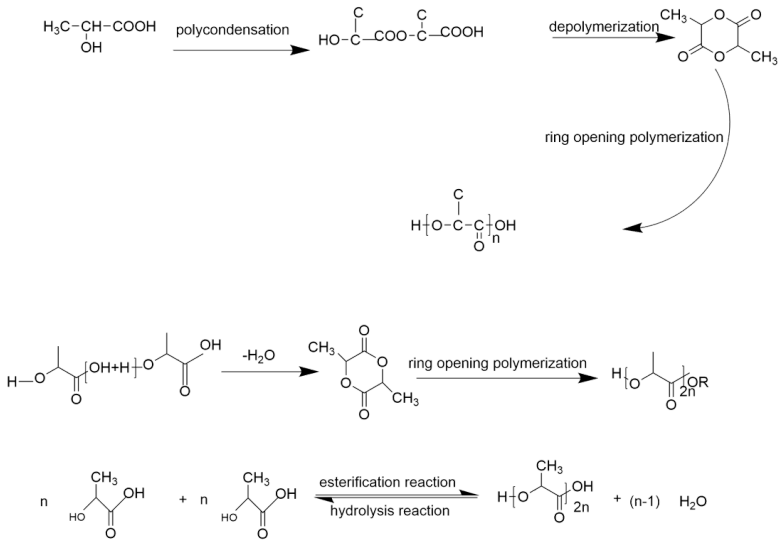


Figure 1 Preparation of lactic acid by ring-opening polymerization and direct polycondensation

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Processing methods determine the final product properties. Conventional melt blending and extrusion can produce films, fibers and molded products but require high processing temperatures (180–230 °C), risking thermal degradation. Additive manufacturing (3D printing) offers design flexibility and tunable porosity for medical scaffolds. Supercritical CO_2 foaming can produce interconnected porous structures with low energy consumption and no solvent residues [4]. Although solvent casting and thermally induced phase separation allow fine structural control, it often includes hazardous solvents or consume large amounts of water. Strategies such as nucleating agents, self-assembly designs and membrane-based solvent recovery can improve efficiency and environmental performance [5].

3. Problems

In the process of preparing PLA, both SPD and ROP have characteristics such as high energy consumption, significant side reactions, large solvent usage and low raw material conversion rates. In SPD, lactic acid monomers undergo solvent-free melt polycondensation to form high-molecular-weight PLA. However, this process requires long reaction times and high temperatures, which may lead to discoloration and performance degradation. The removal of by-products relies on a high vacuum environment, imposing strict requirements on equipment. In industrial practice, organic solvents are often introduced as azeotropes to accelerate water removal and achieve higher molecular weights, but solvent recovery is difficult and poses environmental issues. In ROP, lactic acid is first cyclized to form lactide, which is then polymerized under high temperature and high vacuum conditions. Although the reaction proceeds effectively, energy consumption and carbon emissions are significant and the purification of lactide increases production costs. Additionally, the agricultural production of lactic acid raw materials (such as sugarcane) brings additional environmental problems because of the use of trace elements. Overall, the preparation stage faces sustainability challenges such as energy intensity, solvent dependence, limited conversion efficiency, and complex waste management.

In the processing of PLA, the main issues include thermal degradation during high-temperature operations, difficulties in controlling pore structure during foaming, and reliance on organic solvents with incomplete recovery. The polymer would degrade at high temperature via melt blending and extrusion, typically performed at 180–230°C.Additive manufacturing, specially fused filament fabrication (FFF) enables tunable porous structures, but printing temperatures at 190–230°C increase energy use and emissions. Conventional chemical blowing agents can leave harmful residues, while physical foaming with CO_2 or N_2 is cleaner but hampered by PLA's high melt viscosity, low thermal stability and slow crystallization, which often lead to poor expansion ratios and broad pore size distributions. Solvent casting and phase separation can produce high-performance membranes, yet they rely on toxic solvents such as dichloromethane, resulting in VOC emissions and high recycling costs. Waste streams from PLA production—including gaseous, liquid and solid residues—require costly treatment and heavy-metal catalysts in medical-grade PLA must be strictly removed to avoid safety risks.

4. Solution

In view of the high energy consumption, insufficient raw material conversion rate and environmental burden caused by raw material supply in the current production process, improvement measures should start from the selection of raw materials. Different biomass sources

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vary significantly in terms of economy and environmental footprint. Therefore, the rational allocation and utilization of green raw materials is the first step in optimizing the overall process.

Feedstock suitability is influenced by carbohydrate composition, saccharification efficiency, fermentation pathway and byproduct control. The production of PLA relies on carbohydrate-rich biomass, which is converted into lactic acid via microbial fermentation. Raw materials include corn starch, potato starch, cassava starch, wheat starch, sugarcane sucrose, beet sugar, lignocellulosic biomass and food waste (as shown in Table 1). Lactic acid yields exceed 90%, while lactide purity can reach up to 99%. Starch- and sugar-based feedstocks offer good industrial economics (USD 0.5–0.9/kg) and abundant supply. Lignocellulose and food waste expand the feedstock base and help recycle waste resources. Life cycle assessment (LCA) must also consider agricultural inputs such as pesticide use and water consumption, with results showing that sugarcane-based PLA emits about 406 kg CO_2-eq per ton with an energy demand of ~1028 kWh, whereas microalgae-based routes release up to 12,484 kg CO_2-eq per ton with ~6557 kWh of energy use [1].

Table 1. Summary of composition and yield of raw material

Raw Material	Key Component	Productivity	Industrial Price (USD/kg)
lactic acid	L-lactic acid, D-lactic acid and their mixtures racemic DL-lactic acid	More than 90%	1.06-6.58
lactide	dimer	99-41.4%	~2.30
corn starch	the starch content ranges from 64 to 78%, with an average of 71.3%	37%	~0.53
potato starch	starch	180,000 tons	0.70-1.97
cassava starch	starch	10.6 tons per hectare	~0.87
wheat starch	starch, protein and lipid	5.94tons per hectare	~0.72
saccharose	saccharose	74tons per hectare	~0.70
beet sugar	sucrose, minerals and amino acids	61tons per hectare	~0.70
Lignocellulose	cellulose, hemicellulose, lignin	50-50%	
food waste	starches, sugars, proteins, etc.	0.35-0.85g Lactic acid/g, volatile solid	

At the same time, to address preparation challenges, low-temperature catalytic systems (e.g., vanadium-free catalysts) can be introduced to achieve efficient polymerization at reduced temperatures, lowering energy use and side reactions. Solvent-free polymerization routes, coupled with advanced recovery technologies such as membrane separation or membrane distillation, can minimize solvent consumption and environmental impact [6]. For instance, studies have shown that membrane distillation in PLA solvent recovery can achieve over 90% solvent recovery efficiency, while reducing VOC emissions by more than 70% compared to conventional distillation methods, significantly improving energy efficiency and lowering environmental burdens [7].These findings confirm that appropriate feedstock choice is critical to reducing environmental burdens from the source.

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For processing challenges, green strategies include the addition of nucleating agents or fiber reinforcements to accelerate crystallization, stabilize structure and mitigate thermal degradation during melt processing. In additive manufacturing and foaming, process parameters (temperature, pressure, CO_2 injection rate, screw speed) can be optimized, while model-based supervision and data-driven predictive control help achieve uniform pore structures and reduced energy consumption. sCO_2 foaming is favored over chemical foaming for its cleaner profile and high recovery rates of CO_2 further reduce emissions. In solvent-based methods, replacing toxic solvents with greener alternatives and implementing membrane-assisted recovery can significantly reduce VOC emissions. These combined measures support both high-performance material output and enhanced environmental sustainability.

Waste and energy optimization. LCA data show that for 1 t PLA, sugarcane feedstock emits 406 kg CO_2 eq and consumes 1028 kWh, while microalgae emits 12,484 kg CO_2 eq and consumes 6557 kWh due to energy-intensive dehydration/drying [8]. Sensitivity analysis revealed electricity input (mainly from fossil-based steam/grid) contributes over 71.84% to in the microalgae route. Model supervision can constrain such variables in optimization algorithms to minimize unit energy consumption while meeting product performance targets. In sugarcane PLA production, gypsum waste is 1980 kg/t PLA; predictive recovery and anaerobic digestion can recover 24–28% energy. Among them, the key indicators are as follows: Sensitivity coefficient SC:(1) Used to represent the absolute impact caused by changes in input variables on the environmental impact factor. Sensitivity ratio SR: (2) characterizes the proportional effect of relative changes in input parameters on the output results. In order to achieve the collaborative control of high production capacity and low energy consumption, the following mathematical model is constructed in this paper:(3),the unit energy consumption calculation formula:(4).The parameters were selected based on the process interval of CO_2 foaming experiment reported by Li et al [9]. (CO_2 injection 1.2-2.0 wt%, temperature 130-145°C, screw speed 55-70 rpm) and variable combinations were designed combined with uniform distribution and cross-value strategy. This design not only ensures that the parameter coverage matches the engineering reality, but also provides a good data basis for the subsequent significance analysis, optimal solution optimization and process sensitivity of the model. Carbon dioxide was injected in 0.1-0.2 increments, the screw speed was gradually increased from 55 to 70rpm, and the melt temperature was covered from 130 to 145° C.

$$SC_a^b = \frac{\Delta Z_b}{\Delta X_\alpha} \tag{1}$$

$$SR_a^b = \frac{(\Delta Z_b / Z_b)}{(\Delta X_\alpha / X_\alpha)} \tag{2}$$

Where X_α is the input variable (such as electricity) and Z_b is the impact factor (such as GWP), which is used to assess the marginal sensitivity of the resource to the environmental load

$$E_{specific} = \beta_0 + \beta_1 \cdot C + \beta_2 \cdot S + \beta_3 \cdot T \tag{3}$$

Where is unit energy consumption, and the unit is kWh/ton; C is the injection rate in wt%; S is the speed of the screw, the unit is rpm; T for melt temperature, the unit is ℃

$$E_{specific} = \frac{E_{total}}{Q} \tag{4}$$

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Among them E_{total} for the total kWh energy consumption per unit time, Q time for the unit capacity (T/h), this article set the working condition of 8 representative set of foam combination

Table 2. Comparison of the sets of hypothetical data for Extrusion scCO₂ Foaming Process

Number	CO2 Injunction Rate(wt%)	Screw Speed(rpm)	Melt Temperature(°C)	Total Dissipation(kWh)	Capacity(t/h)	Specific Power Consumption	Model Prediction Epred	Residual
1	1.0	40	130	980	1.10	890.91	891.02	0.11
2	1.2	45	132	1015	1.18	859.32	957.60	-1.72
3	1.4	50	134	1042	1.25	833.60	823.00	-10.60
4	1.5	55	136	1070	1.32	810.61	818.57	7.96
5	1.6	60	138	1100	1.37	802.92	814.14	11.22
6	1.7	65	140	1140	1.41	808.51	809.71	1.20
7	1.8	70	142	1180	1.45	813.79	805.29	-8.50
8	2.0	75	145	1225	1.48	827.03	827.70	0.67

By using the least square method to solve the regression coefficients through these 8 sets of hypothetical data (Table 2), it can be obtained that β_0 =831.03 β_1 =-3.228 β_2 =-7.007 β_3 =9.489

Capacity enhancement. By modeling and predicting the relationship between process parameters and output, model supervision coordinates production speed, foaming ratio and energy consumption for maximum throughput with stable quality. Regression analysis of eight hypothetical extrusion foaming scenarios showed that CO_2 = 1.4 wt%,screw speed = 65 rpm, melt temperature = 134°C yielded the lowest unit energy consumption (1642.58 kWh/t) [10]. The model can extrapolate to new conditions, providing a quantitative basis for optimization.

In order to further explore the combination of process parameters that results in the lowest unit energy consumption during the poly (lactic acid) foaming process, this paper constructs a prediction function based on the established linear regression model: where C is the injection rate of carbon dioxide, S is the screw speed, T is the melt temperature and represents the predicted unit energy consumption. To obtain the global minimum point of the predicted value, the variable search range is set as:$1.2 \leq C \leq 2.0$, $55 \leq S \leq 75$, $130 \leq T \leq 145$, and a three-dimensional network is established within this parameter space. Through the MATLAB program, the predicted energy consumption under each set of parameters is calculated successively and the minimum value is extracted to obtain the optimal combination. At the same time, to visually display the response trend of unit energy consumption to the changes in process parameters, a three-dimensional response surface diagram under the condition of a fixed carbon dioxide injection rate C = 1.5 is drawn, with screw speed and melt temperature as independent variables and unit energy consumption as the Z-axis (Figure 2). The local minimum point in the current section is marked in the figure, and the global optimum point in the entire parameter space is highlighted with a red circle. From the model coefficients, it shows that the coefficients of carbon dioxide injection rate and screw speed are both negative, indicating that their increase helps to reduce the unit energy consumption, while the coefficient of melt temperature is positive, indicating that an increase in temperature leads to an increase in unit energy consumption. This trend is consistent with the results shown in the figure and also conforms to the engineering phenomena in the foaming process such as gas mixing improving fluidity, high-speed transportation enhancing efficiency and high temperature causing heat loss. The illustrated

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process not only enhances the visualization understanding of the model but also provides an intuitive reference for energy response in engineering design.

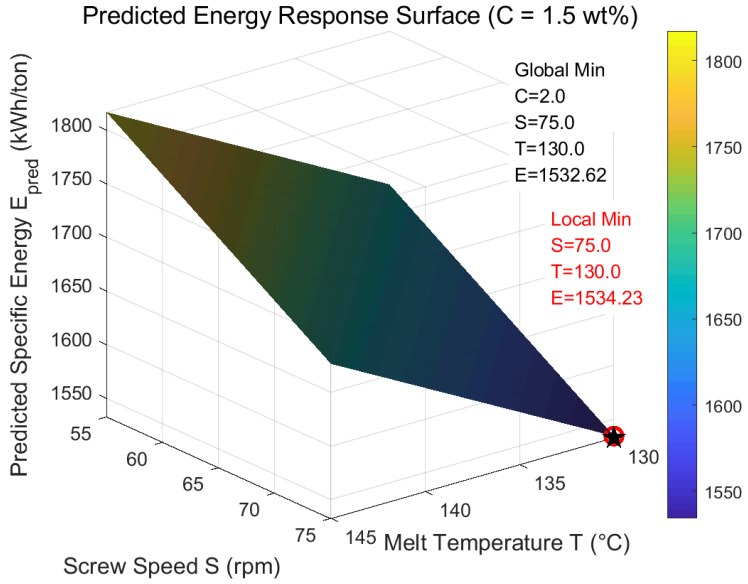


Figure 2. Three-dimensional response surface diagram of unit energy consumption and process parameters (C=1.5)

In summary, this study demonstrates that integrating catalytic process optimization, feedstock selection and model monitoring of sCO₂ foaming can significantly reduce the environmental impact across the entire PLA production chain. Specifically, the use of sugarcane-based feedstock combined with low-temperature catalytic processes can achieve unit energy consumption below 1028 kWh/t and CO_2 emissions of approximately 406 kg/t. Furthermore, by optimizing foaming parameters through modeling (CO_2 injection rate:1.4 wt%, screw speed:65 rpm, melt temperature:134°C), the unit energy consumption can be further reduced to 1643 kWh/t while ensuring uniform foam structure and mechanical performance. However, scaling up these applications still requires overcoming challenges such as data interface compatibility, model transferability and multi-objective trade-offs. Future efforts should focus on building cross-platform model libraries and standardized process databases to advance the manufacturing of biodegradable materials toward low-carbon and intelligent systematic solutions.

5. Conclusions

This study systematically analyzed the green manufacturing and environmental optimization strategies of PLA in aspects such as the polymerization process, raw material selection and processing technology. It pointed out that the main problems at present include: the high-temperature and high-energy consumption polymerization process, the use and recycling difficulties of large amounts of organic solvents, waste discharge and residual heavy metal catalysts, insufficient raw material conversion rate and environmental risks in the process of agricultural raw material supply. Although supercritical CO_2 foaming combined with model monitoring technology shows potential in reducing unit energy consumption, improving the uniformity of pore structure and enhancing production capacity, there are still limitations in terms of data quality, model transferability and multi-objective optimization [11].

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Future research should focus on enhancing the adaptability of processing technologies to diverse biomass raw materials, improving the portability of prediction models across different equipment platforms and integrating LCA into real-time process optimization frameworks. At the same time, efforts should be made to promote the application of low-temperature catalytic systems, solvent-free polymerization routes and efficient CO_2 recovery technologies, in order to further improve the environmental performance of PLA production. These measures not only help to promote the wide application of PLA in packaging, consumer goods and environmental restoration, but also provide a reference technical path for the green manufacturing of other degradable and biobased polymers.

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