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INVITED COMMENTARY

# Recent Advancements in the Life Cycle Analysis of Lignocellulosic Biomass

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## Abstract

**Purpose of Review** In context of progressive depletion of fossil fuel assets along with an accelerating rise in global energy consumption and greenhouse gas (GHG) emissions, energy production from bio-renewable and sustainable sources has gained great significance. Lignocellulosic biomass, abundantly available and inexpensive feedstock, provides incredible potential as raw materials for the large-scale production of biofuels.

**Recent Findings** It is meaningful to estimate the environmental footprints from cradle-to-grave to determine the optimal biofuel strategies. Life cycle assessment (LCA) is an integrative approach incorporating the economic and ecological impacts in a production chain and has been widely adopted to a large number of renewable energy production systems. It provides a comprehensive insight into the interactions between the environment and anthropogenic activities and thus implementing successful strategic planning. Life cycle or cradle to grave assessment approach of lignocellulosic biomass briquettes holds significant importance to evaluate the influence of bioproduction processes.

**Summary** This review briefly presents the significance of lignocellulosic biomass as a potentially attractive feedstock for biofuels production. Particular emphasis has been devoted to analyze the entire life cycle analysis of bioprocess, including different pre-treatment processes employed in biofuels production, that is necessary to achieve its practical implementation.

**Keywords** Life cycle assessment · Lignocellulosic biomass · Pre-treatment · Biofuels · Greenhouse gas emissions

## Introduction

With an accelerating rise in scientific knowledge and worldwide environmental footprints including energy security, economic aspects, climate change, elimination of contaminants, and by-products, the value of lignocellulosic-based biomass (agricultural waste residues or feedstock, agro-industrial wastes, and energy crops) has prominently increased in the recent years [1–3]. Noteworthy attributes such as sustainability, bio-renewability, natural abundance round the year, and recyclability make lignocellulosic *biomass as* petro-alternative and *eco*-friendly *materials* for biofuel production [4••]. In the wake of increasing trends for sustainable energy production and the bioethanol use as a transporting fuel, lignocellulosic ethanol production has garnered exceptional interest in global industrial research as an attractive and a green solution. Lignocelluloses encompass most of the total biomass present in the biosphere in the form of industrial, forest, and agricultural residues [5, 6]. Bioethanol not only diminishes dependence on the imported oil and relieves uncertainties in oil prices but also ensures the mitigation of environmental concerns because of its elevated oxygen content. In a report, Kim and Dale [7] revealed the abundant availability of lignocellulosic biomass from crops to convert into bioethanol in Europe, Asia, and North America. However, a comprehensive assessment from "cradle to grave" should be deliberately conducted to ascertain investments in energy and determine the release of green gas emissions from bioethanol production and consumption process. In this avenue, LCA methodology is usually employed that involves inputs and associated emissions from the bioproduction process accompanied by the

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product fate to identifying possible developments in the manufacturing process (Fig. 1).

## Lignocellulosic Biomass and Compositional Analysis

Lignocellulosic waste is regarded as the principal constituent of bi-renewable resources on the earth and is composed of three main components, including lignin (15–20%), hemicelluloses (25–30%), and cellulose (40–50%) [8]. Cellulose is the major polysaccharide as a component of lignocellulosic biomass. It contains hundred to over ten thousand β-1, 4 linked D-glucose monomer units in the form of unbranched straight chains known as micro-fibrils that are 3–5 nm in width with several micrometers in length. All cellulose chains are connected alongside via van der Waals interfaces and hydrogen bonding into the micro-fibrils arrangement, which is known to contain 24 to 36 chains [9]. Hemicellulose mainly containing branched polysaccharide (mannans and xylans) is organized as strips firmly connected with complex lignin polymer and cellulose polymers in the cell walls of plants. Hemicellulose is a heterogeneous polysaccharide of pentose (arabinose and xylose), hexoses (galactose, glucose, and mannose), and acidic sugars (e.g., galacturonic acid, acetic acid, and glucuronic acid) [10]. Hardwoods contain xylans (15–30% dry weight) as the major hemicelluloses, a polymer of D-xylose units linked through β-1,4 bonds, which might be replaced with other monosaccharides. On the other hand, softwood comprised of hemicelluloses predominantly galactoglucomannan (15–20% of dry mass), a polysaccharide D-glucose, and D-galactose components combined by β,1–4 bond [11].

Likewise, lignin is a complex and most plentiful naturally occurring biopolymer. However, it exhibits very poor biodegradability because of intricate chemical attachment between its monomeric units resulting in the recalcitrant component of lignocellulosic biomasses [12]. Lignin is made up of phenylpropane entities, which is produced by radical polymerization of syringyl units (S), guaiacyl units (G), and p-hydroxyphenyl units (H) from precursor compounds coniferyl, sinapyl, and p-coumaryl alcohol [6]. It is categorized by the presence of an aromatic polymer (high molecular weight) that contains many ester or ether linkages. The cellulose micro-fibrils are embedded in a multifarious milieu comprising lignin and hemicellulose that hinder the accessibility of hemicellulases and cellulases [10]. Due to its high recalcitrance, the deconstruction of lignocellulosic-based agro-industrial materials imports a significant hindrance to economic, sustainable, and environmental development. The simplified sustainability concept is shown in Fig. 2 [13]. The massive generation and buildup of lignocellulosic waste materials from

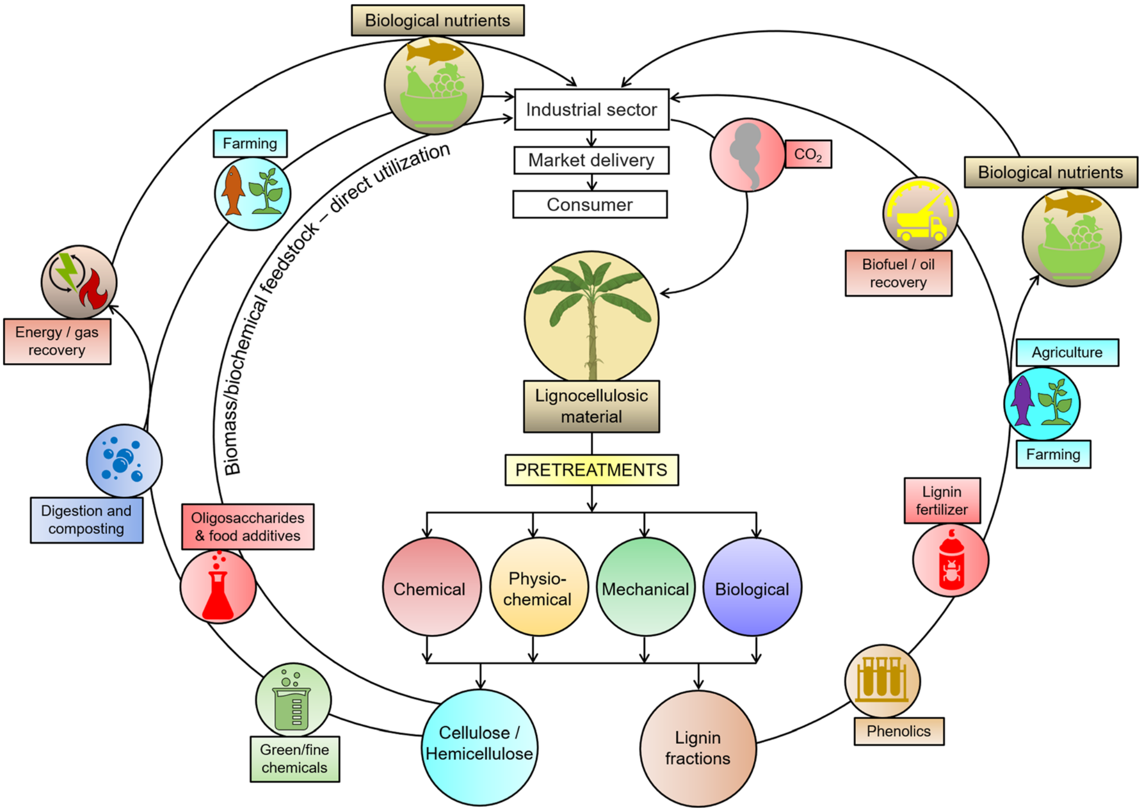

**Fig. 1** Life cycle approach perspective for lignocellulosic material as a resource for the bioproduction process accompanied by the product fate

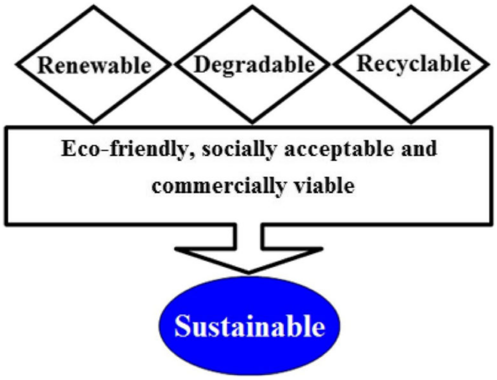

**Fig. 2** A simplified sustainability concept. Reprinted with permission from Ref. [13]

a range of agro-industrial sectors including agricultural waste (200 billion tons/year), sugarcane molasses distilleries (7.5 million tons effluent annually), pulp and paper mill (150–200 $m^3$ effluent/ton), and food industry (1.3 billion ton/year) raises many environmental problems [14–16]. All these lignocellulosic waste form complex compounds as environmental contaminants due to slower degradation and high binding capacities with other positively charged moieties. Consequently, lignocellulosic waste-based agro-industrial biomass is a paramount source of pollution to the environment [17•].

## Cradle to Grave Life Cycle Assessment of Lignocellulosic Biomass Briquettes

The lifecycle analysis is an integrative concept incorporating the economic and environmental impacts in a production chain and has been widely implemented to diverse renewable energy-based productions system. Two categories explicitly fossil consumption/depletion and carbon and GHG discharges into the environment are of increasing significance that is analyzed in LCA studies [18]. The principal purpose of life cycle analyses is to provide a comprehensive insight into the interactions between the environment and anthropogenic activities and thus implementing successful strategic planning [19]. The life cycle or cradle to grave assessment approach of lignocellulosic biomass briquettes holds significant importance to appraise the impact of bioproduction processes. Life cycle analysis of lignocellulosic biofuels implicates the assessment of various environmental factors, which affect the equilibrium of the natural ecosystem or environment and the quantification of the ecological advantages by substituting the conventional system. Moreover, it might also provide a tool for both consumers and policymakers for the determination of the ideal environmentally friendly fuel. Four distinct principles of goal description, inventory assessment, impact analysis, and interpretation are executed as the process [20]. Different inventories in the production process included raw feedstocks, pre-treatment approaches, purification process, energy production rate, and generation of waste by-products during the entire process to the formation of its final product and are appraised to carry out a LCA. It is regarded as a noteworthy environmental management practice, which is applied to identify and assess environmental aspects of a product given the requirement and guidelines of ISO 14040 and 14044 [21, 22]. The application of life cycle analysis to the biomass-based processes for bioenergy production evaluates its usefulness and environmental influence.

## Life Cycle Assessment of Lignocellulose Pre-treatments

The lignocellulosic biomass, as abundantly available and inexpensive feedstock, can be used for the industrial level production of liquid biofuels in the developing nations. Delignification (removal of lignin barrier), cellulose hydrolysis, and fermentation processes are the three major steps for the bioconversion of lignocelluloses to bioethanol production. The presence of well-known organic materials in the lignocellulosic biomass are agro-wastes, agricultural crops, wood, grass, algae, and many other bio-renewable resources [6]. Additionally, the lignocellulosic biomass including wheat straw, rice straw, sugarcane bagasse, wheat bran, woody residues, barley, paper pulps, timothy grass, softwoods, and forestry waste materials have also been widely inspected for biofuels manufacturing in the recent decades [23]. The synthesis of bio-renewable energy has a huge prospective as an intriguing source of low carbon energy that can circumvent environmental toxicity. The effective utilization of lignocellulosic biomass offers a potentially attractive and sustainable resource for bioenergy production because it is often considered as a carbon zero footprint. Nevertheless, a certain amount of GHG was generated and released during their entire life cycle. The feedstock's growth at the farming stage and its bioconversion to biofuels and transportation are regarded as the noteworthy steps accompanied by the life cycle appraisal of biofuel production.

## Key Obstacles in Lignocellulose-Based Biofuels

A vast range of lignocellulosic biomasses including food-based feedstocks (wheat, corn, sorghum, sugarcane, etc.) and non-food-based feedstocks (wheatgrass, corn Stover, sugarcane bagasse, etc.) are known to produce first- and second-generation biofuels. It is demonstrated that the production of lignocellulose-derived biofuels is less toxic and environmentally friendly than that to fossil fuel-based production approaches concerning the direct emission of GHG and carbon footprint [24]. However, apprehensions arise on indirect emanations due to plant growth and bioconversion of food into fuel. Though different grass has been utilized in various industrial sectors, however, the success rate of these industries is still a major problem [24, 25]. Furthermore, the consumption of a huge quantity of fossil fuels in downstream processing also needs to be addressed. The emissions of GHG from nitrogen fertilizers along with prerequisites of land for energy production is contemplated as the impediment in the cradle to grave exploration of ethanol produced from biomass-based feedstock's [18]. The drawback of increasing electricity consumption during the industrial processes can be dealt with the usage of sustainable and green energy sources as a replacement to fossil fuels.

## Pre-treatment Approaches and Life Cycle Analysis

Different pre-treatment approaches, namely, physical, chemical, biological, and physicochemical techniques are predominantly employed for the deconstruction of lignin. Enzyme-based pre-treatment such as LiP, MnP, and laccase have gained incredible importance in the lignocellulose conversion because of their unique properties including exquisite substrate specificity, lack of water requirement, optimal efficiency at gentle environmental conditions, and low risk of inhibitor formation [26–28]. During the saccharification process, treatment with cellulase and xylanase catalyzed the transformation of the cellulose and hemicellulose into glucose and xylose monomers [29–31]. Over the past numerous years, researchers have established a range of pre-treatment processes including mechanical (physical, irradiation, thermal, extrusion, and steam explosion), biological (bacterial, fungal, consortium, and enzymatic), and integrated methods that led to lignin removal by enhancing the substrate approachability yielding high titers of industrially pertinent bio-based products, i.e., biofuels and biogas [32]. The LCA of physicochemical pre-treatments involving steam, liquid hot water, organosolvents, and dilute acid treatment revealed that individual liquid hot water pre-treatment using pressurized-deionized water appeared very promising in decreasing the GHG emission and furnishing high sugar yields for fermentative production of biofuels [33]. In contrast to dilute alkali, acid, and liquid hot water pre-treatments, the use of steam explosion pre-treatment yielded encouraging results using rice straw as a lignocellulosic substrate. Sugarcane was efficiently pretreated to yield better sugars by applying a concerted strategy comprising NaOH (84%) and acid + NaOH (86%) [34]. Investigation of the environmental influence of different chemical reagents consumed in pre-treatment process highlighted the least impact of methanol on acidification, eutrophication, global warming, aquatic and terrestrial ecotoxicity, and biological oxidation demand, while the employment of NaOH postured the maximum adverse consequences on the ecosystem [35]. Combinatorial application of the mechanical treatment, chemical treatment (using alkaline hydrogen peroxide), and enzyme-mediated sugarcane bagasse hydrolysis led to a significant reduction in energy consumption and waste generation in comparison with classical chemical processes [36].

## Biochemical Lignocellulosic-Based Sustainable Biorefineries

The biochemical refinery processing exploits the use of microorganisms or their enzyme system for the deconstruction of lignocellulosic materials to synthesize biofuels and other valuable products. A simplified biorefinery concept is shown in Fig. 3 [4••]. Eco-friendlier and cost-efficient biological transformation of lignocellulosic biomass furnishes liquid as well as gaseous biofuels explicitly bio-ethanol and bio-hydrogen via the fermentative process [37–39]. Three distinct types of high-value compounds including cellulose (C6-sugars), hemicellulose (C5/C6-sugars), and lignin are produced by the biochemical method of lignocellulosic materials that can be further translated into an array of biofuels or commodity products through biorefining process. It is approximated that 75% of cell constituents of lignocellulose are significant fermentable carbohydrate resources to produce liquid biofuels. First, the lignocellulosic biomasses are transformed into sugar intermediates (low-carbon fermentable sources) by the hydrolytic process followed by the production of chemicals and liquid fuels (alcohols) by fermentation technology using various microbial biocatalysts like *Zymomonas mobilis, Saccharomyces cerevisiae, Clostridium thermocellum, C. phytofermentans,* and *Trichoderma reesei*. The sequential pre-treatment and enzymatic hydrolysis of five-carbon sugar monomers of cellulosic biomass yields low carbon carbohydrates, which can be subsequently converted into amino acids, butanol, ethanol, citric acid, and non-polar solvents by microbial fermentation [40]. Similarly, many added-value compounds like xylose, barriers, gelling agents, nylon, and furfural have been produced by the conversion of hemicelluloses (hexose sugars). Lastly, the lignin molecules could be applied as an adhesive, glues, binder, and fuels like syngas and formaldehyde resins, which display high industrial prospects [41•].

## Biorefinery for Biofuels From Lignocellulosic Biomass

The biotransformation of lignocellulose to ethanol, hydrogen, or methane exhibits an enormous perspective as an alternating source of energy. Bioethanol is an intermediate that is

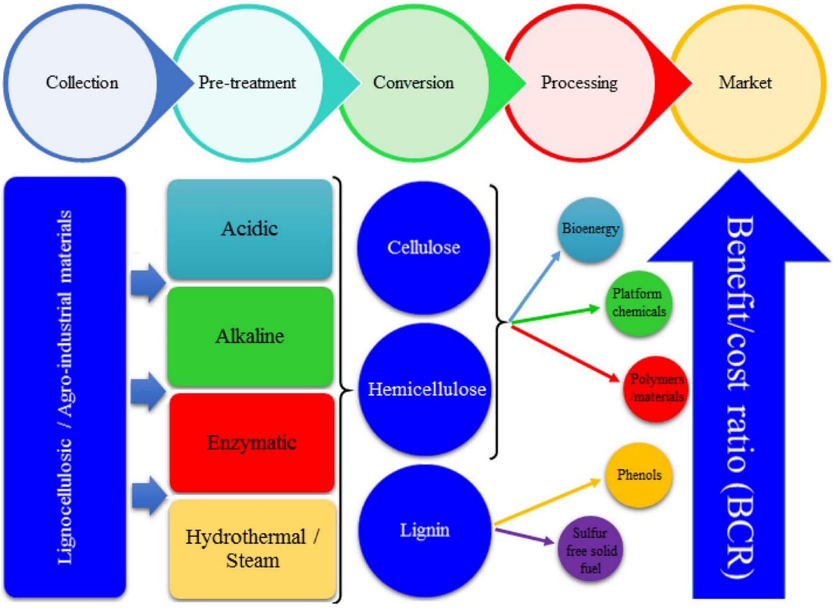

**Fig. 3** A simplified bio-refinery concept. Reprinted from Ref. [4••] with permission from Elsevier. Copyright (2017) Elsevier B.V

produced in the anaerobic digestion process by fermentation of various sugars [42]. The biofuel scope again resurged in the late twentieth century, where the USA and Brazil imitated the production of biofuels from biomass-based feedstocks like maize, sugarcane, and so on [43]. Since then, scientists and researchers are constantly striving for the improvement of biofuels productions that can be broadly classified into four generations.

The biosynthesis of bioethanol from biomass feedstocks such as corn, molasses, starch, sugarcane, vegetable oil, and animal fats is referred to as first-generation biofuels. Based on the feedstock consumption, sugar cane, corn, or molasses were predominantly used for the generation of first-generation biofuels. Approximately, 21 and 60 million $m^3$ ethanol is produced from sugarcane and corn grain-based lignocellulosic feedstocks, around the globe [44, 45]. The extraction and production of fermentable sugars from sugar-based crops implicate pre-treatments (liking crushing and grinding), enzymatic cellulose breakdown, and fermentative process of pretreated substrates for ethanol production. Ethanol produced can be further separated/recovered from the fermented mixture using distillation and dehydration processes. Despite enormous potential, the utilization of such raw feedstock for biofuels production has experienced negative views because of the direct competition with the food supply chain [12, 38, 46]. In addition, this manifesto necessitates enormous agricultural land area to meet the generated raw materials for meeting the ever-increasing demand for the biofuel, which is likely to exert significant negative effects on the ecosystem, biodiversity, etc. [42, 44].

Biofuels obtained from abundantly available and low-priced lignocellulosic biomass that does not conflict with the food resources are known as second-generation biofuels. Lignocellulosic biomasses are accessible in various forms such as forestry residues, agricultural wastes (rice husk, rice straw, banana waste, sugarcane bagasse, crop residues, etc.), and woody and herbaceous energy crops. Second-generation biofuels include cellulosic bioethanol, bio-butanol, Fischer-Tropsch fuels, etc. [47••]. The efficient exploitation of biomass is a challenging task to produce cheaper and renewable biofuel energy sources and needs to be further explored regarding feedstock quality, pre-treatment, and fermentative processes.

For the production of third-generation biofuels, algal biomasses are utilized that offer many advantageous features over the second-generation biofuels, including low-cost, easy growth, carbohydrate content, high lipid content (70% of dry weight basis), high-energy-based feedstock, and non-competition/interference with the natural resources [48, 49]. Additionally, the lack of recalcitrant lignin structures in algae encourages its applicability as a much-appreciated feedstock for energy generation than that to other terrestrial plants. A large number of different algal species like *Botryococcus braunii, Chlorella species, Isochrysis galbana, Chaetoceros calcitrans, Schizochytrium limacinum, Scenedesmus, and Nannochloropsis* sp., has been explored and investigated as a promising candidate for biofuels synthesis [50, 51]. Nevertheless, the lipid content of the algal species may differ widely based on the various species and stress environments. Notwithstanding its wide acceptance for energy production, some technological limitations exist that need to be addressed for the implementation of this technology [49]. LCA of algal growth revealed that the employment of wastewater-based units can act as a favorable medium for cultivation leading to a reduction in the expenditure necessary to develop photoreactors.

Likewise, the LCA analysis of conventional pre-treatment approaches for algal biofuel production demonstrated that the use of alone thermal dewatering process accounts for a substantial quantity of fossil energy [52]. In this avenue, the optimization and use of solar dryers for algal dewatering by a solar-based dewatering system might be an alternative option [53]. Although these types of solar-based methods are not in-practice globally, cooperative research investigations by the consumption of resources in tropical realms could explore innovative solutions in this arena. Recently, a 15-year study by "National Alliance for Advanced Biofuels and Bioproducts" has scrutinized new technologies for the production of algal biofuel with a reduction of 45% GHG emissions compared with traditional techniques [54]. This report including numerous LCA constituents revealed a considerable impact of the utilization of acoustic extraction and harvesting of algae lipids by decreasing the GHG releases. It was also reported that the microalgal transformation into biobutanol rather than biodiesel poses minimum ecological effects on human health and climate change [55].

A recent breakthrough in the field of biofuels is the fourth-generation biofuel that exhibits potential merits over the earlier biofuel generations. This emerging technology involves the direct conversion of $CO_2$-captured raw biomass feedstocks into biofuel based on the combined principles of technology and synthetic biology. The principal objective of this technology is the sustainable production of energy together with $CO_2$ sequestration [56]. Some algal species (*Chlorella species, Botryococcus braunii, Scenedesmus* species, *Schizochytrium* sp., etc.) and microbial strains (*Arthrobacter* sp., *Acinetobacter calcoaceticus, Bacillus subtilis, B. anthracis*, etc.) have been demonstrated as potential biological entities for synthesizing fourth-generation biofuels [40, 51, 57–59]. There is a dire need to explore newer nature-based solutions and develop state-of-the-art synthetic designer microorganisms and microbial cell factories for the effective transformation of solar energy to biofuels. Similarly, the integration of photovoltaics with genetically tailored microbial fuel production pathways could be an impressing development for high-level synthesis of liquid fuels.

## Conclusion and Future Directions

The hurdles of first-generation biofuels (e.g., high-energy requirement, food competitor, environmental damage, poor energy performance, and lower yields) can be partially deciphered by using lignocellulosic biomass, which is easily available, abundant, comparatively cheaper, and promisingly replace petro-fuels. It has been advocated as an attractive raw feedstock for biofuels and an array of other industrially pertinent bioproducts, including fermentable sugars, solvents, designer composites, and drink softeners in an eco-sustainable and cost-effective way. In addition, preliminary studies on LCA highlighted that the lignocellulose-based bio-refinery process could help save up to 60% emissions of GHG in comparison with the fossil-fuel system. In combination with process optimization for minimal energy input and reductions in GHG emission, the deployment of fermentative cellulase biosynthesis and genetically engineered organisms might augment the hydrolysis process. Feedstock resource, waste management, and integrated biorefinery process can effectively increase the total value originated from lignocellulosic biomass and reduce the energy consumption and ecological footprints.

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## Compliance With Ethical Standards

**Conflict of Interest** The authors declare that they do not have any conflict of interests.

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- • Of importance
- •• Of major importance

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