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Review Article

LIGNOCELLULOSIC BIOMASS (LCB) FOR A SUSTAINABLE CIRCULAR ECONOMY

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ABSTRACT

Bio-based materials are derived from a variety of biomass sources and they prove to be potent eco-friendly alternatives to fossil-based products. Lignocelluloses are composed of cellulose, hemicellulose and lignin, each of which can be valorized into high-value products such as biofuels, biofibers, bio-based polymers etc. Biorefinery technologies have enabled harnessing lignocellulosic feedstock for sustainable bio-based materials and drive the circular economy forward. The present review delves into the potential of using lignocellulosic components, their availability and sustainability, emerging advancements for their processing, valorization of the extracted waste or by-products, challenges and transformative opportunities in improving the scalability and bioconversion process. A thorough literature review and comparative case studies on lignocellulosic materials, circular economy models and bio-based innovations have been carried out. This review contributes in addressing research gaps, provide insights into environmental impacts and economic analysis for policy makers, explore zero-waste manufacturing models and functional practices for integration of bio-based materials into circular economy models. Additionally, an assessment of regional specificity is covered in this review.

Keywords: Biofuels, Bioplastics, Circular economy, Lignocellulolytic enzymes, Pretreatment

The existing linear economic model of intensive utilization and reliance on fossil fuels for many decades has now led to unsustainable resource depletion and environmental degradation. This has necessitated our need for a transition towards renewable resources, a shift towards a circular economy that focuses on efficient resource utilization and waste management. Circular economy operates on the principles of designing out waste and pollution, extending product life cycles through repair, reuse, remanufacturing, recycling, and regenerating natural systems to improve ecosystem health. Lignocellulosic biomass (LCB) shows great potential in achieving this transformation because of their abundant availability, renewability and versatility. The sources of LCB include agricultural residues (eg. rice and wheat straw, corn stover, sugarcane bagasse), forest residues (eg. leaf litter, fallen trees), energy crops (eg. switchgrass, miscanthus) and industrial by-products (eg. sawdust, paper mill waste). The valorization of organic wastes and agricultural residues through bioenergy and advanced bio-product generation is pivotal for achieving a sustainable circular economy (Mujtaba *et al.*, 2023). LCB-based refineries offer applications across bioenergy, nutrition, food and biochemical industries (Banu *et al.*, 2021).

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LIGNOCELLULOSIC BIOMASS (LCB)

LCB typically consists of 40-60% cellulose, 20-40% hemicellulose, and 10-24% lignin (Sun *et al.*, 2016). These components vary depending on the plant source and geographical origin and these variations directly impact biomass recalcitrance and downstream conversion efficiency (Sun *et al.*, 2016). Hardwoods like Poplar and Eucalyptus contain higher cellulose and lower lignin content compared to softwoods such as Pine and Spruce, which are more lignified and thus more recalcitrant to enzymatic degradation (Table 1). Likewise, agricultural residues (rice straw, wheat straw, and corn stover) tend to have more hemicellulose and silica, influencing enzyme binding and saccharification potential (Sluiter *et al.*, 2010; Kumar *et al.*, 2009). Moreover, geographical origin influences LCB composition due to environmental conditions such as soil type, climate, agricultural practices, and genetic variability of the plant species. For example, rice straw grown in South Asia have higher ash and silica content than that from temperate regions, affecting pretreatment efficiency and enzyme accessibility (Binod *et al.*, 2010; Zhang *et al.*, 2018). Similarly, the same crop species grown under different climatic conditions (eg.

Table 1. Composition of lignocellulosic biomass (LCB) by source and geographical region

Biomass type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Geographical region	References
Hardwood (Poplar)	45-55	20-30	18-25	Temperate region	Sun *et al.* (2016), Ragauskas *et al.* (2006)
Softwood (Pine)	40-50	20-30	25-30	Boreal	Sun *et al.* (2016)
Rice Straw	32-47	19-27	5-24	South Asia	Binod *et al.* (2010)
Wheat Straw	30-45	20-35	15-20	Europe and Asia	Zhang *et al.* (2018)
Corn Stover	35-50	25-30	15-20	North America	Kumar *et al.* (2008)

Table 2. Composition and structure of lignocellulosic biomasses and their functions (Andlar *et al.*, 2018)

Component	Composition and Structure	Monomers and Bonds	Functions in Plant Cell Wall
Cellulose	Linear homopolymer of D-glucopyranose subunits	β-١,٤-glycosidic bonds, repeating unit is cellobiose (glucose units rotated 180°)	Provides tensile strength and rigidity, forms microfibrils stabilized by intra and intermolecular H-bonds and Van der Waals forces
Hemicellulose	Branched hetero-polymer made from monomeric sugars and sugar acids	Main carbohydrate: Xylan β-1,4- and β-1,3-glycosidic bonds, Common sugars: D-xylose, D-mannose, D-galactose, D-glucose, L-arabinose, 4-O-methyl-glucuronic, D-galacturonic, and D-glucuronic acids	Acts as a filler between cellulose fibrils, contributes to flexibility, easily hydrolysable, lower molecular weight than cellulose
Lignin	Amorphous heteropolymer with a complex, irregular 3D structure	Composed of phenylpropane units (H, G, S): - H (p-hydroxyphenyl) from coumaryl alcohol - G (guaiacyl) from coniferyl alcohol - S (syringyl) from sinapyl alcohol Linked by C–C and C–O bonds	Provides structural support, impermeability, resists microbial attack and oxidative stress, binds cellulose and hemicellulose

tropical vs. temperate) can exhibit marked differences in lignin monomer composition and overall biomass digestibility (Poovaiah *et al.*, 2014). The composition and structure of LCB along with their functions are summarized in Table 2. The structural complexity of cellulose, hemicellulose, and lignin (Fig. 1) underpins their diverse applications.

Pretreatment is a pre-requisite step that has a significant impact in the bioconversion of LCB into functional biofuel (Alvira *et al.*, 2010) by the structural disruption of its complex structure as shown in Fig 2. An ideal pretreatment should be effective and economically feasible. Some important aspects to be considered while working on a pretreatment are - the high lignin and hemicellulose removal and minimal carbohydrate loss with minimum formation of inhibitory compounds (Kumar *et al.*, 2009); the cellulose present in it after pretreatment should be easily and effectively hydrolyzed (Hendriks and Zeeman, 2009); fermentable with low-cost and high yield; its operation must be carried out at a reasonable price with inexpensive chemicals and moderate sized reactors; use of appropriate materials; no solid residues production that might present disposal challenges, low consumption of heat energy and minimal power requirement; environmental friendly (Mosier *et al.*, 2005); lignin and other compositions must be recovered and used to convert them into valuable products; the downstream costs must be manageable; and show potentiality for large-scale industrial application. However, following every single aspect can be very challenging. Therefore, combining the merits of different pretreatments has proven to be efficient. Every treatment uses physical or mechanical treatments as a preliminary technological step. This pretreatment uses mechanical force to break the primary cell wall, making cellulose more accessible. As a result, specific surface area increases, and crystallinity decreases, which overall increases the efficiency

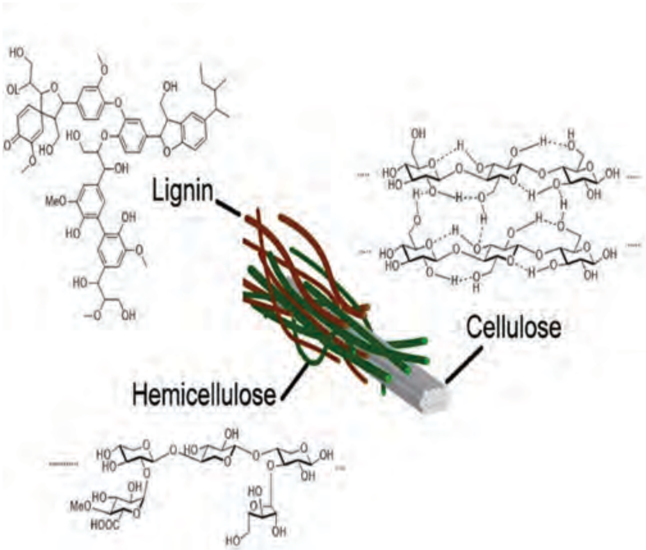

Fig. 1. Chemical structures of cellulose, hemicellulose, and lignin, illustrating their functional groups that enable diverse bio-based applications (Source: Li and Takkellapati, 2018)

PRETREATMENT OF LIGNOCELLULOSIC BIOMASS

PRETREATMENT OF LIGNOCELLULOSIC BIOMASS

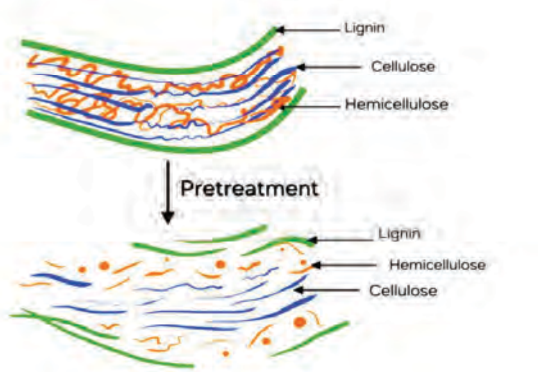

Fig. 2. Overview of pretreatment processes for LCB, highlighting physical, chemical, and biological methods to enhance cellulose accessibility

of the final process (Taherzadeh and Karimi, 2008). Chemical pretreatments have proven efficient in the elimination of lignin structures through solubilization and cleavage of the links that bound cellulose and lignin (Costa *et al.*, 2018). One widely studied method is dilute acid pretreatment that results in high hemicellulose removal, moderate lignin disruption, and enhances cellulose accessibility. However, this method can generate inhibitory compounds such as furfural and 5-hydroxymethylfurfural (HMF). This can be mitigated using detoxification techniques such as over-liming, activated carbon treatment, or enzymatic detoxification (Lloyd and Wyman, 2005). Thermal treatments are environment friendly because there is no use of chemical products. Nevertheless, they can also lead to the formation of inhibitors and requires high energy input (Sidana and Yadav, 2022). An effective approach is steam explosion combined with alkaline treatment. When applied to wheat straw, efficient delignification occurs which improves cellulose hydrolysis. Post-treatment detoxification strategies include washing, pH neutralization, and enzymatic conditioning to remove or reduce the inhibitors formed (Ballesteros *et al.*, 2006). Organosolv pretreatment, typically used for hardwood biomass, is known for its high solubilization of lignin and hemicellulose with minimal sugar degradation generating fewer fermentation inhibitors. Detoxification is done by using low temperature distillation to eliminate volatile inhibitors and recover solvents (Pan *et al.*, 2006). Ammonia fiber expansion (AFEX) is a pretreatment that works particularly well on corn stover by reducing lignin recalcitrance, and generating fewer inhibitors. Unlike many chemical pretreatments, AFEX has a built-in detoxification advantage as the ammonia used can be recovered and reused (Teymouri *et al.*, 2005).

Biological pretreatment is of significant importance because they have low operating costs, can be easily installed and are eco-friendly. The generation of inhibitors is inherently low in biological treatments (Wan and Li, 2012). The microbial enzyme systems produced mainly by fungi and bacteria to catalyze the depolymerization of LCB into fermentable sugars and aromatic building blocks are collectively called lignocellulolytic enzymes. They are broadly classified into hydrolytic enzymes (cellulases, hemicellulases, pectinases and amylases) and oxidative ligninolytic enzymes (laccases and peroxidases). White-rot fungi such as *Phanerochaete chrysosporium*, *Trametes versicolor* and *Pleurotus ostreatus* secrete oxidative enzymes like laccases, manganese peroxidases (MnP), lignin peroxidases (LiP) and versatile peroxidases (VP) which possess the ability to mineralize lignin completely making them highly valuable for biotechnological applications (Andlar *et al.*, 2018). Brown-rot fungi such as *Postia placenta* and *Gloeophyllum trabeum* are efficient cellulose degraders. They use a chelator-mediated Fenton (CMF) reaction, involving oxalic acid, Fe^{2+}/Fe^{3+} cycling, and H_2O_2 to generate hydroxyl radicals that can cleave cellulose chains (Andlar *et al.*, 2018) without extensive enzyme secretion. Many actinobacteria and thermophilic bacterial strains from compost, soil, and rumen environments possess potent lignocellulolytic capabilities (Chukwuma *et al.*, 2020). *Clostridium thermocellum* has the ability to form complex enzyme systems like cellulosomes. Thus, the integration of various pretreatment techniques could be utilized to reduce inhibitors, water and energy consumption and minimize solid waste generation (Fig. 3).

Inhibitors generated during various pretreatments such as furfural, 5-hydroxymethylfurfural (HMF), acetic acid, formic acid, and phenolic compounds significantly affect the fermentation efficiency by interfering with microbial growth and metabolism (Fig. 2). Furfural and 5-HMF inhibit key enzymes like alcohol dehydrogenase and pyruvate dehydrogenase in the glycolytic pathway. This may lead to reduced ethanol production (Modig *et al.*, 2002). Phenolic compounds can disrupt microbial cell membranes. Acetic acids and formic acids lower the intracellular pH and disrupt membrane integrity (Almeida *et al.*, 2007) utilizing microorganisms such as *Aspergillus niger* to biologically detoxify acid hydrolysates (Yin *et al.*, 2023). *Kurthia huakuii*, a bacterial strain could tolerate high concentrations of furfural and vanillin (Wang *et al.*, 2024).

APPLICATIONS OF LCB IN A CIRCULAR ECONOMY

Cellulose is a polysaccharide that provides a structural framework. It can be converted into biofibers, bio-based polymers, and glucose for

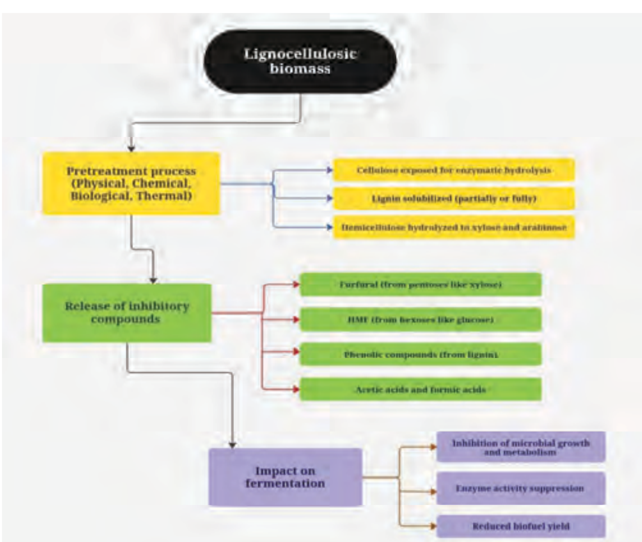

Fig. 3. **Flowchart illustrating how inhibitor formation after pretreatment of ligonocellulosic biomass can impact fermentation and subsequent biofuel production**

biofuel production. Nanocellulose extracted from wood pulp has been used to create lightweight, strong materials for automotive and aerospace applications (Klemm *et al.*, 2011). Hemicellulose is a heteropolysaccharide that acts as a binder, serving as precursor for producing xylitol, furfural, and other bio-based chemicals. Hemicellulose from wheat straw has been utilized to produce biodegradable films for food packaging (Sun *et al.*, 2002). Lignin is an aromatic polymer that imparts rigidity and resistance to microbial degradation. Lignin can be valorized into phenolic compounds, adhesives, and carbon-based materials. Kraft lignin from the paper industry is being explored as a precursor for carbon fiber production (Azadi *et al.*, 2013). Cellulose, hemicellulose and lignin can be valorized into high value products and used in a wide range of processes.

The effective microbial enzymatic conversion of LCB into fermentable sugars and platform chemicals is central to advancing biofuel and bioproduct manufacturing, enhances bioremediation, waste valorization, and eco-friendly industrial processes across textiles, paper, and food sectors (Andlar *et al.*, 2018; Chukwuma *et al.*, 2020). LCB conversion pathways for bioenergy are diverse (Fig. 4). Cellulases play a pivotal role in the enzymatic saccharification of LCB, converting cellulose into glucose for second generation ethanol production. They are also widely utilized in industrial biotechnology. Hemicellulases are used for their thermal and pH stability making them highly sought after in enzyme formulations for biofuels and green chemistry. Laccases are members of the multicopper oxidase family, whose broad substrate specificity and use of oxygen as the terminal electron acceptor make them extremely attractive for various industries (Chukwuma *et al.*, 2020). Lytic Polysaccharide Monooxygenases (LPMOs) are copper-dependent oxidative enzymes that enhance the action of cellulases and hemicellulases by introducing chain breaks in crystalline and amorphous polysaccharides, boost sugar release efficiency in lignocellulose hydrolysis (Østby *et al.*, 2020). The ability of pectinases to depolymerize complex pectin polymers under mild conditions makes them valuable in biowaste management and enzyme-assisted extraction of valuable plant-based compounds. Proteases catalyze protein hydrolysis into peptides and amino acids, serving both nutritional and industrial purposes. Esterases hydrolyze ester bonds and are employed in environmental remediation where they degrade pollutants like phthalates and plasticizers (Chukwuma *et al.*, 2020).

Table 3. **Applications of various enzymes produced by fungi and bacteria that can act on LCB**

Enzyme type	Industrial/Biotechnological applications	References
Cellulases	Bioethanol production, biobleaching in paper and pulp industry, bio-polishing in textiles to increase fabric softness, animal feed enhancement, detergents.	Chukwuma *et al.* (2020), Østby *et al.* (2020)
Hemicellulases	Fruit juice clarification, bread making, xylitol production, textile degumming.	Chukwuma et al. (2020) Østby *et al.* (2020)
Laccases	Lignin degradation, textile dye removal, degradation of pesticides, pharmaceuticals, and endocrine disruptors in contaminated soils and water systems.	Chukwuma *et al.* (2020) Østby *et al.* (2020)
Peroxidases	Biobleaching, industrial effluent detoxification, biosensors for detecting glucose, hydrogen peroxide and xenobiotics, cosmetics, food preservation.	Chukwuma *et al.* (2020)
LPMOs	Enhanced cellulose hydrolysis via oxidative cleavage, synergistic enzyme systems, bioethanol production.	Østby *et al.* (2020) Andlar *et al.* (2018)
Pectinases	Fermentation in food and beverage industry, wine production and stabilization, retting and degumming of fibers.	Chukwuma *et al.* (2020)
Chitinases	Biocontrol agents, seafood waste treatment, biomedical chitooligosaccharide production	Chukwuma *et al.* (2020) Andlar *et al.* (2018)
Amylases	Baking, brewing, starch liquefaction, textile desizing, detergents	Chukwuma *et al.* (2020)
Proteases	Leather bating, food fermentation, pharmaceuticals (wound healing, anti-inflammatory), detergent formulations	Chukwuma *et al.* (2020)
Esterases	Textile processing, flavor, biocatalysis, organic synthesis, pulp and paper treatment.	Chukwuma *et al.* (2020)

Fig. 4. **Conversion pathways for LCBs into bioethanol, biogas, biohydrogen, bio-oil, electricity**

A concise account of various other applications of lignocellulolytic enzymes are summarized in Table 3.

LCBs AS BIOFUELS

Second-generation biofuels represent an advanced class of renewable fuels derived from non-food biomass sources such as LCB, agricultural residues, algae, etc. The utilization of agricultural waste as feedstock for bioethanol production presents a promising avenue for sustainable bioenergy production and waste valorization. Bioethanol from crop residues contributes to waste reduction, resource efficiency, rural development, and greenhouse gas mitigation objectives. Its production involves enzymatic hydrolysis of cellulose and hemicellulose into fermentable sugars, followed by microbial fermentation. Biogas is another significant product which utilizes anaerobic digestion to produce biomethane and biohydrogen, presenting a low-carbon alternative for energy applications (Banu *et al.*, 2021). Addressing technological, logistical, and policy challenges is essential to realize the full potential of agricultural waste bioethanol and advance towards a more sustainable and circular bioeconomy. The transesterification of lipids derived from LCB or oleaginous microorganisms cultivated on LCB-derived substrates results in the conversion of fats and oils into a renewable substitute biodiesel and its coproduct glycerin. Research on genetic engineering of microbial strains is being explored to improve the lipid yields (Uthandi *et al.*, 2022).

LCBs AS BIOPLASTICS AND BIOCOMPOSITES

Synthetic polymers like polyethylene, nylon, polyester, polytetrafluoroethylene, etc has been in use for decades now due to their versatility, however their resistance to degradation makes them a threat to the environment. Concerns worldwide regarding their massive use and waste generation gave birth to the quest for reduced dependency on petroleum based polymers and increased attention to biofibers or biopolymers which are degradable, also referred to as biocomposites or green composites. The potential of agricultural wastes (LCB) in producing green composites which will enhance recycling practices and policies have attracted the interests of many. LCB-based composites, incorporating cellulose fibers or lignin, offer enhanced mechanical properties and environmental benefits. These materials are employed in automotive parts, construction, and 3D printing (Usmani *et al.*, 2021). Green reinforcement materials, commonly known as biofibers derived from plants can be classified as wood based or agricultural biomass based, which are used in diverse polymer composites (Nagalakshmaiah *et al.*, 2019). Green polymer matrices or bioplastics are classified into three categories: renewable source (polylactic acid, polyhydroxyalkanoates, cellulose based or protein based plastics), mixed source (polyesters and thermosets) and fossil fuel-based source (polyvinyl alcohol, aliphatic or aromatic polyesters). Cellulose and lignin are capable to produce nanocomposite films having a variety of properties. PLA is considered the most promising biodegradable material in recent times (Yang *et al.*, 2007). Thus, innovations in processing agricultural residues have enabled cost-effective bioplastic production, with applications spanning packaging, textiles, and medical devices (Kawaguchi *et al.*, 2022). However, incorporation of biocomposites in thermoplastic polymers also has challenges like compatibility issue between hydrophilic cellulose and hydrophobic polymers, sensitivity to moisture, low thermal stability and agglomeration (Nagalakshmaiah *et al.*, 2019).

LCBs AS BIOPESTICIDES AND BIOFERTILIZERS

Chemical pesticides used in modern agriculture pose serious risks to ecosystems, while overuse of chemical fertilizers has led to soil degradation (Aktar *et al.*, 2009). Biopesticides derived from LCB offer an eco-friendly alternative, leveraging natural microbial processes to control pests (Kumar *et al.*, 2021). Utilizing LCB as a raw material aligns with the principles of the circular economy (Tuck *et al.*, 2012). *Bacillus thuringiensis* and *Pseudomonas fluorescens* are commonly used for fermenting lignocellulosic substrates such as rice husks, sugarcane bagasse, and wheat straw, which serve as cost-effective feedstocks (Chakraborty *et al.*, 2022). Enzymatic hydrolysis helps in releasing fermentable sugars, supporting microbial growth and metabolite production (Himmel *et al.*, 2007). Bt-based formulations target specific pests like moths and beetles (Bravo *et al.*, 2011). Biopesticides also combat fungal pathogens such as *Fusarium* and *Alternaria* species (Pal and Gardener, 2006). Residual biomass enhances microbial diversity in soils and improves soil health (Liu *et al.*, 2020).

LCBs AS BIOPHARMACEUTICALS

Biopharmaceuticals, including therapeutic proteins, vaccines, and monoclonal antibodies, are critical components of modern healthcare. Traditionally, their production relies on microbial or mammalian cell culture systems, often dependent on resource-intensive processes. The integration of LCB into biopharmaceutical production offers a renewable and cost-effective alternative that reduces reliance on finite resources (Saratale *et al.*, 2021). Biopharmaceuticals constitute 20% of the global pharmaceutical market (Evaluate Pharma, 2022). Cellulose and Hemicellulose hydrolysates derived from LCB provide a carbon-rich substrate for microbial fermentation. Engineered microorganisms, such as *Escherichia coli*, *Saccharomyces cerevisiae*, and *Pichia pastoris* can utilize these substrates to produce recombinant proteins (Li *et al.*, 2018; Ahmad *et al.*, 2014). Examples include enzymes used as active pharmaceutical ingredients (APIs), such as lipases and proteases and therapeutic proteins like insulin analogs and growth hormones (Demain and Vaishnav, 2009).

CASE STUDIES OF CIRCULAR ECONOMY MODELS FROM AROUND THE WORLD

Companies like DSM and Dyadic have pioneered the development of enzymes with high performance and efficiency that aids in the hydrolysis step of processing LCB for applications in biofuel production (Table 4). Cutting-edge enzymes such as thermostable variants have lowered down production costs (Demain and Vaishnav, 2009; Kumar *et al.*, 2016). Iogen Corporation promotes carbon neutral fuel production technology by turning agricultural residues (wheat straw and corn stover) into clean fuels like drop-in renewable transportation fuels. It follows a unique process of converting renewable natural gas into renewable hydrogen and inserting it into gasoline, diesel and jet fuel. This technology aims to reduce the life-cycle of carbon emissions of automobiles and power a Net Zero world (Iogen Corporation, 2024). NatureWorks LLC are known for manufacturing Ingeo brand Polylactic Acid (PLA) and lactides from annually renewable feedstocks which is a low-carbon alternative to petrochemical based plastics and fibers. These biopolymers have significant applications in sustainable packaging solutions in food service and consumer goods contributing to circular economy pathways (NatureWorks LLC, 2024). Avantium is a Dutch company that has developed novel technologies for the conversion of lignocellulosic sugars into Furandicarboxylic Acid (FDCA), a key monomer in the production of 100% renewable Polyethylene Furanoate (PEF) plastics, used in bottles and textiles. They also lead initiatives in electrochemical conversion of CO_2 into valuable chemicals like Poly(lactic-co-glycolic acid) (PLGA) polymer. PLGA is used in drug delivery, bone regeneration and tissue engineering (Avantium, 2024). GranBio is a Brazilian company manufactures nanocellulose from plant cells and also has a flagship facility Bioflex 1 which produces 82 million litres of cellulosic ethanol annually from sugarcane straw (GranBio, 2024). Clariant's 'sunliquid®' technology converts regionally sourced agricultural residues into advanced bioethanol. This process is divided into four sections, the first being the shredding of straw and thermal pretreatment, secondly enzyme addition for liquefication and splitting of celluloses and hemicelluloses into different fermentable sugar types, while the insoluble lignin is separated to generate energy used to operate the cellulosic ethanol production plant, thirdly the C5 and C6 sugars fermented simultaneously in a one-pot reaction and a highly optimized purification is the final step that yields pure ethanol. Clariant's technology has been adopted in plants across Europe and is now being implemented in Asia (Clariant, 2024; Sugar Asia, 2024). Lenzing is an Austrian company that produces TENCEL™ fibers from natural wood pulp, while their REFIBRA™ technology uses cotton textile waste as raw material. Their innovative closed-loop production processes recycle chemicals and water, abiding by circular economy principles, resulting in close-to-zero wastage. These fibers have a high tenacity profile, adaptive to skin temperature and efficient in regulating moisture are used in clothing and hygiene products (Lenzing, 2024). Anellotech's Bio-TCat™ process converts non-food biomass into aromatics like benzene, toluene, and xylene, essential for producing plastics and synthetic fibers. Their partnership with global corporations has paved the way for bio-based chemicals to enter mainstream supply chains (Anellotech, 2024). Indian Oil Corporation (IOC) has set up a second-generation ethanol plant in Panipat, Haryana which utilizes paddy straw to produce ethanol. This initiative has addressed the problem of stubble burning and contributed to reducing air pollution while converting agricultural waste into renewable energy (Indian Oil Corporation, 2024). Praj Industries in Pune uses feedstocks like rice and wheat straw, sugarcane bagasse, rice husk, cotton stalk, empty fruit bunches etc to produce second-generation (2G) bioethanol and waste water management to meet zero process liquid discharge (Praj Industries, 2024). The Biomass Programme under Ministry of New and Renewable Energy refers to an initiative to support manufacturing

Table 4. Comparative overview of global case studies utilizing LCBs for biofuels, bioplastics, and bioenergy for a sustainable economy

Initiatives by companies	Technological Innovation	Sustainability Impact	Scalability and Adoption
Enzyme Development (DSM, Dyadic)	Advanced enzyme engineering (thermostable cellulase) enables low-cost biomass conversion	Supports low-energy biofuel pathways	Widely adopted in biorefineries
Fuel Innovation (Iogen, GranBio, Clariant, IOC, Praj)	Multiple feedstock use, C5/C6 fermentation, hydrogen integration	Reduces carbon intensity, addresses air pollution	Demonstrated commercial scale; some tech exported globally
Bioplastics (NatureWorks, Avantium, Anellotech)	Green chemistry, sugar-to-FDCA, CO_2 conversion	Reduces fossil-derived plastic dependency	PLA and FDCA are gaining adoption but facing cost competition
Fiber/Textile (Lenzing)	Closed-loop chemical recycling, moisture adaptive fibers	Aligns with circular fashion, reduces textile waste	Scaling across textile markets worldwide
Decentralized/Rural Bioenergy (TERI, Himachal Initiative)	Gasification technology, pelletization	Provides rural access to clean energy	Effective at community level, not yet industrial scale
Government Support (MNRE Programme)	Policy-driven infrastructure development	Drives rural employment, cleaner industrial fuels	Dependent on sustained government incentives

of briquettes and pellets and promotion of biomass (non-bagasse) based cogeneration in industries (Ministry of New and Renewable Energy (MNRE), 2024). Biomass Briquetting Project refers to the collection, processing and compression of agricultural and forest waste such as straws, husks, sawdust, peanut shells, etc into solid briquettes that are used as renewable fuel source for co-firing in thermal power-plants and serves as alternatives to coal for industrial energy gains. Himachal Pradesh Bioenergy Initiative promotes biomass gasification technology, adopted to convert forest residues into electricity and heat. This project supports rural electrification and sustainable management of forests. The Energy and Resources Institute (TERI) has implemented biomass gasification systems in rural parts of India to produce decentralized energy from crop residues and wood waste (TERI, 2023).

CONCLUSION

Eco-innovation is vital for achieving a sustainable future. LCB is not merely an underutilized waste but a cornerstone resource for building a bio-based, low-carbon future. The valorization of LCBs present a transformative pathway for achieving sustainable development across multiple sectors including biofuels, bioplastics, biopharmaceuticals and bioenergy. As technologies mature and integration improves, the circular bioeconomy envisioned today could become the foundation of future sustainable industries. By addressing challenges and leveraging advancements, the integration of bio-based materials into circular economy models can significantly reduce environmental impacts and promote economic growth. A better understanding of lignocellulolytic enzyme systems and their integration with pretreatment technologies, the biochemical pathways of inhibition and implementing detoxification strategies can significantly advance biomass valorization. Emerg-ing tools in redox biology, synthetic biology, and enzyme engineering offer a pathway to economically viable and ecologically sustainable LCB biorefineries. This review highlights the need for continued innovation and collaboration to recognize the potential of bio-based materials in achieving a sustainable future.

Conflict of interests

The authors declare that they have no conflict of interests.

LITERATURE CITED

Ahmad M, Hirz M, Pichler H and Schwab H 2014. Protein expression in *Pichia pastoris*: Recent achievements and perspectives for heterologous protein production. *Appl Microbiol Biotechnol* **98**(12): 5301-17.

Aktar W, Sengupta D and Chowdhury A 2009. Impact of pesticides use in agriculture: their benefits and hazards. *Inter Toxicol* **2**(1): 1-12.

Almeida J R M, Modig T, Petersson A, Hahn-Hagerdal B, Liden G and Gorwa-Grauslund M F 2007. Increased tolerance and conversion of inhibitors in lignocellulosic hydrolysates by *Saccharomyces cerevisiae*. *J Chem Technol Biol* **82**(4): 340-49.

Alvira P, Tomas-Pejo E, Ballesteros M and Negro M J 2010. Pretreatment technologies for an efficient bioethanol production process based on enzymatic hydrolysis: A review. *Bioresour Technol* **101**(13): 4851-61.

Andlar M, Rezic T, Marđetko N, Kracher D, Ludwig R and Santek B 2018. Lignocellulose degradation: An overview of fungi and fungal enzymes involved in lignocellulose degradation. *Eng Life Sci* **18**: 768-78.

Anellotech 2024. *Bio-TCat™ technology overview*. Retrieved from https://www.anellotech.com

Avantium 2024. *Our technologies*. Retrieved from https://www.avantium.com

Azadi P, Inderwildi O R, Farnood R and King D A 2013. Liquid fuels, hydrogen and chemicals from lignin: A critical review. *Renew Sustain Energy Rev* **21**: 506-23.

Ballesteros I, Oliva J M, Manzanares P, Ballesteros M and Negro M J 2006. Ethanol production from steam-explosion pretreated wheat straw. *Appl Biochem Biotechnol* **130**(1-3): 496-508. https://doi.org/10.1385/ABAB:130:1:496

Banu J R, Kavitha S, Yukesh Kannah R, Preethi V, Gunasekaran M and Yogalakshmi K N 2021. Impact of lignocellulosic biomass pretreatment on biogas and biohydrogen production: A review. *Bioresour Technol* **323**, 124598.

Binod P, Sindhu R, Singhania R R, Vikram S, Devi L, Sukumaran R K and Pandey A 2010. Bioethanol production from rice straw: An overview. *Bioresour Technol* **101**(13): 4767-74.

Bravo A, Likitvivatanavong S, Gill S S and Soberon M 2011. *Bacillus thuringiensis*: A story of a successful bioinsecticide. *Insect Biochem Mol Biol* **41**(*7*): 423-31.

Chakraborty M, Das S, Chatterjee A and Dey R 2022. Production of microbial biopesticides using agro-waste as substrate: A sustainable approach. *Bioresour Bioprocess* **9**: 1-15.

Chukwuma O B, Rafatullah M, Tajarudin H A and Ismail N 2020. Lignocellulolytic enzymes in biotechnological and industrial processes: A review. *Sustainability* **12**: 7282.

Clariant 2024. *Sunliquid® technology*. Retrieved from https://www.clariant.com

Costa S, Rugiero I, Larenas Uria C, Pedrini P and Tamburini E 2018. Lignin degradation efficiency of chemical pre-treatments on banana rachis destined to bioethanol production. *Biomolecules* **8**: 141, doi: 10.3390/biom8040141

Demain A L and Vaishnav P 2009. Production of recombinant proteins by microbes and higher organisms. *Biotechnol Adv* **27**(3): 297-306.

Evaluate Pharma 2022. *EvaluatePharma® World Preview 2022, Outlook to 2028*. Evaluate Ltd. https://www.evaluate.com

GranBio 2024. *Bioflex 1 cellulosic ethanol plant*. Retrieved from https://www.granbio.com.br

Hendriks A T W M and Zeeman G 2009. Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresour Technol* **100**(1): 10-8. doi: 10.1016/j.biortech.2008.05.027

Himmel M E, Ding S Y, Johnson D K, Adney W S, Nimlos M R, Brady J W and Foust T D 2007. Biomass recalcitrance: engineering plants and enzymes for biofuels production. *Sci* **315**(5813): 804-807. doi: 10.1126/science.1137016

Indian Oil Corporation 2024. *2G Ethanol Plant Panipat*. Retrieved from https://iocl.com

Iogen Corporation 2024. Fueling the movement to net zero. Retrieved from https://www.iogen.com

Kawaguchi H, Hasunuma T, Ogino C and Kondo A 2022. Bioplastic production from lignocellulosic biomass. *Cur Opin Biotechnol* **73**: 69-75.

Klemm D, Heublein B, Fink H P and Bohn A 2011. Cellulose: Fascinating biopolymer and sustainable raw material. *Ange Chem Int Edi* **44**(22): 3358-93.

Kumar R, Singh S and Singh O V 2008. Bioconversion of lignocellulosic biomass: Biochemical and molecular perspectives. *J Ind Microbiol Biotechnol* **35**: 377-91.

Kumar P, Barrett D M, Delwiche M J and Stroeve P 2009. Methods for pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. *Ind Eng Chem Res* **48**(8): 3713-29.

Kumar R, Tabatabaei M, Karimi K and Sarvari Horvath I 2016. Recent updates on lignocellulosic biomass derived ethanol-A review. *Biof Res J* **3**(1): 347-56.

Kumar S, Singh J, Giri D D and Pandey S 2021. Lignocellulose-based biopesticides: An emerging sustainable alternative. *Sustain Chem Pharma* **20**, 100390.

Lenzing A G 2024. *TENCEL™ and REFIBRA™ Technologies*. Retrieved from https://www.lenzing.com

Li T and Takkellapati S 2018. The current and emerging sources of technical lignins and their applications. *Biofuels Bioprod Biorefining* **12**(5): 756-87.

Li Y, Zhao Z and Bai F 2018. High-density cultivation of *Saccharomyces cerevisiae* in lignocellulose hydrolysate for recombinant protein production. *Bioresour Technol* **247**: 804-10.

Liu Q, Li H, Zhang Y, Zhou X and Gong P 2020. Soil microbial diversity and community composition response to different long-term fertilization regimes. *Appl Soil Ecol* **154**, 103635.

Lloyd T A and Wyman C E 2005. Application of a depolymerizing enzyme mixture to convert biomass to sugars. *Bioresour Technol* **96**(18): 1967-77.

Ministry of New and Renewable Energy (MNRE) 2024. *Biomass Programme*. Retrieved from https://www.mnre.gov.in

Modig T, Liden G and Taherzadeh M J 2002. Inhibition effects of furfural on alcohol dehydrogenase, aldehyde dehydrogenase and pyruvate dehydrogenase. *Biochem J* **363**(3): 769-76.

Mosier N, Wyman C, Dale B, Elander R, Lee Y Y, Holtzapple M and Ladisch M 2005. Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresour Technol* **96**(6): 673-86.

Mujtaba M, Fraceto L F, Fazeli M, Mukherjee S, Savassa S M, Medeiros G A. ... and Vilaplana F 2023. Lignocellulosic biomass from agricultural waste to the circular economy: A review with focus on biofuels, biocomposites and bioplastics. *J Clean Prod* **402**, 136815.

Nagalakshmaiah M, Chakraborty S and Djafari Petroudy S R 2019. A review on biocomposites:

From plant-based fibers to advanced green composites. *Comp Part A: Appl Sci Manuf* **123**, 105121.

NatureWorks LLC 2024. Ingeo™ biopolymer information. Retrieved from https://www.natureworksllc.com

Østby H, Hansen L D, Horn S J, Eijsink V G H and Várnai A 2020. Enzymatic processing of lignocellulosic biomass: Principles, recent advances and perspectives. *J Ind Microbiol Biotechnol* **47**: 623-57.

Pal K K and Gardener B M 2006. Biological control of plant pathogens. *The Plant Health Instructor* 6.

Pan X, Gilkes N, Kadla J, Pye K, Saka S, Gregg D ... and Saddler J 2006. Bioconversion of hybrid poplar to ethanol and co-products using an organosolv fractionation process: Optimization of process yields. *Biotechnol Bioeng* **94**(5): 851-61.

Poovaiah C R, Nageswara-Rao M, Soneji J R, Baxter H, Stewart C N and Mazarei M 2014. Altered lignin biosynthesis using biotechnology to improve lignocellulosic biofuel feedstocks. *Plant Biotechnol J* **12**(9): 1163-73.

Praj Industries 2024. Sustainable biofuel and water solutions. Retrieved from https://www.praj.net

Ragauskas A J, Williams C K, Davison B H, Britovsek G, Cairney J, Eckert C A, ... and Tschaplinski T 2006. The path forward for biofuels and biomaterials. *Science* **311**(5760): 484-89.

Saratale R G, Banu J R, Cho S K, Kim D S and Saratale G D 2021. Bioconversion of lignocellulosic biomass to biopharmaceuticals: Recent trends and challenges. *Bioresour Technol* **340**, 125693.

Sidana R and Yadav S K 2022. Thermal pretreatment strategies for lignocellulosic biomass. *Renew Energy* **195**: 355-65.

Sluiter A, Hames B, Ruiz R, Scarlata C, Sluiter J, Templeton D and Crocker D 2010. Determination of structural carbohydrates and lignin in biomass. *NREL Laboratory Analytical Procedure*. NREL/TP-510-42618.

Sugar Asia 2024. Sunliquid® Technology in Asia. Retrieved from https://www.sugar-asia.com

Sun R, Tomkinson J and Ma X 2002. Hemicellulose-based biodegradable films for food packaging. *Carbohydr Polym* **49**(4): 389-400.

Sun S N, Li M F, Yuan T Q and Xu F 2016. Structural variation of lignin and its impact on enzymatic hydrolysis of lignocellulosic biomass. *Bioresour Technol* **199**: 77-83.

Taherzadeh M J and Karimi K 2008. Pretreatment of lignocellulosic wastes to improve ethanol and biogas production: A review. *Int J Mol Sci* **9**(9): 1621-51.

TERI 2023. Decentralized biomass gasification initiatives. Retrieved from https://www.terriin.org

Teymouri F, Laureano-Perez L, Alizadeh H and Dale B E 2005. Ammonia fiber expansion (AFEX) pretreatment of softwood. *Appl Biochem Biotechnol* **121-124**: 1219-31.

Tuck C O, Perez E, Horvath I T, Sheldon R A and Poliakoff M 2012. Valorization of biomass: Deriving more value from waste. *Science* **337**(6095): 695-99.

Usmani Z, Sharma M, Gupta V K and Bhat R 2021. Lignocellulosic biomass-based bioeconomy: The role of bioplastics and biocomposites. *Curr Res Green Sustain Chem* **4**, 100201.

Uthandi S, Mageswari A and Sadasivam S K 2022. Engineering microbial platforms for sustainable biodiesel production from lignocellulosic biomass. *Biotechnol Adv* **59**, 107977.

Wan C and Li Y 2012. Fungal pretreatment of lignocellulosic biomass. *Biotechnol Adv* **30**(6): 1447-57.

Wang H, Zhu S, Elshobary M, Qi W, Wang W, Feng P, Wang Z and Qin L 2024. Enhancing detoxification of inhibitors in lignocellulosic pretreatment wastewater by bacterial Action: A pathway to improved biomass utilization. *Bioresour Technol* **410**, 131270.

Yang S, Wu Z, Wang Y and Sun W 2007. Preparation and characterization of PLA-lignin bio-composite films. *Poly-Plast Technol Eng* **46**(8): 819-24.

Yin J, Wang C, Li Y, Lv B, Lv H, Xue Y, Wu J and Zhang J 2023. Biological detoxification of the inhibitors in corncob acid hydrolysate using *Aspergillus niger*. *Fermentation* **9**(9): 854.

Zhang Y, Liu R, Wang J and Zhang S 2018. Comparative study on composition and structure of lignin from different regions of wheat straw. *Int J Biol Macromol* **106**: 1090-97.