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Ethyl Lactate as a Green Solvent in Terms of Sustainability and Economic Perspectives in Organic Synthesis Esterification: A Review

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ABSTRACT

This study presents a comprehensive analysis of ethyl lactate as a sustainable green solvent in organic synthesis, with a focus on feedstock evaluation and economic feasibility. A systematic literature-based approach was employed, covering publications from 2020 to 2025, and assessing two key aspects: (i) the source and cost of feedstocks, including whey, sugarcane molasses, rice straw, and starch, and (ii) the performance of ethyl lactate in various organic transformations. Techno-economic analysis estimates the cost of production (CoP) of ethyl lactate from sugarcane molasses in the range of USD 1,300-1,500/ton, while production from rice straw is estimated at around USD 5,600/ton, highlighting the economic advantage of molasses-based routes. Ethyl lactate has also demonstrated high effectiveness, achieving yields of 90-95% in various reactions such as coupling, metathesis, and ester synthesis. These findings reinforce the potential of ethyl lactate to support the chemical industry's transition toward more environmentally friendly processes, offering a compelling combination of technical performance and economic viability.

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INTRODUCTION

The word “solvent” originates from the Latin solvo, meaning to loosen, untie, or solve. Solvents, whether solid, liquid, gas, or supercritical fluid, are substances that dissolve solutes, where a complete dissolution results in a homogeneous solution [1]. Conventional organic solvents, such as chloroform, ether, toluene, and acetone, are widely used in industrial and chemical synthesis due to their effectiveness in dissolving or dispersing a broad range of compounds, including polar and nonpolar organic substrates, reagents, and catalysts, as well as their stability under diverse reaction conditions [2]. However, despite their practical benefits, the use of these solvents presents several significant challenges, especially in the context of green chemistry and sustainability. Many organic solvents exhibit amphiphilic properties, enabling them to penetrate epithelial tissues and potentially pose health risks, particularly to industrial workers [3]. Common solvents such as alcohols, ketones, and ethers are capable of crossing the blood brain barrier, and excessive exposure may lead to neurotoxic effects [3]. According to the Ministry of Manpower, there were 53,000 reported cases of occupational diseases in Indonesia in 2020. From January to September 2021, the number increased to 179,000 cases. According to Presidential Regulation of the Republic of Indonesia Number 7 of 2019 on Occupational Diseases, the most common occupational diseases are associated with chemical exposure in the workplace [4]. Chemical agents account for 41% of work-related illnesses resulting from exposure to occupational hazards, making them the leading cause of such diseases [5]. And as a chemical agent, conventional organic solvents are no exception in regard of contributing to this percentage number.

Traditional organic solvents are commonly sourced from fossil fuels, leading to increased carbon emissions and the exhaustion of non-renewable resources [6]. Therefore, it is mandatory to address the production and use of these solvents are harming the quality of life around. For example, Carbon tetrachloride, formerly utilized in cleaning products and as a solvent, is now tightly regulated because of its contribution to ozone layer destruction and its harmful impact on the liver and kidneys [7]. Methyl chloride (CH_3Cl), a toxic and flammable gas used in refrigeration, petrochemical processing, and foam production, can cause symptoms ranging from dizziness to coma depending on exposure levels [8]. We urgently need to develop and use sustainable solvents for bio-crude extraction. This will help minimize environmental harm and ensure ecological viability.

In recent years, green chemistry and the application of green solvents have rapidly advanced as alternatives to conventional organic solvents [9]. Green solvents are characterized by negligible environmental impact and high biodegradability. These solvents are inherently sustainable, exhibiting properties such as ease of synthesis, non-toxicity, biodegradability, good performance, chemical and thermal stability, non-flammability, renewability, low maintenance requirements, and ease of handling [10]. These characteristics make green solvents highly suitable for reducing environmental degradation and serve as promising reaction media for sustainable synthesis processes [11]. Beyond their environmentally friendly nature, green solvents also enhance reaction efficiency, product selectivity, and compatibility with specific catalysts [12]. These advantages make green solvents ideal candidates to support the chemical industry's transition toward more environmentally benign and sustainable practices.

Common examples of green solvents include ionic liquids (ILs), supercritical carbon dioxide ($scCO_2$), liquid polymers, deep eutectic solvents (DESs), and natural deep eutectic solvents (NADESs) [13]. Recent studies have highlighted the effectiveness of these solvents in a wide range of organic synthesis reactions, including esterification, alkylation, and condensation reactions. For instance, DESs and NADESs have shown improvements in selectivity and efficiency in enzymatic esterification reactions [14], [15]. Moreover, the use of $scCO_2$ as a green solvent has been reported to increase conversion and selectivity in organic solutions [16]. Additionally, ILs continue to receive attention due to their tunable properties, high catalytic activity, and selectivity in organic transformations [17]. Therefore, the role of green solvents in promoting sustainable synthesis extends beyond emission and waste reduction, contributing significantly to enhanced reaction efficiency and overall process safety.

Among the various types of green solvents developed in recent decades, ethyl lactate (ethyl 2-hydroxypropanoate) has emerged as a particularly attractive candidate due to its unique characteristics. Ethyl lactate is an environmentally friendly solvent with the effectiveness of bio-based amphiphilic solvents and an ecotoxicity profile comparable to petroleum-based solvents [18]. The worldwide solvent market is approximately 28 million pounds per year, of which ethyl lactate could have a significant share [19]. In recent years, ethyl lactate has garnered interest as an alternative green solvent due to its favourable properties, such a low toxicity, high biodegradability, non-corrosiveness or harmless to ozone shield [20]. Its relatively low boiling point and ability to dissolve a wide range of organic compounds make it an ideal solvent for various chemical reactions.

In the context of chemical reactions, ethyl lactate has shown great potential as an environmentally friendly green solvent. This compound is widely used in various organic synthesis processes, such as esterification, transesterification, and condensation reactions, because it is able to dissolve a variety of polar and non-polar compounds [21]. Its advantages as a solvent derived from renewable sources make it an ideal choice to substitute conventional solvents that are toxic and not environmentally friendly, such as toluene, chloroform, or acetone. Ethyl lactate is also often used in homogeneous and heterogeneous catalysis, due to its stability under reaction conditions and its compatibility with various types of catalysts [22]. In addition, its use supports the principles of green chemistry, especially in terms of reducing hazardous waste, increasing atomic efficiency, and developing more sustainable processes [23]. From an industrial perspective, ethyl lactate is not only technically advantageous, but also economically promising. According to Allied Market Research, the largest market application of ethyl lactate is as a solvent, accounting for approximately 39.5% of its global usage [24]. In terms of end-user sectors, the food and beverage industry leads with a 32.6% market share, followed by paints and coatings, cosmetics, and pharmaceuticals, which are rapidly adopting green solvents to comply with sustainability goals [24], [25]. An overview of the applications of ethyl lactate and its global market value is presented in Figure 1. Furthermore, the global market for ethyl lactate was valued at USD 1.9 billion in 2023 and is projected to reach USD 3.8 billion by 2032, with an estimated compound annual growth rate (CAGR) of 7.4%, indicating increasing demand for bio-based and environmentally friendly solvents [25].

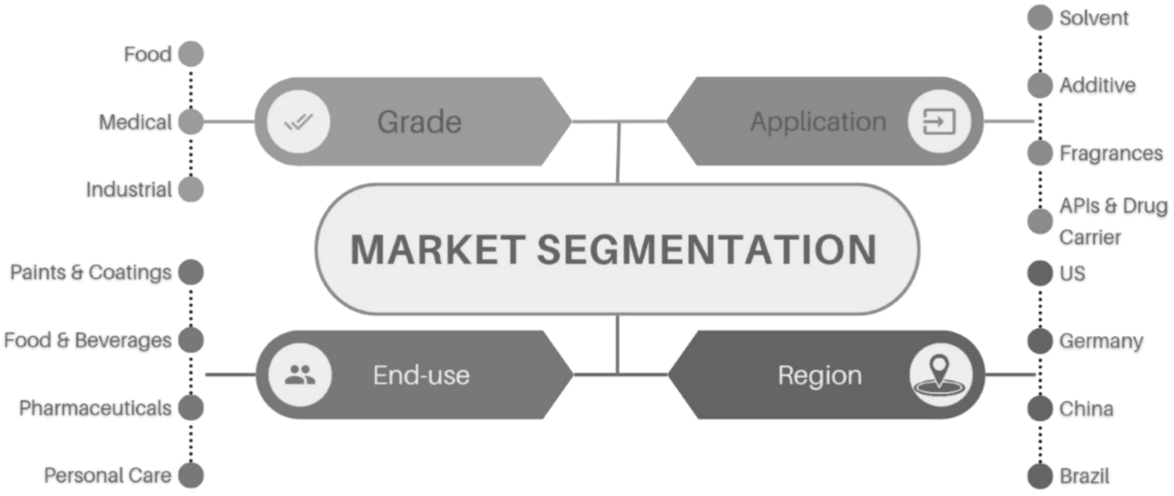


Figure 1. Application ethyl lactate [24] and global ethyl lactate market value [25]

With the increasing urgency to replace hazardous conventional organic solvents with more environmentally friendly alternatives, and in light of its promising potential, ethyl lactate has attracted considerable attention as a green solvent in organic synthesis. However, despite numerous studies investigating its potential, a comprehensive assessment is still required to determine the extent to which this solvent can be relied upon both technically and economically across various types of chemical reactions. Therefore, this review aims to provide an in-depth examination of ethyl lactate as an environmentally friendly solvent in organic synthesis, evaluate its technical performance in different reaction systems, discuss its potential economic and environmental benefits, and offer recommendations regarding the strategic role of ethyl lactate in supporting the transition of the chemical industry toward more sustainable practices.

RESEARCH METHODS

This study employs a systematic literature review (SLR) approach to collect, analyze, and synthesize scientific findings on the use of ethyl lactate as a green solvent in organic synthesis, with special attention to its technical performance and economic feasibility. The methodology used in this review follows established academic protocols for literature-based research, ensuring comprehensiveness, relevance, and objectivity. The data were then synthesized qualitatively to identify trends, advantages, limitations, and gaps in the application of ethyl lactate. Where applicable, comparative tables and schematics were developed to visualize the performance and sustainability metrics of ethyl lactate versus other solvents. The triangulation of data from various sources was subsequently carried out to enhance the validity of the discussion results.

Table 1. Literature Analysis

No.	Research Design	Result	Reference
1.	An experimental study was conducted at the laboratory scale using a reactive distillation (RD) system with a strong acid catalyst, Amberlyst-15. Two configurations, batch and series systems, were compared to optimize energy efficiency and esterification kinetics.	A conversion of lactic acid to ethyl lactate greater than 95% was achieved within approximately 1.8 hours. The series system demonstrated superior energy efficiency and greater scalability compared to the simultaneous system.	[26]
2.	A hybrid bioprocess was developed at laboratory scale to produce ethyl lactate from cheese whey. The process involved two fermentation steps using *Lactobacillus bulgaricus* and *Kluyveromyces marxianus* to produce lactic acid and ethanol, respectively. These were followed by enzymatic esterification using lipase (Novozyme 435) in an organic solvent system (toluene). Various parameters such as substrate concentration, water content, enzyme loading, and solvent ratio were optimized.	Ethanol and lactic acid were produced at 23 g/L and 29 g/L, respectively. Maximum ethyl lactate conversion reached 33% under optimal conditions (5 M substrates, 15% aqueous phase, 85% toluene, 40 mg/mL enzyme). The system demonstrated feasibility for green solvent production from dairy waste.	[27]
3.	A one-pot chemical esterification method was developed using rice straw, a lignocellulosic agricultural residue, as feedstock. The process involved direct acid-catalyzed transformation of sugars in hydrolysates into ethyl lactate using a combined Lewis and Brønsted acid catalyst system, without a separate fermentation step.	The process achieved selective ethyl lactate formation from rice straw, bypassing intermediate purification of lactic acid. This strategy reduced process complexity and demonstrated high yield potential for producing ethyl lactate directly from low-cost agricultural waste under mild reaction conditions.	[28]
4.	This study employed Aspen simulation and pilot-scale reactive distillation (RD) to evaluate various reaction conditions, including temperature, EtOH/LA molar ratio, and catalyst type (sulfuric acid and Amberlyst). A techno-economic analysis was subsequently conducted for a production scale of 1000 kg of ethyl lactate (EL) per hour.	The reaction catalyzed by Amberlyst or sulfuric acid at 50 °C with a five-fold molar excess of ethanol was found to be economically optimal. The reuse of ethanol and solvent significantly reduced overall production costs. With its high yield and low energy consumption, the process is considered viable for industrial-scale implementation.	[29]

5.	This study conducted a life cycle assessment (LCA) and techno-economic analysis of the pilot-scale reactive distillation (RD) process (2019–2022) to identify cost and carbon emission "hot spots" in ethyl lactate production.	The LCA revealed that integrating solvent reuse and intensifying the RD process can significantly reduce both costs and emissions, positioning ethyl lactate as a more environmentally friendly and economically viable alternative to conventional solvents.	[30]
6.	A process intensification strategy was developed using a reactive distillation (RD) and reactive dividing wall column (RDWC) for the esterification of lactic acid with ethanol to produce ethyl lactate. The system was designed and simulated in Aspen Plus using the analysis of statics method, modeling based on the Langmuir-Hinshelwood mechanism with Amberlyst-15 as catalyst.	The RDWC system achieved an ethyl lactate purity of 99%, with a lactic acid conversion of 83.41% and a 38.5% reduction in energy demand compared to a conventional direct sequence (RD + distillation). The use of a RDWC improved energy efficiency, reduced utility needs, and enhanced product yield, demonstrating feasibility for large-scale green solvent production.	[31]
7.	A biocycle fermentation strategy was explored for producing ethyl lactate from starch- or sugar-rich biomass using simultaneous fermentation and esterification. Lactic acid bacteria and ester-forming microbes were co-cultured in a single system, eliminating the need for solvent extraction or separation steps.	The system produced 3.05 g/L ethyl lactate, representing a 2.3-fold increase compared to conventional mixed fermentation. Moreover, the biocatalyst system remained active for at least 7 cycles, highlighting its reusability and cost-effectiveness. This method represents a promising low-energy, solvent-free approach for green solvent synthesis.	[32]

RESULTS AND DISCUSSION

Materials

In this study, various recent literature sources were analyzed to examine the potential of alternative biomass-based feedstocks for ethyl lactate production. Four primary materials reviewed include whey, rice straw, starch, and sugarcane molasses. These feedstocks were selected based on their abundant availability in Indonesia, potential value-added benefits, and alignment with the principles of the circular economy.

Table 2. Comparison of Yields for Each Materials

Materials	Characteristics	Yields	Reference
Whey	Dairy byproduct rich in lactose; fermented using *L. bulgaricus* and *K. marxianus* to produce lactic acid and ethanol; followed by enzymatic esterification in toluene.	Lactic acid: 29 g/L, Ethanol: 23 g/L, Ethyl lactate conversion: 33%	[26]
Sugarcane Molasses	Byproduct of sugar industry, high in sugar (50.68% total sugar), used without nutrient addition, pH controlled at 6.5, fermented with *Lactobacillus acidophilus* for 72 hours.	Lactic acid: 23.1 mg/L (with 5% starter volume)	[31]

Rice Straw	Lignocellulosic agricultural waste; processed via one-pot acid-catalyzed conversion without fermentation.	Ethyl lactate formed selectively; yield not numerically stated in abstract	[27]
Starch	Biocycle fermentation of starch-rich feedstock using mixed microbial cultures for simultaneous fermentation and esterification.	Ethyl lactate: 3.05 g/L (2.3× higher than standard fermentation)	[32]

Based on the table above, it is evident that the four types of biomass analyzed exhibit better selectivity and conversion rates compared to conventional methods or standard feedstocks. Each of these materials also demonstrates significant potential due to their unique properties. For example, whey is a liquid by-product of the dairy industry that is rich in lactose (approximately 70%) and various micronutrients, making it an ideal substrate for fermentation into lactic acid and ethanol, which can subsequently be converted into ethyl lactate through an integrated process [33]. Whey can be fermented using Kluyveromyces marxianus to produce ethanol and lactic acid, which are then esterified via enzymatic or reactive distillation. Recent studies have shown that ethyl lactate yields of up to 90% can be achieved using reactive distillation, with a feed ratio of 4.1 kg EtOH per kg LA in 2.27 hours [34].

Molasses, a by-product of sugarcane processing, contains a high concentration of fermentable sugars and is easily utilized in fermentation processes. It has also been proven to be an economically viable feedstock for industrial-scale lactic acid production due to its richness in nutrients essential for the growth of lactic acid bacteria [35]. Rice straw, another promising candidate, is an abundant post-harvest lignocellulosic waste that does not compete with food resources. Additionally, rice straw can be processed using catalytic approaches (e.g., Lewis acid systems), allowing for the direct conversion into ethyl lactate without the need for lengthy fermentation stages, thus avoiding food-vs-fuel concerns [28]. Starch, on the other hand, yields high amounts of glucose through hydrolysis. The biocycle pathway (hydrolysis–fermentation–esterification) enables efficient conversion without requiring intermediate separation steps, significantly enhancing ethyl lactate yield, up to approximately 2.3 times higher than conventional methods [18]. Starch is also readily available and has been widely used in the fermentation industry, making it well-suited for commercial-scale implementation due to existing infrastructure.

Method

Ethyl lactate is a biodegradable and non-toxic solvent that can be sustainably synthesized from renewable resources through a two-step process: fermentation followed by esterification. The reaction is as presented below.

Fermentation reaction of glucose into lactic acid:

$$\underset{\text{glucose}}{C_6H_{12}O_6} \rightarrow \underset{\text{lactic acid}}{2CH_3CH(OH)COOH} \tag{1}$$

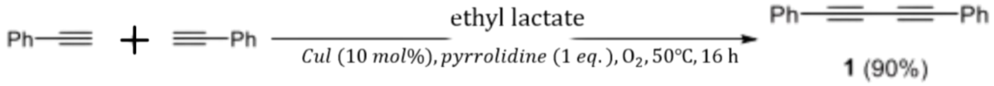
Esterification reaction of lactic acid to ethyl lactate:

$$\underset{\text{lactic acid}}{CH_3CH(OH)COOH} + \underset{\text{ethanol}}{C_2H_5OH} \rightarrow \underset{\text{ethyl lactate}}{CH_3CH(OH)COOC_2H_5} + \underset{\text{water}}{H_2O} \tag{2}$$

In the first stage, carbohydrates such as glucose, sucrose, starch, or agro-industrial byproducts like okara (a soybean pulp waste from tofu and soymilk production) serve as carbon sources for microbial fermentation. These substrates are metabolized by lactic acid-producing bacteria, primarily from the Lactobacillus genus, under anaerobic conditions at temperatures ranging from 30°C to 45°C and a pH between 5.0 and 6.5. [33]. During this process, the microorganisms convert sugars through the Embden-Meyerhof-Parnas (EMP) pathway, leading to the production of either L-(+), D-(−), or racemic lactic acid, depending on the strain used [34]. In a typical procedure, lactic acid (1 mol equivalent) is reacted with a slight excess of ethanol (2–3 mol equivalents) in the presence of sulfuric acid (H_2SO_4, 1–5 wt%) or a solid acid catalyst such as Amberlyst-15. The reaction is carried out at 60–90 °C under reflux conditions for 4 to 8 hours [35]. Homofermentative bacteria yield primarily lactic acid, while heterofermentative strains also produce byproducts such as acetic acid and ethanol.

Performance Of Ethyl Lactate In Specific Organic Reactions

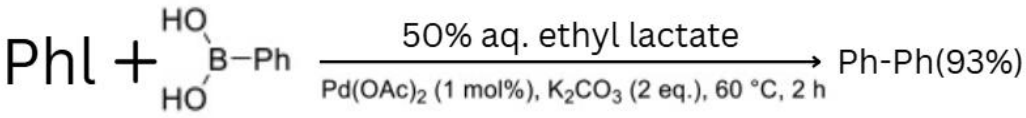
Ethyl lactate has been identified as an effective solvent for the glaser coupling reaction, using phenylacetylene as the model substrate, optimized reaction conditions were developed and subsequently applied to both homo- and cross-coupling of aromatic and aliphatic terminal alkynes, with reaction is as shown below.



Scheme 1. Glaser coupling of phenylacetylene using ethyl lactate as the solvent [18]

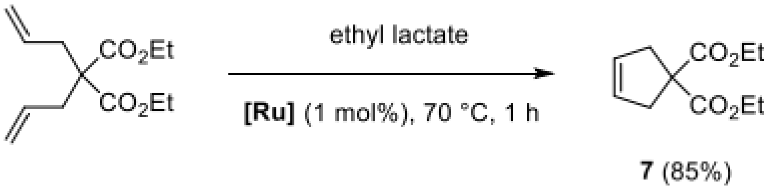
While the yield of the primary product under optimized conditions was satisfactory, the yields of other conjugated alkynes were found to be highly dependent on substrate structure, ranging from 26% to 80% across 20 examples. It was proposed that, beyond serving as the reaction medium, ethyl lactate may also act as a ligand to the copper catalyst, thereby facilitating the coupling process [18].

Furthermore, the Suzuki–Miyaura reaction has been successfully conducted in aqueous ethyl lactate without the need for additional ligands. In a model reaction between iodobenzene and phenylboronic acid, aqueous ethyl lactate yielded the desired product with higher efficiency (93%), as shown in Scheme 2, compared to pure ethyl lactate (62% yield), highlighting the synergistic role of water in improving reaction outcomes [18].



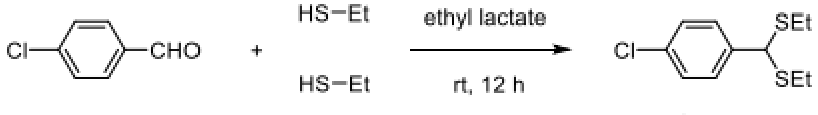
Scheme 2. Suzuki-Miyaura coupling of iodobenzene with phenylboronic acid in aqueous ethyl lactate [18]

Ethyl lactate has demonstrated excellent performance as a green solvent for olefin metathesis reactions. The synthesis of ruthenium-based metathesis catalysts was successfully carried out in this medium, and subsequent application of the catalyst in ring-closing metathesis of dienes afforded the target cyclic alkenes in 85–93% yield under both inert (argon) and open-air conditions, as shown in Scheme 3. The reaction exhibited high substrate compatibility across a series of dienes, with conversions up to 97% and consistent yields regardless of atmosphere [36]. This performance positions ethyl lactate as a viable and sustainable alternative to chlorinated or aromatic solvents traditionally used in metathesis reactions.



Scheme 3. Olefin cross-metathesis in ethyl lactate [18]

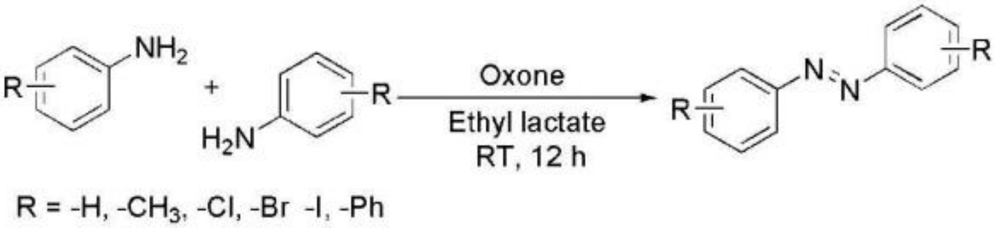
The thioacetalization of aromatic aldehydes, a valuable transformation for carbonyl protection, proceeded efficiently in ethyl lactate under ambient conditions. In the model reaction between 4-chlorobenzaldehyde and ethanethiol as presented in Scheme 4, the desired dithioacetal was obtained in 84% yield without the need for any external catalyst [37]. Notably, only trace amounts of product were formed when the same reaction was conducted in acetonitrile or p-xylene, and no reaction occurred in water, emphasizing the unique solvating and activating properties of ethyl lactate. The method proved general, delivering 59-84% yields across a broad range of aromatic, heteroaromatic, and aliphatic aldehydes



15 (84%)

Scheme 4. Dithiolation reaction of 4-chlorobenzaldehyde with ethanethiol in ethyl lactate [18]

In a recent study conducted by [18], ethyl lactate was demonstrated to be an efficient green solvent for the transition metal-free synthesis of symmetric and unsymmetric azobenzenes via oxidative coupling of amines. The optimized protocol for symmetric azobenzene synthesis involved reacting 1 mmol of aniline with 0.5 mmol of oxone in 1 mL of ethyl lactate at room temperature (25 °C) for 12 hours, as ilustrated in Scheme 5. Using oxone as a mild oxidant, various anilines were transformed into symmetric azobenzenes in up to 78% yield as the highest at room temperature [38].



Scheme 5. The synthesis reaction of symmetric azobenzene from amines [38]

Table 3. Performance ethyl lactate in Specific Organic Reactions

Reaction	Yield
Glaser coupling	90%
Suzuki-Miyaura	93%
Olefin metathesis	85%
4-chlorobenzaldehyde and ethanethiol	84%
Azobenzene from ammines	78%

The chart demonstrates that ethyl lactate serves as an effective green solvent across a variety of organic reactions, consistently providing high product yields. Among the tested reactions, the Suzuki–Miyaura coupling in aqueous ethyl lactate showed the highest efficiency (93%), while the symmetric azobenzene synthesis gave the lowest, yet still notable yield (78%). Overall, ethyl lactate proves to be a versatile and sustainable solvent for diverse chemical transformations.

Economic Analysis

The economic analysis was conducted by estimating the Cost of Production (CoP) for each feedstock. To assess the economic feasibility of ethyl lactate production from various raw materials, the CoP was calculated based on key cost components and data from relevant techno-economic studies [18].

1. Whey

Dairy industry waste with raw material costs accounting for approximately 35% of the total lactic acid fermentation expenses. Techno-economic analysis (TEA) studies report a net present value (NPV) of USD 191 million, an internal rate of return (IRR) of 12.9%, and a payback period of 5.2 years for a processing scale of 500,000 L of whey per day [38].

2. Sugarcane Molasses

Based on techno-economic analysis, low-cost feedstocks such as molasses can reduce the total Cost of Production (CoP) to the range of USD 900–1,100 per ton of lactic acid (approximately USD 1.0–1.1 per kg LA) [39].

3. Rice Straw

A study on lignocellulosic biorefinery reported an estimated annual operating cost of approximately USD 279,291 per year, including expenses for electricity and specialized catalysts [40].

4. Starch

The efficient biocycle pathway yields 3.05 g/L, which is 2.3 times higher than that of conventional methods [39], while techno-economic analyses (TEA) of lignocellulosic processes indicate a Cost of Production (CoP) ranging from USD 894 to 1,281 per ton [39].

Furthermore, techno-economic studies indicate that the reuse of ethyl lactate/ethanol can reduce the Cost of Production (CoP) by 40–70%, depending on the degree of integration and solvent flow management [30]. Additionally, reactive distillation using structured catalytic packing (ZSM-5@SiC) has been shown to significantly lower the Total Annual Cost (TAC) compared to conventional methods [30]. Moreover, according to a techno-economic analysis (TEA) based on corn stover, CoP is highly sensitive to feedstock prices, fermentation yield, plant scale, and solvent reuse strategies [40].

The Role Of Ethyl Lactate In The Transition Of The Chemical Industry

Ethyl lactate has been recognized as an ideal green solvent due to its environmentally friendly nature, biodegradability, low toxicity, and derivation from renewable sources such as starch and biomass [18]. Produced through the esterification of lactic acid and ethanol obtained from biomass fermentation, ethyl lactate aligns with the principles of circular chemistry and the biorefinery model. It is capable of replacing hazardous petroleum-derived solvents in many industrial applications [41]. In addition, ethyl lactate also fulfills at least 5 of the criteria of green solvent based on the 12 principle of green chemistry, as shown in Table 4.

Table 4. The principles fulfilled by ethyl lactate in the 12th principles of green chemistry[42]

Principles	Description
3rd	Synthetic methodologies should be designed to use and generate substances that exhibit little or no toxicity to human health and the environment
4th	Chemical products should be designed to preserve their efficacy while reducing toxicity.
7th	Feedstock should be renewable
9th	Selective catalytic reagents are better then stoichiometric reagents
10th	Chemical products should degrade into harmless substances and not persist in the environment.

Therefore, ethyl lactate is considered an ideal green solvent, as it is derived from renewable feedstocks and yields products that are biodegradable and exhibit low toxicity. Eventually, these characteristics will contribute to reducing side effects on human health and minimizing the persistence of harmful substances in the environment [42].

Specifically, ethyl lactate possesses favorable physicochemical properties, including a density of 1.03 g/cm³, high boiling point (154 °C), high flash point (46 °C), and low volatility. It also exhibits minimal toxicity (LD_{50} > 2,000 mg/kg), approximately 75% biodegradability within 28 days, and is non-carcinogenic [41].

Furthermore, the use of ethyl lactate is in line with global regulatory trends focused on reducing VOC emissions and improving occupational health. Its adoption also enhances corporate reputation, particularly for companies committed to fulfilling Environmental, Social, and Governance (ESG) principles [43].

Besides, the global market demand for ethyl lactate is projected to reach USD 6.3 billion by 2032, with a compound annual growth rate (CAGR) of approximately 7.5%. The Asia-Pacific (APAC) region dominates the market with a 36% share, driven by stricter environmental regulations, lower production costs, and green industry incentives [43].

CONCLUSION

This study confirms that ethyl lactate is a superior green solvent candidate in terms of sustainability and economic potential. Among the analyzed feedstocks, sugarcane molasses emerges as the most economical option (CoP USD 1,300–1,500/ton) due to its high availability and ready-to-use production pathway. In contrast, despite yielding a promising technical yield (~20%) rice straw shows a much higher CoP (~USD 5,600/ton) due to energy-intensive and costly pretreatment requirements. Ethyl lactate conversion demonstrates consistently high yields (≥ 90%) across various applications, highlighting its reliable technical performance. The use of process intensification technologies such as reactive distillation and solvent reuse offers substantial potential for cost and emissions reduction. Overall, the adoption of ethyl lactate aligns with global trends toward green chemistry and the replacement of conventional solvents. Its ecological neutrality, biodegradability, and process compatibility make it a viable alternative for both Indonesian and global industries. Moving forward, research focusing on the optimization of local feedstocks such as tofu waste and rice straw through integrated technologies and life cycle assessments, will further strengthen the case for a sustainable transition.

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