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Biomass: A Versatile Resource for Biofuel, Industrial, and Environmental Solution

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Abstract— **Biomass, noted for its adaptability, has various applications in biofuel generation, industrial use, and environmental cleaning. This study looks into the multiple roles of biomass as a renewable energy source, with a particular emphasis on its vital contribution to biofuel production. Through a thorough evaluation of different conversion routes—thermal, biological, and physical—the study emphasizes thermochemical processes' efficiency, cost-effectiveness, and adaptability. Notably, technologies like gasification and quick pyrolysis are thoroughly investigated, followed by in-depth discussions of reactor optimization strategies to enhance performance and output. The complex structure of biomass, which is dominated by high-molecular-weight polysaccharides such as cellulose and hemicelluloses, demonstrates its significant potential for energy generation. Furthermore, the study categorizes biomass by content, origin, and conversion processes, resulting in a comprehensive inventory of available resources. Biomass from the agriculture and forestry industries, such as starch, sugar, lignocellulose, and organic wastes, is rigorously analyzed for energy production. Furthermore, various biomass processing techniques, including thermochemical, biochemical, and physicochemical conversions, are carefully tested in real-world applications to ensure their efficacy and viability. Beyond its importance in biofuel production, the article underlines biomass' versatility in satisfying industrial needs and contributing to environmental cleanup initiatives. This study lays the groundwork for informed decision-making and innovative solutions in various industries by providing a thorough understanding of biomass's various benefits and applications, including energy provision, industrial processes, and ecological restoration.**

Keywords— **Biomass; sustainability; biofuel; circular economy; wastewater remediation.**

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I. INTRODUCTION

Global warming and environmental pollution have become by far the most meaningful challenge that humanity is now confronted with [1]–[4]. The present estimations indicate that an increase in global temperature of 2 °C will result in the deaths of one hundred million people and the extinction of millions of species of both plants and animals. For the previous several decades, the use of fossil fuels (fossil oil, coal, and natural gas) has surged as a consequence of the development of industrialization as well as rapid population expansion [5]–[8]. The compatibility, availability, and cost of fossil fuels are all within reasonable ranges. Because fossil fuels are the primary source of electricity, heat, fuels, chemicals, and energy, the global economy primarily depends on them [9], [10]. Indeed, 81% of the significant energy supply comes from fossil fuels, five percent comes from nuclear energy, and fourteen percent comes from renewable energy sources, with biomass accounting for around 70% [11]. However, approximately half of the sector's energy inputs are utilized as feedstock for chemical products, even though the chemical industry is responsible for 11% and 8% of the primary demand for oil and natural gas, respectively, throughout the globe. Thus, looking for renewable sources (wind, solar, hydropower, ocean energy, biomass) [12]–[17] and alternative fuels (biofuels, biodiesel, hydrogen, bio-oil, biogas, bioethanol) [18]–[29]. Lignocellulosic biomass (LCB), which is often referred to as lignocellulose, is the biologically renewable component that is found in the most significant quantity on Earth [30], [31]. Through the process of photosynthesis, it is produced from carbon dioxide (CO_2) in the atmosphere and water by harnessing the energy from the sun [32]. Mostly made up of polysaccharides, phenolic polymers, and proteins, this matrix is a complex structure that plays a vital role in forming plant cell walls constituted of wood. LCB has a complex spatial structure consisting of cellulose, a carbohydrate polymer encased in a dense structure made up of hemicellulose, another carbohydrate polymer, and lignin, an aromatic polymer. LCB is often broken down into three categories of waste such as energy crops, virgin biomass, and other types of biomass. Native biomass consists of things like trees, bushes, and sand grasses. Waste biomass, however, includes things like stover, bagasse, and agricultural leftovers. Energy crops are raw materials that are employed in the production of second-generation biofuels because of the high biomass productivity that they possess [33], [34]. A typical overview is depicted in Fig. 1.

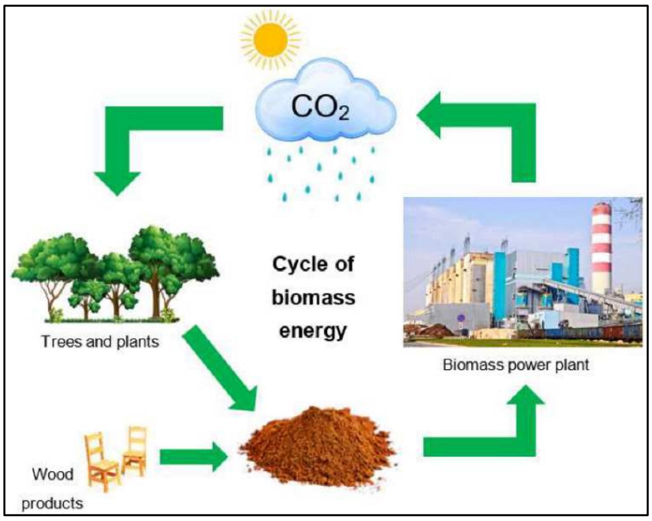

Fig. 1 Typical biomass cycle [35]

The carbon dioxide released during the combustion or thermal conversion process does not contribute to an increase in the amount of carbon dioxide in the environment [36]. This essentially makes biomass material a potent renewable energy resource [37]. Plants may produce biomass, which is an organic substance obtained from plants, in many different ways [38]. One of these ways is called photosynthesis [39], [40]. Carbon dioxide released into the environment because of the breakdown processes of other plants is absorbed by plants as part of a closed cycle in which plants participate. The use of solar energy by plants, incorporating carbon dioxide, and transforming carbon dioxide into organic material are all very significant on several levels [41]. As a direct result of this, it is now feasible for there to be both terrestrial and aquatic organisms dependent on this energy [42]. As a result, the use of biomass to generate energy merely results in the emission of carbon dioxide into the atmosphere, which is then utilized by plants to reproduce biomass [43], [44]. Microorganisms help in decomposing the plants to produce biomass [45]. Alternatively, plants may be burnt and converted into co-incineration in kilns and ashes in thermal incinerators. This process results in the transformation of chemical energy into mechanical or electrical energy during the combustion process. The carbon extracted from biomass feedstock via natural biocomposting processes is released back into the environment as methane or carbon dioxide [35]. It is anticipated that by the year 2050, most industrialized nations will be able to meet more than half of their net energy requirements via the exploitation of waste biomass [46]. Fuel manufacture relies heavily on cellulosic raw materials, which are found in high concentrations in agricultural biomass [47], [48]. This ensures that quality food is preserved while simultaneously lowering the amount of waste produced and satisfying the energy needs [49], [50]. A schematic diagram depicts such an arrangement, showing the application of biomass in this domain.

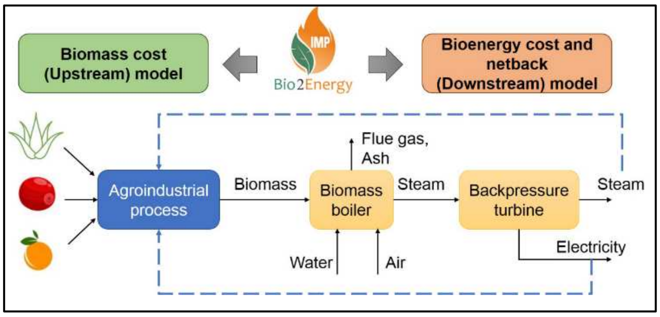

Fig. 2 Overview of biomass application for energy [51]

In order to satisfy the Sustainable Energy for Everyone (SE4All) objective, the International Renewable Energy Agency (IREA) anticipates that the quantity of biomass that will be utilized by the year 2030 will nearly quadruple, reaching 108 EJ of energy per year [52], [53]. The Global Energy Assessment anticipates that a substantial increase in the use of lignocellulosic material and agricultural leftovers will result in a significant expansion of bioenergy, reaching between 80 and 140 EJ by the year 2050. Similar to what was said by the Intergovernmental Panel on Climate Change, a similar rise in the percentage of bioenergy might occur depending on the climate goals pursued and the policy instruments used [54], [55]. More recently, the European Union (EU) has released a new regulation to promote renewable energy use [56]–[58]. The directive emphasizes that fuels that are generated from biomass must adhere to stringent environmental criteria. The emissions of greenhouse gases (GHG) produced by the combustion of fuels generated from biomass must be at least seventy percent lower than those produced by fossil fuels beginning in the year 2021. For the generation of electricity, heating, and cooling based on biomass, the threshold for reducing greenhouse gas emissions may be extended to as much as 80 percent. The Roundtable on Sustainable Biomaterials, an international group, has said that generally, goods derived from biological sources, such as biofuels, bio-composites, and biochemicals, would adhere to voluntary guidelines for sustainability [59], [60]. The following Table I is the summary of recent review works in the domain of biomass application perspective:

TABLE I
SUMMARY OF RECENT REVIEW WORKS

Title	Main theme of review	Main outcomes	Source
"Heterogeneous photocatalytic conversion of biomass to biofuels: A review"	First and foremost, a thorough examination of the photocatalytic transformation of biomass to biofuels has been provided.	Selectivity control represents one of the biggest issues of biomass usage since bio platform chemicals' diverse functions might react with different products.	[61]
"Emerging trends and advances in valorization of lignocellulosic biomass to biofuels"	Modern approaches in this domain were reviewed.	a) Enzymatic hydrolysis and pretreatment enhance yield. b) Genetically engineered proteins boost 40% biomass conversion yield.	[62]
"Bioengineering strategies of microalgae biomass for biofuel production: recent advancement and insight"	Microalgae-based biomass to biofuel conversion reviewed.	Latest environmental data, their importance in global initiatives to advance microalgae-based biomass as sustainable biofuels were reported.	[63]
"Impact of nanomaterials on sustainable pretreatment of lignocellulosic biomass for biofuels production: An advanced approach"	Improving Biomass pretreatment using nanomaterials was the main theme of the study.	Using magnetic nanoparticles and nano-photocatalysts in the process of pretreatment may provide innovative methods to enhance the generation and yield of biofuels.	[64]
"Cellulosic biomass fermentation for biofuel production: Review of artificial intelligence approaches"	Biomass to biofuel using fermentation approach and application of machine learning in such processes was reviewed	a) There is an increasing use of optimization and ML in this domain. b) The artificial neural network is the most used ML technique in this domain	[65]
"Unlocking the potential of lignocellulosic biomass in road construction: A brief review of OPF"	Application of oil palm fibre in road construction	OPF as a binder material towards a sustainable pavement. Oil palm fibre biomass may be utilized to produce environmentally friendly and cost-effective concrete and asphalt.	[66]
"Carbon Fibre Precursor from Oil Palm Biomass Lignin"	It highlights the significant underutilization of lignocellulosic biomass.	Lignin has the potential to be used as a carbon fiber precursor, with qualities comparable with those of polyacrylonitrile and pitch-based precursors.	[67]
"Application of typical artificial carbon materials from biomass in environmental remediation and improvement: A review"	The review explores the synthesis routes and remediation methods of ACMs for heavy metal ions and organic contaminants.	Physicochemical properties of ACMs are directly affected by the composition including cellulose, lignin, and hemicellulose, with lignin being particularly important. Hydrothermal, pyrolytic, and microwave carbonization help convert biomass.	[68]
"Immobilized biomass systems: an approach for trace organics removal from wastewater and environmental remediation"	Wastewater treatment using biomass immobilization entails capturing microorganisms, live or dead, inside a polymer matrix.	a) To remove ECs without harming the microorganisms, immobilized biomass systems are a viable alternative. b) Remediating ECs in soil and water matrices is possible using immobilized biomass.	[69]

The purpose of this literature review study is to look into biomass's many uses, shining light on its potential to revolutionize numerous industries and environmental management. The review examines a broad range of research investigations, technical breakthroughs, and case studies to highlight the role of biomass in advancing sustainable development and reducing the effects of climate change. One of the primary goals is to investigate the variety of biomass feedstocks and conversion pathways, which range from agricultural and forestry residues to dedicated energy crops, and from thermochemical processes such as pyrolysis and gasification to biochemical methods such as fermentation and anaerobic digestion. Furthermore, the article tries to assess the economic feasibility and scalability of biomass-based technologies, taking into account aspects such as feedstock supply, processing costs, and market dynamics. Furthermore, the assessment will include the environmental consequences of biomass consumption, such as its ability to decrease greenhouse gas emissions, enhance air and water quality, and promote ecosystem health via sustainable land management techniques. Through this comprehensive analysis, the paper aims to provide policymakers, industry stakeholders, and researchers with insights and recommendations on how to fully utilize biomass as a sustainable and adaptable resource for encouraging a more resilient, equitable, and environmentally sustainable future.

II. Materials and Method

A wide repository of previously published work was utilized in the process of carrying out the present review work. For the purpose of this review article, the selection of appropriate reference papers required a stringent approach with the objective of collecting a body of literature that is both extensive and authoritative. Several methods were utilized, with the utilization of Boolean search strategies being the most prominent among them, in order to guarantee the incorporation of sources that were both pertinent and of high quality [70], [71]. Combining keywords and operators in order to refine search queries was made possible by the Boolean search approach, which made it possible to systematically identify relevant material. In the beginning, a comprehensive project scoping exercise was carried out in order to identify the most important themes and topics that are associated with the utilization of biomass in the production of biofuels, industrial applications, and environmental solutions. On the basis of this preliminary scoping, a collection of keywords and phrases was identified. These included terms and phrases such as "biomass," "biofuel," "industrial applications," "environmental remediation," and other similar terms [72], [73]. Through the utilization of databases such as PubMed, Web of Science, Scopus, and Google Scholar, Boolean operators like AND, OR, and NOT were strategically utilized in order to design search queries that were specifically customized to each of the subject areas included. For example, searches that combined phrases such as "biomass" and "biofuel" and "gasification" were used to locate publications that particularly addressed the exploitation of biomass in the manufacture of biofuels through gasification processes [74], [75]. In a similar manner, several search terms were applied in order to collect literature that was pertinent to the industrial applications of biomass and its involvement in environmental solutions. The process of searching was iterative, and the search terms were improved depending on the initial findings and the insights garnered from the literature [76], [77]. In addition, citation chaining, which involves looking at the reference lists of relevant publications, was utilized in order to locate additional sources that were not discovered through the first searches. Furthermore, the selection of significant references was further augmented by an examination of foundational works in the field as well as consultations with subject matter experts. The reference articles that were chosen were subjected to a stringent evaluation in order to determine their relevance, credibility, and contribution to the overarching topics that were discussed in the overall review paper [78], [79]. For the purpose of ensuring the trustworthiness and validity of the literature that was synthesised in the review, only publications that had been subjected to peer review, conference proceedings, and authoritative reports from reputable sources were included. Generally speaking, the systematic application of Boolean search algorithms, in conjunction with citation chaining and expert consultation, made it easier to identify and choose a solid set of reference papers that serve as the foundation for the complete analysis that is offered in the present review study [80], [81].

III. Results and Discussion

A. Biofuel Production

Waste lignocellulose material and agricultural leftovers are abundant biomass substrates and valuable supplies for biofuel production [82], [83]. Gasification and enzymatic hydrolysis are the primary processes for turning lignocellulose biomass into biofuels, which serve as a sustainable energy source for transportation [84]. The decline of crude oil sources has sparked interest in biofuel manufacturing. Biofuel production is an inexpensive alternative source for the transportation and energy sectors because it allows the use of low-cost lignocellulose biomass to produce energy, valuable biofuels and chemicals [85]–[87]. However, the majority of the methods are still in the development stage owing to technological hurdles and the variety of lignocellulose biomass composition [88]. Over time, these procedures have been optimized to the point that they can be used on an industrial basis. This overview discusses the origins and compositions of several lignocellulosic biomasses, as well as diverse thermochemical, catalytic, and integrative methodologies for converting them into biofuels and other useful compounds, as shown in Fig. 3.

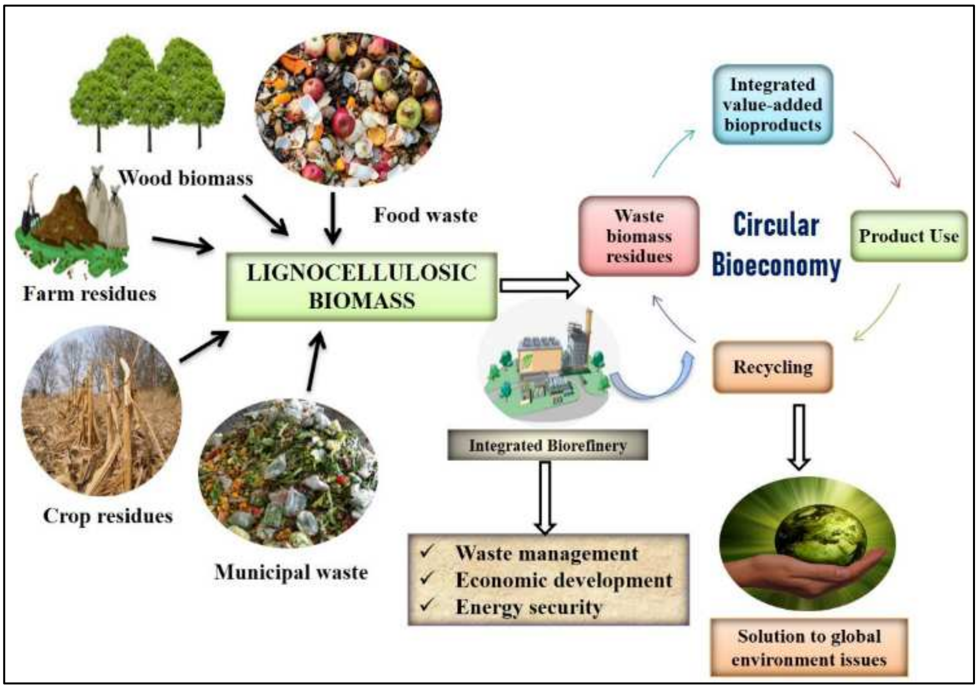

Fig. 3 Biomass to biofuel schematics [89]

1) Pyrolysis:

There are many thermal, biological, and physical ways of converting biomass into biofuel [90]. Pyrolysis is a prominent biomass-to-energy conversion method owing to its ease of storage, transportation, and versatility in applications such as combustion engines, boilers, and turbines [91], [92]. In addition, solid biomass and waste are difficult and costly to manage, which promotes pyrolysis research [93], [94]. However, it is still in its early phases of development and faces a variety of technical and economic obstacles before competing with traditional fossil fuel-based alternatives [95]. The production of bio-liquids along with additional products (gas and char) by pyrolysis of diverse biomass species has been extensively explored in the past [93], [96]. These biomass species include forestry wood, straws, bagasse woody biomass, various seedcakes, and municipal solid waste [97], [98]. Pyrolysis is the heat-based decomposition of biomass that happens in the absence of oxygen [99]. The phrase comes from the Greek words "pyro" (fire) and "lysis" (decomposition or breakdown into fundamental components). Pyrolysis was used to generate charcoal in Southern Europe and the Middle East around 5500 years ago [100]. Since then, pyrolysis technologies have gained popularity and are now often used to make charcoal and coke [101], [102]. There are advantages and disadvantages associated with biomass pyrolysis, which is a thermochemical process that involves heating biomass in the absence of oxygen to produce biochar, bio-oil, and syngas [103]–[105].

The use of abundant and renewable organic resources, such as wastes from agriculture and forestry, as well as energy crops, allows for a reduction in reliance on finite fossil fuels, which is one of the advantages [106]–[108]. In addition, the production of biochar during the process of pyrolysis of biomass may contribute to the sequestration of carbon in the soil, therefore reducing emissions of greenhouse gases and enhancing the fertility of the soil [109], [110]. In addition, biomass pyrolysis provides an alternative source of energy, which is beneficial since it broadens the range of energy sources available and reduces dependency on fossil fuels, so enhancing energy security [111], [112]. Biofuels such as biodiesel, bioethanol, and renewable natural gas may be produced from the bio-oil and syngas that are produced during the process of biomass pyrolysis [113], [114]. These biofuels provide cleaner alternatives to the conventional fossil fuels that are currently in use [115]–[118].

In addition, biomass pyrolysis has the capability of effectively converting organic waste materials into energy products that can be used, hence reducing the negative impact that waste disposal and landfill usage have on the environment. One must, however, take into consideration several potential drawbacks. Because of the necessity for specialized equipment, energy inputs, and maintenance, biomass pyrolysis facilities demand a significant initial investment as well as substantial running expenditures [119], [120]. Because acquiring and transporting considerable quantities of biomass to pyrolysis facilities may be both expensive and time-consuming, particularly in geographic areas that are geographically isolated, the availability of biomass feedstocks and the logistics involved may provide challenges. In addition, the processes of biomass pyrolysis often need high temperatures and energy inputs, which may lead to substantial energy consumption and environmental effects, particularly in the case when fossil fuels are used for heating purposes [121], [122]. A schematic of biomass pyrolysis is depicted in Fig. 4.

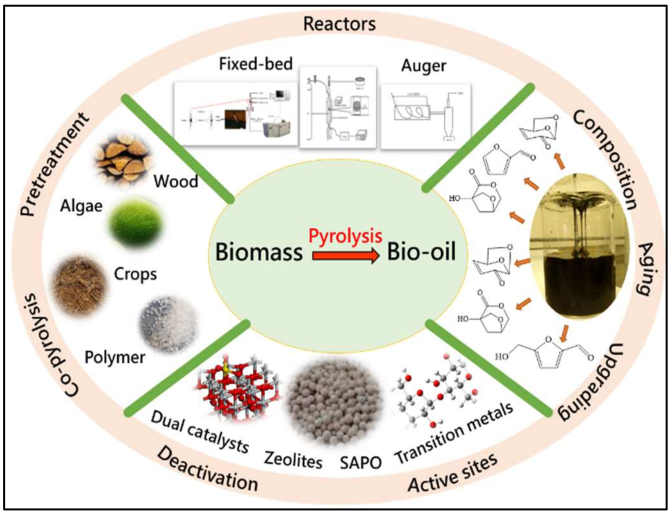

Fig. 4 Biomass pyrolysis for practical applications [123]

Furthermore, the quality and composition of biochar, bio-oil, and syngas that are produced during the process of biomass pyrolysis may vary depending on the kind of feedstock, the circumstances under which the process is carried out, and the design of the reactor. This may have an impact on the range of applications that may make use of these products [124]–[126]. Concerns have also been raised about the emissions of air pollutants that occur during the pyrolysis process. These pollutants include particulate matter, volatile organic compounds, and greenhouse gases. It is necessary to implement appropriate emission controls and monitoring to reduce the negative impacts on the environment [104], [127].

Pyrolysis technology can produce biofuel at high fuel-to-feed ratios. Consequently, pyrolysis has gained popularity as an efficient method of converting biomass into biofuel in the past few years. The goal of this technique is to produce high-value bio-oil that will compete with, and eventually replace, nonrenewable fossil fuels. To achieve this aim, pyrolysis researchers will have to create new technologies.

2) Hydrothermal liquefaction:

Hydrothermal liquefaction (HTL) is a potential technology for producing liquid biofuel because it can turn wet biomass directly and effectively into bio-crude with high heating values while avoiding the energy-intensive drying step. In the presence of water, HTL is operated at temperatures ranging from 280 to 370 degrees Celsius and pressures ranging from 10 to 25 megapascals over a period ranging from 5 to 120 minutes [128]–[130]. The HTL process results in the production of four principal products: gas, char, bio-oil, and aqueous phase extract. The substance known as bio-oil is highly appreciated. The synthesis of bio-oil from high-temperature liquid (HTL) varies from 24 to 64%, with a higher heating value (HHV) suggesting a calorific value of 28 to 38 energy joules per kilogram [131], [132]. As a result of the increase in reactor pressure, residence time, and process temperature, it has been determined that the production of bio-oil and higher heating value (HHV) has improved to a certain degree, although at the price of the economy of the process. The heteroatomic components of bio-oil, such as oxygen, sulfur, and nitrogen, do not meet the specifications for conventional biofuel. This is yet another drawback of bio-oil that is produced from HTL under usual conditions [132],

[133]. Hydrothermal liquefaction (HTL) is an additional way of thermochemical conversion [134], [135]. This approach involves heating biomass with the assistance of water at high temperatures and pressures to produce a liquid bio-oil in addition to other byproducts such as char and gases. It is similar to biomass pyrolysis in that HTL offers both advantages and disadvantages. One of the advantages is the adaptability to employ a wide range of feedstocks, which may include waste biomass and wet biomass such as algae, sewage sludge, and agricultural wastes [136], [137]. The capacity to adapt reduces the amount of competition for space and resources that occurs during the production of food, while also enabling more effective waste management. In addition, HTL has the capability of producing a high-quality bio-oil that has chemical qualities that are equivalent to those of crude oil [138], [139]. This makes it a suitable ingredient for the refining of transportation fuels such as diesel, gasoline, and jet fuel. This bio-oil has the potential to be employed not only as a source of renewable chemicals but also as a feedstock for biochemical processes such as the production of biodiesel. In addition, HTL has the capability of extracting carbon from biomass and storing it as biochar, which results in a reduction in emissions of greenhouse gases and an increase in the amount of carbon that is stored in soil [140]. HTL is an intriguing choice for addressing climate change and promoting environmental sustainability. A schematic of HTL is depicted in Fig. 5**.**

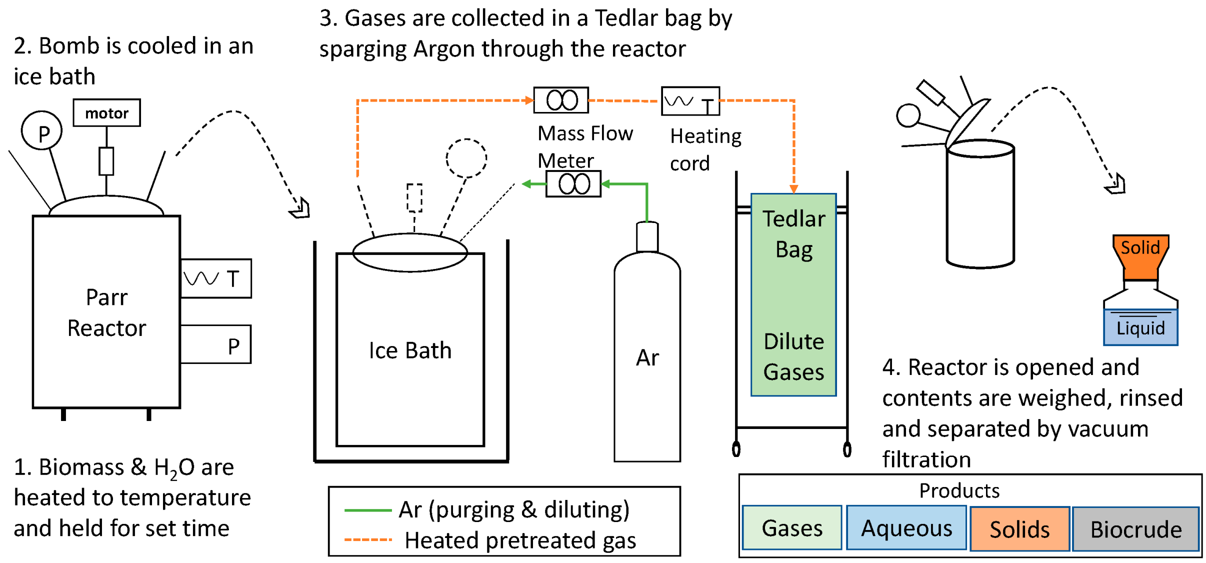

Fig. 5 HTL flow process [141]

One must, however, take into consideration a number of potential drawbacks. It is common for high-temperature, high-pressure processes to need huge amounts of water, energy, and catalysts, in addition to high temperatures and pressures [142], [143]. This may lead to enormous costs for both the initial investment and ongoing operations. Furthermore, the synthesis of bio-oil from HTL could need further refining in order to get rid of pollutants and improve quality, which would result in an increase in the overall complexity and cost of the whole process. Additionally, the scalability of HTL technologies and their ability to integrate into existing infrastructure create challenges [144], [145]. This is due to the fact that large-scale adoption may need significant investments in infrastructure and provision of logistical support. In addition, the environmental repercussions of HTL, which include the treatment of wastewater and the disposal of byproducts, need to be strictly controlled in order to lessen the negative impact that it has on ecosystems and water resources [146], [147].

In summary, it can be said that although hydrothermal liquefaction exhibits potential as a technology for transforming biomass into advantageous biofuels and chemicals, it is essential to address the associated challenges and environmental concerns in order to fully realize the potential of this technology as a sustainable and economically feasible alternative to fossil fuels.

3) Anaerobic digestion:

Organic materials such as animal manure, wastewater biosolids, and food waste may be broken down by bacteria using a process known as anaerobic digestion (AD) [148][149]. This mechanism occurs in the absence of oxygen. Anaerobic digestion occurs inside a reactor to produce biogas. This tank is developed and manufactured in a range of forms and sizes based on the feedstock and location of the biogas production plant [150]. The digester discharges biogas and digestates, the AD process's solid and liquid material end products. These reactors contain complex microbial communities that degrade (or digest) waste, producing biogas and digestate. Co-digestion is the process of mixing several organic materials in a single digester. Manure, food waste (including materials generated by production, distribution, and consumers), energy crops, crop residues, and fats, oils, and greases (FOG) from restaurant grease traps are all examples of co-digested materials [149]. Crop leftovers are another source of co-digestible compounds. Co-digestion has the potential to increase biogas production from organic waste that is either difficult to digest or has low yields. The anaerobic decomposition of organic substances is divided into four steps: hydrolysis, acetogenesis, acidogenesis, and methanogenesis [151]–[153]. The core of AD is in supplying the essential substrates for methane-producing microbes, or methanogens, to convert into CH_4 and CO_2. The AD process relies heavily on acetate (CH_3COO-) as an intermediate product. Under anaerobic circumstances, complex organic material degrades and is converted into CH_4 and CO_2. The flowchart of anaerobic digestion is depicted in Fig. 6.

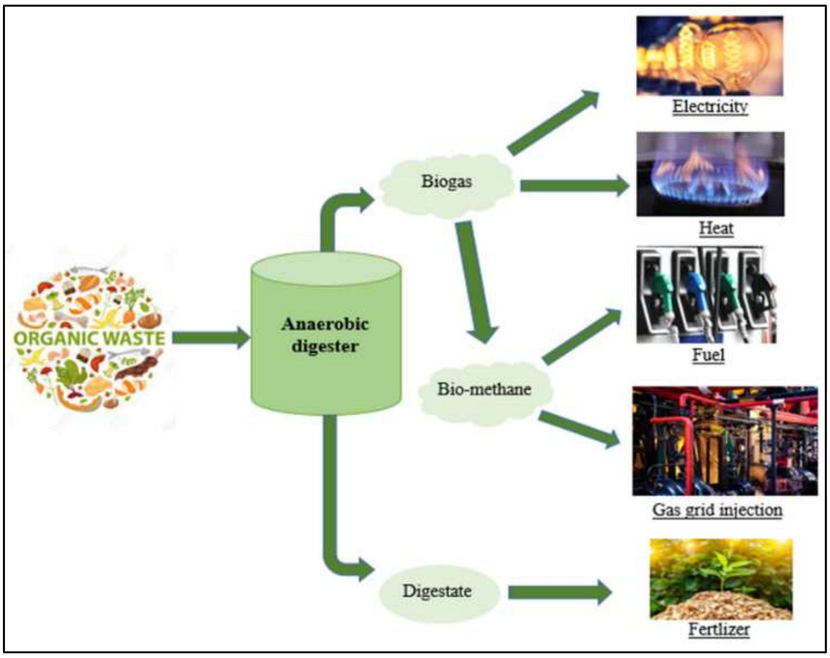

Fig. 6 Flow chart of anaerobic digestion [154]

Anaerobic digestion results in the spontaneous production of biomethane which occurs in four stages. To begin the process of breaking down complex organic polymers, their component constituents, which include sugars, fatty acids, and amino acids, are first released. It is then the fermentative bacteria, also known as acidogens, that are responsible for transforming the monomers into a mixture of short-chain volatile fatty acids. Acetogenic bacteria, which are also referred to as acetogens, are responsible for the conversion of volatile fatty acids into acetate, carbon dioxide, and hydrogen [155], [156]. These three elements are all-natural substrates for the process of methanogenesis, which is the technique that results in the production of biomethane. The AD process has the potential to degrade the organic component of any feedstock to produce biomethane [157], [158]. This includes wastes from agriculture and animals, wastes from food production, and feedstocks that are composed of lignocellulosic materials. On the other hand, the quantity of methane that is generated is very variable and subject to change depending on the substrate. The production of lignocellulosic biomass can only create 330 mL of CH_4 per gram of volatile solids. Sugar and starch crops, for instance, have the potential to produce up to 450 mL of CH_4 per gram of volatile solids [159], [160]. Since lignocellulosic biomass is highly resistant to anaerobic breakdown, which results in low biomethane production [161], the most significant challenge is the intricacy of the structure of the biomass. The stubborn anti-degradation properties of native lignocellulose are referred to as biomass recalcitrance. These characteristics place a significant obstacle in the way of hydrolysis during the early phase of the anaerobic digestion process, which eventually restricts the amount of biomethane that can be generated from lignocellulose for commercial purposes [162], [163]. Different phases in anaerobic digestion are depicted in Fig. 7.

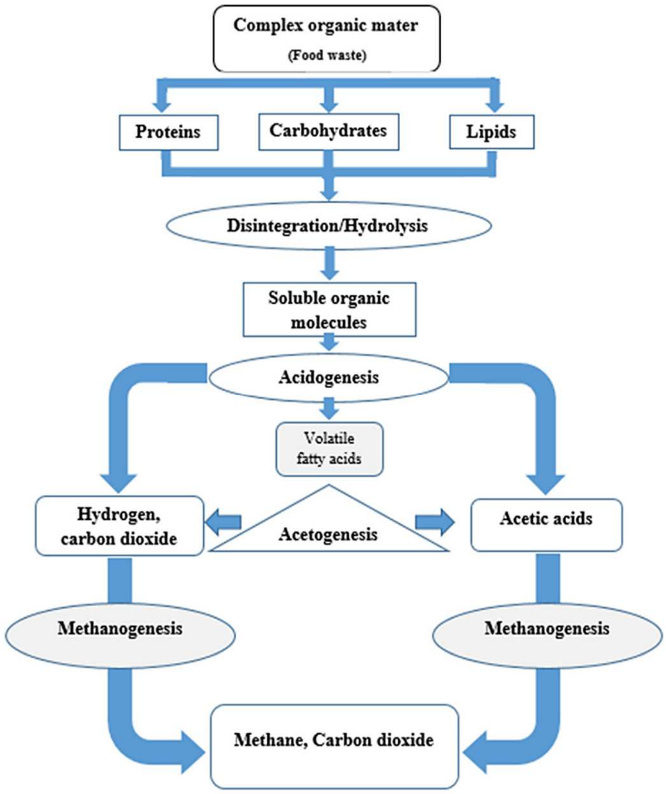

Fig. 7 Different phases in the anaerobic digestion process [154]

The use of anaerobic digestion, which is a biological process that disintegrates organic waste with the lack of oxygen to produce biogas and digest it, is associated with a number of advantages as well as disadvantages. One of the advantages is the versatility of using a wide range of organic feedstocks, such as agricultural wastes, food waste, and wastewater sludge, all of which are readily available and not difficult to get [164], [165]. By converting organic waste materials into biogas, which is primarily composed of methane and carbon dioxide, this method contributes to increased efficiency in the management of waste. To provide a sustainable energy source while simultaneously reducing emissions of greenhouse gases, biogas may be processed into biomethane and then utilized to create heat and electricity [166]. Additionally, biomethane can be injected into natural gas pipelines or used as fuel for automobiles. The concepts of a circular economy are also supported by anaerobic digestion, which allows for the reuse of organic waste, prevents the dumping of trash in landfills, and reduces environmental harm. Digestate, which is a nutrient-rich residue that is produced during anaerobic digestion, has the potential to be used as a biofertilizer or soil additive in order to enhance the fertility and health of the soil [167]–[169].

One must, however, take into consideration a number of potential drawbacks. To function properly, anaerobic digestion systems need a substantial initial investment in addition to continuing running expenses for infrastructure, equipment, and maintenance [170], [171]. It is necessary to carefully regulate operational factors such as temperature, pH, and organic loading rates in order to achieve the highest possible level of biogas production while minimizing the risk of process inhibition. Additionally, there may be a problem with the availability of feedstock and logistics. This is due to the fact that locating and transporting considerable quantities of organic waste to anaerobic digestion facilities may be both expensive and time-consuming, particularly in urban areas [172]. In addition, the processes of anaerobic digestion may result in the release of hydrogen sulfide, volatile organic compounds, and ammonia, all of which have the potential to cause environmental and health issues if they are not well handled. It is necessary to have proper design, operation, and monitoring to limit these emissions and ensure compliance with regulatory requirements [173], [174].

In conclusion, while anaerobic digestion has considerable potential for waste management, the generation of renewable energy, and the recovery of resources, it is essential to solve the related obstacles and environmental issues to fully realize its advantages and ensure that it will be used over the long term.

B. Applications in Industry

1) Utilization of fibers derived from biomass in industry:

Biomass-derived fibers are widely employed in the papermaking industry because of their versatility, strength, and sustainability [175]–[177]. Cellulose fibers derived from a variety of biomass sources, including agricultural waste, wood pulp, and specialty fibers such as hemp and kenaf, provide the base of paper production. These fibers possess inherent properties that enhance the quality and use of paper products in a variety of applications. In the papermaking sector, biomass-derived fibers are recognized for their exceptional strength, which enables the manufacturing of long-lasting and durable paper products [178], [179]. Whether used in packaging materials, printing sheets, or hygiene products, these fibers provide structural integrity and can withstand the rigors of handling and use. Furthermore, their outstanding resistance ensures that paper products maintain their quality over time, hence enhancing customer satisfaction and product longevity. Beyond strength, biomass-derived fibers exhibit adequate printability qualities, making them suitable for applications requiring high-quality printing and graphics. The flat surface of these fibers provides for excellent ink absorption and adhesion, resulting in crisp and brilliant print finishes [180]. This makes biomass-derived sheets suitable for a wide range of printing applications, including journals, catalogs, and promotional materials that need great print quality. Furthermore, using biomass-derived fibers in papermaking promotes sustainability by reducing reliance on virgin wood pulp and promoting the use of renewable and recyclable resources [181], [182]. The paper business decreases its environmental effect and conserves natural resources by using agricultural waste, wood waste, and specialist fibers in its production processes. Furthermore, using biomass-derived fibers supports the circular economy by redirecting organic waste streams beyond landfills and closing the material consumption loop [183]. Fibers made from biomass have a significant impact on modernizing the textile sector by offering a sustainable substitute for conventional resources [184], [185]. These fibers, which come from sustainable biomass sources, are being used more and more in the textile industry to produce a broad range of textiles and clothing items to satisfy the growing consumer demand for textiles that are ethically and environmentally derived. Because of their exceptional properties including softness, breathability, and biodegradability, natural fibers like cotton, bamboo, and hemp have long been in demand in the textile industry [186]. However, there has been a shift in favor of employing fibers generated from biomass in the textile industry as sustainability has gained more attention. These fibers contribute to lessening the environmental impact of the textile industry while offering qualities that are comparable to those of traditional textiles.

The development of renewable cellulose fibers from biomass sources, such as wood pulp and agricultural waste, has made it possible to produce ecologically friendly textiles thanks to technological breakthroughs [187]–[189]. Innovative methods, such as lyocell and viscose production, are used to extract cellulose fibers from biomass feedstocks and transform them into superior fabrics with exceptional drape, moisture-wicking properties, and durability. The characteristics of natural fibers are present in these regenerated cellulose fibers, together with the benefits of sustainability and resource efficiency [190]. Significant industrial sustainability problems including water usage, chemical use, and carbon emissions are also resolved by the use of fibers obtained from biomass in the textile sector. Biomass-derived fibers consume fewer resources and have a lower lifetime environmental impact than standard textile production techniques, which can rely heavily on chemical and water inputs. Moreover, the biodegradability of fibers generated from biomass implies that textile products have a reduced environmental impact at the end of their life cycle, supporting waste reduction and circular economy ideas [191]–[193]. The fiber extraction flowchart from biomass is depicted in Fig. 8.

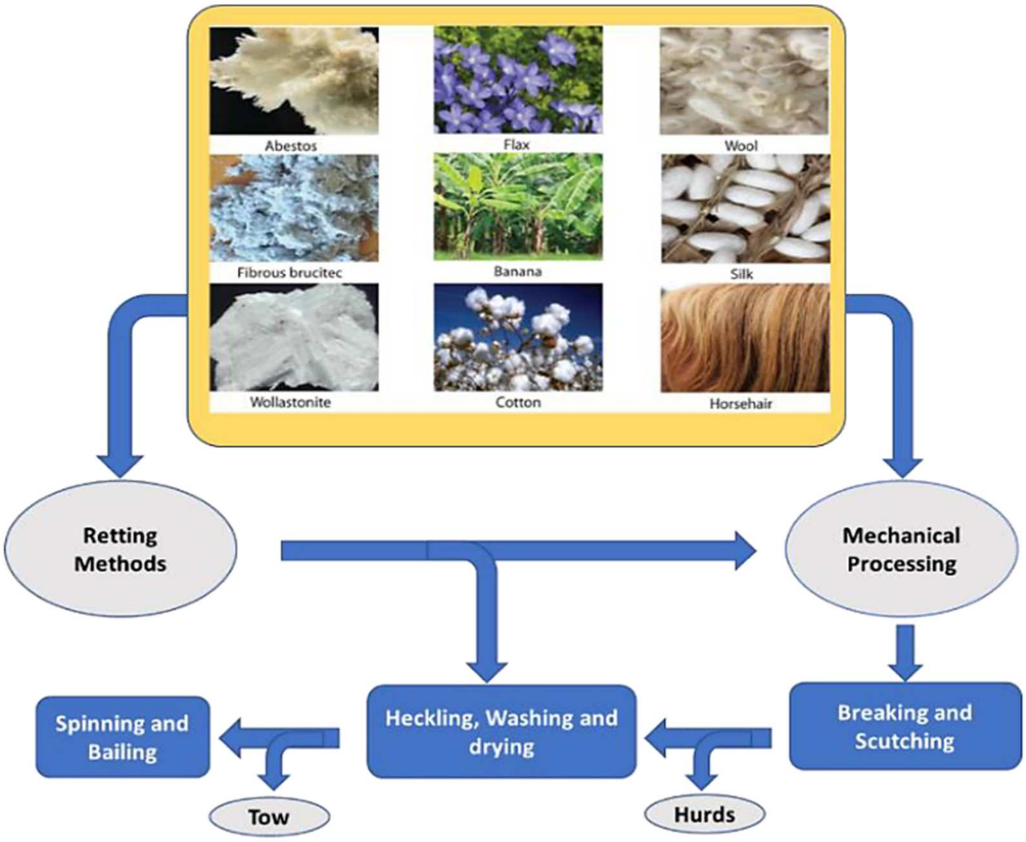

Fig. 8 The fiber extraction flowchart from biomass [194]

2) Biomass utilization in the automotive industry for environmentally responsible manufacturing:

Utilizing biomass in the automobile sector is a major step forward for ecologically friendly production techniques [107]. This novel strategy aims to lessen environmental impact and promote sustainability by integrating materials obtained from biomass into many areas of the automotive manufacturing process, from fuel sources to car components. The creation of bioplastics and biocomposites for both exterior and interior car components is a significant application of biomass usage in the automotive sector. These materials provide an environmentally beneficial substitute for conventional plastics made from petroleum since they are made from renewable biomass sources including plant fibers, starches, and natural resins [195], [196]. Because they are strong, lightweight, and recyclable, bioplastics and biocomposites are perfect for use in structural components, door trims, and interior panels. Automobile manufacturers may lessen their dependency on fossil fuels, cut carbon emissions, and lessen the environmental impact of their vehicle production processes by substituting traditional polymers with alternatives made from biomass.

The manufacturing of biofuels for vehicle propulsion is an additional use of biomass exploitation in the automotive sector [197]. Crop oils, organic waste, and agricultural wastes are examples of biomass feedstocks from which biofuels like biodiesel, bioethanol, and renewable natural gas are produced. When burnt in internal combustion engines, these biofuels provide a cleaner, more environmentally friendly alternative to traditional fossil fuels. Furthermore, biofuels are flexible and compatible with current infrastructure since they may be combined with conventional fuels or used in cars specifically designed to run on biofuels [198]–[200]. Automobile manufacturers may lower carbon emissions, enhance air quality, and support international efforts to mitigate climate change by integrating biofuels into their fleets. The development of biomass-based products for car insulation, acoustic dampening, and thermal management is another way that biomass is used in the automotive sector. When reinforcing composite materials used for car insulation and soundproofing, natural fibers like hemp, flax, and kenaf are used since they provide better performance and sustainability than synthetic substitutes [201], [202]. Furthermore, the integration of biomass-based materials into battery casings and thermal management systems has the potential to improve energy efficiency and increase the range of vehicles.

All things considered, using biomass in the automobile sector has enormous potential to advance ecologically friendly production techniques and encourage sustainability all the way through the automotive supply chain. Carmakers may lower carbon emissions, preserve natural resources, and provide more environmentally friendly transportation options for a future that is greener by integrating biomass-derived materials and biofuels into the design and manufacturing processes of their vehicles.

C. Environmental Applications of Biomass

There are many innovative applications for biomass in the environmental field, such as mitigating environmental issues and promoting sustainability [203], [204]. One sustainable and versatile resource for addressing pressing environmental issues is biomass, which is derived from organic resources including plants, agricultural waste, and organic waste. Biomass offers a number of opportunities for environmental preservation and climate change mitigation, including the production of renewable energy, waste management, soil remediation, and carbon sequestration [205]. Businesses, communities, and governments may embrace environmentally friendly methods that lessen reliance on fossil fuels, cut down on waste production, and support the preservation of natural ecosystems by using the power of biomass. We'll look at a few key environmental applications of biomass in this introductory paragraph, along with some positive changes that could be made in the direction of a more robust and sustainable future [206]. Fig. 9 depicts the potential applications of biomass for environmental applications.

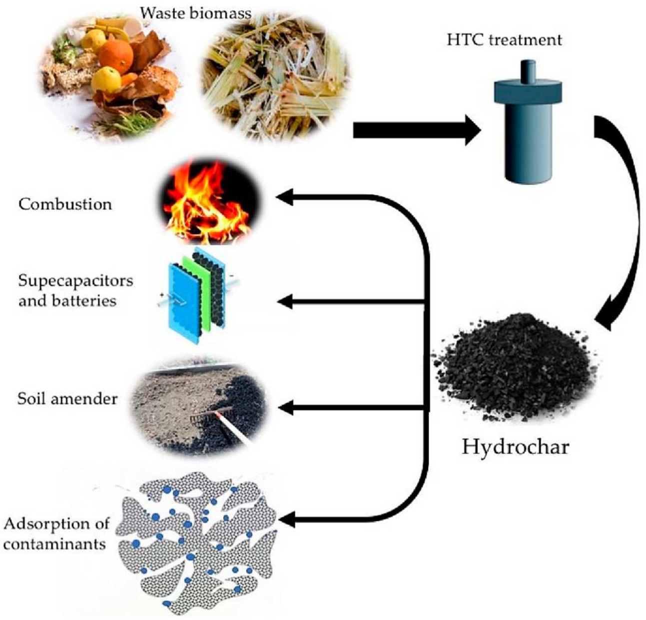

Fig. 9 Potential applications of biomass for environmental applications [207]

1) Role of biomass in oil spill remediation:

Oil spills pose serious environmental threats, threatening the delicate balance of marine ecosystems, disturbing animal habitats, and endangering human health [208]–[210]. In response to these issues, biomass-based sorbent materials became known as very promising solutions, thanks to their availability, renewable nature, and exceptional effectiveness in oil absorption and cleaning operations [211]–[213]. Biomass-based sorbents, which are formed from biomass sources such as peat moss, sawdust, rice husks, rice straw and agricultural leftovers, have intrinsic properties that make them suitable candidates for oil spill recovery [214]–[218]. Their remarkable porosity, large surface area, and inherent hydrophobic qualities allow them to effectively absorb and hold oil pollutants from contaminated water surfaces. Furthermore, the non-toxic, biodegradable, and ecologically friendly properties of biomass-based sorbents assure little secondary contamination and reduce damage to marine habitats.

A variety of cleaning strategies using biomass-based sorbents have been developed to address a wide range of oil spill situations and environmental circumstances [219], [220]. Sorbent booms and barriers, which include biomass materials inside permeable membranes or nets, are strategically deployed to contain and catch oil spills, preventing further dispersion and pollution of coastal and aquatic habitats. Furthermore, the use of airborne and underwater drones equipped with biomass-based sorbents allows the targeted and rapid removal of oil slicks from large water surfaces, increasing cleaning efficiency and simplifying response activities. Furthermore, novel approaches such as bioaugmentation and bioremediation use the natural degrading capabilities of microorganisms found in biomass-based sorbents to accelerate oil breakdown and remediation processes [221], [222]. Researchers want to speed up oil breakdown and restore damaged ecosystems to pre-spill conditions by introducing microbial consortia immobilized on biomass materials into oil-contaminated locations. Despite the hopeful progress achieved in using biomass-based sorbents for oil spill cleanup, a number of problems and issues remain. Further study and improvement are required to address concerns about the scalability, cost-effectiveness, and long-term efficacy of biomass materials as sorbents in real-world oil spill response situations [223]–[225]. Furthermore, detailed research into the ecological consequences and destiny of oil-laden biomass materials after cleaning is required to assess their environmental effect and assure sustainable remediation techniques.

To summarize, the incorporation of biomass into oil spill cleanup efforts ushers in a new age of environmental research, providing novel methods to mitigate the negative consequences of oil spills on marine ecosystems and coastal communities. Researchers and practitioners can advance the field of oil spill response by leveraging the possible benefits of biomass-based sorbents and innovative cleaning approaches, ensuring the health and resilience of our seas and natural ecosystems for future generations [226], [227].

2) Biomass-derived sorbents for heavy metal adsorption in water and soil remediation:

Biomass-derived sorbents are establishing themselves as promising materials for the adsorption of heavy metals in water and soil remediation, providing effective and long-term solutions to reduce environmental pollution and protect human health. Heavy metals, such as cadmium, lead, mercury, and arsenic, are persistent pollutants with serious consequences for ecosystems and human health owing to their toxicity and bioaccumulative qualities [228], [229]. Biomass-derived sorbents, made from sustainable sources such as agricultural wastes, natural fibers, and biochar, have distinct features that make them ideal for the removal of heavy metals and remediation applications [230], [231]. One of the primary benefits of biomass-derived sorbents is their large surface area and porosity, which offer many active sites for heavy metal binding and adsorption. These materials have a strong affinity for heavy metal ions in aqueous solutions, collecting and immobilizing them by processes such as ion exchange, surface complexation, and physical sorption [232], [233]. Furthermore, biomass-derived sorbents often include functional groups including hydroxyl, carboxyl, and amino groups, significantly increasing their metal adsorption capability and selectivity [234], [235].

Biomass-derived sorbents may be used in a variety of wastewater and soil remediation procedures [236]. In water treatment applications, biomass-based adsorbents may be used in batch or continuous flow systems to eliminate heavy metals from polluted water sources such as industrial effluents, mine drainage, and wastewater [237], [238]. These sorbents may be used in filtration systems, packing beds, or artificial wetlands to efficiently absorb and hold heavy metal contaminants, improving water quality and lowering environmental pollution [239], [240]. Similarly, in soil remediation uses, biomass-derived sorbents may be used to immobilize and sequester heavy metal pollutants, preventing them from leaking into groundwater or being absorbed by plants. Sorbent additives, such as charcoal or compost, may be added to polluted soils to improve metal retention and minimize bioavailability, lowering dangers to human health and ecosystems. Furthermore, biomass-derived sorbents may help with the cleanup of brownfield sites, mining tailings, and other polluted land areas, supporting soil regeneration and ecosystem rehabilitation [241]–[243].

Furthermore, biomass-derived sorbents have various benefits over traditional remediation procedures, including lower costs, greater environmental sustainability, and conformity with green remediation principles [244], [245]. These materials are easily accessible, renewable, and often derived from agriculture or forestry leftovers, making them more cost-effective and ecologically benign alternatives to manufactured adsorbents or chemical-based treatments [246], [247]. Furthermore, the usage of biomass-derived sorbents may help with carbon sequestration and soil improvement, which increases their environmental advantages. Finally, biomass-derived sorbents show significant potential for heavy metal adsorption in soil and water remediation, providing effective, long-term, and ecologically responsible solutions to heavy metal pollution concerns [248], [249]. Through continued research and development efforts, as well as real-world use in remediation projects, biomass-based sorbents possess the potential to play an important role in protecting water resources, safeguarding soil quality, and mitigating the negative effects of heavy metal contamination on ecological systems and human health.

D. Technological Challenges in Biomass Conversion and Utilization

Technological hurdles in biomass conversion and usage are important impediments that must be overcome in order to fulfill biomass' full potential as a renewable energy source and sustainable feedstock for a variety of industrial applications [250]. Despite the obvious advantages of biomass consumption, such as its availability, carbon neutrality, and potential to decrease greenhouse gas emissions, several major barriers prevent broad acceptance and commercialization of biomass conversion technology.

One of the key technical problems in biomass conversion is ensuring the creation of efficient and cost-effective conversion systems capable of handling a wide range of biomass feedstocks while producing high-value end products. Biomass is intrinsically heterogeneous, with different compositions, moisture contents, and physical properties depending on its origin and processing processes [251]–[253]. As a consequence, turning biomass into usable products like biofuels, biochemicals, and bioproducts necessitates modern conversion methods that can account for variability and maximize conversion efficiency.

Another significant problem is the scalability of biomass conversion methods to suit industrial-scale production requirements. Many biomass conversion processes, including pyrolysis, gasification, and fermentation, have been shown in the lab or on a pilot scale, but scaling up to commercial production levels presents hurdles [254], [255]. Issues like reactor design, process optimization, and combining with existing infrastructure must be solved in order to build large-scale biomass conversion facilities capable of competing with traditional fossil fuel-based technologies. Also, biomass conversion systems often encounter technological obstacles relating to process efficiency, product quality, and resource usage [256]–[258]. For example, thermochemical conversion methods like pyrolysis and gasification might have poor energy conversion efficiency, incomplete carbon conversion, and undesired byproduct production, which restrict their economic feasibility and environmental sustainability. Similarly, biochemical conversion techniques such as enzymatic hydrolysis and fermentation may face obstacles in inhibiting substrates, enzyme stability, and output recovery, limiting their economic viability. Furthermore, integrating biomass conversion technology into existing energy and manufacturing facilities poses logistical and operational hurdles. Biomass feedstock availability, transportation, storage, and supply chain logistics must all be carefully controlled to maintain a consistent and sustainable feedstock supply for biomass conversion plants [259], [260]. Furthermore, co-producing several products from biomass, like biofuels, electricity, heat, and chemicals, necessitates effective process integration and optimization to optimize resource usage and reduce waste formation.

E. Future Directions and Opportunities for Advancing Biomass-based Solutions

Future opportunities and possibilities for advancing biomass-based solutions include a wide variety of innovative approaches and interdisciplinary collaborations aimed at optimizing the potential of biomass resources to address global sustainability and environmental, and energy-related issues [261], [262]. There are several important areas where biomass-based solutions might play a significant role and encourage positive change:

Technological Innovation: Ongoing research and development in biomass conversion technologies, including gasification, pyrolysis, and biochemical processes, holds great promise for opening new avenues for the valuable conversion of biomass into products like renewable chemicals, biofuels, and bioproducts. Enhancements in the efficiency of processes, variety of products, and amalgamation with current infrastructure would augment the financial viability and expandability of technologies based on biomass [263].

Integration of the Circular Economy: Biomass-based solutions have the potential to be instrumental in developing closed-loop systems that use resources regeneratively and valorize waste streams by adopting the principles of the circular economy [264], [265]. Including biomass in circular economy frameworks offers opportunities to reduce waste output, alleviate environmental consequences, and increase resource efficiency across sectors, from valorizing organic waste to producing biobased materials [266].

Mitigation of Climate Change: By sequestering carbon dioxide via afforestation, replanting, and sustainable land management techniques, biomass-based solutions may assist in moderating climate change. In addition, the production of bioenergy from biomass may be used as a low-carbon substitute for fossil fuels, lowering greenhouse gas emissions and facilitating the switch to a more sustainable energy mix [267], [268]. Achieving climate goals and aiming for carbon neutrality requires investments in carbon capture and storage, sustainable biomass production, and bioenergy infrastructure.

Biomass Valorization in Agriculture: Biomass valorization in agriculture presents opportunities to enhance crop output, promote sustainable land management practices, and improve soil health [269]. By improving soil structure, nutrient retention, and water-holding capacity, using biochar generated from biomass as a soil supplement may raise agricultural output and improve climate resilience. Additionally, biostimulants and fertilizers derived from biomass provide ecologically friendly substitutes for synthetic inputs, reducing their negative effects on the environment and boosting the sustainability of agriculture [270].

Cross-Sector Collaboration: To expedite the development and use of biomass-based solutions, cooperation between academic institutions, business, government, and civil society is essential. Interdisciplinary research initiatives, public-private partnerships, and knowledge-sharing networks might aid in removing obstacles and quickening the adoption of biomass-based solutions [271], [272].

In conclusion, the intersection of technological innovation, circular economy ideas, climate change mitigation, agricultural sustainability, and cooperative governance represents future directions and opportunities for growing biomass-based solutions. Using biomass resources and implementing a holistic sustainable development strategy, we can create a pathway toward a more resilient, equitable, and environmentally conscious future.

IV. Conclusion

To summarize, studying biomass-based solutions provides many opportunities to address pressing global concerns while promoting sustainability and resilience in other domains. This discussion has covered various biomass resource applications and potential, including energy production, environmental restoration, circular economy initiatives, global warming mitigation, and sustainable agriculture. Given the primary findings and implications discussed in this discussion, it is evident that biomass has enormous promise as a renewable resource that is flexible and has the capacity to inspire positive change and support sustainable development. Our investigation's summary emphasizes the following significant results and ramifications:

- Biomass-based solutions, as a viable alternative to fossil fuels, help to promote decarbonization, energy security, and diversity.
- Sustainable production-consumption patterns, waste reduction, and resource efficiency may all be improved by incorporating biomass into circular economy frameworks.
- Because biomass is a carbon sink, it lowers greenhouse gas emissions and encourages the development of carbon-neutral energy systems, both critical components of climate change mitigation.
- Biomass valorization in agriculture enhances sustainable land management and food security by enhancing crop yield, soil health, and climate resilience.
- To fully exploit the potential of biomass-based solutions and overcome implementation challenges, cross-sector collaboration and knowledge exchange are required.

Although significant progress has been made in using biomass resources, further research and development are urgently needed to fully realize the benefits these resources may have on society and the environment. Important areas for further investigation include:

- Advances in biomass conversion technology will increase the profitability, scalability, and efficiency of bioenergy and bioproduct production.
- Developing ecologically friendly feedstock sources and sustainable biomass delivery systems to ensure resource availability.
- Integrating biomass-derived therapies into regulatory incentives, economic processes, and policy frameworks to accelerate investment and adoption.
- Research into innovative applications and high-value biomass-derived products, such as bio-based materials, biochemicals, and biopharmaceuticals.
- The socioeconomic consequences of biomass use activities, such as job creation, rural development, and equitable benefit sharing, will be investigated.

Finally, to fully realize biomass utilization's potential as a transformative and sustainable resource for addressing global issues and accelerating the transition to a more resilient, egalitarian, and environmentally conscious future, research and innovation in this field must continue. We may utilize biomass to promote collaboration, creativity, and a commitment to sustainability, resulting in a more prosperous and sustainable world for future generations.

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