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Review Article

Review of lignocellulosic bio-chemical production: Current challenges, advances, and future perspectives

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ABSTRACT

Lignocellulosic biomass (LCB) constitutes approximately 90 % of the biomass of all plants on earth and is a highly promising green feedstock with the potential to be mass-produced industrially in the form of green bio-chemicals. Due to mounting climate change challenges and the depletion of fossil fuels, LCB has become a key priority in innovation hotspots aiming to lead the world toward a bio-based economy. Three predominant fractions of LCB—lignin, hemicellulose, and cellulose—pose vast opportunities but also corresponding challenging tasks in utilization. The progress in pretreatment technology, enzymatic hydrolysis, and fermentation has been such that the efficiency of conversion of LCB into biofuels, bioplastics, and value-added bio-chemicals such as ethanol, butanol, and organic acids is very high. High enzyme costs, lignin recalcitrance, and the production of inhibitory by-products are, however, problems that cannot be escaped. To this end, this review presents recent progress, current challenges, and prospects for future opportunities in the bio-chemical conversion of LCB with an emphasis on how it can contribute to achieving the world's sustainability targets. This review also provides an overview of advances in technology, including the development of microbial strains using CRISPR/Cas9 and consolidated bioprocessing (CBP) for process integration. Future directions, such as lignin valorization to more valuable chemicals and the incorporation of artificial intelligence for optimization, are highlighted. Policy measures, such as the EU Renewable Energy Directive and carbon-pricing legislation that enable LCB applications, are reviewed. Notwithstanding advances on the spectacular front, economic and technical issues, i.e., product recovery and pretreatment, are hindering uptake to the commercial level. Despite the remarkable advances on the front, economic and technical issues, i.e., product recovery and pretreatment, are hindering commercial adaptation. With international backing and policy support, LCB bio-chemicals have the potential to propel an industrial revolution, reduce carbon emissions, and lead the global bio-economy. Overall, this review provides a synthesizing critique of the novel data, points out critical gaps, and offers pragmatic recommendations for industrialization and future research areas.

1. Introduction

Lignocellulosic biomass (LCB), covering almost 90 % of the plant biomass in the world, is yet more sustainable in nature. Faced with an impending threat posed by climate change and the depletion of fossil resources, LCB is also fueling the world with biofuel and driving the transition to a bio-based chemical industry. Since its high utilization with the sustainability feasibility of LCB production, LCB is strongly linked to bio-economy science [1]. Scientific advancements are addressing the functionality of LCB, drivers of innovation in technology, stimulus policy, future development, and the role of LCB within bio-chemical production streams. Three lignocellulose biomass

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components are hemicellulose (20–35 %), cellulose (35–50 %), and lignin (10–25 %) [2]. Hemicellulose is a heteropolymer containing xylose and mannose sugars, while cellulose is a glucose polymer, both of which contain fermentable sugar contents needed in bio-chemical production [3]. Notwithstanding that, lignin's resistance to degradation continues to hinder the efficient conversion of LCB, except for industrial-scale bio-chemical manufacturing [4,5]. Low-cost and renewable LCB is a propellant for the industrialization of bio-based chemicals and energy [6]. LCB is converted into various forms of biofuels, bioplastics, and other products, depending on the market's and the world's sustainability demands [1]. The bio-chemical conversion of LCB includes pretreatment, enzyme hydrolysis, fermentation, and product separation processes. Pretreatment aims to break down the lignin-carbohydrate complex matrix, thereby separating hemicelluloses and cellulose, making them accessible for enzymatic treatment [7]. Cellulose and hemicellulose are hydrolyzed into fermentable sugars during the pretreatment process. Stability, selectivity, and hydrolysis efficiency have also been improved in enzymes by enzyme engineering technologies, and hydrolysis efficiency has been optimized [8]. However, enzymes are still too costly, and the most limiting factor for their industrial application [6].

Microbial strain optimization for sugar conversion and tolerance to biomass-derived inhibitory compounds, as achieved through CRISPR/Cas9 [9], may reduce costs and make it commercially feasible [5]. In addition, consolidated bio-processing (CBP), which combines enzyme production, hydrolysis, and fermentation as a single process, has also proved to be an available solution for reducing operational costs [10], but microbial scaling up and optimization remains challenging [11,6].

Additionally, techno-economic analysis (TEA) and life cycle analysis (LCA) are becoming increasingly influential in determining the commercial viability and sustainability of LCB-based bio-chemicals [12]. Government initiatives to promote renewable energy and the bio-based economy, such as the European Union's Renewable Energy Directive (RED II) and the US Renewable Fuel Standard (RFS), are key drivers of LCB-based bio-chemical production [2,13]. Policymakers are heavily promoting investment in LCB technologies [6]. To enhance enzymatic solubility, overall stability in bio-refinery processes and delignification of lignocellulosic biomass, recent studies present supramolecular solvent lignin protection [14], the use of advanced microwave-responsive deep eutectic solvents [15], and biobased solvents for enhanced solubility [16].

Some of the new trends are transforming the future of bio-chemical production from LCB. Among them, one of the most important is coupling LCB-based bio-chemicals with a circular economy, waste reduction, and maximizing the use of biomass. The improved feasibility of biorefineries to deliver biofuels, bio-chemicals, and energy in one step from LCB aids this approach [17]. The implications of the foregoing technologies will contribute enormous cost reductions and efficiency improvements across the entire value chain. The long-term sustainability of LCB technologies hinges on aligned technological developments, a favorable policy environment, and market conditions. Public-private partnerships and global collaborations will play a fundamental role in overcoming the challenges of commercialization [6]. LCB is an environmentally friendly raw material for biofuels, bioplastics, and bio-chemical production [18].

Although a large proportion of LCB is lignin, its application is still restricted to low-value purposes such as combustion [5]. Microbial engineering advances for enhancing microbial robustness against pretreatment byproducts (e.g., inhibitors) and lignin-first new biorefineries have the potential to open up new, high-value chemical routes [9]. Furthermore, the decentralized deployment of biorefineries can prevent scalability issues, providing a viable route to the low-cost and sustainable production of bio-chemicals [10,19]. Therefore, this review aims to present LCB as a green, sustainable bio-chemical feedstock material encompassing its composition, technological progress, policy orientations, and economic instruments. The review also accounts for future prospects and challenges, including the valorization of lignin and the utilization artificial intelligence, towards readiness for commercialization [20]. The pathways of the future lie in overcoming such impediments to interdisciplinarity, aiming for modular, zero-waste biorefineries within circular bio-economy paradigms.

2. Study methodology

The research strategy for this review incorporates a critical analysis of the literature to examine the recent advances, challenges, and potential future trends in bio-chemical production from LCB. Integrating an evidence-based approach, the review synthesizes data from peer-reviewed literature, technical reports, and expert books, emphasizing the potential of LCB as a renewable feedstock for sustainable bio-chemical applications [5,1]. Major scientific databases, including Scopus, Web of Science, ScienceDirect, PubMed and Google Scholar, were used as data sources and search strategies for a systematic literature search. To enable a wide range of relevant studies to be included, keywords were used, such as "lignocellulosic biomass", "bio-chemical production", "pretreatment technologies", "enzymatic hydrolysis", "lignin valorization", "circular bio-economy". To obtain the most recent research progress and being comprehensive and relevant globally, the review only included journal articles, book chapters from academic books, institutional reports and grey literature published during the period of 2015 – 2025 [21,22]. For thematic extraction and analysis, a standardized method was used from each scientific article, including year of publication, overall focus, type of lignocellulosic biomass, bio-chemical production, pretreatment technologies, technology or methodology used [23]. Such categorization enabled comparative analysis across technologies, regions, stages of the value chain, etc. In this context, articles were classified if (a) they presented primary or secondary research on above respective topics, (b) if they presented results (c) if they summarized multidisciplinary discussions with impact on technological feasibility, economic sustainability or environmental impacts, and (d) if they were published in English. Articles that had no empirical or theoretical basis, or were published before 2010 were excluded. After reviewing the full text, 296 articles met the inclusion criteria and were analyzed in depth [24].

~~Priority was given to top-ranked, recent high-impact publications that present novel findings, reflecting new insights on important processes, including pretreatment, enzymatic hydrolysis, fermentation, and product recovery were given precedence.~~ Publications were selected based on their relevance to LCB conversion processes, technological advancements, including microbial strain design and consolidated bio-processing, and their emphasis on sustainability from a circular bio-economy perspective [10,25]. Geographic trends and local bio-economy policies were also considered in order to ensure a global perspective [1]. This review is structured around four thematic groups: LCB structure and properties, highlighting cellulose, hemicellulose, and lignin functions in bio-chemical production [5]; technological advancement in pretreatment, hydrolysis, and fermentation processes [25]; and policy structure and impact on market scale-up [13]. Through integrating the integration of evidence across these dimensions, the review not only reports the state-of-the art but also reveals areas of the research that remain open and devises actionable recommendations for advancing LCB-based bio-chemical manufacture. The Critical Appraisal Skills Program (CASP) checklist methodology was used to assess the methodological quality of the studies included in the review, focusing on the relevance of the studies in the context of lignocellulosic bio-chemical production [26]. Accordingly, studies were considered to be of high and moderate quality, and those with low methodological rigor were excluded from the synthesis. Based on defined research goals focused on proven results, replicable methodologies, technological challenges and gaps, interdisciplinary and cross-sectoral approaches in the science of lignocellulosic bio-chemical production, were integrated to provide comprehensive solutions of research advances and best practices.

3. Lignocellulose biomass: composition and characteristics

LCB is composed of three main organic compounds in addition to ash: 1) cellulose; 2) hemicellulose and 3) lignin. The composition of LCB varies due to conditions such as the age of the plant, soil quality, fertilizer addition, and harvest time, (Table 1). Cellulose is the most abundant component in LCB, consisting of glucose molecules arranged in a complex crystalline structure, mainly with some non-crystalline parts, and has a high molecular weight. Hemicellulose, the second abundant component, is a branched polysaccharide that attaches to cellulose fibers and is non-crystalline. The gap between cellulose and hemicellulose is filled by lignin [27], a complex, non-crystalline polymer composed of aromatic units linked in a 3D network. The primary role of lignin is to hold plant fibers together, providing strength and rigidity, which makes it very difficult to break down into smaller molecules [28, 29].

Agricultural biomass, forestry residues, and energy crops are the most readily available types of LCB. Examples of each kind of LCB are presented in Table 1. Agricultural biomass is often considered a low-cost feedstock for biofuel and bio-chemical production, although it requires specific conditions and soil quality to grow optimally [42]. Among agricultural biomass sources, sugarcane bagasse is the most abundant, with a global production of 1870 million tonnes (MT) in 2022, followed by corn, wheat, and rice [43]. On the other hand, forestry biomass encompasses not only the woody part but also branches, roots, and leaves. Forestry residues are commonly used as feedstock for biorefineries after purification, to produce biofuels and value-added bio-chemicals [44]. Globally, forests contain approximately 665 gigatonnes of LCB, with 8 % classified as dead biomass [45]. Unlike other crops, energy crops such as *Miscanthus* and *switchgrass* (often referred to as fuel crops) can thrive in poor soil with minimal maintenance [42]. The annual production of energy crops, at 9.3 billion tonnes [46], exceeds that of agricultural and forestry biomass. Although this review adopts a general approach to LCB for biochemical production, energy crops, which are non-food biomass sources, may be the most suitable feedstock for biorefineries due to their consistent availability and minimal cultivation requirements.

3.1. Pretreatment methods

The pretreatment methods currently reported in the literature and the summary of the methods are presented in Table 2 and Fig. 1, respectively. The methods are often applied either alone or in combination with a few other methods to produce bio-chemicals such as bioethanol and biomethane through biological recycling methods (e.g., anaerobic digestion, fermentation). Mechanical pretreatment methods such as milling, cutting, and grinding are used to reduce the particle size of biomass and increase its surface area [47], thereby decreasing heat and mass transfer limitations during the process [48]. Chemical pretreatment methods aim to decrease the crystallinity of cellulose and remove the lignin fraction by using solvents. However, challenges remain, including the recycling and separation of solvent mixtures as well as the development of green alternatives. Additionally, the practical application of chemical pretreatment methods to lignin-rich LCBs is an area that requires further research. The application of physicochemical methods eases the processing of cellulose by removing lignin and hemicellulose. However, these methods are energy- and water-intensive, requiring costly high-pressure-resistant equipment. Biological pretreatment methods are generally more environmentally friendly compared to other methods. However, these processes are often slow, requiring several days of operation to complete. Genetic modifications of microbial agents to reduce or prevent the production of inhibitors represent a promising area for research. Combining pretreatment methods has shown the potential to improve the efficiency of lignin separation and cellulose hydrolysis. To reduce costs, integrating pretreatment units into biorefineries could offer more feasible and scalable solutions. This integration not only lowers expenses but also supports the sustainable production of bio-based products. Recent pretreatment advances include biphasic solvent systems for efficient lignin-polysaccharide fractionation [49], valorizing food waste into biopolymers for sustainable bioinks [50], and converting furfural residues into biofuels and biochar for environmental remediation [51].

Table 1
Chemical composition of some LCB (Dry basis).

		Composition (wt. %)			
Type of LCB	Source	Cellulose	Hemicellulose	Lignin	Reference
Wheat straw	AB	31- 50	22–37	5 – 25	[30]
Rice straw	AB	31 – 42	20 –27	9 – 19	[31,32, 33]
Corn Stover	AB	38	26	17	[34]
Sugarcane bagasse	AB	39	28	18	[35]
Birch wood	FR	38	17	28	[36]
Switch grass	EC	34 – 38	32 – 36	3 – 9	[37,38]
Miscanthus	EC	30 – 38	18 –24	9 – 26	[39,40, 41]

AB: agricultural biomass; FR: forest residue; EC: energy crops.

3.2. Bio-chemical conversion processes

The conversion of LCB into biofuels, bio-chemicals, and other high-value products is a cornerstone of sustainable bio-economy strategies. This process involves multiple stages that transform complex biomass structures into simpler molecules for energy and material applications. These stages, broadly categorized into pretreatment, hydrolysis, fermentation, and thermochemical methods, are underpinned by decades of research and technological advancements [69-71].

A significant challenge in enzymatic hydrolysis is the inherent recalcitrance of LCB, primarily due to the structural complexity and crystalline properties of cellulose and the protective lignin barrier. Research has consistently focused on optimizing enzyme mixtures to enhance hydrolysis efficiency, with studies demonstrating the effectiveness of enzyme cocktails that include cellulases, β-glucosidases, and hemicellulases in achieving higher sugar yields [72]. The hydrolyzed sugars are subsequently subjected to fermentation, where microbial consortia or engineered microorganisms convert them into desired bioproducts, including ethanol, butanol, organic acids, and bio-based polymers. Among these, bioethanol production has garnered significant industrial attention. Traditionally, *Saccharomyces cerevisiae* and *Zymomonas mobilis* have been the preferred microorganisms for ethanol fermentation due to their high tolerance to and productivity of ethanol. However, the inability of these organisms to ferment pentose sugars, which are abundant in hemicellulose hydrolysates, necessitates the use of genetically modified strains or alternative microorganisms such as *Pichia stipitis* [73].

Furthermore, co-fermentation strategies that enable the simultaneous utilization of glucose and xylose are under intense investigation, with promising results reported in recent studies [74]. Although the fermentation of LCB has traditionally focused on bioethanol production, the process has expanded significantly to encompass the production of a diverse range of biomaterials, including bioplastics, organic acids, polyhydroxyalkanoates (PHAs), polyhydroxybutyrate (PHB), and single-cell proteins (SCPs). These products offer sustainable alternatives to petroleum-based materials, with applications in packaging, agriculture, healthcare, and other industries.

Studies have demonstrated that bacterial strains such as *Cupriavidus necator, Ralstonia eutropha, Burkholderia cepacia, Halomonas campisalis,* and engineered *Escherichia coli* can efficiently convert lignocellulose-derived sugars into PHAs [65,75–77]. Recent advancements focus on optimizing fermentation conditions and genetic engineering to enhance PHA yield and tailor its properties for specific applications. Table 3 presents the products obtained via bio-chemical processing of LCBs.

Table 2
Pretreatment methods used for LCB.

Pretreatment method	Process/agent	Process Conditions	Advantages	Disadvantages	Ref.
Physical					
Mechanical	- Ball mill - Grinding - Cutting	- Moderate temperatures - Days of operation	- Simple operation	- High energy demand - Difficulties in scaling up	[52]
Irradiation	- Microwave radiation - Gamma rays - Ultrasonic waves - Electrons	- Varies from 10 kHz to 300 GHz depending on the irradiation source	- Increase enzymatic efficiency - Moderate reaction times	- High electricity consumption - Need for another pretreatment method - Low efficiency of sugar recovery	[53]
Extrusion	- Single screw - Double screw - Acid, alkaline, and steam extrusion	–75–150 °C - Kg scale biomass intake - Minutes of operation	- Time efficiency - High feed capacity	- High energy consumption - Less effective unless combined with other pretreatment methods	[54,55]
Chemical					
Ionic liquids	- 1-Ethyl-3-methylimidazolium acetate - Cholinium lysinate - NH_3 - Urea	- Up to 10 % of solid loading - 120 °C - Stirring hours of operation	- High thermal and chemical stability - Mild operation temperature - Low vapor pressure	- Expensive operation - Toxicity due to the solvents used - Enzyme deactivation	[56,57]
Acid treatment	- HCl - H_2SO_4 - H_3PO_4	- 80–200 °C - Up to 10 % acid usage - Stirring - Minutes to hours of operation	- Short process duration - Low cost - Effective in isolating the sugar fraction	- Need for corrosion-resistant reactors - Toxic - Low recovery	[54,58]
Alkali treatment	- NaOH - KOH - $Ca(OH)_2$	- 50–200 °C - Up to 10 % acid usage - Stirring - Minutes to days of operation	- Decrease the crystallinity of cellulose - Improves porosity and surface area - Low salt formation as a by-product	- Environmental pollution - Low recyclability of the chemicals - High energy requirement - Scale-up difficulties - Long residence time	[27,46, 52,59]
Organasolv	- Ethanol - Methanol - Ethylene glycol - Acetone	- 140–200 °C - Up to 70 % concentration of solvent - Minutes of operation	- High-purity lignin and cellulose recovery - Short reaction time	- Safety concerns due to the usage of flammable organic solvents - Requires high temperature (150–220 °C) to obtain higher purity of the fractions - Expensive operation - Low solvent recovery for the solvent with a high boiling point	[60–62]
Physicochemical					
Hot water treatment	- Water	- 140–240 °C - 2–5 MPa - Minutes of operation	- No additional chemicals required - Cost-efficient - Short operation	- Not efficient for lignin removal	[63–65]
Steam explosion	- Steam - SO_2	- 160–260 °C - 0.7–5 MPa - Minutes of operation	- Ability to process LCB with a large particle size	- High inhibitor formation - Sugar degradation - High equipment cost	[66]
Biological					
	- Fungi (e.g., soft rot, brown rot) - Bacteria (e.g., *Bacillus* sp., *Clostridium* sp.) - Enzymes (e.g., cellulases, hemicellulases)	- 20–55 °C - pH 4–5 - Hours to days of operation	- Low energy consumption - Moderate process conditions	- Long process duration - Decrease in efficiency due to inhibitors (by-products) - Low selectivity	[67,68]

Advanced fermentation techniques, including CBP, have emerged as game-changers in biomass conversion. CBP integrates enzymatic hydrolysis and fermentation into a single step, reducing process complexity and operational costs [78]. Microbial strains capable of both producing hydrolytic enzymes and fermenting sugars concurrently are at the forefront of CBP research [79]. Recent advancements in metabolic engineering have facilitated the development of robust CBP strains, with several studies highlighting their potential to streamline LCB conversion [80].

3.3. Thermochemical conversion processes

While bio-chemical conversion processes such as hydrolysis and fermentation are central to LCB valorization, thermochemical methods offer alternative pathways for biomass conversion. Thermochemical conversion processes, including hydrothermal treatment, torrefaction, pyrolysis, gasification, and combustion, are particularly suited for biomass types with high lignin content or when rapid energy recovery is required.

Pyrolysis, conducted in the absence of oxygen at high temperatures (300–800 °C), decomposes biomass into bio-oil, syngas, and biochar [99]. Fast pyrolysis, a subset of this process, has been extensively studied for its potential to produce high yields of bio-oil, which can be further refined into transportation fuels and chemical feedstocks [100]. Recent advancements in catalytic pyrolysis have shown the potential for producing bio-oils with enhanced stability and calorific value, addressing some of the limitations of conventional pyrolysis [100,101].

Torrefaction is a thermochemical pretreatment process for biomass, conducted at temperatures ranging from 200 to 320 °C in the absence of oxygen [102,103]. It enhances biomass properties by increasing energy density, hydrophobicity, and carbon content while reducing oxygen content [104]. Torrefied biomass serves as a solid fuel alternative to coal, improving its handling and storage properties. It is classified by severity into mild (235–275 °C), intermediate (275–300 °C) and severe (300–320 °C) [102]. Torrefaction reduces moisture and volatile matter, yielding lightweight, high-calorific-value biochar [104]. It is

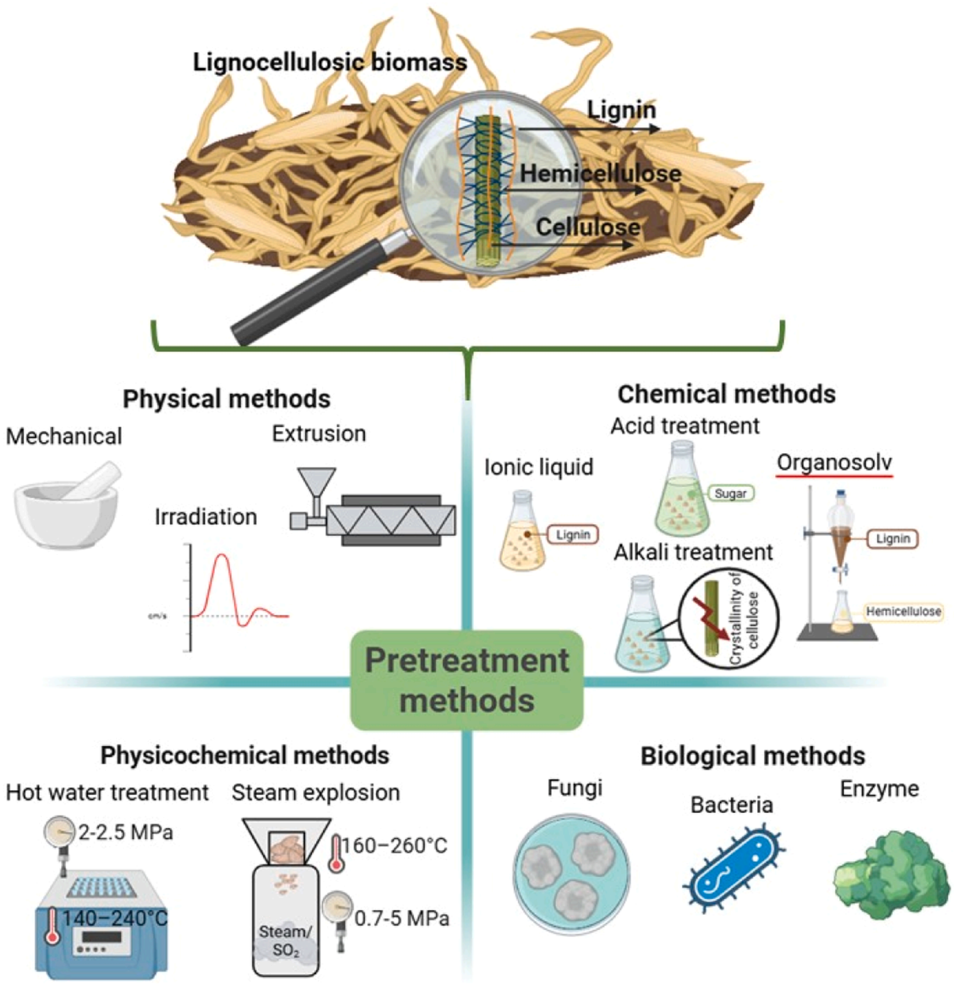


Fig. 1. The composition of lignocellulosic biomass and the summary of pretreatment methods.

Table 3
Products obtained from the bio-chemical process of LCBs.

Substrate	Pretreatment	Microorganism(s)	Product	Yield (g product/ g sugar)	Reference
Corn fiber	Diluted acid and alkaline	*E. coli* FBR5	Bioethanol	0.46	[81]
Sugarcane bagasse	Diluted acid	*Scheffersomyces shehatae* UFMG-HM 52.2		0.38	[82]
Watermelon rind	Ultrasonic and deep eutectic solvent (DES)	*Saccharomyces cerevisiae*		0.458	[83]
Rice straw	Enzymatic hydrolysis and alkaline	PVA immobilized *Clostridium acetobutylicum* ATCC 824	Butanol	13.8 (g/L)	[84]
Soybean hulls and birch wood chips	Size reduction	*Aspergillus niger, Trichoderma reesei* and *Phanerochaete chrysosporium*	Succinic acid	0.24	[85]
Sugarcane bagasse	Alkali extraction and alkaline hydrogen peroxide treatment	*Actinobacillus succinogenes* GXAS137		0.80	[86]
Waste paper	Hydrogen peroxide and enzymatic hydrolysis	*Burkholderia sacchari* DSM 17,165	PHB	0.44	[87]
Sugarcane bagasse	Size reduction	*Saccharomyces cerevisiae* PTCC 5269	SCP	0.13	[88]
Corn Cob	Alkaline	*Bacillus subtilis* LMA-ICF-PC 001	Biosurfactants	0.08 and 0.32	[89]
Potato crop residues	Organosolv	*Xanthomonas campestris*	Xantan gum	0.13	[90]
Musa paradisiaca peels	Size reduction	*Aspergillus niger*	Citric acid	0.029	[91]
Peanut hull	Hydrogen peroxide-acetic acid, enzymatic hydrolysis and detoxification	Engineered *E. coli* YJM21	Isoprene	338.6 (mg/L)	[92]
Sweet sorghum bagasse	Acid and enzymatic hydrolysis	*Propionibacterium freudenreichii*	Propionic acid	0.51	[93]
Corn cob	Mechanical, hot water, and enzymatic hydrolysis	*Komagataeibacter* sp. *CCUG73629*	Bacterial cellulose	0.14	[94]
Corn straw	Acid and enzymatic hydrolysis	*Rhizopus delemar*	Malic acid	120 (g/L)	[95]
Corn cob	Size reduction	*Aspergillus oryzae*	Fumaric acid	0.16	[96]
Sago biomass	Biological	*Clostridium butyricum A1*	Biohydrogen	2.65	[97]
Cassava residue	Size reduction	*Clostridium lentocellum* Cel10		4.08	[98]
Rice straw				3.0	

energy-efficient, has a low carbon footprint, and promotes a stable thermochemical conversion [105]. However, its widespread adoption remains limited.

Gasification, another thermochemical conversion technique, involves partial oxidation of biomass at high temperatures to produce synthesis gas (syngas), primarily composed of carbon monoxide and hydrogen [106,107]. Syngas can be converted into various biofuels and chemicals via catalytic processes such as Fischer-Tropsch synthesis, and methanol and dimethyl ether production [108,109]. The scalability and flexibility of gasification processes make them an attractive option for integrated biorefineries. Moreover, advancements in gasification technologies, including the use of multifunctional fluidized bed reactors, supercritical water and plasma gasification, have enhanced the efficiency and environmental performance of these systems [110–112].

Combustion remains the most straightforward method for converting LCB into heat and power (800–1600 °C) [113]. Despite their simplicity, combustion processes have undergone significant evolution, with modern systems achieving higher efficiency and lower emissions. Co-firing LCB with coal in existing power plants is a widely adopted practice, allowing for the gradual transition to renewable energy sources requiring significant infrastructure modifications [114,115]. Integrating of advanced combustion technologies, such as oxy-fuel combustion, further enhances the environmental footprint of biomass-based energy systems [116].

Besides these primary conversion methods, the valorization of lignin, a complex aromatic polymer, has gained considerable interest [117]. Once considered a low-value by-product of biomass processing, lignin is now recognized as a valuable feedstock for producing aromatic chemicals, polymeric materials, carbon fibers, and bio-based adhesives [118]. Lignin-first bio-refinery approaches, which prioritize the extraction and upgrading of lignin before processing other biomass fractions, have shown great promise in maximizing the economic potential of lignocellulosic feedstocks [119,120]. Catalytic depolymerization of lignin using metal catalysts, ionic liquids (ILs) and DES has been extensively studied, with several pilot-scale demonstrations highlighting the feasibility of these technologies [121]. Table 4 presents studies that utilize thermochemical conversion methods for the valorization of lignocellulosic feedstock.

In the context of lignocellulosic biomass valorization, it is crucial to compare biochemical and thermochemical conversion pathways to understand their relative strengths, limitations, and suitability for different biomass types. Fig. 2 provides a comparison of key parameters, including substrate compatibility, process conditions, product yields, and technical challenges.

The comparison highlights the complementary nature of biochemical and thermochemical conversion technologies in the valorization of lignocellulosic biomass. Biochemical conversion is generally more suited for carbohydrate-rich feedstocks due to its reliance on enzymatic hydrolysis and microbial fermentation, which operate under mild conditions and yield specific, high-purity products such as ethanol, lactic acid, and PHAs. In contrast, thermochemical processes are better adapted for lignin-rich or heterogeneous biomass. These methods, including pyrolysis and gasification, operate at high temperatures and enable rapid conversion to energy-dense products like syngas and bio-oil, although they suffer from challenges like tar formation and lower selectivity [69,145].

Technological bottlenecks also differ such as biochemical processes face challenges like enzyme cost, inhibitor formation, and the difficulty of fermenting pentose sugars, while thermochemical methods often struggle with product upgrading, energy intensity, and the presence of ash or slag during conversion. Integrating both processes in a hybrid bio-refinery can enhance overall system efficiency by directing carbohydrate-rich fractions toward fermentation and lignin-rich residues toward thermochemical treatment [146,71]. This comparative view serves as a foundational step in designing integrated or hybrid bio-refinery.

Table 4
Summary of studies utilizing thermochemical conversion methods for the valorization of lignocellulosic feedstock.

Biomass	Method	Product	Reference
Rice husk		Xylooligosaccharides	[122]
Mango seed shell			[124]
Oat husk and pine sawdust		Biofuel	
Rice husk		Adsorbents (activated hydrochar)	[122]
Soybean hull	Hydrothermal processing		[123]
Corn fiber			[124]
Coconut shell		Hydrochar	[125]
Ripe banana peels			[126]
Cocoa pod husk			
Coconut husk		Formic acid Acetic acid	[127]
Camelina straw	Fast pyrolysis		[128]
Wheat straw	Pyrolysis	Bio-oil	[129]
Banana peel	Catalytic pyrolysis		[130]
Orange peel	Pyrolysis	Syngas and aromatic chemicals	[131]
Pomegranate peel	Flash pyrolysis	Biochar	[132]
Citrus peel	Pyrolysis		[133]
Cassava peel	Catalytic flash pyrolysis	Hydrocarbon-rich bio-oil	[134]
Mango peel	Pyrolysis	Bioenergy and bio-based chemicals	[135]
Forest waste	Fixed bed pyrolysis	Liquid bio-fuel	[136]
Jute sticks	Fixed bed torrefaction and pyrolysis	Coal	[137]
Orange peel	Fluidized bed torrefaction	Solid biofuel and liquid bio-chemical	[138]
Ponkan peel		Solid with high heating value, liquid composed of furan, acid, and ketone groups, and gases	[82]
Bean husk	Torrefaction	Biochar	[139]
Sesame stalks			
Ananas comosus peels			[140]
Coconut shell, coconut husk, and banana peduncle	Co-gasification with coal and petcoke		[29]
Rice husk and straw	Fast pyrolysis and gasification		[141]
Almond shells and husks		Syngas	[142]
Macadamia husk			[143]
Rice husk, cashew shell, and cashew husk	Gasification		[144]

3.4. Process integration and optimization

Lignocellulosic biomass valorization has gained significant attention as a sustainable pathway to produce biofuels, bio-chemicals, and bio-materials. Lignocellulosic biomass, comprising cellulose, hemicellulose, and lignin, presents a renewable resource that can be converted into a wide array of value-added products. However, the efficient conversion of lignocellulosic feedstock is challenging due to its recalcitrant structure, necessitating advanced process integration and optimization strategies to enhance overall efficiency, reduce costs, and improve product yields [147-149].

Process integration refers to the strategic design and operation of interconnected unit processes to maximize energy efficiency, minimize waste, and enhance the overall productivity of a bio-refinery. In the

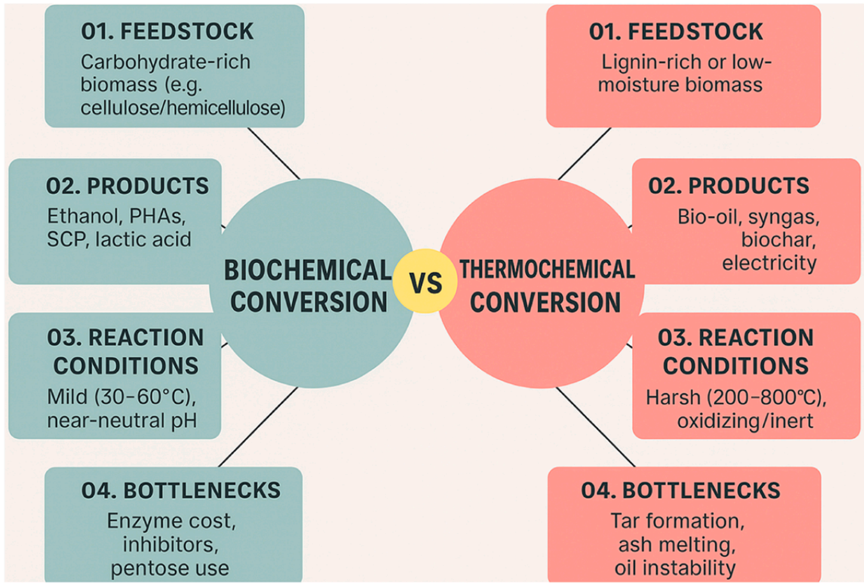


Fig. 2. Comparison of bio-chemical and thermochemical biomass conversion methods.

context of lignocellulosic biomass valorization, process integration involves harmonizing different pretreatment, conversion, and downstream processing steps. To achieve efficient conversion, biochemical and thermochemical methods are often integrated [47,69,70,150]. Fermentation, which converts sugars into desired products such as ethanol, butanol, or biochemicals like lactic acid and succinic acid, also benefits from process integration. Studies have shown that the pretreatment step is crucial for overcoming the recalcitrance of lignocellulosic biomass [151,152]. Simultaneous Saccharification and Fermentation (SSF) and Consolidated Bioprocessing (CBP) are examples of integrated approaches that combine pretreatment and fermentation in a single step [78,153,154]. These strategies not only simplify the process flow but also reduce the risks of sugar loss and contamination. Furthermore, advances in metabolic engineering have enabled the development of robust microbial strains capable of co-fermenting glucose and xylose, improving carbon utilization efficiency [155].

The optimization of enzymatic hydrolysis, which converts cellulose and hemicellulose into fermentable sugars, is another critical component. This step often requires high enzyme loadings to achieve satisfactory yields, contributing significantly to the operational cost. Advances in enzyme engineering and process conditions optimization, such as temperature, pH, and solid loading, have shown potential in reducing enzyme usage while maintaining high sugar conversion rates [156]. Additionally, the integration of continuous or semi-continuous hydrolysis processes can improve throughput and reduce processing times.

Process optimization encompasses a range of methodologies, including experimental design, process modeling, and real-time monitoring, aimed at maximizing the performance of each process step. Techniques such as response surface methodology (RSM) and machine learning algorithms have been employed to identify optimal operating conditions for multi-variable systems, enhancing product yields and process stability. Life Cycle Assessment (LCA) and techno-economic analysis (TEA) further guide process optimization by evaluating the environmental and economic performance of different conFigureurations, ensuring sustainability and market competitiveness [157].

The valorization of lignin, a by-product of lignocellulosic biomass processing, is another area where process integration and optimization play a crucial role. Traditionally considered a low-value product used for heat and power generation, lignin can be converted into high-value products such as phenolic resins, carbon fibers, and aromatic chemicals through advanced catalytic and thermochemical routes. Integrating lignin valorization pathways within bio-refineries not only enhances overall profitability but also contributes to waste minimization and resource efficiency [158].

4. Advances in technology - recovery and purification

Following the pretreatment methods mentioned above, it is common for inhibitors to be produced, in addition to fermentable cellulosic and hemicellulosic sugars. 5-Hydroxymethylfurfural (HMF) is generated from the dehydration of cellulosic or hemicellulosic sugars and can further decompose into formic acid and levulinic acid by another dehydration reaction. Acetic acid, another typical inhibitor, is formed during the hydrolysis of hemicellulose. Additionally, phenolic compounds are produced through the dehydration and dehydroxylation of lignin. Enzyme activity and microbial growth are decreased due to inhibitors, resulting in a negative impact on ethanol yield and fermentation efficiency during the fermentation process. Detoxification of these inhibitors before fermentation is essential for the efficient and cost-effective production of bioethanol. Detoxification not only facilitates the process, but may also enable the recovery of valuable byproducts, depending on the method employed.

Detoxification methods can be categorized as physical, chemical, or biological. Physical methods include activated charcoal, membrane separation, ion exchange resins, and simulated moving bed separation. Activated charcoal works via adsorption, targeting the removal of phenolic compounds [159,160]. Membrane separation is an advanced filtration technique including microfiltration, nanofiltration, ultrafiltration, and reverse osmosis, that allows small molecules, such as acetic acid, to pass through the membrane while separating larger molecules, such as sugars [161]. The ion exchange resin method operates by swapping ions and adsorbing ions of the same charge onto the resins and is primarily applied in batch or semi-batch operations. These resins are easily cleaned and reused while maintaining their activity due to the weak physical bonds between the adsorbent and adsorbate, which enables efficient and cost-effective operations [162]. Anionic resins (e.g., IRA-400, XAD-4, Amberlyst-IRN78) are effective in removing phenolics [163], and HMF [164]. It should be noted that the selectivity of the resins is highly dependent on pH, pore size, and temperature. Simulated Moving Bed Separation (SMBS) is a chromatographic technique designed to separate inhibitors and purify chemicals, particularly acids (e.g., acetic acid, sulfuric acid), HMF, and sugars [165]. The method includes two phases: 1) Mobile Phase, involving the carrier liquid and the chemical mixture to be separated; 2) Stationary Phase, where separation occurs based on the adsorption affinity of the chemicals. Different from the ion exchange resin method, SMBS can be operated continuously, making it suitable for large-scale applications.

Chemical methods for separating inhibitors can be divided into four main categories: 1) neutralization, 2) solvent extraction, 3) selective extraction, and 4) salting-out extraction. Neutralization involves treating acid hydrolysates with basic chemicals such as calcium hydroxide ($Ca(OH)_2$), potassium hydroxide (KOH), or sodium hydroxide (NaOH) to neutralize acidic inhibitors [166,167]. Solvent extraction is used to separate inhibitors and ethanol in the fermentation broth based on their solubility in an organic solvent (e.g., 1-butanol [168]). Selective extraction techniques are used to isolate sugars by removing other chemicals such as alcohols and phenols, thereby enhancing the efficiency of the fermentation process [169,170]. Salting-out extraction works by reducing the solubility of the target inhibitors in the aqueous phase by adding salts (e.g. sulfate, phosphate) to a mixture of organic and aqueous phases [171]. This drives the inhibitors into the organic phase, where they can be separated efficiently. The methods could be combined with microwave heating and evaporation to increase efficiency. Although these methods offer high selectivity and yield, which increases fermentation efficiency, the use of toxic byproducts such as calcium sulfate and solvents requires the development of greener alternatives to ensure sustainability.

Biological detoxification involves microorganisms and enzymes. Microorganisms show resistance to specific inhibitors (e.g., phenolics, furans) [172,173]. Biological detoxification, using enzymes such as laccase and peroxidase, effectively removes these inhibitors and facilitates sugar recovery with no loss [174,175]. This detoxification process can be performed in-situ, enabling the simultaneous removal of inhibitors and isolation of the sugars. A one-pot treatment approach can make bio-chemical production more cost-efficient by reducing equipment costs and enhancing fermentation efficiency.

Detoxification, product recovery, and purification are interconnected steps in the bio-chemical production process. Physical detoxification methods, such as adsorption and membrane separation, aim to remove inhibitors that negatively affect fermentation efficiency. The physical techniques overlap with product recovery processes, which can also isolate and purify valuable byproducts. Similarly, chemical detoxification methods, such as solvent extraction and ion exchange resins, serve dual roles in detoxification and product recovery, depending on their application. The fractionation of bio-chemicals (e.g., ethanol, n-butanol, and acetone) and the dehydration of these chemicals after fermentation require advanced separation techniques [176]. Methods based on boiling point differences, such as distillation and gas stripping, are employed for these purposes [177]. Ordinary distillation is cost-efficient for ethanol-water mixtures containing <15 wt. % water [178]. However, for mixtures with higher water content, more advanced distillation techniques, such as azeotropic distillation using an entrainer solvent, may be necessary. Additionally, extraction methods previously discussed as detoxification techniques can also be utilized for fractionation and separation, further enhancing the purity of bio-chemicals.

5. Challenges and opportunities in LCB bio-chemical production

Apart from the significant technical and research advancements previously discussed and the promising opportunities for bio-chemical production through the utilization of LCB contributing to a sustainable future, the process still faces a number of technical, economic, and environmental challenges and considerations [179]. Typically, issues related to the pretreatment of LCB [180], the use of non-environmentally friendly solvents, energy-intensive operations (e.g., physical pretreatment, high pressure, or high temperature) [181], low product titers [74], and higher energy consumption for product recovery during downstream operations represent critical barriers to the achievement of industrial-scale applications [182].

More specifically, when evaluating the process viability in terms of financial performance, one of the main problems is considerably high capital investment and annual operational costs, which prevents the bio-chemicals from competing with fossil-based alternatives [183]. These costs are mainly due to the feedstock cost, low microbial productivity, and low substrate loading, which result in a high amount of water and nutrient media usage, leading to larger fermenter volumes and higher heating and cooling requirements [184,185]. Although lignocellulosic substrates require comprehensive pretreatment processes, they are considerably cheaper and more widely available than starch-based and sugar-based feedstocks. Regarding feedstock costs, it has been reported that, depending on the substrate type, raw material cost can contribute up to 60 % of the annual operational expenses [186]. Consequently, the utilization of low-cost feedstock (lignocellulosic materials) and optimizing the pretreatment process are vital to ensure economical biofuel and bio-chemical production [187].

Similar to raw material cost, pretreatment costs are considered another critical contributor to unit production costs. The pretreatment step can account for up to 40 % of the overall process expense in bioethanol production [188]. To eliminate this barrier, several studies have evaluated different types of pretreatment processes of LCB and estimated the unit cost of bioproducts. Kumar & Murthy estimated the unit production cost of ethanol from grass straw as 0.83 $/L, 0.88 $/L, 0.81 $/L, and 0.85 $/L using dilute acid, dilute alkali, hot water, and steam explosion pretreatment methods, respectively [189]. Similarly, Cheng et al. applied a number of pretreatment methods to corn stover and calculated the unit production cost of sugar to range between 0.11 $/kg and 0.54 $/kg. It is notable from these production cost ranges and as previously discussed, that each pretreatment method for LCB utilization presents unique challenges. However, several researchers are putting effort into validating the feasible industrial-scale production [190].

More specifically, the financial barriers of these methods include: (i) the expense associated with commercial enzyme application (e.g., CTec2 with a cost of 24 $/kg) [191], (ii) solvent cost and recovery requirements for ILs, organosolv, and DES pretreatment [192], (iii) reproducibility, continuity and long process time of on-site enzyme production and microbial destruction of the lignocellulosic structure [193], and (iv) higher operational costs due to temperature and pressure requirements of AFEX, steam explosion, and hot water pretreatment can be noted as critical troubles in terms of reaching the low-cost conversion process [190] .

Based on the applied bio-chemical conversion process, such as dark fermentation, photofermentation, or anaerobic digestion for producing bio-chemicals, microbial challenges constraints primarily limit the higher substrate loading, and thus higher final product concentration. Factors such as the carbon to nitrogen (C/N) ratio in digestion and product toxicity in fermentation define the optimum raw material loading, which remains below the economically feasible level [194]. This low substrate loading resulted in higher water usage and larger fermenter volumes. Olivieri et al. (2021), noted that the cost of fermenters can account for up to half of the equipment purchase cost [195]. Similarly, Ozturk et al. revealed that conducting ABE fermentation with 100 g/L fermentable sugar instead of 50 g/L could decrease the total investment cost by approximately 39.9 % [187]. Therefore, it is critical to optimize operational conditions and employ genetic modification in microorganisms to enhance stress tolerance and increase product yields.

Finally, it is worth mentioning the economic importance of the downstream operations, which cannot be underestimated considering their portion of the total annual expenses [196]. Generally, product recovery costs in bioprocesses are relatively high due to the low concentration of product. Patraşcu et al. [197] noted that the low biobutanol concentration in ABE fermentation increases energy requirements ranging from 14.7 to 79.05 MJ/kg biobutanol. Similarly, Haelssig et al. showed that increasing ethanol concentration from 40 g/L to 80 g/L can reduce both capital investment and operational expenses by approximately 30 % [198]. Moreover, Kwan et al. identified a critical drawback in the lactic acid production process, where the majority of heating and cooling costs are attributed to the evaporation and the distillation process due to the massive amount of steam usage [199].

Based on these economic aspects and challenges of the bioconversion processes, Table 5 summarizes a number of techno-economic assessment studies related to the utilization of different LCB for bio-chemical production. It is noticeable that the unit production cost varies across studies, primarily reflecting differences in operational parameters, raw material costs, plant locations, bioprocess conversion efficiencies, and assumptions made by the researchers regarding the potential cost items [187]. Nevertheless, these results demonstrate that further technological development and microbial engineering will improve the financial competitiveness of these bioproducts, making them potential candidates for replacing fossil-based alternatives.

A consistent and uniform lignocellulose biomass supply is taken into consideration in the economic performance of various industrial-scale lignocellulose biomass utilization processes for both biofuel and biochemical production investigations. The supply chain for biomass is currently disorganized and fragmented. Large-scale biorefinery setup is also practically constrained by the absence of transportation and infrastructure like coffee cut stems (Feedstock cost: 18 $/MT) [200], corn stover (153.5 60 and 110.5 $/MT) [192,202], sugarcane bagasse and leaves (SCBL; Feedstock cost: 9.98 $/MT) [213] yields biobutanol (production cost: 1.36 $/kg), biobutanol (production cost: 2.77, 1.75, 1.85 $/kg), lactic acid (production cost: 0.94 $/kg) etc., respectively which all are well presented in Table 5. Further, some other LCB materials and their biochemical products like corn [201], de-oiled rice bran (DRB) [203], macroalgae cellulosic waste (MCR) [207], Spruce [206], sugarcane bagasse (SCB) [12], LCB [204], eucalyptus wood [211], brewers' spent grain (BSG) [215], salix [205], etc., for the biochemical products biobutanol, bioethanol, 2,3-butanediol, etc., are also given in Table 5. A multidisciplinary approach from several disciplines, including industrial, chemical, agricultural engineering, and operational research, is needed to improve the biomass supply chain network. Thus, the key to lignocellulose biomass materials lies in the methods used to achieve efficient biomass distribution to the bio-refineries. Overall, although further work is needed to achieve industrial-scale production in a feasible bio-refinery process, LCB presents numerous advantages as a low-cost resource for biofuel and bio-chemical production [216]. Apart from these waste sources, dedicated energy crops such as poplar, sorghum, and *Miscanthus* are valuable resources for increasing global access to raw materials [217]. Lastly, in addition to technical advancement, government regulations, stakeholder unity, and public awareness about fossil fuels and renewable energy sources are crucial for increasing the number of industrial-scale bio-refinery plants [218,219].

The global environmental issues have led to move more quickly towards the renewable energy sources and away from the non-renewable ones. The promise of LCB-based bio-refineries to serve as a sustainable and profitable substitute for the conventional fossil fuel-based refineries has obviously led to their increased popularity. The LCB materials like wood, grasses, agricultural leftovers, other non-food plant materials, etc., can be converted into high-value added bio-chemicals as well as biofuels, *via* lignocellulosic bio-refineries [184]. The secret to successful commercialization, however, lies in a number of obstacles, including reduced enzyme and feedstock costs, improved heat and mass integration, co-product synergy, and generation of cost-effective pretreatment procedures. Because, the LCB bio-refineries possess greater running costs or a lower yield, they may not be economically viable for generating the biofuels [220]. Consequently, this kind of bio-refinery ability to produce high-value added bio-chemicals and biofuels together can boost the profits while lowering the risk of demand swings. The effective utilization of leftover biomass materials will result from the synergistic effect of co-production, which will advance the idea of circular bio-economy. More opportunities for energy integration and process optimization are also presented by the combined production of high-value products and biofuel [221]. The integrated bio-refinery designs are made even more economically feasible and environmentally sustainable by the market requirements of high-value added bio-chemical products and the possibility of earning carbon credits. Additionally, there are not many research using data-driven technology for techno-economic analysis (TEA). The data integrity of TEA might be greatly improved by data-driven technologies like blockchain, AI, IoT, etc. Nevertheless, the price of cloud computing networks, Cyber-Physical Systems (CPS), and other related expenses must be included in the cost of such smart industries. Furthermore, the current articles that take into account various technical issues and are available in literature [222,223]. Consequently, in order to provide decision-makers with specific conclusions, there must also be a lack of

Table 5
Economic performance of various industrial-scale LCB utilization processes for biofuel and bio-chemical production.

Feedstock	Product	Plant Capacity	Feedstock cost	Production cost	Reference
Coffee cut stems	Biobutanol	80 tonnes of coffee cut stems/h	18 $/MT	1.36 $/kg	[200]
Corn	Biobutanol	18 tonnes of corn/h	153.5 $/MT	1.60 $/kg	[201]
Corn stover	Biobutanol	6.8 MT of corn stover/h	60 $/MT	2.77 $/kg	[202]
Corn stover	Biobutanol	18 MT of corn stover/h	60 $/MT	1.75 $/kg	
Corn stover	Biobutanol	912,000 tonnes of corn stover/year	110.5 $/MT	1.85 $/kg	[192]
De-oiled rice bran (DRB)	Biobutanol	314.8 MT of DRB/year	50 $/MT	1.41 $/kg	[203]
LCB	Biobutanol	40,000 tonnes of butanol/year	60 $/MT	1.43 $/kg	[204]
Salix	Bioethanol	200,000 dry tonnes/year	88 $/dry MT	0.87 $/L	[205]
Corn stover	Bioethanol	200,000 dry tonnes/year	79 $/dry MT	0.86 $/L	
Spruce	Bioethanol	200,000 dry tonnes/year	84 $/dry MT	0.69 $/L	
Forest residue	Bioethanol	200,000 dry tonnes/year	103 $/dry MT	0.77 $/L	[206]
Macroalgae cellulosic waste (MCR)	Bioethanol	183 tonnes of MCR/day	72.6 $/tonne	0.4 $/L	[207]
Olive tree pruning (OTP)	Bioethanol	30,000 tonnes of OTP/year	106 $/ton	2.55 $/L	[208]
Empty fruit bunch (EFB)	Biohydrogen	144 kg EFB/day	12 $/MT	2.11 $/kg	[209]
Agricultural residue	Biohydrogen	6.4 tonnes of residue/day	27 $/MT	1.69 $/kg	[210]
Eucalyptus wood	Industrial sugars	200 dry MT/day	0.05 $/kg	0.33 $/kg	[211]
Corn stover	Industrial sugars	349,000 tonnes of corn stover/year	0.06 $/kg	2.7 $/kg	[192]
Switchgrass		398,000 tonnes of switchgrass/year	0.07 $/kg	3.2 $/kg	
Poplar		354,000 tonnes of poplar/year	0.10 $/kg	3.0 $/kg	
Miscanthus	Industrial sugars	1500 dry *Miscanthus* MT/day	88 $/MT	0.34 $/kg	[212]
Sugarcane bagasse and leaves (SCBL)	Lactic acid	200 tonnes of SCBL/day	9.98 $/MT	0.94 $/kg	[213]
Corn stover	Lactic acid	100,000 MT of lactic acid/year	119 $/tonne	1.28 $/kg	[214]
Miscanthus	Lactic acid		89 $/tonne	1.14 $/kg	
Sugarcane bagasse (SCB)	2,3-butanediol	96 MT of SCB/day	50 $/MT	1.13 $/kg	[12]
Brewers' spent grain (BSG)	2,3-butanediol	2000 MT of BSG/day	50 $/tonne	1.07 $/kg	[215]
SCB	2,3-butanediol	17.6 MT of SCB/h	–	1.90 $/kg	[12]

uniformity and benchmarking. Even though there are significant advancements in the production of bio-chemicals from LCB, there are still challenges in terms of technology, cost, and the environment. For directing future research and developing sustainable solutions, identifying these challenges is very important. There are several critical issues to be solved in terms of overall process efficiency, cost, and environmental footprint while transitioning the promising solutions from lab scale to viable industrial scale. Table 6 summarises the challenges to be solved, implications, current solutions, and future research directions.

Table 6
Challenges and solutions in advancing LCB-based bio-chemical processes to industrial-scale.

Challenges	Implications	Current Solutions	Future Research Directions
Lignin Recalcitrance	- limited cellulose accessibility - reduced sugar yields	- effective pretreatment - combined pretreatment methods	- novel green solvents - catalytic/ microbial lignin valorisation
Inhibitor Formation	- decreased enzyme activity and microbial growth - reduced product yield	- detoxification methods (physical, chemical, biological)	- tolerant microbial strain development - in-situ detoxification - lignin-first bio-refineries
Low Microbial Productivity/ Tolerance	- limited substrate loading - larger fermenter volume - high water usage	- microbial strain optimization for stress tolerance and higher product titers	- advanced metabolic engineering - tolerant microbial strain development
High Capital Investment	- lack of financial competitiveness	- larger plants - optimization of operating hours - strategic integration of processes	- decentralized bio-refinery designs - usage of co-processing
High Pretreatment Cost	- energy intensive	- optimization of existing methods	- energy efficient pretreatment technology development - integrating pretreatment units into bio-refineries
High Enzyme Cost	- lack of commercial enzymatic hydrolysis	- enzyme engineering for enhanced stability and selectivity	- development of enzymes with superior performance
High Operational Cost	- influenced by feedstock, energy, water, nutrient media	- feedstock utilization optimisation - reduced water usage - lower heating/ cooling requirements	- advanced process control and optimisation - waste heat recovery
Downstream Product Recovery Cost	- high energy consumption due to low product concentration.	- advanced separation techniques - combination of detoxification and recovery methods	- highly selective separation technology development
Regulatory & Market Barriers	- lack of standardized regulation - cost of production	- policy incentives - public-private partnerships - LCA for sustainability validation	- global harmonization of regulations - stringent certification programs - multi-product bio-refineries for market resilience

6. Case studies on lignocellulosic bio-chemical refinery (LCBR)

The promising general model of 5-carbon (C_5) and 6-carbon (C_6) sugars has eventually been produced using the fractionation of a lignocellulosic matrix. These are consequently transformed into valuable bio-chemicals, which serve as the building blocks / platform chemicals through chemical / biotechnological processes. Therefore, the commercial viability of the biomass materials, particularly in terms of the cost of the required raw materials, must be considered when evaluating the economic sustainability of the LCBR. Furthermore, it has been suggested that the process for designing and LCA can be combined to optimize the production process by economic and environmental standards [224]. Globally available potential biomass supply is nearly 53 EJ. By 2050, it is expected to reach a value of 153 EJ, accounting for 25 % of the primary energy supply [225]. The lignocellulosic-derived bio--chemicals have garnered keen interest from academics and investors over the past decade due to their environmental advantages and commercial success. Some noteworthy techno-economic studies on sugarcane bio-refineries to produce valid bio-chemicals have already been reported [226]. The literature contains several examples of techno-economic performance evaluations for their production. Moreover, comparing the outcomes is challenging because many projects have employed different methodologies . It has been suggested that an effective lignocellulosic bio-chemical production process for the future will co-produce numerous bio-chemical products and bio-fuels in relatively low quantities, in line with contemporary petro-chemical commodities. In this case, the relative volume of bio-chemical production should be significant if the bio-chemical co-production is required to ensure the economic viability i.e., a reduction of fuel costs by $1/GGE. For example, if bio-chemical production made up only 5 % of the bio-fuel production, the margins needed to support the bio-fuel production would be too high. For instance, if value-added chemicals were co-produced at a 1:5 ratios along with the bio-fuel, $<$3 % of the US fuel demand would be satisfied by the biofuel, which would cover the entire US need for that bio-chemical productivity, i.e., 3.45 MT/year [227]. Herein, the optimization of economic feasibility, research needs and methodological challenges, as well as upgrading strategies for lignocellulosic derived bio-chemicals, the financial viability of value-added bio-chemicals from LCBR, and the circular bio-economy via bio-chemical technologies have been discussed.

6.1. Optimization of economic feasibility

Naturally, the technology and supply chains for bio-energy crops would greatly increase the operating and design complexity towards the lignocellulosic bio-refineries. It is observed that, for a given amount of LCB materials, a greater yield results in a higher bio-chemical output and that a decreased energy demand which all suggest that a larger fraction of lignin may be converted to the bio-chemicals. As a result, the production of bio-chemicals rises and the literature reports that lignin-to-bio-chemical product yield range from 10 to 20 %, thereby the average gross profit margins for such bio-commodities account for 13 % and 5 % of their total cost, respectively [228].

Due to the economic impact, larger manufacturing plants/bio-refineries could operate on a larger scale, which could reduce the cost of production of the bio-chemical products per unit. Consequently, the amount of bio-chemicals produced by the same capital investment results in an increase in the annual productivity of the bio-refinery with an increase in the operating hours. As a result, the cost of production of bio-chemicals per unit decreases as the annual operating hours increase. The reactor raises the overall cost of capital investment and equipment, which in turn raises the cost of production of bio-chemicals [229]. To optimize the economic feasibility and carbon efficiency, the distinct niches occupied by thermal and biological processes should be clearly defined for the strategic development of an integrated bio-refinery [230]. The commercial bio-chemical plants may be established more quickly if cellulosic material is converted into fermentable sugars via economically feasible techniques. Some business sectors are commercializing the use of fermentable bio-products derived from the biomass to produce numerous bio-materials like bio-surfactants, etc. [231]. Some of these bio-products are regarded as intermediates or platform chemicals for the development of further domestic chemical commodities. The global market for bio-renewable chemicals reached $6.8 billion in 2015. Furthermore, Bautista-Herrera et al. showed that the price of bio-products like bio-gasoline is currently between $3.70 and $4.10 USD per gallon [232]. While small and medium-sized bio-refineries may need tax incentives and subsidies to preserve the profitability and competitiveness, and the large bio-refineries may be cost-effective when the price drops intensely (2–3 US dollars) [233].

6.2. Research needs and methodological challenges

The TEA essentially provides the insights by combining the economic benefits to the relevant technology, which can lower the costs [223]. The average cost of producing one gallon of cellulosic bioproducts for low, medium, and high conversion rates is 3.72–3.86, 3.23–3.26, and 2.85–2.92 US dollars, respectively [234]. Table 7 lists the most recent techno-economic investigations on sugarcane conversion to bio-chemicals. It was observed that utilization of the entire sugarcane bagasse biomass through a homo-fermentative pathway is a commercially viable option [235].

6.3. Upgrading strategy for lignocellulosic-derived bio-chemicals

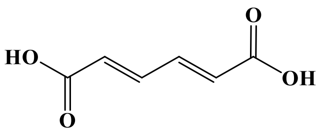
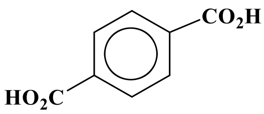
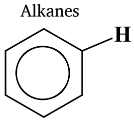
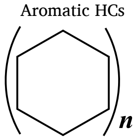
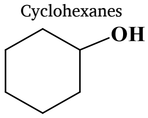
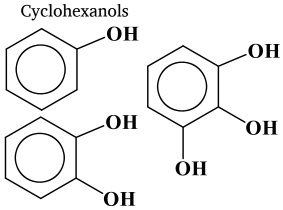
The monomeric upgrading strategy for lignocellulosic-derived bio-chemicals is given in Table 8. In the economic enzymatic hydrolysis and fermentation processes, the hydrolysate from the dilute acid, hot water, and AFEX pretreatments is directed into one of the multiple parallel saccharification vessels, where enzymes are added. Due to the lower variable cost, enzymatic hydrolysis and catalytic hydrothermal hydrolysis (CHH) had the lowest production costs, with a difference of 0.06 $/L compared to the other processes. Similarly, compared to enzymatic hydrolysis, CHH has a 1 % higher CAPEX, mostly due to the harsher operating conditions and associated equipment expenditures. However, owing to the expense of the feedstock, enzymatic hydrolysis has a 25 % higher variable cost than CHH [245].

Furthermore, the enzymatic hydrolysis has a more sustainable environmental impact than CHH, with emissions that are almost 50 % lower. Its extensive industrial utilization results from its lower investment cost, increased bio-chemicals yield, and smaller environmental footprint. The untreated biomass has an enzyme loading of 31.3 mg protein / g cellulose, and the saccharification residence time is about five days. the expense associated with commercial enzyme application [246]. Assuming the same enzyme and loading parameters leads to the greatest comparison of different pre-treatment options. In the base case scenario, enzyme-related operating costs are $0.28 per LGE annually. Enzymatic treatments have generally been performed at relatively low substrate consistency. However, recent research has shown that this can clearly boost the productive adsorption of enzymes and is economically advantageous [247]. although the effect depends on the hydrolytic enzymes used, which might differently affect the yield. The properties, catalytic sites, and enzymatic mechanism of hydrolases can be investigated to increase the yield. It is also anticipated that new enzymes with exceptional thermal stability and high catalytic efficiency will be discovered, and that environmentally friendly and cost-effective procedures will be used to increase the yield and concentration of the bio-products. Furthermore, to guarantee low cost, low energy consumption, and environmental friendliness of the process, consideration should be given to both economic effectiveness and environmental safety [248]. The design and cost-based assumptions for all enzymatic hydrolysis equipment are the same as in previous studies, using the standard hydrolytic operations [249]. Furthermore, the kind of 304SS equipment is used in the manufacturing of enzymatic hydrolysis [195]. By streamlining the production procedures of bio-products and boosting the conversion efficiency, the producers can lower the prices while their market demand surges. Additionally, by implementing multi-product revenue models, the bio-refineries can strengthen their resistance towards the unpredictability of the market [250]. However, more investigation is required, specifically to assess how various microbes affect the profitability of the product manufacturing. Koutinas et al. [237] studied the techno-economic evaluation of 2,3-butanediol production via a fermentation process, using significant carbon sources such as glycerol, sucrose, and sugarcane molasses. They found that the minimum supporting price varied from 2.6 to 4.8 USD / kg for sugarcane molasses. Considering the market price of bio-chemical products like butanediol, reported as 1800 to 3200 $/tonnes in the year of 2013, this procedure could be financially advantageous [251]. Compared to the base case scenario, the product value (PV) from the on-site enzyme production process is about $1.42/LGE, greater by $0.06 / LGE. Results show that a substantial fraction of the feedstock, about 9.2 % of the hydrolysate, is abstracted towards the region where enzymes are produced, which lowers the plant capacity by 22.7 million litres of the products per year. The economy-of-scale benefits that come with growing the plant size are diminished by the decrease in product capacity. The integration of bio-based polyol production with a sugar-producing bio-refinery using LCB as feedstock has not yet been investigated. Howecer, Dessbesell et al. [252] assessed the economic viability of bio-based polyol production in a kraft lignin bio-refinery with a capacity of 1500 dry metric tonnes of biomass per day. For an exact material and energy balance of a planned bio-refinery, a process model is generated in Aspen Plus®. The size of the process equipment units is then determined by the mass and energy balance findings from the process model, as well as the operating conditions [252]. To determine the minimum sugar selling price (MSSP) at a 10 % internal rate of return (IRR), the capital investments are entered into a modified discount cash flow rate of return (DCFROR) analysis, along with the additional expenses like variable operating costs for feedstock, catalyst, enzyme, waste disposal, input energy, by-products, fixed operating costs including labour and maintenance costs, etc., thereby commercially accessible equipment and that significant technical obstacles have been resolved. The techno-economic performance of each bio-refinery should be carefully examined in order to compare their viability whether they follow thermo-chemical or bio-chemical paths, or bio-refineries with varying degrees depending on the technology employed. According to some research, the cost of the feedstock and the technology used have a significant impact on the conversion of biomass to bio-commodities [253]. Utilization of second-generation biochemical products through techno-enviro-economic conversion pathways has yielded notable

Table 7
TEA study on sugarcane bagasse-derived bio-chemicals.

Feedstocks	Biochemicals	Location	Plant capacity (t bagasse/h)	Reference
Bagasse	Furfural/Xylitol	Argentina	–	[236]
Molasses / Sucrose	2,3-butanediol	Brazil	–	[237]
Molasses	EtOH, PHBs	Colombia	200	[238]
Bagasse & trash	EtOH/ Butadiene	South Africa	300	[239,153]
Bagasse & trash	EtOH/Lactic acid	South Africa	300	[240]
Bagasse	Liquid biofuels	Australia	10	[241]
Bagasse	Liquid crude biofuels	Australia	10	[242]
Bagasse	Xylitol	United Kingdom	4	[243]
Bagasse	EtOH	Denmark	165	[243]
Bagasse	Fermentable sugar	India	15.7	[244]

Table 8
Monomeric Upgrading Strategy for lignocellulosic-derived bio-chemicals.

Bio-chemical products	Value of products	Monomeric upgradation method	Reagents	Ratio of C:H:O	Process involved
 Muconic acid  Terephthalic acid	Precursors of adipic acid, dicarboxylic acids, pyridine, fatty acids	Biological	Copper, iron like base metals, noble metals like Pd, Pt, Ru	Low (H:C), High (O:C)	β-ketoadipate pathway, β-oxidative deacetylation, canonical β-oxidative pathways
$R-CH_2-(CH)_n-CHR$ Alkanes	Low (additives of fuels)	Chemocatalysis	Noble metals (Pd, Pt, Ru, Rh, etc.)	High (H:C)	Monomeric ring opening
 Aromatic HCs	Mid-range (additives of fuels)	Chemocatalysis	Co-Mo, Fe-Mo-P, MoO_3, Ni-Mo, Pd-Fe/C, Pt-Co/C, Ru/TiO_2	Low (H:C) and (O:C)	Gas phase, high temperature, low H_2 pressure (<1 bar) for hydrogenation of CO, deoxygenation of products
 Cyclohexanes	Mid-range (additives of fuels)	Chemocatalysis	Ni, CH_3–COOH, H_3PO_4, Acidic ILs, HBEA, HZSM-5,	Low (O:C)	Monomeric ring opening, deoxygenation of products
 Cyclohexanols	Feed for the synthesis of high-value products like adipic acid, polyethylene terephthalate, etc.	Chemocatalysis	CoN_x/C, Ni/CeO_2, $Ni/SiO_2–Al_2O_3$, Raney Ni, $Ru–MnO_x/C$, $Ru/ZrO_2–La(OH)_3$, Ru/C–MgO	High (H:C) and (O:C)	Liquid phase, partial HDO, Demethoxylation, aromatic reduction
 Phenols	Feed for the synthesis of high-value products like aromatic-ols, ethylene, propylene, terephthalic acid	Chemocatalysis	Base metals, noble metals	Low (H:C), High (O:C)	Selective demethoxylation

economic benefits in Europe, the US, and Brazil. In this regard, numerous studies have widely employed the TEAs to concentrate on the production of second-generation bio-products at the plant scale [254].

6.4. Economic viability of value-added bio-chemicals from LCBR

Nowadays, the economic viability of value-added bio-chemicals produced from biomass optimizes feed utilization, thereby increasing product value through the combination of multiple primary conversion processes and integration via downstream upgrading operations. Therefore, the bio-refinery is recommended as the best option to minimize bio-waste and pollution while optimizing both economic and environmental benefits. Strains with low inhibitor tolerance make it more difficult to produce certain bio-chemicals like bio-butanol from lignocellulosic hydrolysates [255]. The current state of lignocellulose bio-refineries and the potential of the circular economy were examined by Garlapati et al., [256]. Among all the LCB components, lignin is the second most prevalent polymer and can make up 15–30 % (dry weight). To achieve the greatest possible socio-economic and environmental benefits thorough research, a techno-economic assessment is recommended as it is influenced by the regional policies, as the governments may be less likely to support bio-products in certain regions with significant financial restrictions, which would lower their demand [257].

The commercialization of lignocellulosic bio-chemicals, i.e., their techno-economic characteristics, is still being optimized. Their deployment has widely utilized the leftover biomass, which is also still under progress. Further advancements in the lignocellulosic sector are anticipated shortly. Meanwhile, the process of their commercial deployment might take into consideration the findings from the sustainability analysis for developing lignocellulosic value chains that always employ the residual biomass [258]. The requirement for forestry and agricultural residues to fulfil their ecological and mandatory economic roles must be met before implementing a sustainable value chain at the oblique feedstock supply. For farming and forestry leftovers to fulfil their environmental and financial roles, it is crucial first to meet their demand, particularly if the residues are being used to produce low-value energy. By the plan to decarbonize the energy sector and develop bio-chemical industrial product, a comprehensive sustainability analysis at the regional and national levels will be required to assess the financial and environmental impacts of diverting the residues from such utilization to higher-value applications.

To maximize the research direction, the economic feasibility of the lignocellulosic-based bioprocesses has been examined, using comprehensive process design data [223]. However, considering the varying developmental stages of pretreatment options, the study acknowledged that it was not entirely fair to make commercial comparisons. Furthermore, a significant amount of certain reagents, like lime, was needed to maintain the pH levels during the bacterial and fungal-based pathways in the production process, as the costs of production were quite sensitive to the use of gypsum / lime. In the purification and recovery process, a significant amount of gypsum was also co-produced during the recovery process of certain bio-chemicals like lactic acid [259]. As a result, the cost of producing the products was sensitively depending on the method of handling the additives like gypsum, which in turn affected the cost of producing the bio-chemicals. Because the miscanthus and maize stover have variable amounts of cellulose and xylose, their sensitivity to certain factors obviously varies via finding economically and technically viable ways to produce the products from lignocellulosic resources may help to contribute to a sustainable bio-economy in the near future.

The break-even pricing for succinic acid has been estimated as about $660 (AU$990), $2260, and $9000 per metric tonne; it is mainly depending on the feedstock cost, productivity *via* fermentation, and system performance. Generally, the ABE fermentation, using corn stover, is expected to yield bio-butanol priced at 0.6–1.8 $/L [260]. According to Myriant Corporation data, the bio-chemical industrial emissions from the manufacture of corn stover derived succinic acid range from 0.87 to 2.4 kg CO_2 eq/kg [261]. The exception is acetic acid, adipic acid and *p*-xylene. These bio-based chemicals decrease the GHG emissions, when compared to their fossil-derived counterparts. In order to promote sustainable growth and development, the concepts of the bio-economy and circular economy have been presented as alternate models of commercial bio-chemical production [45]. Such models highlight the need to change the political, economic, and financial perspectives. As an alternative to petro-chemical resources, the utilization of lignocellulosic feedstock from both the forestry and agricultural sectors offers enormous potential to mitigate climate change and promote economic growth.

6.5. Circular bio-economy via bio-chemical technologies

The 2G-waste biomass resources and associated industries have significant potential and are essential players in a circular bio-economy, which would help ensure a sustainable and resource-efficient future, leading lignocellulosic bio-refineries *via* bio-chemical technologies [45]. The economic and environmental facts for the co-production of bio-chemicals still require research and development. In addition to financial feasibility, environmental impact is a crucial component in supporting the long-term growth of bio-refinery systems. Further, LCA, a cradle-to-grave evaluation method, is formalized by the International Organization for Standardization [262]. The input and output flows, along with environmental burdens, were therefore divided based on the corresponding value and quantity of the co-products in multi-output systems, using an economically feasible technique as the default method [263]. Cellulose is converted into 2 G sugars by Abengoa S.A., DuPont, Beta-Renewables S.A., and Poet-DSM Advanced Biofuels, LLC in the production of their large-scale conversion into bio-ethanol and a number of valuable bio-chemicals. Furthermore, at its plant in Vonore, Tennessee, DuPont has established a fully integrated system capable of producing 250,000 gallons of bioethanol annually. A variety of biomass can be converted into bio-ethanol using the pilot-scale technology. Moreover, many other potential bio-chemicals have surfaced recently. They are expected to be in high demand including ethylene (Braskem Inc., Brazil), isobutanol (Gevo Inc., Colorado, USA), farnesene (Amyris Inc., Brazil), epichlorohydrin (PTT, Map Ta Phut, Thailand), p-xylene (Virent, Madison, WI, USA), acrylic acid and adipic acid (ADM and BASF, Germany), 5-HMF (AVA Biochem, Germany), and some other products which are based on the plant cell wall chemistry may be essential towards the bio-economy [181].

A business plan integrating plantation with lignocellulose bio-refinery was more recently proposed by Galbe & Wallberg [264]. Fig. 3. illustrates a generalized business model on LBR.

The product tonnage per unit of land used annually was included to evaluate different feedstocks. In order to maximize overall production efficiency and provide a beneficial scenario for all the shareholders in

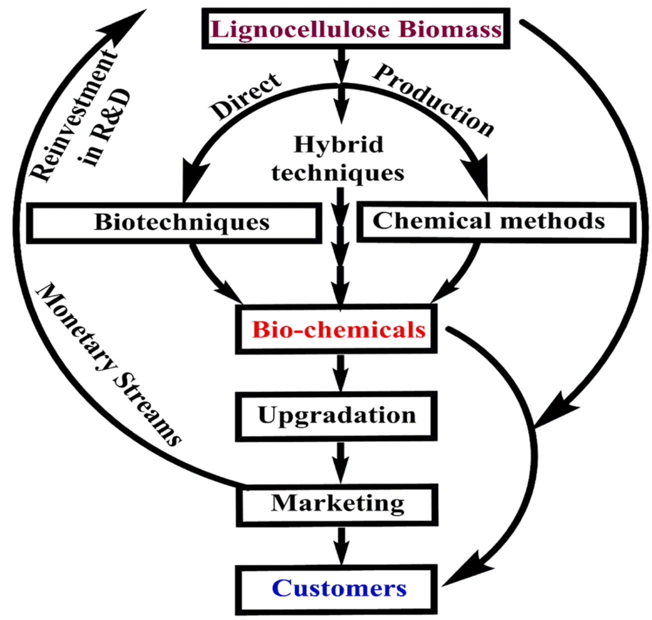


Fig. 3. A generalized business model of LCB resources (LCBR) in bio-chemical production.

the poplar biomass bio-refinery. This economic model can connect farmers and consumers. Generally, the volume of renewable bio-chemicals (apart from biofuels) is approximately about 50 billion kg annually, and it is steadily increasing at a compound annual growth rate (CAGR) of 3–4 % [265]. The global market for bio-chemicals was projected to reach about $12.2 billion in 2021. The direct sales of bio-chemicals in the USA came to about $126 billion in 2013. The details of fascinating bio-chemicals (chosen by NREL-2009, CO, USA), including their manufacturing company and production capacities, excluding biofuels, are shown in Fig. 4 [181]. Many industries throughout the world have established demonstration and production facilities for generating lignocellulosic bio-products using maize stover, sugarcane bagasse, or sugarcane straw. However, Fig. 5. summarizes a number of obstacles that must be overcome in order to implement bio-refinery operations successfully. From a corporate and strategic perspective, a bio-refinery SWOT analysis evaluates four key parameters: external and internal facts viz. opportunities & threats and strengths & weaknesses, respectively. In addition to the important research findings and the large bio-chemical industries show favourable interest in funding the bio-refinery projects, a number of positive prospects have been presented by those projects for minimizing GHG emissions [266]. However, recent project failures in bio-chemical production have raised serious concerns. However, the current scenario for the production facilities may support the development of the potential bio-chemical product in the coming years.

7. Emerging technologies in biochemical production from LCB: future perspectives

The future of bio-chemical production from LCB presents exciting potential for progress in several critical areas. Breakthrough technologies are expanding the current possibilities, although research gaps still exist that call for continued innovation. Meanwhile, the commercialization and scalability of these technologies are influenced by policy frameworks and market trends.

This overview delves into these elements, emphasizing the most important future directions for LCB-based biorefining. The necessity of moving toward a bio-based economy has spurred significant technological advances by means of many bio-chemical processes in converting LCB into many bio-chemical products (Fig. 6.), composed primarily of

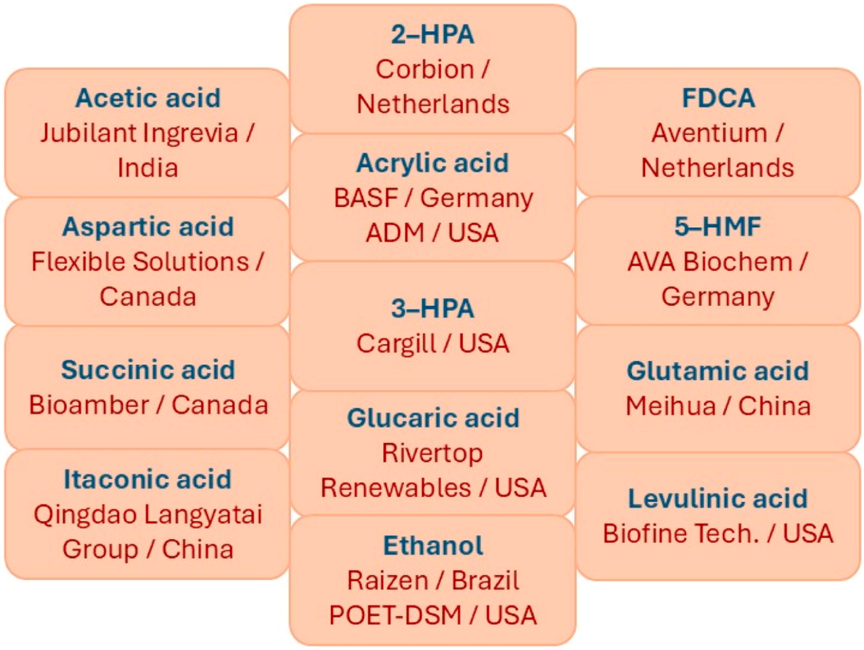


Fig. 4. LCB- derived bio-chemicals and their manufacturers.

cellulose, hemicellulose, and lignin, into valuable bio-chemicals. Despite its potential, the complexity of LCB remains a challenge. The future of this field hinges on overcoming these challenges through innovative technologies.

Enhanced Pretreatment Technologies: Pretreatment is the first, and often most expensive step in the bio-chemical production process. Emerging technologies are focusing on improving this process by making it more energy-efficient and cost-effective.

ILs and DESs: These green solvents offer an eco-friendly way to break down the strong linkages between lignin and polysaccharides. However, advancements are needed in their recyclability and reuse to reduce both environmental impacts and costs [25].

Genetic Engineering of Microorganisms: The future of bio-chemical production is also tied to advances in genetic engineering. CRISPR/Cas9 technology and metabolic engineering will likely improve microbial efficiency in fermenting lignocellulosic sugars into high-value chemicals like biofuels and bioplastics [9].

Breakthroughs in Fermentation and Bioprocessing Fermentation technology will likely evolve from traditional batch processes to continuous fermentation systems, enhancing productivity and reducing costs. CBP offers a promising approach, integrating pretreatment, enzyme production, and fermentation in a single step [10].

Lignin Valorization: Lignin is often overlooked, yet it constitutes up to 30 % of LCB. Lignin-first bio-refineries, which focus on maximizing lignin extraction before processing cellulose, could unlock new revenue streams. Advances in catalytic depolymerization will be essential to convert lignin into high-value chemicals like vanillin and phenols [267].

Advanced Reactor Designs: Reactor designs are critical for improving the efficiency of bio-refineries. Membrane bioreactors and Microbial Electrochemical Systems (MES) are emerging technologies that could enhance product yield while reducing energy consumption [8,268].

Sustainability and Circular Bio-economy Integration: The future of bio-chemical production from LCB aligns with the principles of the circular bio-economy, aiming to reduce waste and maximize resource efficiency. Zero-waste bio-refineries could become the norm, utilizing every part of the biomass and even converting byproducts like CO_2 into useful chemicals [269].

8. Research gaps on bio-chemical production from LCB: future directions

Incredible progress has been made, but some research gaps need to be filled to exploit the potential of LCB-based bio-refineries. High-priority areas should include pretreatment, lignin valorization, microbial engineering, and integrated bio-refinery models.

Lignin Valorization: While excellent, lignin is not yet maximally utilized. Depolymerization and conversion of lignin to high-added-value products should be the area of research. Catalytic and microbial conversion of lignin could pave the way for new opportunities in the production of bio-chemicals [267]. Integrated bio-refinery models optimize bio-chemical processes for the sustainable production of biofuels and platform chemicals, advancing recovery and purification technologies [270,271].

Microbial Engineering: The current microorganisms used for fermentation remain ineffective at the utilization of all biomass components, especially pentoses. There is also a requirement for enhanced microbial resistance to inhibitors formed during pretreatment. Future research must be focused on the development of resilient strains by employing CRISPR and synthetic biology [9].

Integrated Bio-refineries: Current bio-refinery ideas have poor integration between the processes, and this results in inefficiencies. Research must be focused on componentized, adjustable bio-refineries capable of converting various biomasses. CBP can reduce the complexity of operation [10].

Policy and Market Trends in Bio-chemical Production from LCB: Market forces and policy measures are significant drivers of the evolution of LCB-based bio-refineries. As there is an increasing focus on environmentally friendly production worldwide, favorable government policy measures and changing consumer behaviors will propel the demand for bio-based products. In this regard, Table 9 presents a SWOT analysis of national policies related to lignocellulosic biomass utilization.

Policy Incentives: Government policies such as the EU's Renewable Energy Directive (RED II) impose that a very high proportion of energy consumption has to be in the form of renewables such as LCB-based biofuels. Additionally, carbon pricing policy instruments, such as taxation and cap-and-trade policies, also incentivize the use of low-carbon technologies [13]. The Ireland and other European countries in

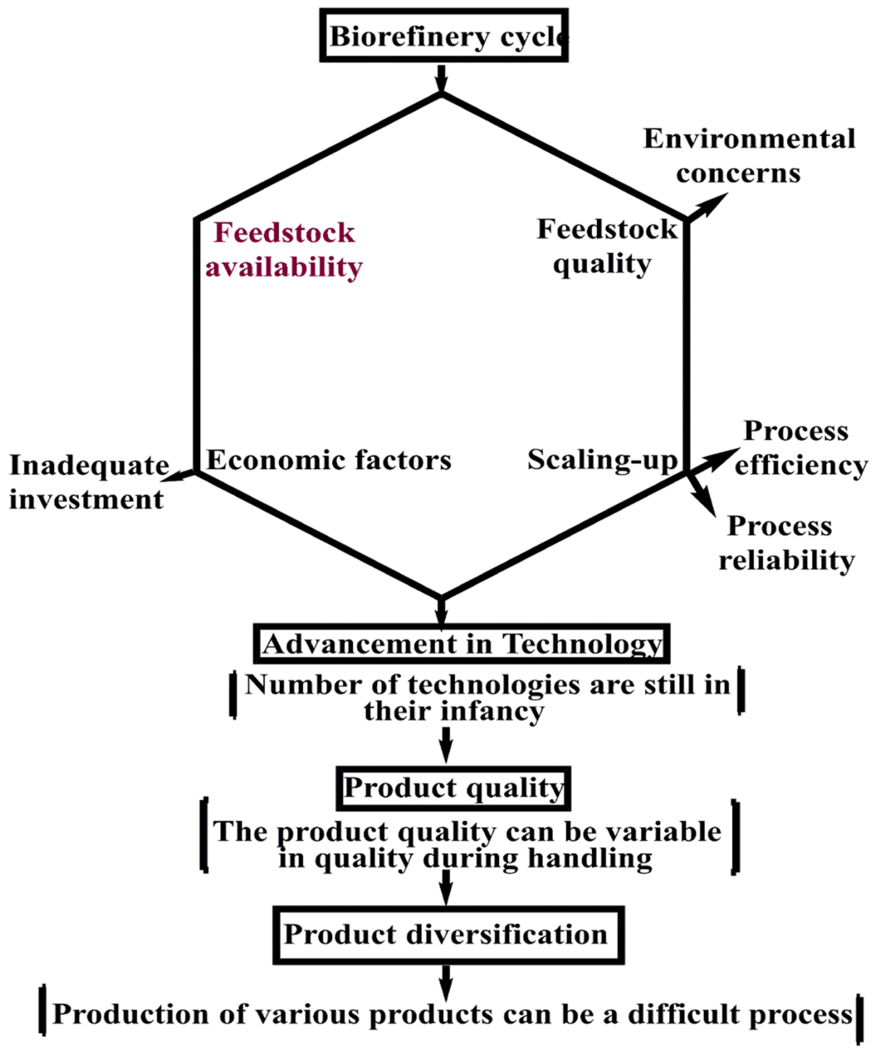


Fig. 5. Illustration of obstacles in the establishment of lignocellulosic bio-refineries.

general have expressed the concerns about the impacts in lack of regulatory support for bio-economy operations towards for the LCB processes. For instance, similar to the US Bio-Preferred program, a reduced value-added tax (VAT) on LCB-based goods could increase demand in the domestic market. The government Bio-economy Implementation Group 2023 progress report details state the investment in bio-economy development to date. It also emphasizes the need to establish a clear and consistent investment pathway for LCB bio-economy in order to support the co-operative collaborations in the growth and expansion of infrastructure and innovation [272]. The report mentions the possibility of using LCB bio-refining and bioprocessing, for instance, to produce the alternatives to carbon-intensive products. Similar issues have been raised elsewhere, such as when the OECD [273] urges for priority action to remove the legislative barriers to invest for the LCB-based products. It emphasizes this point in regard to promote the local supply chains and making bio-based building materials attractive. This is because, although the businesses usually make their investment decisions quickly and prioritize less expensive materials that are readily available on the global open market, advantages like reduced carbon foot-prints and local economic benefits typically manifest over a longer time span [274]. The studies showed how rules and regulations assist the growth of bio-chemicals and bio-fuels, and they highlight to the need for similar programs to support the LC bio-refineries. Both the UK and Austria have experienced the effects of regulatory support or lack thereof for bio-products and renewables. For instance, in the UK, such projects were adversely affected by feed-in tariff reductions and changes to investment tax relief rules, whereas in Austria, biomass-based bio-chemical and biofuels have been developed from a specialized industry [275]. Recurring to the Irish context, it is unclear if the upcoming national Bio-economy Action Plan, which was scheduled for mid-2023, would include any additional steps to address the financial support for bio-economy development [276]. Furthermore, the development and execution of a successful bio-economy regulatory framework would necessitate the pragmatic, continuous assistance of policymakers, who in turn need the resources to accomplish it since there is no "one-size--fits-all" solution to bio-economy regulation and knowledge of context-specific issues [277]. In addition to foster the dynamic innovation, there should be aid in the development and use of more potent solutions to overcome the policy and system deficiencies, needed for sustainability transitions and system transformation.

Regulatory Challenges: The biggest challenge is that globally standardized regulation does not yet exist for bio-based chemicals. Reducing the duration of regulatory approvals and developing stringent certification programs for bioproducts is instrumental in expansion opportunities in the market [278].

Market Barriers and Competition: Although such positive trends exist, the sector faces strong competition in the form of first-generation biofuels and bio-chemicals that are simpler to produce since they are derived from food plants. The cost of production is a high barrier to industrial-scale deployment of LCB [68].

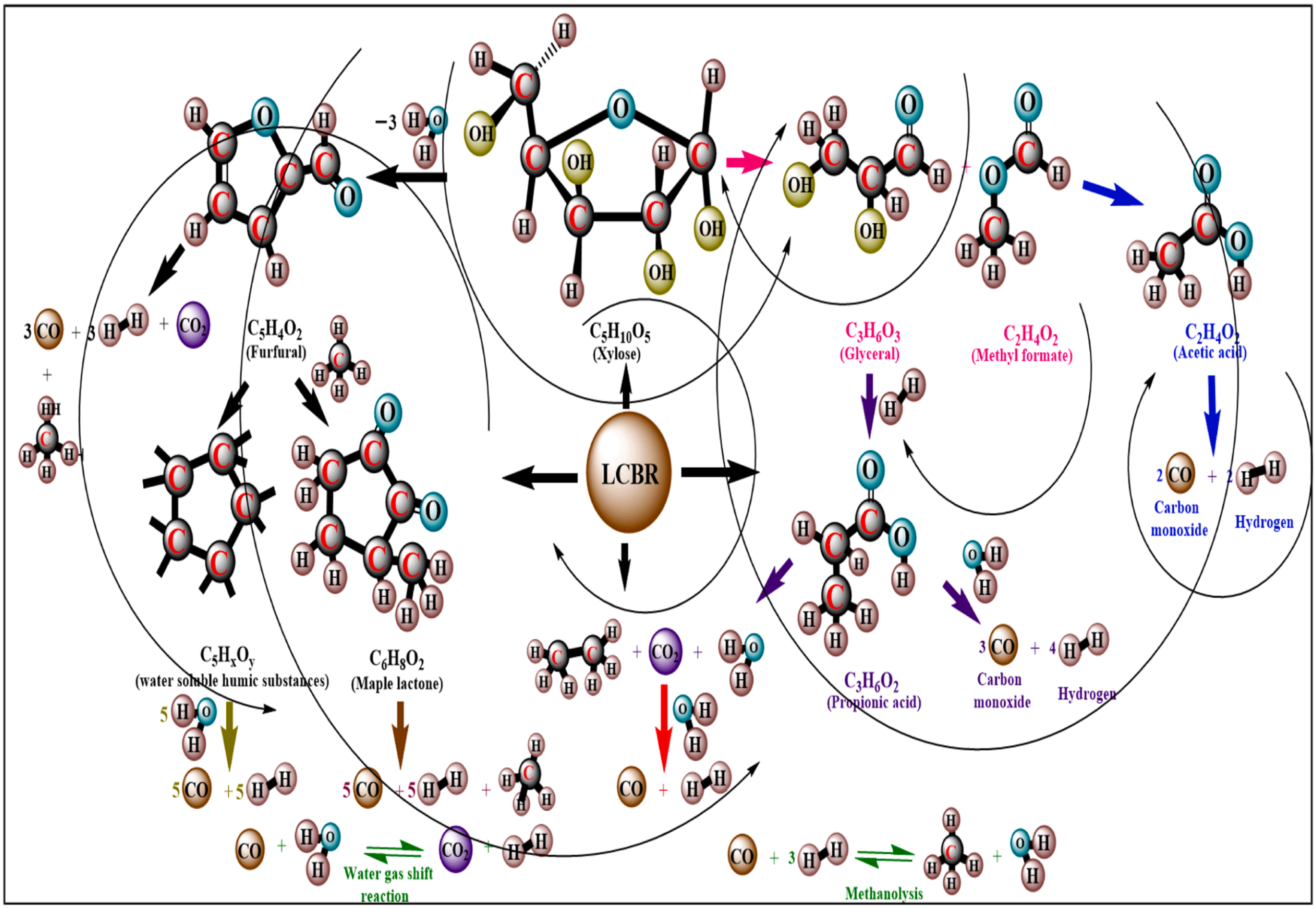


Fig. 6. Bio-chemical processes in the conversion of LCB into valuable bio-chemical products.

Table 9
SWOT analysis of the national policies influencing lignocellulosic biomass deployment.

Region	Strengths	Weaknesses	Opportunities	Threats
United States	- Renewable Fuel Standard (RFS2) mandates a certain level of biomass-based fuels - Financial support and funding opportunities from DOE and USDA for pilot-scale -Carbon sequestration supports	- Price fluctuations in renewable identification numbers (RINs) - Support volatility and discontinuity in biomass utilization regulations	- Integration with the Inflation Reduction Act (IRA) incentives by the U.S. Environmental Protection Agency (EPA) - Valorisation of rural biomass and carbon markets opportunities	- Potential political pressure and lobbying from the petroleum sector stakeholders - Huge lands and poor feedstock logistics infrastructure
European Union	- Strong sustainability targets and GHG initiatives - Fundings of Horizon Europe and Circular Bio-based Europe Joint Undertaking (CBE JU) - Support of RED II/III for broader application of biofuels	- Slow progress due to regulation requirements and strict certification necessities - High capital and operational expenses	- Circular bio-economy strategy - Growing awareness, support, and market for bio-based materials	- Competition with alternative biomass-using industries (e.g., pulp and paper sector) - Restricted area for energy crops
Brazil	- Significant support from RenovaBio towards sustainability - Abundance of second-generation ethanol feedstocks	- Domination of 1 G ethanol feedstocks - Lack of logistics and infrastructure	- Potential exports to neighbouring countries and the EU - Valorisation of forest residues	- Discontinued political support risks - Concerns arise due to deforestation
China	- 15th Five-Year Plan (2026–2030) period policy backs green, low-carbon, and circular development - Air pollution reduction supports	- Weak standards of sustainability - Lack of industrial-scale applications	- Abundance of crop residues - Rural waste management opportunities	- Dependence on fossil-based fuels - Slow policy execution due to centralized governance
India	- Compressed Biogas (CBG) encouragements by the Sustainable Alternative Towards Affordable Transportation (SATAT) scheme - Supports of the national bioenergy programme	- Plant commissioning delays - Issues with feedstock aggregation	- Enhanced feedstock availability due to stubble burning bans - Public-private partnership for the bio-based sector	- Lack of obligations on a higher concentration of biofuel blending - Fragmented landholdings

Future Outlook: There are bright prospects for lignocellulosic biorefineries if policy stability, as well as international collaboration, continue to become better. Private-public partnerships would be necessary for scaling up and de-risking investment in fresh technology [273]. Globally, the bio-chemical future from LCB looks encouraging, though challenges still lie in the distance that need to be overcome. Technologies such as improved pretreatment technologies, AI-supported process optimization, and lignin valorization are opportunities for successful and sustainable bio-refineries. However, difficulties such as microbial engineering difficulties, enzyme functionality challenges, and a combined model of the bio-refinery have yet to be overcome. Policy stimuli and new market situations will need to facilitate the diffusion of LCB-based bio-refineries, but market competition by first-generation biofuels and the economics of production make real obstacles. In the forthcoming years, inter-disciplinary research, harmonized policies, and global cooperation will have a pivotal role in unlocking the maximum capabilities of LCB-based bio-refineries and making them a part of a bio-economy. Based on the above data and the need for progressive reflection in terms of limitation, biochemical yield and process efficiency, the most urgent challenges and gaps include lignin valorization and microbial engineering [9,15]. Considering the increasing demands for intensive technological developments of this nature, short-term prioritization should be addressed in microbial resistance and pre-treatment optimization. While long-term perspectives should address integrated bio-refinery models, regulatory standardization and economic sustainability to ensure industrial scalability [279,270,280]. Rapid actions in these areas are necessary to accelerate the commercialization of LCB-based bio-refinery processes.

Furthermore, the modern technologies like artificial intelligence (AI), CBP, microbial engineering, machine learning (ML), and process automation in LCB bio-refineries of the future can should be optimized and controlled for the bioprocesses on account of wastewater valorization [223]. The real-time monitoring and control, process efficiency, and operating expenditure are all made possible by these advances, which promote data-driven and sustainable decision making. A greater emphasis on such technologies by promoting a closed-loop system whereby the leftovers are valued in multiple ways, reduces environmental impacts and boosts resource efficiency. Ongoing research into the development of engineered or genetically modified microorganisms specifically designed for the production of various bio-products should be improved [281]. The specificity and effectiveness of LCB bio-refinery processes can be enhanced by customized microorganisms, allowing for the treatment of a range of LCB materials with varying compositions. By increasing the specificity and efficiency of such technologies in the LCB bio-refinery processes, tailored microbes enable the treatment of a wide range of biomass materials with different compositions [223]. The generation of genetically altered / engineered microbes intended for the effective production of bio-chemicals and biofuels in addition to energy necessitates more investigation. creation of multifunctional bio-refineries that may produce materials, specialty chemicals, and medications among other valuable products. Besides, a summary of several LCB bio-refinery designs, feedstocks, and their corresponding TRL (Level of technological readiness) is given in Table 10 [282,223]. Thereby, the four elements of the newly selected classification system viz. feedstock, platform, conversion process, and products are generally the technological deployment barriers for establishment of the LCB bio-refineries.

A dry corn mill ethanol plant now has a median unit capital cost of $757 per ton, whereas thermochemical and lignocellulosic ethanol bio-refineries have median costs, worth of $3042 and $2899 per ton, respectively. With a capital cost of $465 per ton, the renewable diesel is less expensive than the median oil-to-biodiesel facility ($589 per ton). Furthermore, a ton of the median seeds crushing-to-biodiesel facility costs $751 [283]. The patterns of cost estimates in bio-refineries are comparable to those in traditional process plants. New bioprocessing technologies are essential for the industrial-scale deployment of lignocellulosic feedstocks. Overcoming the financial and environmental obstacles related to the use of lignocellulosic biomass requires advancements in pretreatment techniques, enzyme recovery, and integrated bio-refineries [223]. From sophisticated nanomaterials to sustainable aviation fuel, life-cycle assessments showed that these developments might drastically lower the carbon footprint of bio-based products. Though, to maintain the bio-refineries economic sustainability, there are still recurring issues, such as eliminating unwanted inhibitors, recovering valuable byproducts, and improving process efficiency [284]. Furthermore, certain major factors that influencing the widespread adoption of such sustainable technologies include legislative and regulatory frameworks. These ideas will not be able to scale without significant public and political support. Energy crops and woody plants possess a notable increase in bioprocessing efficiency due to changes in cell wall composition. But these feedstocks have mostly been used for the manufacturing of biofuels and bio-chemicals, with little attention paid to create sustainable bio-products for wide applications, such as electrical, and medicinal fields [285]. Thereby, the lignocellulosic feedstocks present a promising and possibly the only way to lessen the dependency on fossil-derived fuels and promote a sustainable bio-economy using advanced techniques. But, the development of advanced processing approach is both economically and environmentally viable is still in its early stages [284,286]. In order to address various bottlenecks, future studies should take into account the following aspects; (1) using readily converted lignocellulosic biomass materials, (2) comprehending the characteristics of various feedstocks to adopt an appropriate pre-treatment method, (3) designing large-scale integration to minimize energy consumption and prevent needless losses, (4) optimizing and rationalizing the equipment to improve the process of economics, (5) effectively separating and using the by-products and maximizing the recovery of reaction reagents and (6) encouraging strong political and economic backing to provide a competitive edge to the budding companies for the bioconversion of lignocelluloses [45].

Table 10
Category of bio-refinery, feedstocks and TRL of biomass materials.

Bio-refinery	Feedstocks	TRL
Aquatic	Macroalgae (seaweed) and microalgae	05–06
Conventional	Beets, cassava, corn, starch crops, sugar, sugarcane, wheat, and wood	09
Oleo-chemical	Oil crops	07–09
Rich in lignocellulosic	Chaff, miscanthus, reed, straw, and wood, and	06–08
Wet greeneries	Green crops and leaves viz. grass, Lucerne clover and sugar beets	05–07
Whole crop grains	Maize, rye, and wheat straw	07–08

9. Conclusion

The current review shows the potential of LCB as a cost-effective green feedstock for the production of green bio-chemicals. The critical features are the technological improvements in pretreatment, specifically microbial and ionic liquid pretreatments, which provide maximum cellulose accessibility by reducing lignin-associated resistance. Additionally, process yield, and product efficiency can be considerably improved with recent advancements in enzymatic hydrolysis and microbial strain improvement, such as through CRISPR/Cas9. Apart from these advancements, CBP is highly promising as it integrates pretreatment, hydrolysis, and fermentation into a single process, offering low operation costs and complexity. Despite such progress, commercialization of enzymatic hydrolysis is being retarded by the prohibitive cost of enzymes, production of inhibitors during pretreatment, and underutilization of lignin. The review has significant implications for research, industry, and policy. From a research perspective, it highlights the primary in enzyme optimization, lignin valorization, and the scale-up of the combined bio-refinery model. Policymakers are similarly involved in action with the obligation to offer incentives in the form of the EU Renewable Energy Directive (RED II) and carbon price fees to encourage bio-based production. Overall, LCB bio-chemicals have tremendous potential for reducing fossil fuel reliance, embracing circular bio-economy concepts, and facilitating global sustainability objectives. Market actors, researchers, and governments will require concerted efforts in order to address the limitations of costs, process effectiveness, and regulatory constraint within the markets. With growing innovation and cooperation from around the globe, LCB is going to become the backbone of the bio-economy, leading society into a greener future.

CRediT authorship contribution statement

Hysen Bytyqi: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Gamze Nur Mujdeci:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Ecrin Ekici:** Writing – review & editing, Writing – original draft, Data curation. **Abdullah Bilal Ozturk:** Writing – review & editing, Writing – original draft, Data curation. **Evrim Celik Madenli:** Writing – review & editing, Writing – original draft, Data curation. **Gopalakrishnan Kumar:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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