BioEnergy Research
https://doi.org/10.1007/s12155-024-10792-x

Biomass Valorization for Bioenergy Production: Current Techniques, Challenges, and Pathways to Solutions for Sustainable Bioeconomy

Neelu Raina[1] · **Santi Chuetor**[1] · **Doha Elalami**[2] · **Saida Tayibi**[3] · **Abdellatif Barakat**[4]

Received: 31 January 2024 / Accepted: 1 August 2024

Abstract
Biomass and organic residues are increasingly recognized as valuable resources for bioenergy production. Lignocellulosic biomass offers sustainable alternatives to fossil fuels for generation of bioenergy (such as biogas, bioethanol, biodiesel, and biohydrogen). Pretreatment plays a crucial role in a biomass biorefinery. It increases biomass homogeneity and production yields, thereby overcoming transportation and storage problems. However, the absence of a clear plan for biomass pretreatment represents a challenge for biomass conversion procedures. The socio-economic effects of biomass utilization are not unequivocally constructive. High investment and capital costs, technological maturity of biofuels, large-scale biomass supply, and policy and regulatory issues are among the key challenges. Despite these challenges, with the right strategies and solutions, complete biomass valorization is achievable. Solutions such as quick capital cost estimation, upgrading existing plants, optimizing biomass feedstock blends, utilizing waste biomass resources, and improving machinery efficiencies can address these challenges. Policy and regulatory challenges can be tackled through clear and long-term targets, financial and fiscal incentives, mandates and obligations, and sustainability governance supported by regulations and certifications. However, the realization of these benefits would depend on various factors such as the specific context of the biomass utilization, the available resources, and the market conditions. Thus, this work critically reviews the status of bioenergy production, the socio-economic challenges of biomass pretreatment, and its diversity in the bioenergy set-up.

Keywords Biofuels · Pyrolysis · Hydrolysis · Thermochemical · Bioethanol · Bioconversion

Introduction

Global boiling era has recently become an essential environmental issue nowadays. With the increase in population, the global energy demand is expected to increase till 2040 with one-third of the share consumed by the buildings, industrial and transportation sector [1]. However, to supply the global energy demand, carbon emissions by conventional energy resources are still being generated hence causing environmental issues. In order to tackle this challenge, the conference of the parties (COP)-26 and 27 continuously monitors how to tackle the climate change situation, which would thus hinder global carbon neutrality by 2050. Biomass and bioenergy are renewable resources that can help mitigate climate change by reducing greenhouse gas (GHG) emissions. When biomass is grown, it absorbs CO_2 from the atmosphere during photosynthesis. This CO_2 is then released back into the atmosphere when the biomass is burned for generation of energy, creating a closed carbon cycle. It can thus contribute to energy security and independence by providing domestic sources of energy, thus reducing dependence on foreign oil. Using waste energy streams for bioenergy production can contribute to sustainable energy management.

Biomass biorefinery can be a potential facility to accomplish not only energy security but also several sustainable development goals (SDGs), in particular SDGs 7, 9, 11, 12, 13, and 15. The biorefinery process is a collective chemical,

✉ Abdellatif Barakat
abdellatif.barakat@inrae.fr

[1] Department of Chemical Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok 10800, Thailand

[2] Department of Process Engineering, Mohammadia School of Engineering, Mohammed V University, 10090 Rabat, Morocco

[3] Mohammed VI Polytechnic University, 43150 Ben Guerir, Morocco

[4] IATE, University of Montpellier, INRAE, Agro Institut, 34060 Montpellier, France

physical, and biological process that is typically used to systematically valorize components of the biomass into multi-biobased products including biofuels, biochemicals, and biomaterials [2]. Biorefineries can convert biomass into biofuels, biopower, and bioproducts thus providing a renewable source of energy. This helps to reduce the dependence on fossil fuels and promote the use of affordable and clean energy (SDG 7-Affordable and Clean Energy). It represents an innovative bioprocess industry that can transform waste and biomass into valuable products. Biorefineries can integrate with the already existing infrastructure and thus enable the transformation of a wide range of biological feedstocks/substrates into a variety of bio-based materials (SDG 9-Industry, Innovation, and Infrastructure). By converting biomass waste into bioenergy and other useful products, biorefineries contribute to sustainable waste management, which is critical to building sustainable cities and communities (SGD 11-Sustainble Cities and Communities). They also promote the efficient use of resources and the reduction of waste thus aligning with the goal of responsible consumption and production (SDG 12). By replacing fossil fuels with bioenergy, biorefineries help reduce GHG emissions, therefore contributing to climate action (SDG 13). Sustainable sourcing of biomass for biorefineries can contribute to sustainable land use and forest management thus helping to protect, restore, and promote sustainable use of terrestrial ecosystem (SDG 15-Life on Land). However, sustainable sourcing of biomass and efficient conversion technologies encounters several challenges that need to be addressed.

Lignocellulosic biomass (LCB) is a heterogeneous complex of biopolymers—cellulose, hemicellulose, and lignin. It also contains some additives (extractives, oil, starch, and proteins) in minor amounts [3]. LCB presents a renewable bioresource for producing bio-based products such as biofuels and biochemicals, pivotal for a sustainable bioeconomy [4, 5]. In order to valorize lignocellulosic biomaterial, one of the most important processes in biorefinery is the pretreatment process. However, cellulosic or advanced ethanol production technologies are not yet fully commercialized. The production of advanced biofuels through innovative industrial technologies is a crucial factor for the cellulosic bioeconomy supply chain to run smoothly and sustainably. The biorefinery sector is thus directly related to the technology and manufacturing sector through which biofuels and related by-products arrive at the end-users. Technically, advancements in biotechnology, research and development (R&D), and innovation can enhance the maturity and efficiency of biofuels technology. The pretreatment process typically aims to deconstruct the complex and recalcitrant structure of lignocellulosic biomaterial for isolation of biomolecules. Due to its dependence on the use of chemicals and energy, pretreatment has been recognized as a bottleneck in bioenergy generation and thus influences the sustainability, economic feasibility, and eco-friendliness of the overall biofuel production process [6, 7]. Pretreatments and other such biomass densification technologies tend to increase biomass homogeneity and energy density, thereby overcoming transportation, storage, handling, and combustion problems, although they have a multitude of other technological, economic, and social constraints as well.

Solvents recently used during pretreatment such as organic co-solvents, acid hydrotropes (class of acids that have hydrotrope properties towards lignin), ionic liquids (ILs), and deep eutectic solvents (DESs) have showed effective biomass fractionation under mild conditions of temperature and pressure as well as preserved high-quality cellulose and lignin fractions in bioprocess reaction mixtures [8, 9]. During IL pretreatment, lignin and hemicellulose structures remain unaltered thereby allowing their selective extraction. It also increases cellulose accessibility under ambient pressure and temperature conditions without the formation of toxic inhibitors. Physicochemical methods like carbon dioxide explosion (CO_2) causes rupture of the LCB structure as well. Since high pressure CO_2 molecules can enter the tiny biomass pores and release in pressure results in the cellulose structure being disrupted, eventually increasing substrate accessibility to enzymatic hydrolysis. On the other hand, ammonia fiber explosion (AFE) pretreatment changes lignin structure, results in biomass swelling, and increases substrate accessible area in addition to the degradation of hemicellulose to oligomeric sugars. The increase in the biomass surface area may also result in increasing water retention potential and biomass digestibility as well. Liquid hot water (LHW) pretreatment causes partial dissolution of the hemicellulosic component. Partial degradation of hemicellulose thus results in the removal of lignin eventually increasing the accessibility of enzymes to cellulose in the next step. Sulfite pretreatment method employed especially for woody biomass feedstocks has shown high scalability for industrial applications. This method uses a number of sulfite and bisulfite solutions having a broad range of pH and temperature conditions thus weakening the structural components of the LCB. Steam pretreatment method that uses steam at high pressure disrupts the hemicellulose structure by causing its hydrolysis followed by cleavage of ether bonds present in lignin. Commonly used methods such as acid pretreatment (concentrated/dilute) causes breakdown of hemicellulose and lignin. The hydrolysis of hemicellulose components yields monomeric sugars (such as xylose and mannose) increasing cellulose accessibility whereas lignin depolymerization releases phenolic compounds thereby reducing biomass recalcitrance. Under alkaline pretreatment conditions, swelling and solubilization of hemicellulose takes place. As cellulose remains relatively intact, the lignin component is partially dissolved. This results in increased porosity and enhanced enzymatic digestibility as well. Biological pretreatment which partially degrades and solubilizes hemicellulose is a cost-effective and environment friendly method. It can modify lignin making it more accessible but is time-consuming and faced by challenges such as choosing the right microbial consortium for optimal yield [10]. Pretreatment processes are mainly involved in effective separation of the complex interlinked fractions (cellulose, hemicellulose, and lignin) and thus increase the accessibility of each individual component. However, a major hurdle is the removal of lignin, a sturdy and rugged component which is highly resistant to solubilization and is also a major inhibitor for hydrolysis of cellulose and hemicellulose.

The selection of pretreatment process depends exclusively on the application. As compared to the conventional single pretreatment process, integrated processes combining two or more pretreatment techniques is beneficial in reducing the number of process operational steps besides minimizing the production of undesirable inhibitors. Inhibition of lignin-derived phenolic compounds to cellulase is also a significant challenge. Lignin-derived phenolic compounds are universal in the hydrolysate of pretreated lignocellulosic biomass. The phenolics reduce the efficiency of enzymatic hydrolysis and increase the cost of bioethanol production. The inhibition of soluble phenolics can hardly be entirely removed by increasing enzyme concentration or adding blocking proteins due to the dispersity and multiple binding sites of phenolics than insoluble lignin [11]. However, extensive research is still required for the development of new and more efficient pretreatment processes for lignocellulosic feedstocks yielding promising results.

Pretreatment is a crucial step in biofuel production, especially when using lignocellulosic bioresources. The goal of pretreatment is to break down the complex structure of these biomaterials to make the entrapped sugars more accessible for fermentation. However, there are several challenges associated with pretreatment technologies such as the following: (i) Generation of fermentation inhibitors: During pretreatment, toxic compounds can be produced that inhibit the fermentation process. These inhibitors can reduce the efficiency of biofuel production by suppressing cell growth, limiting sugar consumption, and lowering ethanol yield [12]. For example, furfural and hydroxymethyl furfural are enzymes and yeast inhibitors generated during steam-explosion pretreatment. Levulinic acid is more inhibitory to glucose fermentation than acetic acid, while formic acid is more toxic for xylose fermentation than levulinic acid. (ii) High costs: The high cost of pretreatment is one of the major bottlenecks hindering large-scale production of biofuels. This includes both high capital and operation costs. (iii) Water consumption: High water consumption is another challenge that can unfavorably affect the pretreatment performance [13]. (iv) Feedstock limitations: Current commercial usage of refined vegetable oils for biodiesel production is impractical and uneconomical due to high feedstock cost and priority as food resources. (v) Technical challenges: Some pretreatment methods fail due to health or sustainability problems, complex apparatus, low scalability, or poor performance. While pretreatment technologies are essential for efficient biofuel production, they come with their own set of challenges that need to be addressed for the sustainable and economical production of biofuels. All these challenges and their proposed solutions are discussed in the following sections of this review.

Demonstrated use of a large variety of available feedstocks represents the potential of a technology in terms of its maturity level. However, an ideal direction and development of technology through feasibility studies should be a prominent aspect of bioenergy generation studies. Despite significant enhancements in biomass pretreatment solvents, some major challenges remain, such as feedstock variability, valorization of non-cellulosic components of the biomass, economic constraints of the overall bioenergy process, and balancing the eco-friendliness of the pretreatment solvent/catalyst. These obstacles categorized under technical, economic, and environmental aspects of biomass pretreatment should be considered essential drivers of future biomass energy generation processes. However, it is essential to note that the field of biomass valorization continues to evolve, and ongoing research contributes to our understanding of biomass pretreatment. The optimal pretreatment method depends on the biomass type, intended application, and economic feasibility. Thorough evaluation is crucial for successful bioenergy production. Despite a number of pretreatment methods being available, we have not been able to come across a method that can disintegrate a wide variety of biomass types in a cost-effective manner and also be socially sustainable and environmentally favorable. Different questions have been proposed from time to time in order to answer the sustainable utilization of lignocellulosic material as bioresources. The choice is very critical and depends on several parameters. Policy-wise, clear, and long-term targets, financial and fiscal incentives, and sustainability governance supported by regulations and certifications can create a conducive environment for bioenergy production. To this end, the following literature review is presented to analyze the latest research methods, identify relevant indicators, and to assess their suitability for production of bioenergy and value-added products. This review reports the different challenges of biomass pretreatments and socio-economic aspects, along with their opportunities, and future research perspectives, to promote a higher technology readiness level for a successful scaling up for bioenergy production. In the following sections, the limitations, and possibilities for improvements in ex-ante quantitative research methods and socio-economic scenarios for investigating technical, environmental, social impacts of biomass valorization on bioenergy generation have been presented.

An overview *of Major* Biofuel Types and the Key Pretreatment Techniques

Due to the fixed stock of the non-renewable resources (fossil fuel-coal, oil, and natural gas) and their detrimental impacts on the environment, it has become imperative to seek alternative, cost-effective, and eco-friendly substitutes for the production of biofuels. Biomass, an organic matter derived from plant or animal remains can be transformed into valuable products such as industrially significant chemicals and by-products as well as for bioenergy. The annual, worldwide production of biomass is estimated to be around 130 billion tons. Bioenergy being a prominent part of the energy economy accounts for approximately 70% of the renewable energy supply [1]. It can be derived from lignocellulosic or agro-industrial biomass and is abundant in carbohydrates, lipids, and proteins. LCB forms the main biomass constituent in the agricultural (such as corn cob, rice straw, corn and cereal straw, paper industry residue, rice husk, sugarcane bagasse, and sugarcane tops) and forestry (such as sawmill and paper mill discards) sector residues. Among various bioconversion methods, the biochemical conversion route (anaerobic digestion and fermentation) is considered to be effective. Anaerobic digestion (AD) process offers several significant environmental benefits. AD processes organic materials (such as food scraps, commercial food processing waste, fats, oils, greases, and yard waste) that would otherwise end in landfills. By keeping these out of landfills, we can reduce methane emissions that contribute to climate change. AD produces biogas, a renewable source of energy used to power engines and generators. The nutrient-rich slurry or digestate produced by AD can be applied to agricultural land as a fertilizer or soil amendment to improve soil health by increasing organic content. AD systems capture methane and convert it into a beneficial resource. AD can also be used to manage manure thus reducing odors, pathogens, and the volume of solid waste. It thus offers a promising solution to the growing energy economy in a sustainable way (Fig. 1). In this section, the pathways for generating different types of bioenergy in the form of biofuels from organic residues have been discussed.

Biogas, also known as renewable natural gas (RNG) or biomethane, is a renewable bioenergy source. It is produced when organic matter breaks down to produce bioenergy in the form of heat, electricity, and fuel. The composition of biogas primarily depends on the type of feedstock used and the production pathway involved. The production of biogas through AD offers numerous advantages when compared to aerobic digestion. These benefits include lower energy consumption, reduced quantities of solids generated, lower nutrient demands, and significant energy recovery from

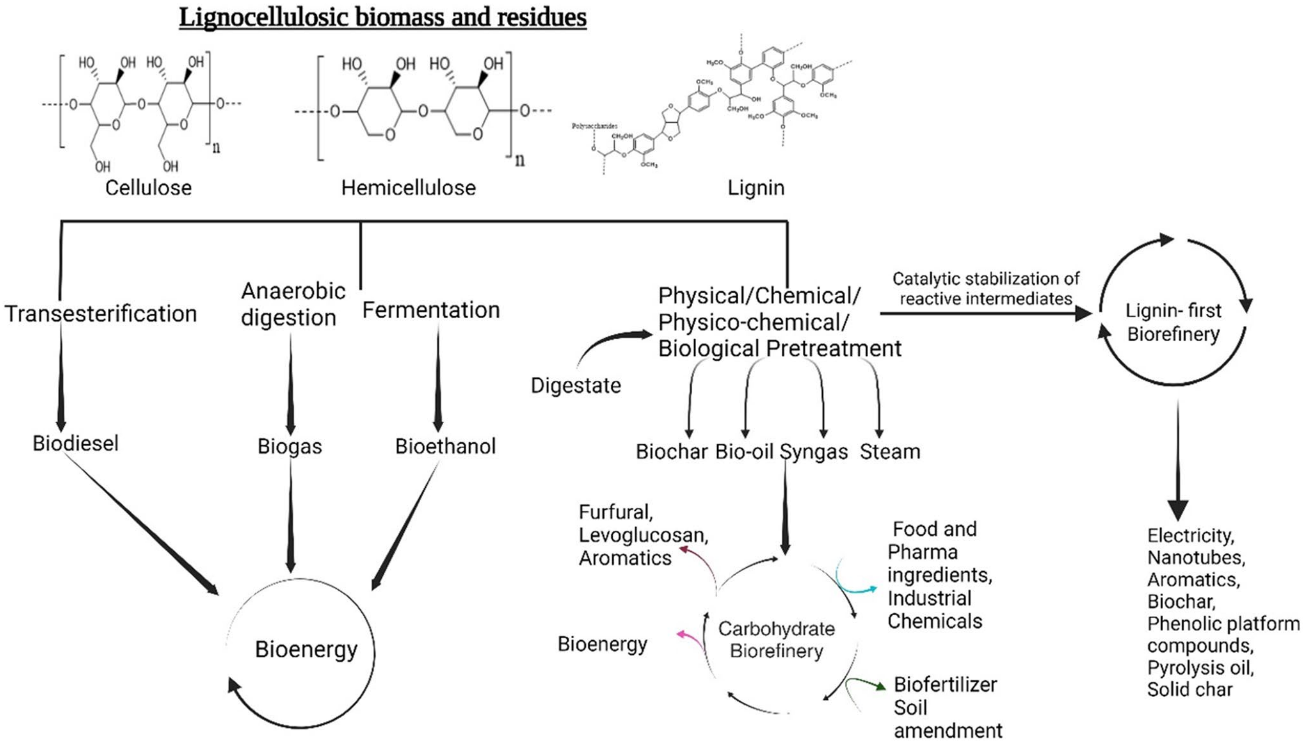

Fig.1 Different routes of biomass valorization for bioenergy production in a circular economy concept

the biogas produced [14, 15]. The by-product of anaerobic digestion, called digestate, serves as an organic fertilizer. Biogas systems thus contribute to rural economic development. Biogas can improve access to clean energy in rural communities. It provides reliable electricity and heat, enhancing livelihoods. It reduces pollution from chemical fertilizers. By optimizing its production, utilization, and integration into circular economies, we can drive positive environmental and socio-economic change. Circular economy principles optimize resource use, thus benefiting developing countries. The AD process involves four sequential steps, starting with the conversion of several different types of organic compounds (carbohydrates, lipids, and proteins) into smaller monomeric components (sugars, fatty acids, and amino acids) through the action of hydrolytic bacteria (e.g., *Pseudomonas* sp.). This initial step, known as hydrolysis, is facilitated by extracellular enzymes (cellulases, amylases, proteases, and lipases). The next step is acidogenesis, where the sugars and smaller compounds are further degraded into volatile fatty acids, such as butyric, propionic, and valeric acids, primarily derived from lipids. This process is carried out by acidogens (e.g., *Lactobacillus* sp.) and is notably faster compared to hydrolysis. Following acidogenesis, two groups of acetogens coexist in the mixture. The dominant group produces acetate, CO_2, and H_2 from fatty acids. The final metabolic stage involves methanogens, which are also divided into two groups. The first group, acetoclastic methanogens, produces methane from acetate (around 70%), while the second group, hydrogenotrophic methanogens, converts H_2 and CO_2 into methane (approximately 30%), both of which occur at a neutral pH. For the AD process to be optimal, certain conditions need to be maintained (i) The pH should be kept between 6.5 and 7.5, (ii) The temperature should be around 33–40 °C, and (iii) the *C*/*N* ratio should vary between 20:1 and 25:1.

Biohydrogen is an intermediate product of AD. It holds greater value compared to biogas and shows promise as a clean energy source. Its conversion results in the generation of only water without releasing any GHG emissions. Biohydrogen can be produced from renewable resources such as biomass and biological waste such as agricultural residues, food waste, and other organic materials. The production of biohydrogen can be carbon–neutral or even carbon-negative. This signifies that it does not contribute to the increase in GHGs in the atmosphere. Biohydrogen production pathways must minimize energy input while maximizing hydrogen yield. Understanding and enhancing the activity of hydrogenase enzymes in microorganisms are critical for efficient hydrogen production. Biohydrogen can be a by-product of waste treatment processes. Integrating hydrogen production with wastewater treatment or organic waste management adds value. Developing safe and efficient hydrogen storage methods is thus essential. Liquid carriers, solid-state materials, or biological systems can store excess hydrogen. Techno-economic assessments should consider capital costs, operating expenses, and revenue streams. Emerging techniques like microbial electrochemical cells (MECs) allow direct conversion of organic matter into hydrogen. MECs hold promise for efficient and sustainable biohydrogen production. Some photosynthetic microorganisms can produce hydrogen directly from splitting water using light as an energy source. It has high energy content, in fact far higher than any other fuel making it an ideal fuel. To prevent methanogenic activity during the AD process, specific parameters can be adjusted, such as pretreating the inoculum, implementing a short hydraulic retention time, and maintaining an acidic pH. This modified process is referred to as dark fermentation, leading to the production of hydrogen, soluble metabolites, volatile fatty acids and alcohols [16]. Enhancing hydrogen production can be achieved by co-fermenting organic wastes, which helps balance the *C*/*N* ratio and increases the concentration of fermentable sugars available. However, it is essential to note that only a small portion of the organic load is converted into hydrogen through the dark fermentation process. Therefore, combining dark fermentation with other processes becomes necessary to achieve higher recovery yields [17]. One example is producing methane by AD of effluents rich in volatile fatty acids (VFAs) and undegraded solids. This combination of processes can lead to a more efficient utilization of organic waste for bioenergy production. However, organic waste plays a significant role in the circular economy and environmental sustainability as well. The integration of biowaste into the cutting-edge circular economy has the potential to significantly increase the production of sustainable bioproducts and bioenergy. Recent research on microbial profiles of biowaste has led to the discovery of mechanical bioproducts. The study also discusses the circular economy of biowaste as a source of bioproducts and bioenergy businesses, and the biowaste biorefinery methods that could be used to evaluate financial models for updated bioproducts [18].

Organic waste is one of the most substantial shares in the biomass waste management system [19]. New and significant infrastructure has been developed to turn organic waste into valuable bioresources. For example, municipal solid waste (MSW) can be converted into heat by direct approach and to syngas, bio-oil, biochar, digestate and humas via indirect approach. Waste management plays a crucial role in circular economy as it enables us to create a sustainable system that aids in reducing waste and transforms it into new products [20]. This in-turn helps to alleviate their environmental impact, create new jobs, and support the growth of eco-friendly industries. However, significant challenges are encountered in the process. Thus, locally based new studies are of primary importance to enhance energy utilization. Biowaste remediation and valorization are aided by artificial intelligence (AI) in a bid to overcome several difficulties and in closing the gap between practicability and applicability of the bioremediation process [21]. In a recent study, a hybrid technique was developed by blending the modern machine learning (ML) algorithms with cooperative game theory-based Shapley Additive exPlanations (SHAP). The technique proposed in this paper provides substantial insights into the biochar manufacturing process, allowing for the improved control of biochar properties and increasing its use in numerous applications [22]. Similarly, another interesting study underscores the potential of explainable artificial intelligence (XAI) in tackling challenges associated with integrating renewable energy (RE) sources into traditional energy systems. The study focuses on the intersection of RE and XAI. The research explores XAI applications in energy forecasting, system optimization, and grid management, discussing the benefits, drawbacks, and existing applications. Ethical concerns, such as privacy, liberty, and discrimination, have also been addressed, emphasizing the need for stakeholder inclusion in XAI design and implementation [23]. Another study analyzes the potential of fruit and vegetable wastes (FVWs) in the modern circular economy. The authors discuss the generation of bioenergy and bioproducts from FVWs and how it has piqued global interest in achieving a cutting-edge circular economy. The integration of FVWs into the cutting-edge circular economy has the potential to significantly increase the production of sustainable bioproducts and bioenergy [24].

Bioethanol being the predominant biofuel is utilized primarily by the transportation sector. It is a colorless liquid mainly used as an additive to petroleum (gasoline) as a vehicular biofuel, reducing carbon emissions. It serves as an oxygenated additive, enhancing combustion efficiency. The typical stages of bioethanol production are pretreatment, hydrolysis, fermentation (pentoses and hexoses), and, finally, the separation/distillation of the resulting products. The process begins with the pretreatment of feedstock (corn, wheat, grasses, agricultural residues, etc.) to breakdown complex biomass polymers and make the sugars accessible. The pretreated feedstock is then subjected to hydrolysis that breaks down cellulose into fermentable sugars. The resulting sugars are then subjected to fermentation by microorganisms to produce bioethanol. Bioethanol production thus offers a carbon–neutral pathway. In order to attain sustainable bioenergy production, renewable waste biomass being low-priced and ready accessible is an amiable option. Exploring diverse feedstocks enhances sustainability. Choosing appropriate feedstocks is thus critical. Balancing food security, land use, and environmental impact is therefore an essential requirement. Utilizing agricultural residues and organic waste for bioethanol production reduces waste disposal and promotes circular economy principles. The breakdown of complex biopolymers via pretreatment hastens the subsequent process of biomass hydrolysis. Pretreatment facilitates the breakdown of the LCB by reduction of cellulose crystallinity, surface area enhancement and decrease in the lignin concentration. Estimated to be around 19% of the total cost of biofuel production, pretreatment serves as a bottleneck in the bioconversion of biomass to bioethanol [25]. As the complete bioprocess mainly relies on the cost and energy usage of the pretreatment, this leads to higher capital expenditures of the whole process. The recent progression in the pretreatment techniques thus emphasize especially on the combined pretreatment methods [26] (Fig. 2). Bioethanol holds immense promise as a renewable energy source. Assessing the process energy balance is hence crucial. Bioethanol production should focus on minimizing energy input while maximizing ethanol yield.

Current biomass pretreatment methods focus on disintegrating the biomass organics for increasing the availability/exposure of the substrates effectively for energy efficient and eco-friendly bioenergy production. The structural changes in the biomass are generally carried out by technological advancements using specific pretreatment methods which can be categorized into physical, chemical, physiological, biological, and integrated (combined) methods (Table 1). Effective pretreatment focuses on improving the concentration of reducing sugars and prevents by-product formation which can thereby inhibit hydrolysis and fermentation processes. Some recent studies using different pretreatment techniques employing a wide range of feedstocks and their process conditions have been tabulated below.

TS is the total solid concentration in kg/m^3; *COD* is chemical oxygen demand where biodegradability is expressed in terms of COD/COD, organic load in terms of gCOD/m^3, volume of the reactor in m^3, and hydrogen yield in mL/gCOD; *VFA* is total volatile fatty acids; *SS* is suspended solids; *VS* is volatile solids, *MPa* is mega pascals.

Pretreatments such as physical methods (mechanical, microwaves, ultrasonic, and thermal) and chemical (acidic, alkaline) or biological (enzymatic, fungi) have been carried out for the release of biomolecules from renewable substrates. A pretreatment process can primarily lead to (i) increased surface area of LCB, (ii) depolymerization of cellulose, (iii) solvation of lignin-polysaccharide linkages, and (iv) lignin content reduction. Mechanical pretreatment, such as grinding, is one of the most important steps during the conversion of biomass into bioenergy. It reduces the size of lignocellulosic matrix and makes it more accessible to enzymes and microbial breakdown. In addition, mechanical pretreatments can be used without the use of chemical reagents, and thus, are more environment friendly and their application on a larger scale is also feasible [41]. Physical pretreatment on the other hand results in the disruption of cellulosic biomass structure resulting in defibrillation thereby enhancing carbohydrate accessibility

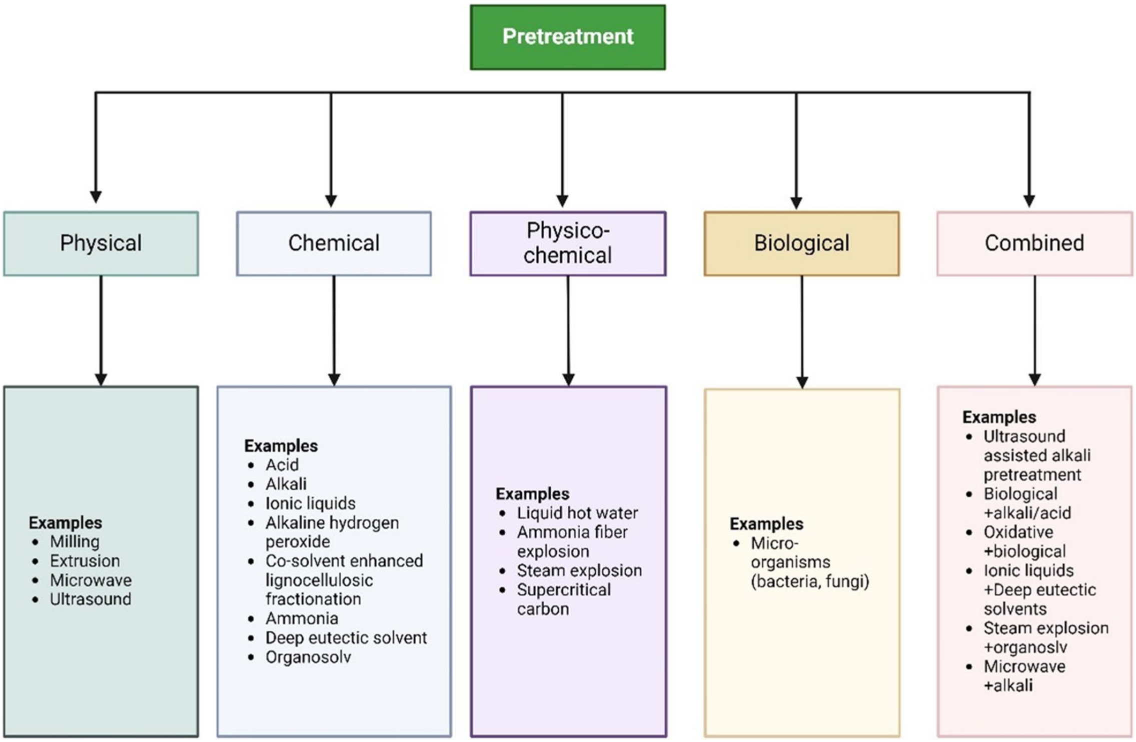

Fig. 2 Different types of biomass pretreatment methods

during enzymatic hydrolysis process. Although, studies have shown that the combination of grinding or extrusion with alkaline, acid or even enzymatic reagents can improve the solubilization of lignin, cellulose and hemicelluloses [42]. Another physical pretreatment called pulsed-electric-field (PEF) causes rapid electrical breakdown and thereby structural changes in the cell wall membrane. This results in the rupture of biomass tissue [43]. However, this method is not suitable for hardwoods. Combining different pretreatment techniques should be optimized in order to minimize operational costs and, therefore, impact on the environment as well. Compared to biological and chemical conversion technologies, thermochemical processes such as pyrolysis and gasification offer the advantage of not requiring extensive pretreatments to break down complex biomass structures. A recent research article uses machine learning model as the best gasification route for a given biomass [44]. This eliminates the need to add complexity to the process and thus cost to the overall process while increasing the accessibility to produce biofuels in the form of bio-oil, syngas and other industrially significant molecules (Fig. 3). Pretreatments to enhance bioenergy generation will be discussed in detail in the later parts of this review.

After pretreatment, the next step that follows is hydrolysis. Hydrolysis in bioethanol production can be categorized broadly into two types: chemical and enzymatic. Among these, dilute acid hydrolysis is one of the most employed techniques to break down cellulose polymer into soluble (fermentable) sugars. This process is carried out in two stages. In the first stage, dilute hydrolysis occurs under conditions of approximately 1% H_2SO_4 at a temperature of 190 °C. This stage aims to promote the degradation of hemicelluloses. Subsequently, cellulose undergoes hydrolysis in the second stage, using approximately 0.4% H_2SO_4 for a short duration at a higher temperature, typically around 215 °C. This step is crucial for breaking down cellulose into fermentable sugars that can be utilized in the subsequent fermentation process to produce bioethanol. The main drawback of dilute acid hydrolysis is its limited glucose yield, which typically reaches around 50%. However, this limitation can be overcome by employing concentrated acid hydrolysis, which involves using higher concentrations of acid (ranging from 10 to 30%) and longer reaction time period. This method enhances sugar recovery; thereby increasing the overall efficiency of the hydrolysis process. In general, chemical hydrolysis requires only mechanical pretreatment to reduce the size of the biomass, which can be considered as a pretreatment method. However, it is essential to be aware that during chemical hydrolysis, the formation of inhibitors may occur, which can impede downstream processes. On the other hand, the use of enzymes in hydrolysis process allows for selective degradation of hemicelluloses and cellulose. Enzymes are focused on the cellulose hydrolysis for improved fermentation efficiency. Compared to chemical

Table 1 Different biomass feedstocks, pretreatment conditions, and performance

Biomass type	Pretreatment type	Pretreatment method	Experimental conditions	Results	Ref
Rice straw	Combined	Ozone-thermal	Ozone dosage = 0.006 gO^3/g biomass; temperature = 55 °C	VFA production = 537.20 ± 17.09 mg/L/d; reducing sugar = 1.18 ± 0.06 mg/L/d; methane yield = 374 ± 6 mL CH_4/g-VS	[27]
Marine macroalgae *Ulva fasciata*	Combined	Microwave-surfactant	Microwave power = 40%; ammonium dodecyl sulphate = 0.0035 g/g SS	COD solubilization = 34.2%; biohydrogen production = 54.9 mL/gCOD	[28]
Corn stover	Combined	Ammonia combined with a bismuth ferrite Fenton-like process	Temperature = room temperature; solid loading = 26%; time = 3 days	Delignification of 57% Lactic acid yield of 0.52 g/g in batch reactor	[29]
Poplar sawdust	Combined	NaOH-Fenton	Temperature = 100 °C for NaOH treatment, solid loading = 6.6% w/v for both treatments; time = 1 h for NaOH treatment and 7 h for Fenton treatment	Enzymatic hydrolysis rates of cellulose of 86.65% and hemicellulose of 43.9%	[30]
Unbleached bamboo kraft pulp	Combined	Ozonation and cellulase hydrolysis	Solid loading = 5% w/w; temperature = 30 °C; pH = 2.5	Treatment with ozone and cellulase increased fiber flexibility by about 7 times compared to the control sample	[31]
Wood dust mahogany	Single	Ozonation	Temperature = room temperature; biomass = 25 g; moisture = 40%; pH = 11; time = 45 min	Biohydrogen production accumulation of 84 mL/g total solids	[32]
Sugarcane bagasse	Combined	Sweeping frequency ultrasound and deep eutectic solvents pretreatment	Ultrasound = sweeping frequency of 40 kHz, sweeping cycle of 500 s, 600 W, pulse on/off time of 10 s/3 s; time = 60 min; temperature = 30 °C; solid loading = 10%	Glucose, xylose, and cellobiose yield after enzymatic hydrolysis were 86.76, 38.68, and 20.76%, respectively	[33]
Lipid and food waste originating from hot pot restaurants	Single	Ultrasound	Solid loading = 5 g of volatile organic compounds in 100 mL of mixed liquid; time = 100 s; ultrasound = 500 W and 20 kHz	Methane yield of lipid and food waste after anaerobic digestion increased by 43.3% and 27.7%, respectively	[34]
Water hyacinth	Combined	Alkaline (AWAO) and simple wet air oxidation	Temperature = 170 °C; solid loading = 5% w/v; time = 30 min	WAO and AWAO increased methane production rate by 63% and 117%, respectively	[35]
Yard waste	Single	Electrochemical	Solid loading = 20%; time = 42 min; current intensity = 32.77 A/m^2; pH = 9.0	Methane production of 434 mL/gVS Net profit of 119.29 US$ Reduced lignin from 19.9 to 14.9%	[36]
Rice straw	Single	Electrochemical	Temperature = 35 C; solid loading = 16.7%; time = 5 h; current intensity = 1.5 A, 5 V	Cumulative methane production increased by 14% compared to NaOH pretreatment	[37]

Table 1 (continued)

Biomass type	Pretreatment type	Pretreatment method	Experimental conditions	Results	Ref
Sugarcane tops	Single	Ionic liquid	Ionic liquid (IL) concentration was set at 40% w/w, with a pH of 5.5, biomass loading of 5% w/w, a temperature (T) of 60 °C, and a duration (t) of 4 h Antisolvent: acetone	Enhances sugar yield to about 1.57-fold. Greater fractionation	[38]
Oil palm biomass	Single	Ionic liquid	Anti-solvent-acetone/water mixture of 1:1	Feed size less than 250 mm, $T = 110$ °C, $t = 8$ h under N_2 condition	[39]
Reed biomass	Single	Liquid hot water	T: 160–240 °C; P: > 5 MPa	Glucose recovery 73.1%	[40]

hydrolysis, enzymatic hydrolysis provides higher yields at lower temperatures, avoiding corrosion problems associated with concentrated acid usage. This makes enzymatic hydrolysis a more attractive option, as it offers improved efficiency and better overall performance in the bioethanol production process. The biochemical conversion step that follows enzymatic hydrolysis is fermentation by using microbes (bacteria, yeast). The lignin and hemicellulose fractions encapsulate cellulose microfibrils thereby leading to restriction of cellulose accessibility to microorganisms during fermentation. For improving the production of bioethanol, fermentation strategies have been generally categorized into separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), and consolidated bioprocessing (CBP). However, the bioethanol production from LCB requires the co-fermentation of pentose (C5) and hexose (C6) sugars which can decrease the processing time as well as the concentration of inhibitory compounds. The fermentation parameters in bioethanol production can vary depending on the nature of the microorganism used. Typically, the culture conditions requires either an acidic pH or higher temperature conditions to support optimal fermentation yield. Under suitable conditions, the bioethanol yield and productivity can reach impressive levels. Among the various microorganisms employed for bioethanol production, *Saccharomyces cerevisiae* and *Zymomonas mobilis* are the most widely used yeast types [45]. These microorganisms have demonstrated excellent capabilities in efficiently converting fermentable sugars into bioethanol, making them preferred choices for industrial-scale bioethanol production processes. The bioethanol production using different fermentation approaches from various LCB substrates has been performed considerably in recent years [46, 47]. Overall, some factors play a crucial role in broadly determining the efficacy of bioethanol production process including selection of feedstock, pretreatment conditions and fermentation strategies. However, a substantial amount of in-depth research is still desired, aimed broadly at the cost and energy efficient production process based on the complete utilization of the biomass. The economic benefits of complete biomass utilization include reduced dependence on imported fuels, revenue streams, economic growth, job creation, and savings from reduced fuel imports. These benefits thus highlight the economic potential of utilization of biomass organic residue.

Biobutanol, another bioenergy resource, possesses superior biofuel properties compared to bioethanol. It exhibits higher miscibility with gasoline, making it a more attractive option as a blend in conventional fuels. Additionally, biobutanol is considered safer for storage and handling. The production of biobutanol involves microbial fermentation, often utilizing *Clostridium* strains. In addition to butanol, the fermentation process generates organic acids like acetic, lactic, and butyric acids, along with gases such as CO_2 and

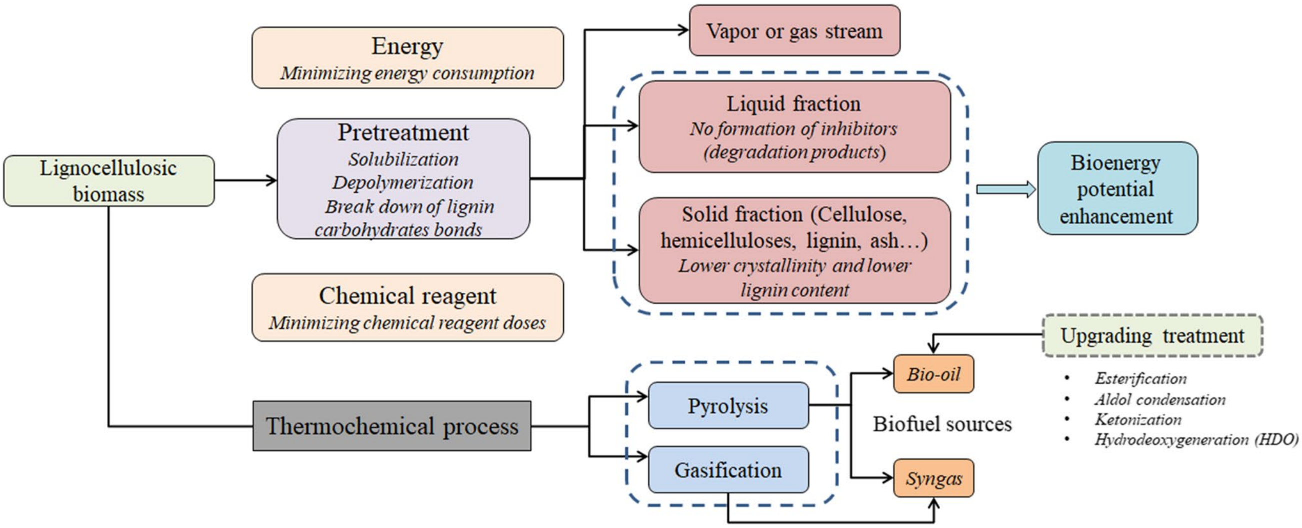

Fig. 3 Pretreatment mechanisms and challenges

H_2. Similar to bioethanol production, the process of biobutanol production involves essential steps like pretreatment, hydrolysis, and fermentation. Pretreatment and hydrolysis are necessary to break down the feedstock biopolymers into fermentable sugars, which are then converted into biobutanol and co-products during the fermentation process. Low butanol concentrations, productivity, and raw material costs remain the challenges for industrial-scale biobutanol fermentation. The yield of biobutanol therefore depends on various factors, including the composition of the feedstock, the specific microbial strains used for fermentation, and the fermentation strategies employed, such as fed-batch or continuous processes. Optimizing these factors is crucial to achieving higher yields and improving the overall efficiency of biobutanol production.

Biodiesel is an alternative to petroleum-diesel/petrodiesel, the most common type of diesel fuel. The word "bio" refers to renewable and biological origin whereas the diesel specifies that it is dedicated to the diesel engine. Biodiesel production utilizes recycled cooking grease, animal fats, and other organic wastes. It is composed of fatty acid alkyl esters generated through transesterification of triglycerides [48]. The medium length C_{16}-C_{18} fatty acid chain contains approximately a little more than 10% oxygen by weight. As an example, microalgae and biomasses such as olive residues can be used to produce biodiesel after lipid extraction. However, the efficiency of conversion of lipids into biodiesel depends mainly on lipid extraction and transesterification conditions. Pretreatment may be needed to enhance cell wall disruption leading to effective lipid extraction. Among these pretreatments, milling, high-pressure homogenization, enzymatic hydrolysis, electroporation, and drying constitute the major ones. The choice of the appropriate pretreatment method depends on its effectiveness, capital costs, energy consumption, and their scalability. The significant advantages of biodiesel consist of low toxicity, biodegradability, engine lubrication improvement, and low emission profile [49]. The percentage composition of biodiesel in a mixture is expressed as "BXX" where XX refers to the ration of biodiesel in the mixture.

Bio-oil and syngas: Thermochemical processes can effectively handle a diverse range of LCB types and thus represent a promising option for efficient biomass-to-biofuel conversion technologies. Pyrolysis, defined as the thermal decomposition of biomass at elevated temperatures in the absence of oxygen yields bio-oil, syngas, and biochar [50]. On the other hand, gasification converts biomass into combustible syngas in the presence of a quantity of oxygen less than what is required for the stoichiometric combustion process [51]. Bio-oil is characterized by a color ranging from light to dark brown, primarily composed of a complex mixture comprising hundreds of organic molecules. It contains water (typically 15–35 wt.%) and hundreds of organic chemicals, including acids, phenols, ethers, alcohols, ketones, and other oxygenates. Managing water content, separating valuable compounds, and improving stability are some of the ongoing challenges. The effectiveness of bio-oil is limited due to the intricate nature and unfavorable properties, most notably its high oxygen content, depending on the biomass feedstock, and operation conditions employed, whereas these issues can be overcome by subjecting bio-oil to a number of upgrading processes and reactions such as hydrodeoxygenation (HDO) [52]. The primary objective of these treatments is two-fold: firstly, to reduce the oxygen content in the bio-oil, and secondly, to promote the formation of carbon–carbon bonds. These transformations ultimately yield sustainable hydrocarbons suitable for transportation fuel formulations (Fig. 4). Syngas is mainly composed of CO_2, CH_4, CO, and H_2 and exhibits a notable high calorific content [53]. This characteristic makes it an attractive supplementary energy source with potential applications in heat and power generation using various systems, including boilers, engines, fuel cells, steam turbines, and gas turbines. The yield and quality of syngas depend significantly on factors such as operating conditions, reactor type, and composition of the feedstock [54]. Integrating syngas fermentation with acetogenic bacteria can produce alcohols and other high-value biochemicals. Moreover, syngas can be also be used for hydrogen generation and other chemicals such as methanol and Fischer Tropsch diesel which hold a significant commercial value [55].

Furan-based biofuels such as 2,5-dimethylfuran (DMF) are gaining attention due to their promising properties such as high energy content. Furan compounds including 5-hydroxymethylfurfural (HMF) and furfural (FF) serve as versatile platform molecules. They are derived from degradation of LCB thus making them a renewable and sustainable source of energy. They can also act as potential molecules for various intermediates (such as 2,5-furandicarboxylic acid (FDCA), alkyl alcohols, amines, hydrocarbons, and ketones), for polymer technology and solvent design as well. DMF has shown outstanding advantages in terms of emissions compared to fossil fuels [56]. When burned, DMF can achieve zero-soot emission [57]. As a biofuel, DMF has high energy density, it is insoluble in water, has high octane rating, low volatility and is stable during storage as well. A recent study discusses the transformation of waste carbohydrates into furan-based biofuels specially DMF using catalysts thus summarizing the important aspects for enhanced DMF yield. Significant number of catalysts such as zeolites, noble-metals and electrocatalytic materials are discussed along with their effects in deriving carbohydrates to DMF [58]. While DMF shows promising results in terms of emissions, a comprehensive assessment considering all aspects such as the source of the biomass, the efficiency of the conversion process and the overall life cycle of the biofuel is necessary to understand its environmental impact. Similarly, another review discusses a comprehensive analysis of the use of 2-methylfuran (MF) as a biofuel [59]. MF is recognized as a critical platform substance and an ideal green solution on the pathway of finding alternate fuels. The article provides a thorough review of its production pathways from biomass, combustion progress and applications in engines. However, further studies are suggested on engine durability, compatibility, and tribology behaviors.

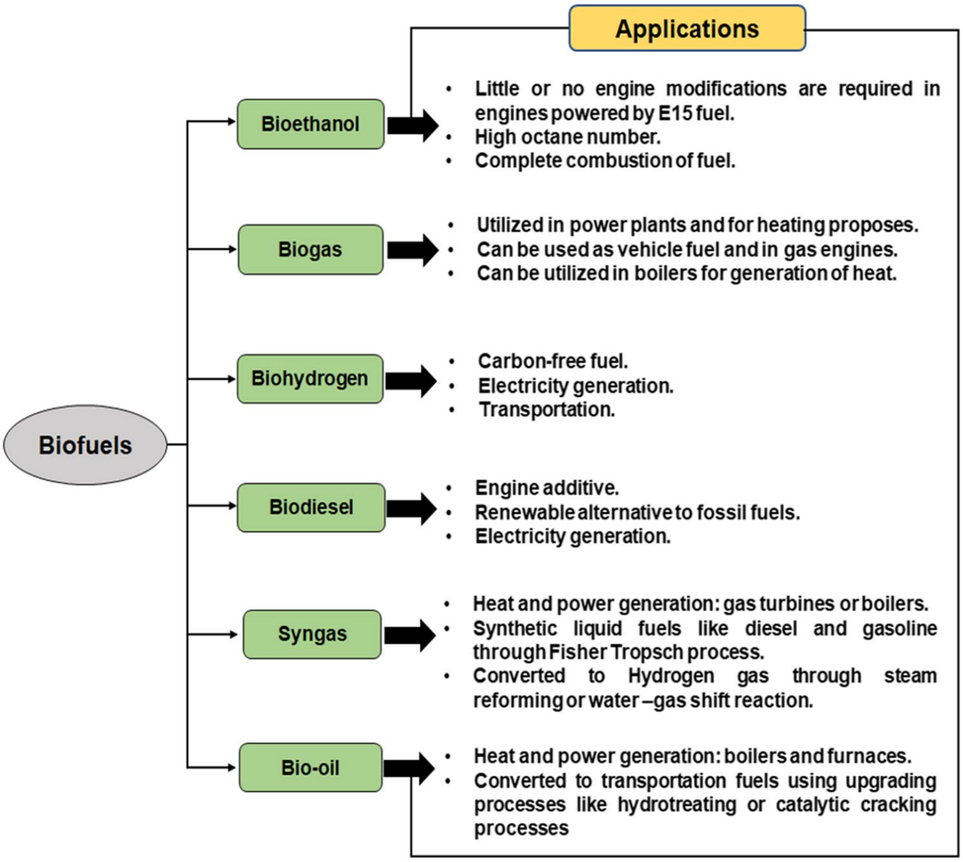

Fig. 4 Major biofuels and their broad applications

Pretreatment Techniques to Enhance Bioenergy Production

Milling plays a crucial role as the initial step in the physical pretreatment process, aiming at enhancing the surface area of substrate molecules. In the physical pretreatment, feedstocks can undergo chipping, milling, and grinding leading to reduction in particle size in the range of a few millimeters (0.2–10 mm). Dry milling, while effective, is associated with a high energy consumption, which can be addressed by adopting wet milling techniques. Wet disc milling has emerged as a popular pretreatment method due to its lower energy requirements. In comparison to hammer milling, which results in finer bundles, disc milling demonstrates an advantage in promoting cellulose hydrolysis by generating more fibers. When it comes to biomass size reduction, attrition and planetary mills are more effective than ball milling. Furthermore, different milling methods may yield varying quantities of glucose and galactose, with planetary milling showing the highest production levels of these sugars during the pretreatment process. Milling serves as a preparatory step before enzymatic hydrolysis and other pretreatment procedures like chemical or physicochemical approaches. The choice of milling method, whether chemical or mechanical, depends on whether it is classified as dry or wet, and this decision is determined by the type of biomass used. For dry biomass, such as maize stover, processing is commonly carried out using extruders, roller mills, cryogenic mills, and hammer mills. On the other hand, wet biomass (including energy cane, wheat bran, or wheat straw) can undergo pretreatment using methods like colloid milling, fibrillation, and dissolving. Recent research has shown promising results in improving biohydrogen production from corncob biomass through ultrafine grinding thus achieving a notable increase of 36%. The study indicates the potential of advanced milling techniques in enhancing the efficiency of biofuel production processes [60]. For pretreating LCB to improve biogas production, single and twin-screw extruders are commonly utilized. Effective extrusion pretreatment considers parameters such as screw speed and extruder temperature. Hjorth et al. found that methane production was enhanced by 68% after straw extrusion at 33 °C. For particles larger than 1 mm, the particle size reduced by 50%, although no significant impact on cellulose, lignin, or hemicellulose content was observed [61]. Ball milling has been reported as an efficient pretreatment method prior to pyrolysis. It significantly reduced cellulose crystallinity by 44%, leading to a lower energy requirement for cellulose activation [62]. More recently, Falls et al. studied the impact of shock treatment based on sudden shock waves ensured by a metal cylinder. It was found that 24 h glucan enzyme digestibility of shock treated bagasse, corn stover, poplar, and sorghum was more effective compared to ball milled biomass types. However, ball milling gave more interesting results when resident time was increased [63]. A recent study has evaluated the comprehensive effects of particle size on biomass preprocessing, pretreatment and enzymatic hydrolysis by assessing biomass compositional and morphological features, characterizing biomass crystallinity and enzyme accessible surface area including hydrolysis sugar yield and its efficiency. The results of the study indicated that the sub-millimeter small particles experienced greater pretreatment severity and 5–10% more structural composition removal than their millimeter level counterparts. Although, small particles had about 10% higher enzymatic hydrolysis efficiency, the low pretreatment solid and sugar recoveries neutralized their enzymatic hydrolysis advantage over large particles [64]. Another study examines the impact of switchgrass particle size on the efficiency of three different pretreatment types (ammonia fiber expansion, dilute acid, and ionic liquid) with ionic liquid showing the greatest advantage especially for larger biomass particles [65]. Considering that the milling process is generally energy-intensive, various studies have combined milling with chemical pretreatment to decrease energy consumption and improve the accessibility of lignocellulosic biomaterials for further bioconversion steps [66, 67]. These combined approaches aim to optimize the overall efficiency of bioconversion processes while minimizing energy demand.

Microwave irradiation has been widely reported as one of the most commonly used pretreatment methods for LCB. This technology offers an effective alternative to conventional heating methods, as it enables rapid heating of a large volume of substrate, thus reducing pretreatment time leading to significant energy savings [68]. Indeed, microwave pretreatment has demonstrated remarkable results. For instance, pretreatment of wheat straw using microwave at 150 °C resulted in a 28% increase in biogas production compared to the untreated biomass [69]. However, it is important to state that the impact of microwave pretreatment may be the opposite when process temperature exceeds 200 °C. At higher temperatures, the formation of recalcitrant or inhibitory compounds (such as phenols) might occur, leading to adverse effects on the bioconversion process [70]. Therefore, careful consideration of microwave pretreatment conditions is crucial to maximize its benefits without resulting in undesirable outcomes. Recently, Naik et al. studied the effect of microwave with the lowest energy input (300 W) combined to dilute NaOH (0.2%) pretreatment on biogas production from rice straw. It was found that the combination increased biogas concentration by 10% compared to that by using dilute NaOH alone. The efficiency of mild microwaves was thus low [71]. Microwave pretreatment can improve biohydrogen production by increasing the bioavailability of substrates to the microorganisms involved in the fermentation process. This technique can also facilitate the release of fermentable sugars and volatile compounds into the biomass, thereby increasing biohydrogen production. However, it should be noted that the effects of microwave pretreatment may depend on several factors such as the power and duration of the treatment, the chemical composition of the biomass, the particle size, and the environmental conditions of the fermentation process. Therefore, maximizing biohydrogen production necessitates the optimization of microwave pretreatment conditions. This pretreatment method is preferred due to several reasons, including its ability to efficiently degrade the cellulose structure, ease of process operation, minimal formation of inhibitors, rapid and high heating capacity, and low energy consumption. A 13% biohydrogen production increase was reported when microwave pretreatment (140 °C for 15 min, 1000 W) was applied on *Laminaria japonica* biomass. Combining microwaves and acid pretreatment (1% H_2SO_4) resulted in doubling the hydrogen yield compared to the control fraction [72]. In the context of bioethanol production, microwaves have proven to be effective in improving the degradation of the lignocellulosic matrix. These findings underscore the potential of microwave pretreatment as an energy-saving technique in bioethanol production from LCB. However, at high pressure, microwaves can allow the HMF (hydroxymethylfurfural) and furfural presence in liquid phase, as reported by Mikulski and Kłosowski [73]. In this paper, microwave power was fixed and only pressure and pretreatment time were the conditions that were varied. Consequently, furfural concentration doubled in case of 93 psi pretreatment as compared to 54 psi while the glucose content reduced by 15% [74]. The study suggested the use of activated carbon to detoxify the fermentation media and enhance the product yields.

Ultrasound irradiation reduces pretreatment time and chemical/enzyme requirements, making it an eco-friendly and highly efficient technique. The mechanical vibrations disrupt the lignocellulose matrix, facilitating subsequent enzymatic or chemical treatments. Ultrasound generates localized heating within the biomass, leading to microscale temperature variations. This promotes lignin softening and cellulose accessibility. It is particularly favorable for pretreating inoculums (such as activated sludge) in hydrogen production through dark fermentation. Cassava wastewater was subjected to ultrasonic pretreatment under 50 kHz and 45 min before dark fermentation and as a result 40% higher COD removal was achieved [75]. In the same manner, ultrasonic pretreatment can improve biohydrogen production by breaking up the biomass particles and increasing the specific surface area, which increases the bioavailability of the substrates to the microorganisms involved in the fermentation process. In addition, this method can also improve the release of fermentable sugars and volatile compounds into the biomass, thereby increasing biohydrogen production. The application of ultrasound (40 kHz for 5 min) as a pretreatment method for corn residue led to improved glucose and ethanol yields by 3% and 11%, respectively [76]. A recent study investigated the impact of combining ultrasonic pretreatment and enzymatic hydrolysis on methane production. In fact, an increase of 80% was found under 20 W for 60 min, and 5.46% solids content and enzymatic hydrolysis conditions of 32.68FPU/gTS cellulase and 14.56 IU/gTS β-glucosidase [77]. Ultrasound parameters (frequency, intensity, and duration) impact pretreatment efficiency. Optimization studies are essential for consistent results. Also, combining ultrasound with other pretreatment methods (e.g., steam explosion and acid hydrolysis) may yield synergistic effects. Scaling ultrasound pretreatment to industrial levels requires addressing reactor design, uniformity, and cost-effectiveness.

Liquid hot water (LHW) is a thermal pretreatment technology known for its ability to improve surface area and biomass accessibility. It is a hydrothermal pretreatment process that uses pressurized water to break down biomass. In this process, biomass is subjected to high-pressure cooking in hot water, maintaining the water in a liquid phase. The hot water effectively penetrates the biomass, hydrating cellulose, solubilizing hemicelluloses, and partially removing lignin. A recent study examines LHW as a sustainable pretreatment technology. It discusses the challenges of using LHW for biomass pretreatment including its reaction mechanism as well as the techno-economic challenges and prospects involved. One challenge that the study highlights is that LHW can degrade sugars, which can reduce the yield of biofuels. Another challenge mentioned was that it can produce inhibitory compounds that can slow down the fermentation process. The review concludes that LHW pretreatment method could be widely employed for bioenergy processing from biomass but circular economy based advanced pretreatment techniques should further be studied in order to achieve maximum efficiency and minimum cost [78]. Researchers like He et al. [79] have demonstrated that hydrothermal treatment at 150 °C for 20 min can result in a significant increase of 23% in methane potential when compared to the untreated rice straw substrate. This underscores the effectiveness of hydrothermal pretreatment as a means to enhance the bioconversion potential of lignocellulosic biomaterials, making them more amenable to biogas production [79]. In addition, 16% biomethane potential enhancement was obtained in corn stover at less severe conditions (100 °C) for 30 min [80]. Steam explosion is a pretreatment method involving the sudden decompression of biomass to atmospheric pressure. This process utilizes hot steam at temperatures between 180 and 240 °C and pressure ranging from 1 to 3.5 MPa to achieve its desired effects [81]. It can be employed using chemical reagents as catalysts. Among the effects of this pretreatment include (i) degradation of hemicelluloses and (ii) slight depolymerization of cellulose and degradation of lignin through cleavage of β–O–4 linkages [82]. The LCB rigid structure is disrupted due to the shear force produced by the pressure. Steam explosion remains one of the most applicable methods at full scale. It can be applied to every biomass while consuming lower energy compared to milling [83]. To enhance hydrogen generation, thermal pretreatment is generally used on the inoculum. It allows eliminating the methanogens while facilitating the growth of the hydrogen producing bacteria. The inoculum is a source of microorganisms that is used to start the fermentation process of biomass for biohydrogen production. Thermal pretreatment of the inoculum prior to its use can have a significant effect on biohydrogen production. In general, thermal pretreatment of inoculum can increase the activity of microorganisms involved in biomass fermentation. This may be due to the increased concentration of certain chemical compounds in the inoculum after heat treatment, such as volatile fatty acids (VFAs) or fermentable sugars. In addition, thermal pretreatment of the inoculum can also improve the resistance of the microorganisms to adverse environmental conditions, such as high temperatures, acidic or alkaline pH, and high concentrations of inhibitory compounds. This may allow the microorganisms to survive and maintain their metabolic activity under harsh conditions, possibly increasing biohydrogen production. However, it should be noted that the effects of thermal pretreatment of the inoculum may depend on several factors such as the type of inoculum, the method of thermal pretreatment, and the environmental conditions of the fermentation process. Hence, optimizing the thermal pretreatment conditions of the inoculum is important for maximizing biohydrogen production. The pretreatment time and temperature are two crucial parameters that need optimization for effective pretreatment. Enhanced hydrogen production can be guaranteed when operating under short pretreatment time and low temperature, which inhibits hydrogen consumption. When microalgae biomass was thermally pretreated under 100 °C for 60 min, hydrogen production attained 77 mL/gVS while the control produced only 13 mL/gVS [84]. Another study showed that combining thermal (70 °C for 60 min) and free ammonia (pH 9) pretreatment enhanced hydrogen production of waste activated sludge by 57% [85]. LHW pretreatment efficiently delignifies LCB. The high-temperature water disrupts hydrogen bonds, solubilizes hemicellulose, and partially removes lignin. The effectiveness of LHW depends on temperature and residence time. Balancing delignification with cellulose preservation is thus crucial. Furthermore, LHW generates soluble compounds (e.g., furfural and acetic acid) and efficient recovery and utilization of these byproducts is essential. LHW can be part of an integrated biorefinery. The recovered lignin and hemicellulose components can serve as feedstocks for value-added chemicals.

Freezing and thawing are employed to disrupt cells and release intracellular components at room temperature. Freezing involves two stages: the phase change from liquid to solid and a temperature decrease. Ice formed during freezing has a lower density than liquid water. The freezing process is mainly used for large-scale food preservation, where crystal formation is required, and a significant heat gradient exists. Freezing/thawing can create pores in the cells of the microorganisms, allowing for better diffusion of substrates and metabolic products through the cell membranes. This technique can also increase the specific surface area of the cells, improve nutrient availability, and reduce the viscosity of the inoculum, thereby promoting fermentation and biohydrogen production. When combined with potassium ferrate (0.15 g/g TS), a recent study found that freezing of waste-activated sludge at − 12 °C for 24 h had the highest impact on hydrogen production which increased 30% compared to the use of potassium ferrate alone [86]. Moreover, corn stalk was pretreated by freezing–thawing to enhance its methane potential. After 21 days of pretreatment, methane production increased by 40% with 27% higher VS removal [87]. However, it is important to note that freeze/thaw pretreatment can also damage the cells of microorganisms and reduce their metabolic activity. Therefore, it is important to optimize the freezing/thawing conditions to minimize the negative effects on the microorganisms and maximize biohydrogen production.

Alkaline pretreatment is primarily employed to remove lignin by breaking the lignin-carbohydrate linkage, which enhances the reactivity of the remaining polysaccharides. Alkali reagents facilitate the decomposition of lignin into low molecular weight compounds by cleaving the α- and β-aryl ethers and glycosidic bonds, resulting in a more accessible breakdown of the lignocellulose matrix and an improvement in its porosity [88]. Karimi et al. reported that alkali pretreatment can lead to partial degradation of hemicelluloses and cellulose through various reactions, depending on specific conditions [89]. These reactions include (i) at temperatures above 100 °C, a peeling-off reaction occurs, involving the degradation of reducing end-groups (aldehydes) present in cellulose; (ii) at temperatures above 150 °C, hydrolysis of glycosidic bonds and acetyl groups takes place; (iii) at high alkali doses (6–20%) non-degraded polysaccharides dissolve [89]. Among the alkali reagents used for LCB pretreatments, sodium hydroxide is considered one of the most effective choices. At a dosage of 6% at room temperature, NaOH increased methane production of rice straw by 42% [90] while at 10% the lignin of *Miscanthus* decreased by 35% and its methane potential was 55% higher compared to untreated biomass [91]. However, NaOH can affect the digestate quality and may hinder its utilization as fertilizer because of the risk of soil salinity. More safe alkali reagents (such as lime and potassium hydroxide) may be used as alternatives to NaOH. Song et al. [92] obtained 105% more methane content from lime pretreated corn straw. Alkaline solutions saponify the ester bonds present in lignocellulosic substrates, leading to the disintegration of their crystalline structure and consequent enhancement of hydrolysis. They are also effective in attacking and degrading lignin. Dilute alkali pretreatment is well-suited for subsequent hydrolysis by enzymes and promotes reactions of residual polysaccharides. For example, at 6% CaO and 121 °C, a maximum H_2 yield of 114 mL/g of total solids (TS) was achieved using wheat straw, surpassing the yield obtained from hot water treatment at 121 °C (43.2 mL/g TS) [93]. Furthermore, alkali pretreatment (2% at 120 °C for 60 min) facilitated enzymatic hydrolysis, resulting in the production of 129 g butanol per kg of corncob [94].

The primary objective of **acid pretreatment** is to hydrolyze hemicelluloses, making cellulose more accessible for further processes. Additionally, acid pretreatment can lead to lignin solubilization and precipitation, with a more pronounced effect observed at higher acid concentrations. However, this method can also result in the formation of toxic compounds such as furfural and HMF, which can be degraded by methanogens but only at concentrations lower than 4 g/L [95]. Lately, the organic acids have won the interest of researchers, since they are more environment-friendly reagents [96]. Peng et al. [97] found that methane produced was enhanced by 24% after the acetic acid pretreatment while 23% of hemicelluloses were solubilized from biomass. Furthermore, Kootstra et al. [98] discovered that maleic or fumaric acids could be promising alternatives to sulfuric acid, as they generate less furfural. Boonsombuti et al. [99] achieved a 67% sugar yield by using phosphoric acid (1% at 50 °C for 30 min, then 121 °C for 1 h) to pretreat corncob for biobutanol production. Similarly, Qureshi et al. [100] reported the effectiveness of a hammer mill coupled with sulfuric acid pretreatment for biobutanol production. Acid-based pretreatment application is an effective process for biorefineries that aims to optimize the production of desired products while minimizing by-products. However, acid pretreatment has certain disadvantages, including the corrosion of reactors and the potential formation of inhibitory compounds. Additionally, adjusting the pH after acid pretreatment can complicate the process and lead to increased operational costs as well. There are many environmental concerns and challenges (acid type, acid concentration, reaction time) involved in using acid pretreatment methods which need to be addressed in order to aim for sustainable bioenergy production [101]. Studies have highlighted that the production technology of an acid-based catalyst for pretreatment of biomass plays a significant role in the production costs. Finding the right technology that is cost effective and limits the formation of undesirable by-products needs to be addressed.

Acid and alkali pretreatments are widely used for enriching or eliminating hydrogen-consuming bacteria (HCB) in inoculums, considering the pH sensitivity of non-sporulating hydrogen consumers [46]. The most commonly used acids are HCl, H_2SO_4, and HNO_3, having a concentration ranging from 0.1 to 6.0 M and pH varying from 2.0 to 4.0. Regarding alkali pretreatment, NaOH, KOH, and $Ca(OH)_2$ are the commonly used solvents, with concentrations varying from 1.0 to 8.0 M and pH values ranging from 10 to 12. Acid and alkali pretreatments are employed for selective dark fermentation by enriching the media with hydrogen producing bacteria. Oxidative reagents are also used for lignocellulosic components removal. The main reactions that take place include (i) electrophilic substitution, (ii) displacement of side chains, and (iii) breakdown of alkyl aryl ether linkages. As for alkali and acid pretreatments, the oxidants can generate furanic and phenolic compounds which may inhibit methanogens. Song et al. reported that a dose of 3% hydrogen peroxide reduced hemicelluloses, cellulose and lignin by 50, 37, and 24%, respectively, which eventually increased methane potential of corn straw by 115% compared to the untreated biomass [92].

Ozonolysis is an efficient oxidative pretreatment method to treat lignocellulosic substrates such as wheat straw and bagasse. It enhances sugar release and thus increases hydrogen productivity. Moreover, no harmful compounds are released which makes this process safe. Oxidation with ozone or H_2O_2 has also been used to pretreat sludge. The ozonation allows disrupting cells and solubilizing hardly degradable materials. It also leads to mineralization of matter at higher doses. The use of ozone to delignify wheat straw and release glucose has already been reported. It was found that 50% of lignin was removed and 75% of glucose was solubilized when using an ozone concentration of 0.44% under 60 L/min and 5 h with moisture content of 95%. Another study reported 34% lignin removal and 88% of glucose released from wheat straw under an ozone concentration of 2.7% and a moisture of 40%. The contradictory results may be related to the particle size of wheat straw ($<$0.2 mm in the first study and 3–5 mm in the second one) [74]. When compared to H_2SO_4 pretreatment, ozonolysis (60 min, 1% solid content) produced 0.52 g sugar per gram marine biomass compared to 0.56 g/g marine biomass after acid pretreatment (30 min, 1% solid content). However, the latter generated 5-HMF unlike ozonolysis [102]. Bioethanol production was thus more interesting in ozone treated biomass (three-fold the ethanol production from acid treated biomass).

Chloroform ($CHCl_3$) has been employed as an inhibitor of methanogenic microorganisms to enhance biohydrogen production during dark fermentation. Its role is to restrict the conversion of methyl-CoM to methane by inhibiting methyl-CoM reductase (MCR), consequently limiting the activity of corrinoid enzymes. By avoiding the hydrogenotrophic methanogenesis step, the hydrogen generated during dark fermentation remains unconsumed, leading to an increase in hydrogen yield. Numerous studies have explored the use of chloroform to suppress HCB in mixed microflora. The concentration of chloroform has been varied in the range of 0.0005% to 5%, with different time intervals, typically between 17 and 24 h, at room temperature. Despite the use of chloroform in the dark fermentation process, Singh et al. [46] stated that chloroform pretreatment did not significantly affect the hydrogen yield. Not all biomass types respond uniformly to chloroform. Assessing feedstock-specific effects is crucial. Chloroform pretreatment thus offers an innovative pathway for sustainable biofuel generation. By addressing safety concerns and optimizing processes, we can explore its potential in the bioenergy landscape.

Biological pretreatment offers a mild and environment friendly approach, where enzymes can be generated in-situ by microorganisms. Unlike other pretreatment methods, biological pretreatment is considered a time-consuming but mild and environment friendly approach. In this method, enzymes are utilized to biologically degrade lignocellulosic substrates. Various microorganisms, including white and soft-rot fungi, actinomycetes, and bacteria, can be harnessed for the pretreatment of lignocellulosic wastes. These microorganisms possess the enzymatic capability to solubilize lignin through the action of enzymes such as peroxidases and laccases. Moreover, laccase and peroxidase under 30 °C for 24 h can enhance methane production by 15% from corn stover biomass [103]. In fact, using white rot fungi as a source of laccase and peroxidase under 30 °C for 24 h can lead to an increase of 25% compared to untreated corn stover. In addition, enzymatic pretreatment of solid cattle manure using a mixture of cellulase, hemicellulase, xylanase, pectinase, xylan esterase, pectin esterase, lipase, amylase, glucosidase, and protease under 40 °C for 3 h was reported to enhance methane volume by 105% [104]. In another study conducted by Kainthola et al. [105], the impact of three fungal pretreatments on LCB degradation has been extensively explored. Among the tested fungi, *Phanerochaete chrysosporium* has emerged as the most effective for LCB degradation. The application of this particular fungal pretreatment resulted in an impressive 40% degradation of lignin and a remarkable two-fold increase in methane production compared to the untreated substrate [105]. Such findings highlight the promising potential of biological pretreatment as a sustainable and efficient method for enhancing lignocellulosic waste conversion and biogas production. This finding agrees with Liu et al. [106] study in which *Phanerochaete chrysosporium* was found to increase methane production of corn stover silage by 19% with 22%, 15%, and 10% of hemicelluloses, lignin, and cellulose degradation respectively. In addition, aerobic pretreatment is an easy technique to increase accessibility to hemicelluloses and cellulose. However, it often results in carbon loss through respiration which diminishes the methane yield [107]. Poplar leaves, rich in lignocellulosic content, have been identified as a viable substrate for biohydrogen production. The leaves underwent separate pretreatments with acids, alkali, and a mixture of enzymes. Notably, the use of a specific enzyme mixture (VicozymeL-2%) resulted in a significant 34% increase in cumulative H_2 production compared to the conventional acid and alkali pretreatment methods [107]. Some of the improvements for future research in this field must focus on the right selection of the microbial consortium, optimization of pretreatment parameters, development of new pretreatment technologies, use of cost-effective hydrolytic enzymes, enhancing the enzymatic digestibility of the biomass components, minimizing the loss of sugar, cost-effectiveness of pretreatment processes, and in-depth research on the production and nature of inhibitory compounds, thus generated. Table 2 below gives a breakdown of biofuel production from various LCB resources and the corresponding pretreatment techniques employed.

S/L solid/liquid, *Temp* temperature, *N. R* not reported.

The above description of the modes and effectiveness of pretreatment technologies on bioenergy production showed that pretreatment is a critical choice for complete biomass utilization, but it is still a rapidly evolving bioprocess in the biorefinery industry [114]. Researchers are increasingly interested in unlocking its potential through valorization. By substituting fossil fuels with bioenergy, we contribute to reducing carbon emissions and mitigating climate change. The review emphasizes the positive impact of bioenergy on environmental sustainability. At present, several existing pretreatment technologies have certain advantages and drawbacks in terms of substrate types and pretreatment conditions. Overcoming challenges such as biomass recalcitrance, generation of inhibitory compounds, optimization of operational conditions, decreasing operational costs for their large-scale implementation, efficiency, and scalability of the process are still under development. Moreover, several existing pretreatment technologies are highly-energy consuming, result in formation of high inhibitor concentration, as well as undesired waste generation [115, 116]. Understanding the mechanisms behind each conversion process (e.g., transesterification and pelletizing) is crucial for efficient bioenergy production. Specific measures to address influencing factors ensure optimum performance efficacy. In general, a single pretreatment technology is usually inadequate to achieve the highly expected biological conversion of lignocellulosic biomass. Therefore, a combination of pretreatment technologies owns the most recent development potential for lignocellulosic valorization in the near future.

Table 2 Pretreatment methods employed for biomass valorization

Lignocellulosic biomass	Cellulose (~ %)	Hemicellulose (~ %)	Lignin (~ %)	Ash (~ %)	Pretreatment type	Pretreatment conditions	Yield	Ref
Oil palm empty fruit bunch	40–43	22–25	19–21	6.87	H_2O_2	6% H_2O_2, 180 °C, 45 min	362 mL CH_4/g VS	[108]
Wheat straw	33–38	26–32	17–19	3.74	NaOH	NaOH concentration: 2% S/L ratio: 1:10 Temp.: 80 °C Time: 2 h	Glucan recovery: 89.5% Delignification: 71.8% Increase in enzymatic saccharification efficiency: 32.4%	[109]
Cotton straw	38.7	23.5	25.8	N. R	H_2SO_4	H_2SO_4 concentration: 2.28% (v/v) Temperature: 121.7 °C Time: 36.82 min	Maximum sugar concentration: 20 g/L Maximum ethanol concentration: 7.21 g/L	[110]
Sugarcane biomass	45	32	17	Variable	H_3PO_4	H_3PO_4 concentration: 4.95% *S*/*L* ratio: 1:15 Temp.: 80 °C Time: 375 min	Monosaccharide yield: 8.7 g/L (98% glucose)	[111]
Rice straw	31	26	14	12	Choline chloride-glycerol	Solid loading: 5% Temp.: 150 °C Time: 15 h	Glucan retention: 96.5% Delignification: 52.3% Increase in glucan digestibility: 21–87%	[112]
Corn stover	38–40	28	7–21	3.6–7.0	Microbial consortium	Detoxification bacterium *Pseudomonas putida* and lactic acid production specialist *Bacillus coagulans* Temp.: 30 °C Time: 24 h	Degradation rate of organic acids (acetate, levulinic acid) and conversion rate of furan aldehyde: 100%	[113]

Technical and Socio-economic Challenges

Increased efforts to obtain stable energy reservoirs without deteriorating the environment have paved the way for growth of renewable bioenergy production and complete biomass utilization strategies. Globally, the largest source of renewable energy is modern bioenergy, accounting for over 6% of the global energy supply and more than 50% of renewable energy supply [117]. The biomass derived bioenergy industry including the bioprocess biorefineries have thus shown exponential growth in various sectors. The concept of biorefineries, where multiple bioenergy products (including biofuels, biochemicals, and power) are produced from biomass in an integrated manner, enhances resource efficiency and promotes economic viability. Owing to the collective efforts by industry and academia alike and aided by the government and institutional policies within the social frameworks, there is a need to aim at the upliftment and progress of the society. However, the current bioenergy domain requires not only large-scale technological innovations but also socio-economic reforms for the biomass conversion efficiency to expand and considered sustainably fractionating the residual lignocelluloses. It is thus the utilization of LCB from a single component (i.e., cellulose) vision to entire biomass components for a wide range of biorefinery applications with zero-waste generation to become commercially viable on a biorefinery scale [118]. However, till the time, the biorefineries are able to outperform the petroleum refineries in terms of viability and sustainability, the requirement of petroleum refineries is expected to continue in the near future. For realization of this goal, the potential role of pretreatment methods needs to be reviewed and focused efforts ought to be made in this direction. Subsequently, the implementation of biomass biorefinery processes based on renewable bioresources (mainly LCB) has taken precedence for the future energy demand to be achieved [119]. However, economic, social, and environmental concerns compel us to focus on developing and evaluating effective policy instruments in addition to developing eco-friendly pretreatment technologies to serve the biorefinery industry in the long run. While bioenergy generation is often strongly advocated for its potential socio-economic benefits, it is important to note that these impacts are not universally positive (Fig. 5).

Techno-economic Assessment (TEA) and Process Design of Lignocellulosic Biorefineries for Integrated Sustainability

As a promising sustainable energy source, LCB has garnered major interest in a number of biomass valorization studies for bioenergy and industrially significant bio-based products. The motivation for the development of biofuels comes from the possibilities of reduced GHG emissions, high energy demands, the need for co-production of biofuels, and biochemicals along with the concerns for energy security and effective waste disposal. However, the degradation of biomass is still a substantial challenge despite the current availability of several bioconversion processes. Integrating these processes could enhance the overall product yield, decrease the reaction time, and can also be cost-effective thus enhancing the commercial value of the bioprocess. Process integration through sustainable biorefinery technologies using closed-loop approach could significantly guide the bioprocess towards circular economy (CE) approach. Biorefinery integrated with biocircular economy is thus a concept related to the valorization of LCB into high value-added products such as biofuels, biomaterials and bio-based chemicals [115]. Efficient utilization of LCB with a biorefinery concept is one of the sustainable strategies to address the current global energy crisis and achieve carbon neutrality [120]. However, the carbon neutrality of lignocellulosics for bioenergy production involves multiple factors. Use of pretreatment technique for the isolation of different biopolymeric components is indispensable. In terms of LCB conversion, high cost of processing, development of harmful inhibitors, and detoxification of inhibitors have produced major degree of challenges [121]. Several technological innovations have however, contributed to improve bioprocess systems. Nanotechnology has proved significant success by providing insights and development tools thus contributing to economic progress. The use of biological compounds by microalgae as reducing agents for the synthesis of inorganic nanoparticles has shown promising results such as cost-effectiveness and environmental friendliness [122]. Carbon-rich residue, biochar synthesized from LCB, can be diverted towards industrial applications and energy harvesting as well. Bioenergy with Carbon Capture and Storage (BeCCS) has been discussed in the context of climate change mitigation [123]. BeCCS, being a promising carbon reduction technology offers a permanent net removal of CO_2 from the atmosphere. However, still a number of major challenges are needed to be overcome in order to make it a viable solution for carbon neutrality.

On the other hand, the economic effectiveness of a biorefinery system is dependent on several factors such as capital and operational costs (material, energy, and fixed operating costs), feedstock availability, and logistics which differ greatly based on region and other specifications. To

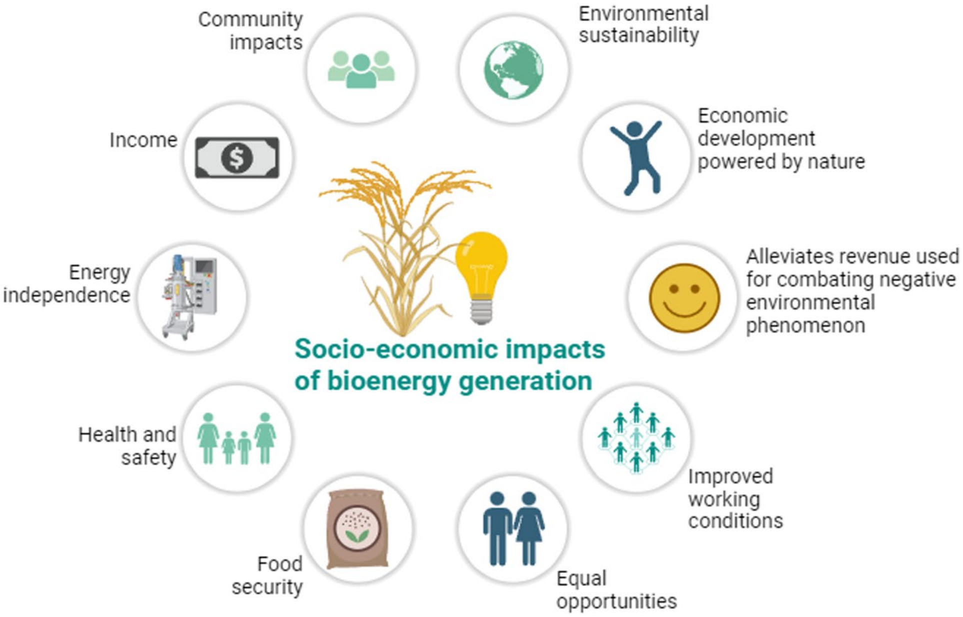

Fig. 5 Key socio-economic impact categories associated with the generation of bioenergy

overcome these hindrances process development needs to align with economic assessment strategies in an effort to make bioprocess biorefinery a success. This includes the analysis of capital and operating cost as the primary goals of any biorefinery process. A techno-economic assessment (TEA) is a key factor in providing decision-making data for the investment aspect of biorefinery. TEA provides an estimated data of biorefinery plant during the life cycle period of product development and commercialization. It includes two primary activities, i.e., (i) process designing and (ii) process analysis whose main aim is to integrate knowledge streams from engineering and scientific disciples at various levels of detail and description. Selection and arrangement of unit operations using economic feasibility to produce quality desired products are included under process designing. Assessment and comparison of different process design solutions encompasses the domain of process analysis. At present, the TEA has become an important part of process development and process synthesis of the biorefinery industry to clarify the technical, economic, and energy consumption related to the economic feasibility to the biorefinery model [124]. Many studies perform TEA for understanding the comprehensive numerical data in order to benchmark the values of different bio-based products and clarify the feasibility of the related integrated technologies to be applied in the potential bioenergy and biomaterials market. The various stages included under TEA are the evaluation of technical feasibility, operating costs (OPEX), capital costs (CAPEX), return on investment (ROI), profitability measures, and payback-period [125]. Installation, construction, engineering, contingency, and equipment costs are included under CAPEX. The OPEX includes the estimation of the general expenses, direct production cost, fixed costs, and other overhead expenses [126]. ROI, a simple technique, can measure the profitability of a biorefinery plant. Both payback-period and ROI are economic indicators but depend on the financial risks of the project involved. Instead, payback-period is a sub-categorized profitability measurement index of a biorefinery plant. Studies have shown that combining the techno-economic assessment and process design studies of the LCB biorefinery has proven to be a key factor for sustainable biomass utilization in a biorefinery industry. A recent example of TEA on vanillin production from Kraft lignin compared it to its petroleum-based product form. The study revealed that the different separation units provided the payback period and internal rate of return (IRR), which were comparable with the commercial process. Besides, Sharma et al. analyzed the TEA of hydrogel production process with the annual operation cost of $9,671,000/year and the annual revenue was $12,230,000/year [38]. The obtained results demonstrated that the process model was more profitable and thus recommended commercialization of the process. Another recent study focused on the techno-economic feasibility assessment of the co-production process of furfural and levoglucosenone (including lignin, hemicelluloses, and biochar) pretreated using ILs in an integrated biorefinery process. Accordingly, the study suggested that the plant would be able to produce around 6.9 MAU$ (million Australian dollar) net benefits after 30 years with a payback time period of 15.4 years [127]. An economic feasibility study for hydrogen production by soybean straw using supercritical water gasification produced a net rate of return (NRR) of 37.1% and a payback-period of 2.5 years [128]. On the other hand, the TEA not only provides technical and economic feasibilities but it is also a beginning stage for process design in large-scale production operations. Moreover, various studies on development of an eco-friendly and techno-economic feasible process for bioenergy production from LCB emphasizes mostly on the process optimization on a lab-scale, which is inadequate to scale up the technologies for commercialization. However, some research studies focused on the coupling of TEA and Life Cycle Assessment (LCA) to provide numerical data showing the potent resource for sustainable bioenergy production. The TEA therefore becomes a key factor for the biorefinery industry to analyze the process development, which is not only bioenergy production but also bio-based products to make the process more economically profitable and technologically feasible. Another study integrated TEA and LCA study with experimental processes for fermentable sugar production from sugarcane bagasse. In the study, the pretreatment methods were shown to influence the capital costs directly that subsequently affected the product cost as well [129].

Technical and Socio-economic Challenges and Perspective Strategies

The journey towards a sustainable bioeconomy, while promising, is not without its share of challenges on the technical and socio-economic front. These challenges span across operational, economic, social, policy and regulatory changes. Addressing these requires strategic planning and implementation. The operational challenges can be sub-categorized into a number of types. Agricultural residues and biomass wastes are the most commonly available renewable feedstocks. Biomass feedstocks are generally available in raw or processed form, divided mostly into three categories—wastes, crops, and forest residues. The feedstock supply should be not only abundantly available but also available at a low cost. Partial feedstock unavailability due to other competitive uses, in-efficient resource management, incompatibility of the production technology with respect to the available feedstocks, and indifferent approach by the government agencies in crafting a flexible bioenergy policy are the key factors which hinder the expansion of the biomass bioenergy industry in this respect. Diversification of feedstock, developing efficient and reliable supply chains, and understanding the risks that affect feedstock supply chains can help in ensuring a steady supply of feedstock. Seasonal variation in availability of biomass feedstock results in the fluctuation of fuel prices creating a situation of unrest by creating instability in the bioenergy market and uncertainty for both producers as well as consumers. The surplus availability of biomass feedstock rather than its demand for other applications (such as animal feed, fodder, or animal shed floor bedding) largely affects the price of the feedstock in bioprocess industries. As the energy density of the biomass is low, acquisition of land for harvesting and storage becomes a difficult task. In addition to this, the significant need for infrastructure required for transportation and biomass bioprocessing is an added challenge. Efficient storage solutions can thus ensure a steady biomass supply for bioenergy production. For successful implementation of the bioenergy projects, biomass storage requires peculiar necessities like concrete flooring, adequate roads for safe transportation, and handling along with ready means of cheap transport [130]. Several sustainability concerns are related with the production of bioenergy, especially in relation to the impacts of land use to produce dedicated energy crops. Synergy in terms of a balance between production of GHGs and other SDGs while keeping up with the development of the bioenergy sector is a challenge that we need to overcome using sustainable means. Some of these strategies include but are not limited to (i) sustainable land use planning, (ii) implementing systems where energy crops can be grown along with the food crops or can be done in a crop rotational system in order to optimize land use, (iii) choosing energy crops that have high yield per unit area can help alleviate the land requirement, (iv) use of marginal lands can be employed for growing some selective dedicated energy crops, (v) sustainable land use planning can aid in the non-competitive growth of energy crops with food producing ones, (vi) algae can be grown on non-arable lands and can thus produce high biomass yield per unit area thus making a profitable and promising solution, and (vii) advanced research and development strategies can aid in improving the biomass yield. However, the effectiveness of these strategies can depend on a wide range of factors and the type of biofuel being produced as well. Transportation of feedstock load could also amount to a leading portion of the bioenergy generation cost due to the establishment of bioenergy production sites far off from the location of the bioprocess plants. In addition, because of the variation in biomass moisture content, transporting wet biomass from the region of plantation to the site of production becomes energetically unfavorable. With increase in distance, it gives rise to tedious logistic procedures which are also economically straining since large volumes are required for bioenergy production thus making the overall bioprocess impractical. Therefore, biomass needs to be densified into briquettes/pellets making it cost-effective and easier to transport. Also, instead of using dedicated energy crops agricultural waste biomass can be used as substrate for bioenergy generation. Biomass also needs to be processed into immediate products such as syngas/bio-oil near the source area which can decrease the total volume that needs to be transferred, and advanced logistics and supply chain management can aid in optimizing the collection, storage, and transportation of biomass for reducing the overall process cost and environmental effects. A mature bioprocess technological procedure requires blending of different types of biomass feedstocks in a suitable composition. However, inherent differences in the biomass compositions make it difficult to obtain the right blend of elements in a heterogeneous biomass mixture. These inherent biomass characteristics (natural variability) can thus impact their conversion performance. The raw material biomass needs to be optimized efficiently to produce bioenergy and biomaterials for industrial applications using efficient pretreatment strategies. The focus of biorefineries should thus be shifted from energy driven designs to more versatile facilities and deeper understanding into the composition of the specific biomass being used is required for effectively designing the biorefinery process [131]. Since there is no one-size-fits-all pretreatment method, recommendations for suitable pretreatment method after careful considerations of raw material characteristics should be based on evaluation of the techno-economic factors. In case of bioprocess units dealing with diverse energy sources, technical barriers result from the lack of uniform standards governing bioenergy systems and the related apparatus. Therefore, the pretreatment process required to prevent biodegradation and loss of heating value not only increases the production cost but also raises investments made in terms of the equipment put in use. The equipment thus needs to have a proven track record and only trained and qualified personnel should be employed to handle them to avoid additional hassles. Due to fluctuating energy markets, it is almost impossible to obtain long term contracts for maintaining a consistent feedstock supply at a reasonable price. The possibility of gaining profits is thus low, and it is a profound reason that many upstream firms lack driving forces in the field of technology reformation. Conducting a comprehensive value chain analysis in order to mark the gasps and shortcomings in the entire bioenergy production process covering aspects such as feedstock supply, conversion technologies, waste management, complete biomass utilization, and product distribution are certainly needed. Adapting an integrated biorefinery approach where biorefineries are not limited to a single product from the same substrate, investing in the research and development sector to uncover advanced bioconversion technologies and exploring novel genetic engineering techniques to enhance microbial conversion rate thereby increasing the energy output can be essentially worked on. In addition, waste valorization (e.g., address waste streams, convert by-products, and residues into value-added products for nutrient recovery and irrigation), collaboration and networking between stakeholders (such as researchers, industry, policymakers, lawmakers, and local communities), policy support, and incentives to encourage investment in the bioenergy infrastructure (grants and subsidies) can lead to better alignment of industrial bioprocess chains.

The production of bioenergy presents various economic challenges that need to be addressed for the sustainable development of this promising bioenergy sector. These challenges encompass a range of factors, from investment costs to sustainable post-processes. In this context, the main economic challenges and their possible solutions are summarized. The biomass power generation is subjected to constraints regarding excessive investment and high operating costs. Because of the de-centralized capital, poor market profitability, and frequent fluctuations in the international crude oil prices (due to international policies, regional disparities, and high market risk), there are hardly any investors who take an initiative in the biomass power generation industry or running this trade. Biomass pretreatment technologies have additional costs involved, which the fuel companies working on small scale and those involved with farming energy crops cannot possibly afford. Cost variation can be considered a substantially significant variable for selecting a suitable bioenergy bioprocess on an industrial scale. The cost of production must be more reasonable than that of the market price for the successful application of a bioenergy product. Method estimating capital cost investment of biorefineries that introduces a modular approach to cost estimation by breaking down a biorefinery into its main process blocks and using separate cost power functions can provide a framework for uncertainty modeling and also help in deciding the contingencies for biorefinery investment as well [132]. Another study comparing heuristic techniques for early-stage cost estimation of biorefinery processes has been conducted [133]. The study recommends the most appropriate rapid cost methods and stresses on the development of an improved early-stage capital cost investment tool which is suitable for biorefinery processes. Biorefinery plants need to be upgraded in order to increase their biofuel processing footprint and meet their de-carbonization goals in addition to accommodating the growing biofuel demand. For example, the use of efficient valorization and recovery technologies can aid in efficient recovery and valorization of wastewater making the biorefinery more sustainable [134]. There is a scarcity of literature on the economic analysis of bioenergy production case studies which also limits the transition of a technology from the laboratory to commercial scale application since there is no realistic data to compare. Life cycle cost and economic assessment [135], TEA, and LCA can aid in examining a variety of substrates, their usage disposal, product output, operating cost, and environmental implications [136]. Literature and contemporary practice can provide elements of consideration, recommendations and dangers while addressing the topics like process commercialization [137]. These steps can fulfill the gap in the literature and provide a comprehensive understanding of the economic aspects of bioenergy production. The large fractions of biomass resources are scattered and loosely distributed creating pockets of high and low density. To reduce the cost of transportation, biomass projects increasingly need to make efforts to occupy land close to the bioresources thus leading to centralization of biomass biorefinery projects. Optimizing biomass feedstock blends to achieve the requisite cost of delivered biomass feedstock, waste biomass resources can be channeled for the utilization of additional purposes such as construction and demolition waste, logging and forest residues [138]. Lignocellulosics are currently not technologically mature as most of the bioenergy still comes from first generation biofuels thus decreasing their economic attractiveness for bioenergy generation. Advances in the synthetic biology can offer innovative solutions to improve the production process of converting biomass into biofuels thus speeding-up the development and commercialization and making them attractive to industrial partners. A case study of advanced biofuel production technologies states that large first-of-its-kind plants requires special regulation that can gradually be shifted from specific to general with increasing maturity and number of plants [117]. In order to make lignocellulosic bioprocess a challenging sector, sustainable post-processes are needed to valorize waste and by-products to make the process economically and environmentally suitable when compared to the petroleum refineries.

In terms of social challenges, bioenergy production holds great promise in delivering substantial socio-economic benefits to communities and playing a vital role in the shift towards a sustainable and renewable energy landscape. Nevertheless, it is important to acknowledge the social challenges that arise from bioenergy production. These challenges can be categorized into various distinct areas. The prominent one is the land use issues which lead to the loss of ecosystems and derails their preservation policies. Also, these are the homes of indigenous people affecting their lives as well. Thus, the process of decision-making with reference to the selection of the plant location, routes, bioprocess technologies and supplier is a critical factor and needs proper communication and handling skills. By strengthening leadership and implementing the responsibilities, the stakeholders should be fully informed of the economic, environmental, and social wealth of bioresource utilization. The biomass plantation increases the loss of biodiversity, depletes nutrients from soil and promotes aesthetic degradation. Other social impacts may also result from the installation of bioenergy farms within rural sectors such as increased traffic, need for diversified manpower and increased need for providing services. One of the promising ways to reduce energy emissions from land use change (LUC) is to increase the number of lignocellulosic feedstocks for bioenergy that can be grown on low carbon pasture lands as they are less suitable for growing annual crops. Solving issues at field scale within the domain of the said agricultural scenario is a challenging affair but an unignorable necessity [139]. A study identified the main synergies and trade-offs associated with the land use for dedicated energy crops using the United Nations SDGs framework. The work highlighted the importance of considering context specific conditions in evaluating the said highlighted synergies and trade-offs [140]. An International Energy Agency (IEA) report examines the bioenergy sector's advantages and limitations in order to address the climate change. This report emphasizes the importance of avoiding conflicts at the local level with other land uses notably for food production and biodiversity protection [141]. In spite of the benefits attached with the new and permanent employment generation; the potential negative social impacts appear strong enough to be ignored.

The policy and regulatory challenges related to bioenergy production can be classified into various levels and aspects, which encompass a number of issues. These issues and their constraints need to be addressed on an immediate basis. The government sector at present is subsidizing the domestic fuel prices with the intention of making the electricity generation cost from conventional bioresources less in comparison to the power production cost from renewable fuels. However, the gap is far reaching to fulfill the case of the cellulosic bioenergy field. At the systemic level, there are no rules to regulate the work of utilization of lignocellulosic bioresources. In addition, there is no special mechanism in place to manage the development of biomass bioresources industry, and no specialized department has been assigned to manage the implementation of the necessary national standards and policies at the systemic level. An effective strategy can be that the policymakers can incentivize sustainable land use practices by implementing regulations that promote them. Reforming subsidies that drive unsustainable land use can help promote more sustainable practices. Establishing clear and long-term targets can provide a stable environment for investors and stakeholders. Implementing financial incentives such as subsidies for sustainable practices, taxes on unsustainable practices, fees for the use of public resources, and trading schemes for environmental credits can encourage sustainable land use. Providing training and financial support to producers to identify and enhance ecosystem services can promote sustainable land use. Strengthening rural economies by investing in infrastructure, sanitation, healthcare, and education can support sustainable land use. Restoring degraded land through public–private partnerships can also help in promoting sustainable use of land. Some other strategies that can address this issue include clear and long-term targets, fiscal incentives, skill development and training and support for Research, Development and Demonstration (RD&D) [142]. Artificial intelligence (AI) can also play a significant role in promoting sustainable land use practices in several ways. As such, AI can analyze large amounts of data on crop yields, climate conditions, and land use patterns to predict optimal planting times, identify sustainable farming practices, and maximize output while minimizing environmental impact [44]. It can be used to monitor land use and enforce regulations thus help in preventing unsustainable practices. AI can help optimize the use of resources in agriculture and other land-based industries, reducing waste and improving efficiency. AI can also be used to address the needs of a planet on life support, including the development of new climate solutions, land management practices, water security, environmental justice, prediction of air and groundwater pollution, preventing extinction, and optimizing nature for human health and well-being. The development, deployment, and use of AI technologies should be done in a sustainable manner, considering the environmental, social, and governance aspects. AI technologies should be developed, deployed, and used with responsibility, ethical principles, and appropriate governance mechanisms, in order to prioritize long-term sustainability.

Problems with the Biomass Large-Scale Supply

One of the major issues related to the large-scale supply of biomass is its energy density. Additionally, the shape of biomass feedstock such as chipped, pelletized, rounded, and baled has a strong influence on the bulk density of the biomass. This also affects the transportation economics. Besides the bulk and energy density, large scale biomass supply is affected by a wide range of bottlenecks including raw material initial cost, biomass producers' involvement, environmental regulation, and sustainability. In field preprocessing, alternate storage designs and utilization of biomass blending can help in overcoming the challenges faced by biorefineries with respect to biomass large scale supply. Finding solutions to all these issues in turn will lead to finding the solution for the creation of future biomass commodities on a global scale. Contribution of biomass supply chains to the SDGs when implemented for bioenergy production can have far reaching effects with ripples crossing barriers.

Bioeconomy: Characteristics, Perspectives, and Challenges in Terms of Biomass Utilization

"Bioeconomy" or "bioeconomics," the term introduced by Nicholas Georgescu-Roegen, connects the dynamics of both physics and economics. It describes a concept that recognizes the research and innovation potential of biotechnology for the sustainable growth of economy and society. He viewed the economic process from a collective biological and thermodynamic point of view meaning that according to the laws of entropy all economic activities must be understood as eventually degrading the physical environment, thereby increasing the entropy of the system. In this context, the concept of "bioeconomics"—"continuously highlights the biological origin of economic process and the human problems associated with a limited stock of accessible resources that are unevenly located and unequally appropriated" [143]. Going by this, Nicholas supposedly meant bioeconomy to signify a new kind of economy which serves the purpose of conserving resources with controlled development and use of technologies to serve all humanity. However, the core significance of bioeconomy is still far behind to be realized. It is an emerging field and there is no commonly accepted definition. Priority sectors determine the strategy field of the bioeconomy design depending on the social, ecological, economic, geographical, and technological scenarios in place. The modern concept of "bioeconomy" is known to originate near the mid-2000s. Its essence is, however, deeply ingrained in the strategic considerations for research and innovation policy directed by the Organization for Economic Co-operation and Development (OECD) and the European Union (EU) [144]. In addition, the term "bioeconomy" was devised not only to include sectors such as agriculture, forestry, and marine but also include a particular way to process, market and harness the natural resources sustainably using biotechnology and commercialization tools. Understanding the specific needs of countries and their desirable outcomes shapes their bioeconomy strategies. Bioeconomy sector is thus of significant attraction as a potential solution for advancing sustainable green growth and competitive economic boost through new technologies [145, 146]. An effective global initiative is therefore an absolute necessity to achieve the UN SDGs. Several government projects around the world are henceforth including bioeconomy strategies in their policy frameworks. However, the uncertainties and disagreements around the concept can lead to a certain ambiguity and uncertainty when it comes to implementing and conceptualizing the bioeconomy strategies. Nonetheless, bioeconomy still offers a relatively new conceptual and strategic basis for the already existing policy areas in this field.

The concept of bioeconomy is ingrained in the "Western" world (OECD), although it has spread to the other parts of the world due to increasing concerns with the industrial consequences of technological advancements in the field of biology. It has assumed different shapes and forms according to the specific social, political, and geographical contexts based on the respective regions and countries in discussion [147]. However, bioeconomic strategies fulfill some basic objectives such as reducing dependence on foreign imports in terms of procuring raw materials, creation of job opportunities in urban and rural areas, and promotion of innovation and development through technology improvement. At the same time, the disorganization in the working principles/transformational nature of the bioeconomy strategies results in conflicts in objectives and governance issues. In this pursuit, the political agenda of governments worldwide is looking at combining the concepts of bioeconomy and circular economy. They are increasingly combined to describe a "circular bioeconomy" (CBE) concept, which emphasizes the value retention of renewable resources and increased circularity of biomaterials in various value chains thus easing down the global sustainability pressures [148]. Moreover, some cases underpin efforts to create additional bioresource value by using waste streams or industrially significant by-products by highlighting the resource significant areas resulting in improved sustainability functions [149]. The transformation towards the complete realization of the concept of bioeconomy in its desirable shape faces or may face some issues (in the future) and need to be constantly monitored.

Recommendations and Perspectives for Bioenergy Bioeconomy

The three most common factors for any bioenergy study should include a full-scale feasibility study, a wide area survey of the biomass feedstock availability, full-scale analysis of the production technology and a market survey for the chemicals and by-products generated by the bioprocess facility. On the other hand, a cascading recovery (Fig. 6) is essential and must be developed and integrated into all the ways and processes of biomass bioprocess transformation to produce bioenergy and make the process profitable in comparison to barrel of petrol cost in kWh (kilowatt-hour) produced by bioethanol, biogas, or biohydrogen. In addition, the integration of the concept of circular economy has become obvious in biomass transformation to bioenergy schemes in order to limit the environmental impacts and generate additional benefits. Besides these, some of the essential success factors for future can be briefly summarized below.

Potential risks and future possibilities need to be identified very early in the development of a bioprocess technology with the aid of TEA, LCA and AI tools. Cascade valorization is essential to make various pretreatment processes profitable and limit biomass waste generation and promote zero waste biorefineries. Support from the policy makers and public awareness can help in placing the bioenergy sector in competition with other sectors in terms of price, market regulations, subsidies, and tax spending. A good synergy matrix between the bioenergy sector and other allied businesses such as those related to forestry and

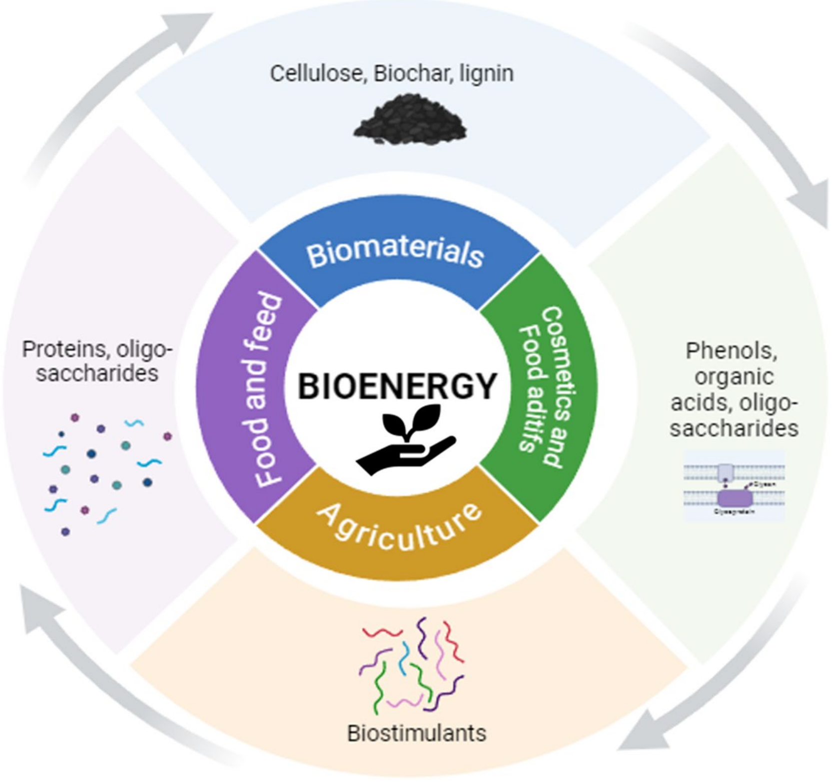

Fig. 6 Cascade valorization of biomass and circular economy

agriculture in terms of infrastructure, feedstock, and equipment may favor the development of a sustainable bioenergy on a large scale. Competition will, of course, brings out improved technologies thus increasing demand at competitive prices. Use of a flexible framework for the assessment of new or emerging bioenergy markets can help spot critical factors for bioenergy growth for the assessment of real problems where actual drivers and barriers for the future development of bioenergy growth must be identified. Collection, documentation, and sharing of data across different bioenergy fields between scientific communities will help in creating a sustainable technology sustainable for all in the long run. Government policies should be directed at encouraging the documentation of the origin of all biomass types consumed in any form in the bioprocess markets in order to ensure their sustainable use. A commitment by the government to suggest short- and medium-term policy proposals would encourage the widespread adoption of bioenergy by highlighting major economic benefits, such as job creation and income generation, both at the local and national levels [150]. Cooperation between business organizations calls for taking appropriate actions which are good for all where common issues are concerned. More case studies will be required to reach a widely accepted, generalized understanding of the different aspects related to the origin and functioning of a biorefinery plant. To evaluate the environmental impacts of a product's life cycle, standardized methods such as LCA using AI techniques could be explored to address the specific indicators and their impact. Simulation-based optimization tools which evaluate sustainability from economic, environmental, and social aspects need to be generalized for bioenergy studies.

Future Prospects of Bioenergy Generation

Bioenergy plays a crucial role in achieving a sustainable and low-carbon energy system. It is a versatile, renewable bioenergy resource that can contribute to reducing greenhouse gas emissions keeping in pace with our growing energy needs. As bioenergy extends beyond electricity production, recognizing the non-power benefits of bioenergy (e.g., waste management, and rural development) is crucial. Liquid biofuels (e.g., bioethanol and biodiesel) for transportation, bioproducts: bio-based chemicals, biomaterials, and value-added products, waste reduction by utilizing agricultural residues, forestry waste, and organic waste streams thus need to be prioritized. For consistent development in this direction, we need to accelerate capacity generation and expansion systematically through effective policies and long-term planning. Techno-economic assessments, life cycle analyses, and sustainability evaluations can successfully guide decision-making. Scaling up bioenergy quickly and sustainably requires overcoming several challenges including infrastructure, policy support, feedstock availability, efficient conversion technologies for complete biomass valorization, and environmental and social factors. Establishing well-defined infrastructure for biomass harvesting, processing, and biorefinery operations and continued policy support is essential to incentivize investment in bioenergy projects. A holistic approach should thus consider economic viability, environmental impact, and social acceptance in unison. Modern bioenergy is therefore expected to have the biggest growth in renewable resources in the following decades. The continuous advancements in technology are thus expected to improve the efficiency of biomass conversion processes. This includes the development of novel pretreatment techniques, optimization of enzymatic hydrolysis, and the design of more efficient bioreactors. The integration of artificial intelligence and machine learning in process optimization could also lead to significant improvements. The optimistic outlook for bioenergy signifies renewable energy solutions, economic prospects, and the potential for waste reduction. Thus, emphasis on sustainable practices in biomass cultivation and harvesting is expected to increase. This will ensure a more secure and sustainable bioenergy system. In conclusion, this review highlights the importance of continued innovation, collaborative efforts, and strategic solutions to achieve a sustainable bioeconomy standing tall on the pillars of bioenergy. The transition from first-generation to complete biomass valorization with well-established infrastructure for harvesting, processing, and further valorization through biorefinery however depends on the need and willingness of consumers, producers aided by the political willingness to bring forth a change to the current system. The prospects for bioenergy generation are bright. Though, still there are various challenges to be addressed; technical, economic, environment and social aspects should therefore be considered in all the future biomass bioprocesses.

Conclusion

Biomass utilization in biorefineries offers a sustainable solution for bioenergy production, yielding biofuels and biomaterials while reducing carbon emissions. Despite challenges like economic viability, technological maturity, biomass supply, and policy issues, solutions exist. Costs can be reduced by quick capital estimation and plant upgradation, while technology can be advanced through R&D and innovation. Biomass supply can be optimized using waste resources and efficient machinery. Policy issues can be addressed with clear targets, incentives, and sustainable governance. With these strategies, biomass valorization is achievable, leading to a sustainable bioenergy future. Despite reservations in the progress, current efforts being made are significant.

Author Contribution All authors contributed to the paper conception. Conceptualization of the paper was performed by all the authors. The first draft of the manuscript was written by Neelu Raina, Santi Chuetor, Doha Elalami, and Saida Tayibi. The manuscript was supervised, revised, and edited by Abdellatif Barakat.

All authors read and approved the final manuscript.

Funding The authors are grateful for the financial support from Mohammed VI Polytechnic University (UM6P) Morocco, INRAE France and King Mongkut's University of Technology North Bangkok (KMUTNB) under contract No. KMUTNB-Post-67–13.

Declarations

Competing Interests The authors declare no competing interests.

References

1. Preethi MG, Banu JR (2023) Indexing energy and cost of the pretreatment for economically efficient bioenergy generation. Front Energy Res 10:1060599. https://doi.org/10.3389/fenrg.2022.1060599
2. Mussatto SI, Dragone GM (2016) Biomass pretreatment, biorefineries, and potential products for a bioeconomy development. In: Biomass fractionation technologies for a Lignocellulosic Feedstock based Biorefinery. Elsevier, pp 1–22
3. Rajesh Banu J, Preethi KS et al (2021) Lignocellulosic biomass based biorefinery: a successful platform towards circular bioeconomy. Fuel 302:121086. https://doi.org/10.1016/j.fuel.2021.121086
4. Ali A, Kumari M, Manisha et al (2024) Insight into the biomass-based briquette generation from agro-residues: challenges, perspectives, and innovations. Bioenergy Res. https://doi.org/10.1007/s12155-023-10712-5
5. Zhai Z, Lu Y, Liu G et al (2024) Recent advances in biomass-derived porous carbon materials: synthesis, composition and applications. Chem Res Chin Univ 40:3–19. https://doi.org/10.1007/s40242-024-3259-6
6. Basak B, Kumar R, Bharadwaj AVSLS et al (2023) Advances in physicochemical pretreatment strategies for lignocellulose biomass and their effectiveness in bioconversion for biofuel production. Bioresour Technol 369:128413. https://doi.org/10.1016/j.biortech.2022.128413
7. Da Silva ARG, Torres Ortega CE, Rong B-G (2016) Techno-economic analysis of different pretreatment processes for lignocellulosic-based bioethanol production. Bioresour Technol 218:561–570. https://doi.org/10.1016/j.biortech.2016.07.007
8. Chuetor S, Panakkal EJ, Ruensodsai T et al (2022) Improvement of enzymatic saccharification and ethanol production from rice straw using recycled ionic liquid: the effect of anti-solvent mixture. Bioeng 9:115. https://doi.org/10.3390/bioengineering9030115
9. Panakkal EJ, Cheenkachorn K, Chuetor S et al (2022) Optimization of deep eutectic solvent pretreatment for bioethanol production from Napier grass. Sustain Energy Technol Assessments 54:102856. https://doi.org/10.1016/j.seta.2022.102856
10. Banerjee N (2023) Biomass to energy — an analysis of current technologies, prospects, and challenges. Bioenergy Res 16:683–716. https://doi.org/10.1007/s12155-022-10500-7
11. Qin L, Li W-C, Liu L et al (2016) Inhibition of lignin-derived phenolic compounds to cellulase. Biotechnol Biofuels 9:70. https://doi.org/10.1186/s13068-016-0485-2

12. Galbe M, Wallberg O (2019) Pretreatment for biorefineries: a review of common methods for efficient utilisation of lignocellulosic materials. Biotechnol Biofuels 12:294. https://doi.org/10.1186/s13068-019-1634-1
13. Cheah WY, Sankaran R, Show PL et al (2020) Pretreatment methods for lignocellulosic biofuels production: current advances, challenges and future prospects. Biofuel Res J 7:1115–1127. https://doi.org/10.18331/BRJ2020.7.1.4
14. Elalami D, Carrere H, Monlau F et al (2019) Pretreatment and co-digestion of wastewater sludge for biogas production: Recent research advances and trends. Renew Sustain Energy Rev 114:109287. https://doi.org/10.1016/j.rser.2019.109287
15. Hidalgo-Sánchez V, Behmel U, Hofmann J, Borges ME (2023) Enhancing biogas production of co-digested cattle manure with grass silage from a local farm in Landshut, Bavaria, through chemical and mechanical pre-treatment and its impact on biogas reactor hydraulic retention time. Sustainability 15:2582. https://doi.org/10.3390/su15032582
16. Moscoviz R, Trably E, Bernet N, Carrère H (2018) The environmental biorefinery: state-of-the-art on the production of hydrogen and value-added biomolecules in mixed-culture fermentation. Green Chem 20:3159–3179. https://doi.org/10.1039/C8GC00572A
17. Ahmed SF, Rafa N, Mofijur M et al (2021) Biohydrogen production from biomass sources: metabolic pathways and economic analysis. Front Energy Res 9:753878. https://doi.org/10.3389/fenrg.2021.753878
18. Jain A, Sarsaiya S, Kumar Awasthi M et al (2022) Bioenergy and bio-products from bio-waste and its associated modern circular economy: current research trends, challenges, and future outlooks. Fuel 307:121859. https://doi.org/10.1016/j.fuel.2021.121859
19. Hoang AT, Varbanov PS, Nižetić S et al (2022) Perspective review on municipal solid waste-to-energy route: characteristics, management strategy, and role in circular economy. J Clean Prod 359:131897. https://doi.org/10.1016/j.jclepro.2022.131897
20. Bandh SA, Malla FA, Wani SA, Hoang AT (2023) waste management and circular economy. In: Bandh SA, Malla FA (eds) Waste Management in the Circular Economy. Springer International Publishing, Cham, pp 1–17
21. Aniza R, Chen W-H, Pétrissans A et al (2023) A review of biowaste remediation and valorization for environmental sustainability: artificial intelligence approach. Environ Pollut 324:121363. https://doi.org/10.1016/j.envpol.2023.121363
22. Le AT, Pandey A, Sirohi R et al (2023) Precise prediction of biochar yield and proximate analysis by modern machine learning and Shapley Additive exPlanations. Energy Fuels 37:17310–17327. https://doi.org/10.1021/acs.energyfuels.3c02868
23. Nguyen VN, Tarełko W, Sharma P et al (2024) Potential of explainable artificial intelligence in advancing renewable energy: challenges and prospects. Energy Fuels 38:1692–1712. https://doi.org/10.1021/acs.energyfuels.3c04343
24. Adamu H, Bello U, Yuguda AU et al (2023) Production processes, techno-economic and policy challenges of bioenergy production from fruit and vegetable wastes. Renew Sustain Energy Rev 186:113686. https://doi.org/10.1016/j.rser.2023.113686
25. Alawad I, Ibrahim H (2024) Pretreatment of agricultural lignocellulosic biomass for fermentable sugar: opportunities, challenges, and future trends. Biomass Convers Biorefin 14:6155–6183. https://doi.org/10.1007/s13399-022-02981-5
26. Rahmati S, Doherty W, Dubal D et al (2020) Pretreatment and fermentation of lignocellulosic biomass: reaction mechanisms and process engineering. React Chem Eng 5:2017–2047. https://doi.org/10.1039/D0RE00241K
27. Patil R, Cimon C, Eskicioglu C, Goud V (2021) Effect of ozonolysis and thermal pre-treatment on rice straw hydrolysis for the enhancement of biomethane production. Renew Energy 179:467–474. https://doi.org/10.1016/j.renene.2021.07.048
28. Dinesh Kumar M, Godvin Sharmila V, Kumar G et al (2022) Surfactant induced microwave disintegration for enhanced biohydrogen production from macroalgae biomass: thermodynamics and energetics. Bioresour Technol 350:126904. https://doi.org/10.1016/j.biortech.2022.126904
29. Li H, Ke X, Li M et al (2021) Bismuth ferrite Fenton-like pretreatment improves lactic acid production from corn stover without detoxification by *Bacillus coagulans*. Biofuels Bioprod Bioref 15:1753–1762. https://doi.org/10.1002/bbb.2274
30. Li F, Lu X, Li Y et al (2022) Effect and optimization of NaOH combined with Fenton pretreatment conditions on enzymatic hydrolysis of poplar sawdust. Chem Pap 76:533–544. https://doi.org/10.1007/s11696-021-01887-2
31. An X, Zhang R, Liu L et al (2022) Ozone pretreatment facilitating cellulase hydrolysis of unbleached bamboo pulp for improved fiber flexibility. Ind Crop Prod 178:114577. https://doi.org/10.1016/j.indcrop.2022.114577
32. Praptyana IR, Budiyono, (2022) Biohydrogen production from wood dust mahogany (*Swietenia mahagony*) by dark fermentation using Enterobacter aerogenes: effect of ozone pretreatment time and pH. Mater Today: Proc 63:S203–S209. https://doi.org/10.1016/j.matpr.2022.02.406
33. Ji Q, Yu X, Yagoub AE-GA et al (2021) Synergism of sweeping frequency ultrasound and deep eutectic solvents pretreatment for fractionation of sugarcane bagasse and enhancing enzymatic hydrolysis. Ultrason Sonochem 73:105470. https://doi.org/10.1016/j.ultsonch.2021.105470
34. Yue L, Cheng J, Tang S et al (2021) Ultrasound and microwave pretreatments promote methane production potential and energy conversion during anaerobic digestion of lipid and food wastes. Energy 228:120525. https://doi.org/10.1016/j.energy.2021.120525
35. Castro YA, Agblevor FA (2022) Effect of wet air oxidation on the composition and biomethanation of water hyacinth. Biomass Convers Biorefin 12:2737–2748. https://doi.org/10.1007/s13399-020-00825-8
36. Panigrahi S, Sharma HB, Tiwari BR et al (2021) Insight into understanding the performance of electrochemical pretreatment on improving anaerobic biodegradability of yard waste. Renew Energy 180:1166–1178. https://doi.org/10.1016/j.renene.2021.08.123
37. Sun S, Zhang Y, Yang Z et al (2022) Improving the biodegradability of rice straw by electrochemical pretreatment. Fuel 330:125701. https://doi.org/10.1016/j.fuel.2022.125701
38. Sharma R, Kumar S, Bhawna, et al (2022) An insight of nanomaterials in tissue engineering from fabrication to applications. Tissue Eng Regen Med 19:927–960. https://doi.org/10.1007/s13770-022-00459-z
39. Roy S, Chundawat SPS (2023) Ionic liquid–based pretreatment of lignocellulosic biomass for bioconversion: a critical review. Bioenergy Res 16:263–278. https://doi.org/10.1007/s12155-022-10425-1
40. Lu J, Song F, Liu H et al (2021) Production of high concentration bioethanol from reed by combined liquid hot water and sodium carbonate-oxygen pretreatment. Energy 217:119332. https://doi.org/10.1016/j.energy.2020.119332
41. Barakat A, Mayer-Laigle C, Solhy A et al (2014) Mechanical pretreatments of lignocellulosic biomass: towards facile and environmentally sound technologies for biofuels production. RSC Adv 4:48109–48127. https://doi.org/10.1039/C4RA07568D
42. Aktas-Akyildiz E, Masatcioglu MT, Köksel H (2020) Effect of extrusion treatment on enzymatic hydrolysis of wheat bran. J Cereal Sci 93:102941. https://doi.org/10.1016/j.jcs.2020.102941

43. Prasad BR, Padhi RK, Ghosh G (2023) A review on key pretreatment approaches for lignocellulosic biomass to produce biofuel and value-added products. Int J Environ Sci Technol 20:6929–6944. https://doi.org/10.1007/s13762-022-04252-2
44. Gil MV, Jablonka KM, Garcia S et al (2023) Biomass to energy: a machine learning model for optimum gasification pathways. Digit Discov 2:929–940. https://doi.org/10.1039/D3DD00079F
45. Keshwani DR, Cheng JJ (2009) Switchgrass for bioethanol and other value-added applications: a review. Bioresour Technol 100:1515–1523. https://doi.org/10.1016/j.biortech.2008.09.035
46. Singh H, Tomar S, Qureshi KA et al (2022) Recent advances in biomass pretreatment technologies for biohydrogen production. Energies 15:999. https://doi.org/10.3390/en15030999
47. Ebrahimi M, Caparanga AR, Villaflores OB (2021) Weak base pretreatment on coconut coir fibers for ethanol production using a simultaneous saccharification and fermentation process. Biofuels 12:259–265. https://doi.org/10.1080/17597269.2018.1468979
48. Yadav AN, Rastegari AA, Yadav N, Gaur R (2020) Biofuels production – sustainability and advances in microbial bioresources. Springer International Publishing, Cham
49. Ennetta R, Soyhan HS, Koyunoğlu C, Demir VG (2022) Current technologies and future trends for biodiesel production: a review. Arab J Sci Eng 47:15133–15151. https://doi.org/10.1007/s13369-022-07121-9
50. Tayibi S, Monlau F, Fayoud N-E et al (2021) Production and dry mechanochemical activation of biochars derived from Moroccan red macroalgae residue and olive pomace biomass for treating wastewater: thermodynamic, isotherm, and kinetic studies. ACS Omega 6:159–171. https://doi.org/10.1021/acsomega.0c04020
51. Sansaniwal SK, Rosen MA, Tyagi SK (2017) Global challenges in the sustainable development of biomass gasification: an overview. Renew Sustain Energy Rev 80:23–43. https://doi.org/10.1016/j.rser.2017.05.215
52. Roy P, Jahromi H, Rahman T et al (2023) Hydrotreatment of pyrolysis bio-oil with non-edible carinata oil and poultry fat for producing transportation fuels. Fuel Process Technol 245:107753. https://doi.org/10.1016/j.fuproc.2023.107753
53. Tayibi S, Monlau F, Marias F et al (2021) Industrial symbiosis of anaerobic digestion and pyrolysis: performances and agricultural interest of coupling biochar and liquid digestate. Sci Total Environ 793:148461. https://doi.org/10.1016/j.scitotenv.2021.148461
54. Tezer Ö, Karabağ N, Öngen A et al (2022) Biomass gasification for sustainable energy production: a review. Int J Hydrogen Energy 47:15419–15433. https://doi.org/10.1016/j.ijhydene.2022.02.158
55. Sikarwar VS, Pohořelý M, Meers E, et al. (2021) Potential of coupling anaerobic digestion with thermochemical technologies for waste valorization. Fuel 294. doi: 10.1016/j.fuel.2021.120533.
56. Hoang AT, Nižetić S, Pham VV (2021) A state-of-the-art review on emission characteristics of SI and CI engines fueled with 2,5-dimethylfuran biofuel. Environ Sci Pollut Res 28:4918–4950. https://doi.org/10.1007/s11356-020-11629-8
57. Zhang P, Su X, Chen H et al (2020) Assessing fuel properties effects of 2,5-dimethylfuran on microscopic and macroscopic characteristics of oxygenated fuel/diesel blends spray. Sci Rep 10:1427. https://doi.org/10.1038/s41598-020-58119-y
58. Hoang AT, Pandey A, Huang Z et al (2022) Catalyst-based synthesis of 2,5-dimethylfuran from carbohydrates as a sustainable biofuel production route. ACS Sustain Chem Eng 10:3079–3115. https://doi.org/10.1021/acssuschemeng.1c06363
59. Tuan Hoang A, Viet Pham V (2021) 2-Methylfuran (MF) as a potential biofuel: a thorough review on the production pathway from biomass, combustion progress, and application in engines. Renew Sustain Energy Rev 148:111265. https://doi.org/10.1016/j.rser.2021.111265
60. Li Y, Zhang Z, Jing Y et al (2022) Forecasting of reducing sugar yield from corncob after ultrafine grinding pretreatment based on GM (1, N) method and evaluation of biohydrogen production potential. Bioresour Technol 348:126836. https://doi.org/10.1016/j.biortech.2022.126836
61. Hjorth M, Gränitz K, Adamsen APS, Møller HB (2011) Extrusion as a pretreatment to increase biogas production. Bioresour Technol 102:4989–4994. https://doi.org/10.1016/j.biortech.2010.11.128
62. Khan M, Shahzad N, Xiong C et al (2016) Dispersion behavior and the influences of ball milling technique on functionalization of detonated nano-diamonds. Diam Relat Mater 61:32–40. https://doi.org/10.1016/j.diamond.2015.11.007
63. Falls M, Madison M, Liang C et al (2019) Mechanical pretreatment of biomass – part II shock treatment. Biomass Bioenergy 126:47–56. https://doi.org/10.1016/j.biombioe.2019.04.016
64. Yang Y, Zhang M, Zhao J, Wang D (2023) Effects of particle size on biomass pretreatment and hydrolysis performances in bioethanol conversion. Biomass Conv Bioref 13:13023–13036. https://doi.org/10.1007/s13399-021-02169-3
65. Dougherty MJ, Tran HM, Stavila V et al (2014) Cellulosic biomass pretreatment and sugar yields as a function of biomass particle size. PLoS ONE 9:e100836. https://doi.org/10.1371/journal.pone.0100836
66. Areepak C, Jiradechakorn T, Chuetor S et al (2022) Improvement of lignocellulosic pretreatment efficiency by combined chemo - mechanical pretreatment for energy consumption reduction and biofuel production. Renew Energy 182:1094–1102. https://doi.org/10.1016/j.renene.2021.11.002
67. Chuetor S, Ruiz T, Barakat A et al (2021) Evaluation of rice straw biopowder from alkaline-mechanical pretreatment by hydro-textural approach. Bioresour Technol 323:124619. https://doi.org/10.1016/j.biortech.2020.124619
68. Hoang AT, Nižetić S, Ong HC et al (2021) Insight into the recent advances of microwave pretreatment technologies for the conversion of lignocellulosic biomass into sustainable biofuel. Chemosphere 281:130878. https://doi.org/10.1016/j.chemosphere.2021.130878
69. Jackowiak D, Bassard D, Pauss A, Ribeiro T (2011) Optimisation of a microwave pretreatment of wheat straw for methane production. Bioresour Technol 102:6750–6756. https://doi.org/10.1016/j.biortech.2011.03.107
70. Pellera F-M, Gidarakos E (2017) Microwave pretreatment of lignocellulosic agroindustrial waste for methane production. J Environ Chem Eng 5:352–365. https://doi.org/10.1016/j.jece.2016.12.009
71. Naik GP, Poonia AK, Chaudhari PK (2022) Maximization of biogas by minimal microwave and alkaline pretreatment of rice straw. Biomass Convers Biorefin. https://doi.org/10.1007/s13399-022-03539-1
72. Yin Y, Wang J (2018) Pretreatment of macroalgal Laminaria japonica by combined microwave-acid method for biohydrogen production. Bioresour Technol 268:52–59. https://doi.org/10.1016/j.biortech.2018.07.126
73. Mikulski D, Kłosowski G (2020) Microwave-assisted dilute acid pretreatment in bioethanol production from wheat and rye stillages. Biomass Bioenergy 136:105528. https://doi.org/10.1016/j.biombioe.2020.105528
74. Travaini R, Martín-Juárez J, Lorenzo-Hernando A, Bolado-Rodríguez S (2016) Ozonolysis: an advantageous pretreatment for lignocellulosic biomass revisited. Bioresour Technol 199:2–12. https://doi.org/10.1016/j.biortech.2015.08.143
75. Leaño EP, Babel S (2012) Effects of pretreatment methods on cassava wastewater for biohydrogen production optimization. Renew Energy 39:339–346. https://doi.org/10.1016/j.renene.2011.08.030

76. Nikolić S, Mojović L, Rakin M et al (2010) Ultrasound-assisted production of bioethanol by simultaneous saccharification and fermentation of corn meal. Food Chem 122:216–222. https://doi.org/10.1016/j.foodchem.2010.02.063
77. Cıggın AS, Yılmaz F, Perendeci NA (2023) Efficient environmentally friendly enzymatic and ultrasonic pretreatment of lignocellulosic wastes for enhanced methane production. Biomass Convers Biorefin. https://doi.org/10.1007/s13399-023-04629-4
78. Chen W-H, Nižetić S, Sirohi R et al (2022) Liquid hot water as sustainable biomass pretreatment technique for bioenergy production: a review. Bioresour Technol 344:126207. https://doi.org/10.1016/j.biortech.2021.126207
79. He L, Huang H, Zhang Z et al (2017) Energy recovery from rice straw through hydrothermal pretreatment and subsequent biomethane production. Energy Fuels 31:10850–10857. https://doi.org/10.1021/acs.energyfuels.7b01392
80. Song X, Wachemo AC, Zhang L et al (2019) Effect of hydrothermal pretreatment severity on the pretreatment characteristics and anaerobic digestion performance of corn stover. Bioresour Technol 289:121646. https://doi.org/10.1016/j.biortech.2019.121646
81. Bandyopadhyay-Ghosh S, Ghosh SB, Sain M (2015) The use of biobased nanofibres in composites. In: Faruk O, Sain M (eds) Biofiber reinforcements in composite materials. Elsevier, pp 571–647. https://www.sciencedirect.com/science/article/pii/B9781782421221500198?via%3Dihub
82. Shrotri A, Kobayashi H, Fukuoka A (2017) Catalytic conversion of structural carbohydrates and lignin to chemicals. In: Song C (ed) Advances in catalysis. Elsevier, pp 59–123. https://www.sciencedirect.com/science/article/pii/S0360056417300020?via%3Dihub
83. Hoang AT, Nguyen XP, Duong XQ et al (2023) Steam explosion as sustainable biomass pretreatment technique for biofuel production: characteristics and challenges. Bioresour Technol 385:129398. https://doi.org/10.1016/j.biortech.2023.129398
84. Stanislaus MS, Zhang N, Yuan Y et al (2018) Improvement of biohydrogen production by optimization of pretreatment method and substrate to inoculum ratio from microalgal biomass and digested sludge. Renew Energy 127:670–677. https://doi.org/10.1016/j.renene.2018.05.022
85. Wang D, Wang Y, Liu X et al (2019) Heat pretreatment assists free ammonia to enhance hydrogen production from waste activated sludge. Bioresour Technol 283:316–325. https://doi.org/10.1016/j.biortech.2019.03.090
86. Hu J, Guo B, Li Z et al (2021) Freezing pretreatment assists potassium ferrate to promote hydrogen production from anaerobic fermentation of waste activated sludge. Sci Total Environ 781:146685. https://doi.org/10.1016/j.scitotenv.2021.146685
87. Li J, Wachemo AC, Yuan H et al (2019) Natural freezing-thawing pretreatment of corn stalk for enhancing anaerobic digestion performance. Bioresour Technol 288:121518. https://doi.org/10.1016/j.biortech.2019.121518
88. Poletto M (2018) Lignin - trends and applications. InTech
89. Karimi K, Shafiei M, Kumar R (2013) Progress in physical and chemical pretreatment of lignocellulosic biomass. In: Gupta VK, Tuohy MG (eds) Biofuel technologies. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp 53–96
90. Xin L, Guo Z, Xiao X et al (2019) Feasibility of anaerobic digestion on the release of biogas and heavy metals from rice straw pretreated with sodium hydroxide. Environ Sci Pollut Res 26:19434–19444. https://doi.org/10.1007/s11356-019-05195-x
91. Thomas HL, Arnoult S, Brancourt-Hulmel M, Carrère H (2019) Methane production variability according to miscanthus genotype and alkaline pretreatments at high solid content. Bioenergy Res 12:325–337. https://doi.org/10.1007/s12155-018-9957-5
92. Song Z, GaiheYang LX et al (2014) Comparison of seven chemical pretreatments of corn straw for improving methane yield by anaerobic digestion. PLoS ONE 9:e93801. https://doi.org/10.1371/journal.pone.0093801
93. Zhang J, Kong C, Yang M, Zang L (2020) Comparison of calcium oxide and calcium peroxide pretreatments of wheat straw for improving biohydrogen production. ACS Omega 5:9151–9161. https://doi.org/10.1021/acsomega.9b04368
94. Cai D, Li P, Luo Z et al (2016) Effect of dilute alkaline pretreatment on the conversion of different parts of corn stalk to fermentable sugars and its application in acetone–butanol–ethanol fermentation. Bioresour Technol 211:117–124. https://doi.org/10.1016/j.biortech.2016.03.076
95. Monlau F, Kaparaju P, Trably E et al (2015) Alkaline pretreatment to enhance one-stage CH_4 and two-stage H_2/CH_4 production from sunflower stalks: mass, energy and economical balances. Chem Eng J 260:377–385. https://doi.org/10.1016/j.cej.2014.08.108
96. Vanegas C, Hernon A, Bartlett J (2014) Influence of chemical, mechanical, and thermal pretreatment on the release of macromolecules from two Irish seaweed species. Sep Sci Technol 49:30–38. https://doi.org/10.1080/01496395.2013.830131
97. Peng J, Abomohra AE-F, Elsayed M et al (2019) Compositional changes of rice straw fibers after pretreatment with diluted acetic acid: Towards enhanced biomethane production. J Clean Prod 230:775–782. https://doi.org/10.1016/j.jclepro.2019.05.155
98. Kootstra AMJ, Beeftink HH, Scott EL, Sanders JPM (2009) Comparison of dilute mineral and organic acid pretreatment for enzymatic hydrolysis of wheat straw. Biochem Eng J 46:126–131. https://doi.org/10.1016/j.bej.2009.04.020
99. Boonsombuti A, Luengnaruemitchai A, Wongkasemjit S (2015) Effect of phosphoric acid pretreatment of corncobs on the fermentability of Clostridium beijerinckii TISTR 1461 for biobutanol production. Prep Biochem Biotechnol 45:173–191. https://doi.org/10.1080/10826068.2014.907179
100. Qureshi N, Saha BC, Cotta MA (2007) Butanol production from wheat straw hydrolysate using *Clostridium beijerinckii*. Bioprocess Biosyst Eng 30:419–427. https://doi.org/10.1007/s00449-007-0137-9
101. Hoang AT, Nizetic S, Ong HC et al (2021) Acid-based lignocellulosic biomass biorefinery for bioenergy production: advantages, application constraints, and perspectives. J Environ Manag 296:113194. https://doi.org/10.1016/j.jenvman.2021.113194
102. Sulfahri MS, Langford A, Tassakka ACMAR (2020) Ozonolysis as an effective pretreatment strategy for bioethanol production from marine algae. Bioenerg Res 13:1269–1279. https://doi.org/10.1007/s12155-020-10131-w
103. Schroyen M, Vervaeren H, Vandepitte H et al (2015) Effect of enzymatic pretreatment of various lignocellulosic substrates on production of phenolic compounds and biomethane potential. Bioresour Technol 192:696–702. https://doi.org/10.1016/j.biortech.2015.06.051
104. Hosseini Koupaie E, Dahadha S, Bazyar Lakeh AA et al (2019) Enzymatic pretreatment of lignocellulosic biomass for enhanced biomethane production-a review. J Environ Manag 233:774–784. https://doi.org/10.1016/j.jenvman.2018.09.106
105. Kainthola J, Kalamdhad AS, Goud VV (2019) A review on enhanced biogas production from anaerobic digestion of lignocellulosic biomass by different enhancement techniques. Process Biochem 84:81–90. https://doi.org/10.1016/j.procbio.2019.05.023
106. Liu S, Li X, Wu S et al (2014) Fungal pretreatment by *Phanerochaete chrysosporium* for enhancement of biogas production from corn stover silage. Appl Biochem Biotechnol 174:1907–1918. https://doi.org/10.1007/s12010-014-1185-7

107. Brémond U, De Buyer R, Steyer J-P et al (2018) Biological pretreatments of biomass for improving biogas production: an overview from lab scale to full-scale. Renew Sustain Energy Rev 90:583–604. https://doi.org/10.1016/j.rser.2018.03.103
108. Lee JTE, Khan MU, Tian H et al (2020) Improving methane yield of oil palm empty fruit bunches by wet oxidation pretreatment: mesophilic and thermophilic anaerobic digestion conditions and the associated global warming potential effects. Energy Convers Manage 225:113438. https://doi.org/10.1016/j.enconman.2020.113438
109. Wang W, Wang X, Zhang Y et al (2020) Effect of sodium hydroxide pretreatment on physicochemical changes and enzymatic hydrolysis of herbaceous and woody lignocelluloses. Ind Crop Prod 145:112145. https://doi.org/10.1016/j.indcrop.2020.112145
110. Yildirim O, Ozkaya B, Altinbas M, Demir A (2021) Statistical optimization of dilute acid pretreatment of lignocellulosic biomass by response surface methodology to obtain fermentable sugars for bioethanol production. Int J Energy Res 45:8882–8899. https://doi.org/10.1002/er.6423
111. Morais WG, Pacheco TF, Corrêa PS et al (2020) Acid pretreatment of sugarcane biomass to obtain hemicellulosic hydrolisate rich in fermentable sugar. Energy Rep 6:18–23. https://doi.org/10.1016/j.egyr.2020.10.015
112. Hossain MA, Rahaman MS, Yelle D et al (2021) Effects of polyol-based deep eutectic solvents on the efficiency of rice straw enzymatic hydrolysis. Ind Crop Prod 167:113480. https://doi.org/10.1016/j.indcrop.2021.113480
113. Zou L, Ouyang S, Hu Y et al (2021) Efficient lactic acid production from dilute acid-pretreated lignocellulosic biomass by a synthetic consortium of engineered *Pseudomonas putida* and *Bacillus coagulans*. Biotechnol Biofuel 14:227. https://doi.org/10.1186/s13068-021-02078-7
114. Naz T, Nazir Y, Fazili ABA et al (2020) Transformation of lignocellulosic biomass into sustainable biofuels: major challenges and bioprocessing technologies. Am J Biochem Biotechnol 16:602–621. https://doi.org/10.3844/ajbbsp.2020.602.621
115. Ashokkumar V, Venkatkarthick R, Jayashree S et al (2022) Recent advances in lignocellulosic biomass for biofuels and value-added bioproducts - a critical review. Bioresour Technol 344:126195. https://doi.org/10.1016/j.biortech.2021.126195
116. Phojaroen J, Jiradechakorn T, Kirdponpattara S et al (2022) Performance evaluation of combined hydrothermal-mechanical pretreatment of lignocellulosic biomass for enzymatic enhancement. Polym 14:2313. https://doi.org/10.3390/polym14122313
117. IEA (2022) Tracking report. https://www.iea.org/reports/tracking-sdg7-the-energy-progress-report-2022. Accessed 29 May 2024
118. Mergbi M, Galloni MG, Aboagye D et al (2023) Valorization of lignocellulosic biomass into sustainable materials for adsorption and photocatalytic applications in water and air remediation. Environ Sci Pollut Res 30:74544–74574. https://doi.org/10.1007/s11356-023-27484-2
119. Ubando AT, Felix CB, Chen W-H (2020) Biorefineries in circular bioeconomy: a comprehensive review. Bioresour Technol 299:122585. https://doi.org/10.1016/j.biortech.2019.122585
120. Wu Y, Ji H, Ji X (2023) Biomass pretreatment using biomass-derived organic solvents facilitates the extraction of lignin and enzymatic hydrolysis of glucan. Cellulose 30:2859–2872. https://doi.org/10.1007/s10570-023-05061-7
121. Sankaran R, Markandan K, Khoo KS et al (2021) The expansion of lignocellulose biomass conversion into bioenergy via nanobiotechnology. Front Nanotechnol 3:793528. https://doi.org/10.3389/fnano.2021.793528
122. Chan SS, Low SS, Chew KW et al (2022) Prospects and environmental sustainability of phyconanotechnology: a review on algae-mediated metal nanoparticles synthesis and mechanism. Environ Res 212:113140. https://doi.org/10.1016/j.envres.2022.113140
123. Hanssen SV, Daioglou V, Steinmann ZJN et al (2020) The climate change mitigation potential of bioenergy with carbon capture and storage. Nat Clim Chang 10:1023–1029. https://doi.org/10.1038/s41558-020-0885-y
124. Baksi S, Saha D, Saha S et al (2023) Pre-treatment of lignocellulosic biomass: review of various physico-chemical and biological methods influencing the extent of biomass depolymerization. Int J Environ Sci Technol. https://doi.org/10.1007/s13762-023-04838-4
125. Mussatto SI, Bikaki N (2016) Technoeconomic considerations for biomass fractionation in a biorefinery context. In: Biomass fractionation technologies for a lignocellulosic feedstock based biorefinery. Elsevier, pp 587–610. https://doi.org/10.1016/B978-0-12-802323-5.00025-6
126. Gezae Daful A, Görgens JF (2017) Techno-economic analysis and environmental impact assessment of lignocellulosic lactic acid production. Chem Eng Sci 162:53–65. https://doi.org/10.1016/j.ces.2016.12.054
127. Halder P, Shah K (2023) Techno-economic analysis of ionic liquid pre-treatment integrated pyrolysis of biomass for co-production of furfural and levoglucosenone. Bioresour Technol 371:128587. https://doi.org/10.1016/j.biortech.2023.128587
128. Okolie JA, Nanda S, Dalai AK, Kozinski JA (2021) Techno-economic evaluation and sensitivity analysis of a conceptual design for supercritical water gasification of soybean straw to produce hydrogen. Bioresour Technol 331:125005. https://doi.org/10.1016/j.biortech.2021.125005
129. Scown CD, Baral NR, Yang M et al (2021) Technoeconomic analysis for biofuels and bioproducts. Curr Opin Biotechnol 67:58–64. https://doi.org/10.1016/j.copbio.2021.01.002
130. Abulnour AMG, Sayed MME, Sorour MH et al (2023) Bioethanol production from rice straw: economic drivers and environmental challenges in Egypt. In review. https://doi.org/10.21203/rs.3.rs-2800217/v1
131. Wang H-M, Yang W, Sipponen MH, Dai L (2023) Editorial: Lignocellulosic biomass-based materials: design, fabrication, and applications. Front Bioeng Biotechnol 11:1188168. https://doi.org/10.3389/fbioe.2023.1188168
132. Tsagkari M, Kokossis A, Dubois J (2020) A method for quick capital cost estimation of biorefineries beyond the state of the art. Biofuel Bioprod Bioref 14:1061–1088. https://doi.org/10.1002/bbb.2114
133. Tsagkari M, Couturier J, Kokossis A, Dubois J (2016) Early-stage capital cost estimation of biorefinery processes: a comparative study of heuristic techniques. Chem Sus Chem 9:2284–2297. https://doi.org/10.1002/cssc.201600309
134. Jiao H, He X, Sun J et al (2024) A critical review on sustainable biorefinery approaches and strategies for wastewater treatment and production of value-added products. Energ Ecol Environ 9:1–24. https://doi.org/10.1007/s40974-023-00312-6
135. Homagain K, Shahi C, Luckai N, Sharma M (2016) Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario. Canada For Ecosyst 3:21. https://doi.org/10.1186/s40663-016-0081-8
136. Kouser R, Bharti A, Azam R et al (2023) Techno-economic analysis and life cycle assessment of bio-based waste materials for biogas production: an Indian perspective. In: Verma P (ed) Ind microbiol biotechnol. Springer Nature Singapore, Singapore, pp 729–748
137. Ali S, Yan Q, Sun H, Irfan M (2023) Techno-economic analysis of biogas production from domestic organic wastes and locally sourced material: the moderating role of social media

based-awareness. Environ Sci Pollut Res 31:6460–6480. https://doi.org/10.1007/s11356-023-31543-z

138. Thompson VS, Aston JE, Lacey JA, Thompson DN (2017) Optimizing biomass feedstock blends with respect to cost, supply, and quality for catalyzed and uncatalyzed fast pyrolysis applications. Bioenerg Res 10:811–823. https://doi.org/10.1007/s12155-017-9842-7
139. Kaur S, Sarao LK, Ankita, Singh H (2023) Bioenergy: challenges ahead and future. In: Srivastava N, Verma B, Mishra PK (eds) Agroindustrial waste for Green fuel application. Springer Nature Singapore, Singapore, pp 281–311
140. Vera I, Wicke B, Lamers P et al (2022) Land use for bioenergy: synergies and trade-offs between sustainable development goals. Renew Sustain Energy Rev 161:112409. https://doi.org/10.1016/j.rser.2022.112409
141. IEA (2021) Net zero by 2050. https://www.iea.org/reports/net-zero-by-2050. Accessed 29 May 2024
142. Ahmed I, Zia MA, Afzal H et al (2021) Socio-economic and environmental impacts of biomass valorisation: a strategic drive for sustainable bioeconomy. Sustainability 13:4200. https://doi.org/10.3390/su13084200
143. Vogelpohl T, Töller AE (2021) Perspectives on the bioeconomy as an emerging policy field. J Environ Pol Plan 23:143–151. https://doi.org/10.1080/1523908X.2021.1901394
144. Patermann C, Aguilar A (2018) The origins of the bioeconomy in the European Union. New Biotechnol 40:20–24. https://doi.org/10.1016/j.nbt.2017.04.002
145. DeBoer J, Panwar R, Kozak R, Cashore B (2020) Squaring the circle: refining the competitiveness logic for the circular bioeconomy. For Pol Econ 110:101858. https://doi.org/10.1016/j.forpol.2019.01.003
146. Papadopoulou C-I, Loizou E, Chatzitheodoridis F (2022) Priorities in bioeconomy strategies: a systematic literature review. Energies 15:7258. https://doi.org/10.3390/en15197258
147. Global bioeconomy (2020) International advisory council on global bioeconomy. https://www.iacgb.net/. Accessed 29 May 2024
148. Devi A, Bajar S, Kour H et al (2022) Lignocellulosic biomass valorization for bioethanol production: a circular bioeconomy approach. Bioenerg Res 15:1820–1841. https://doi.org/10.1007/s12155-022-10401-9
149. Temmes A, Peck P (2020) Do forest biorefineries fit with working principles of a circular bioeconomy? A case of Finnish and Swedish initiatives. For Pol Econ 110:101896. https://doi.org/10.1016/j.forpol.2019.03.013
150. Fertahi S, Elalami D, Tayibi S et al (2023) The current status and challenges of biomass biorefineries in Africa: a critical review and future perspectives for bioeconomy development. Sci Total Environ 870:162001. https://doi.org/10.1016/j.scitotenv.2023.162001