VOLUME 01 ISSUE 02 (2026)

Journal of Waste to Value System

Biomass Waste Valorization for Bioenergy and Value-Added Bioproducts: Emerging Technologies and Sustainability Perspectives

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Abstract

The increasing generation of biomass waste from agricultural, forestry, industrial, and municipal activities has intensified the need for sustainable resource recovery strategies that simultaneously address environmental challenges and energy security. Biomass waste valorization has emerged as a key component of the circular bioeconomy by transforming renewable organic residues into bioenergy and high value bioproducts. This review critically examines recent advances in biomass valorization technologies, including thermochemical, biochemical, and integrated biorefinery approaches, highlighting their potential for producing biofuels, biohydrogen, bio-based chemicals, biopolymers, functional carbon materials, and other value-added products. The review further discusses the influence of feedstock characteristics, biomass availability, and conversion pathways on process performance and product yield. In addition, sustainability perspectives are evaluated through environmental, economic, social, and life cycle considerations, emphasizing the contribution of biomass valorization to greenhouse gas mitigation, resource efficiency, and circular resource utilization. Emerging innovations such as artificial intelligence, digital biorefineries, synthetic biology, advanced catalysts, nanotechnology, and carbon capture technologies are also explored for their potential to improve process efficiency and commercial scalability. Despite considerable technological progress, challenges related to feedstock heterogeneity, pretreatment, economic feasibility, and industrial implementation remain significant. Overall, biomass waste valorization represents a promising pathway toward sustainable energy production, renewable material development, and low-carbon industrial transformation, supporting the global transition to a resilient and resource-efficient circular bioeconomy.

Keywords- Biomass waste valorization, Bioenergy, Biorefinery, Circular bioeconomy, Sustainable bioproducts

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1. INTRODUCTION

Rapid population growth, urbanization, agricultural expansion and industrial activities have created an ever-growing biomass waste that has become an environmental problem, and an opportunity to make use of a resource in an environmentally sustainable manner. The biomass waste refers to the residues from agriculture, forestry industries, food processing, animals and organic wastes from municipalities, which are generated in large amounts globally. Traditionally, these materials have been landfilled, burned in the open, or dumped in uncontrolled locations, resulting in emissions of GHGs, air pollution and poor utilization of renewable resources. Therefore, the global approach to biomass waste has changed from merely disposing of waste to using it as a renewable resource for creating clean energy and valuable products (Khobragade, 2024). This shift coincides with the international efforts to become carbon neutral, more efficient in resource usage and to achieve sustainable development by using the resources in a circular manner.

Resource recovery has become a key concept of the modern waste management system, which focuses on turning biomass residues into economically and environmentally friendly products. Circular resource systems aim to harvest energy, nutrients and materials from waste streams, thereby lowering the environmental burden and reducing reliance on fossil-based resources, as opposed to the conventional linear "produce–use–dispose" model (Otoo & Drechsel, 2018). Those innovative waste management practices, coupled with the use of digital technologies and applications from the industry 4.0, have also helped to improve biomass collection, segregation, monitoring, and recycling, therefore making biomass utilisation across industrial and municipal sectors more sustainable (Kurniawan et al., 2023).

Biomass waste valorisation includes a wide variety of thermochemical and biochemical technologies which convert renewable biomass into bioenergy and into value added bioproducts. Thermochemical processes like combustion, pyrolysis, and gasification are extensively used for fuel production (heat, power, bio-oil, syngas, and biochar), whereas biochemical processes (anaerobic digestion and fermentation) produce biofuels like biomethane, bioethanol, and biohydrogen.

Lignocellulosic biomass, in particular, has been the subject of considerable interest due to its large availability and to the fact that it can be used to produce second-generation biofuels without competing for food production. The conversion efficiency of biomass has been greatly enhanced by the recent developments in pretreatment processes and integrated biorefinery technologies, which are also in line with the principles of a circular bioeconomy (Devi et al., 2022).
Finally, the emerging circular bioeconomy has reinforced the relevance of biomass waste for cascading use of bio-based renewable resources for the generation of energy, chemicals, biomaterials, fertilizers and other high value products. Integrated biorefineries aim to use a single type of biomass for several different products and with minimum waste generation. The use of agricultural residues, food waste, forestry biomass, and industrial organic waste has great potential for circular bioeconomy platforms that can help mitigate greenhouse gas emissions and enhance overall sustainability, as evidenced by bibliometric research (Ranjbari et al., 2022). In addition, industrial biomass residues are a valuable renewable energy source that can provide energy security, waste reduction, and low carbon industrial development, but the issues of variable feedstock, logistics, and economic viability need to be addressed (Kalak, 2023).
Apart from the production of renewable energy, biomass is also in focus as a renewable carbon source to produce bio-based chemicals, advanced materials and sustainable polymers. The development of high value bioproducts which can also replace petroleum derived alternatives has been accelerated due to recent advances in green chemistry, biotechnology and catalytic conversion, which can help support cleaner industrial processes and climate change mitigation (Queneau & Han, 2022). Thus, this review provides an overview of the recent developments in biomass waste valorization technologies, their applications in bioenergy and value-added bioproducts production, assesses the sustainability aspects, and identifies new innovations and future research directions to support the bioeconomy transition towards a circular and resource-efficient economy.

2. RESEARCH OBJECTIVES

- To review major biomass waste resources and emerging technologies for bioenergy and value-added bioproduct production.
- To evaluate the contribution of biomass valorization to circular bioeconomy principles and sustainability.
- To identify key challenges, technological innovations, and future research directions for sustainable biomass waste utilization.

2. BIOMASS WASTE RESOURCES AND VALORIZATION POTENTIAL

Biomass waste refers to waste materials which are generated from the various activities of agriculture, forestry, food processing, livestock, municipal and industrial activities, and are renewable in nature. Major agricultural residues account for rice straw, wheat straw, corn stover and sugarcane bagasse, while the forestry biomass is comprised of sawdust, bark, wood chips and logging residues. Fruit peels, vegetable waste, spent grains and oilseed residues are waste streams produced by the food processing industries and contain a high amount of carbohydrates, proteins and bioactive compounds that have potential for bioenergy and bioproducts production. Another significant biomass source is animal manure, which is rich in organic matter and has the potential for anaerobic digestion, as well as municipal organic wastes. Appropriate biomass resource classification helps in choosing proper conversion technologies and enhances the efficiency of resource recovery (Asghar et al., 2022; Sharma et al., 2020).
Physicochemical properties of biomass have a significant impact on their valorization potential. Moisture content impacts storage, shipping and efficiency of thermochemical conversion, and lignocellulosic composition defines biomass suitability for biochemical and thermochemical processing. High cellulose and hemicellulose content biomasses are preferred for bioethanol and biochemical production while lignin rich biomasses have high calorific value suitable for heat and power. Other key factors such as carbon to nitrogen ratio, biodegradability, and energy content, affect the process efficiency and microbial activity, and yield of products. The natural biopolymers and valuable compounds found in food processing waste can also be extracted prior to energy conversion, boosting the economic value of IBs (Silvestri et al., 2023).
Reliable feedstocks availability and good supply-chain management are also essential for sustainable biomass valorization. The selection of the feedstock is based on the availability of biomass in the region, seasonal variation, transportation distance, storage stability and conversion efficiency. Thanks to recent developments in integrated biorefinery technologies, efficient pretreatment, fractionation and biomass pre-extraction methods have led to increased sugar recovery, better lignin quality and greater process flexibility (Smit et al., 2022). Moreover, the current development of lignocellulosic biorefineries is a trend toward their production of bioenergy in addition to chemicals, biomaterials and other value-added products, further enhancing the circular bioeconomy. Although the problem of feedstock heterogeneity and commercialization remains, technological innovation has been making biomass waste valorization increasingly economically and environmentally sustainable (Kn et al., 2023; Asghar et al., 2022).

Table 1. Classification of Biomass Waste Feedstocks, Key Characteristics, and Valorization Pathways

Biomass Category	Representative Feedstocks	Key Characteristics	Major Valorization Products	References
Agricultural	Rice straw, wheat straw,	High lignocellulosi	Bioethanol,	Sharma et al.

residues	corn stover, sugarcane bagasse	c content; abundant and seasonal	biochar, syngas, biogas	(2020); Asghar et al. (2022)
Forestry residues	Wood chips, sawdust, bark, logging residues	High energy density; lignin-rich	Bio-oil, pellets, activated carbon, heat and power	Sharma et al. (2020); Kn et al. (2023)
Food processing waste	Fruit peels, vegetable residues, spent grains, oilseed cakes	Rich in carbohydrates, proteins, and bioactive compounds	Biopolymers, bioethanol, organic acids, enzymes	Silvestri et al. (2023); Asghar et al. (2022)
Animal manure	Cattle, poultry, and swine manure	High organic matter and nutrient content	Biogas, digestate, biofertilizers	Asghar et al. (2022)
Municipal and industrial biomass waste	Food waste, garden waste, pulp and paper residues, agro-industrial by-products	Variable composition; high resource recovery potential	Biomethane, bioenergy, platform chemicals, bio-based materials	Sharma et al. (2020); Smit et al. (2022)

3. EMERGING TECHNOLOGIES FOR BIOENERGY PRODUCTION FROM BIOMASS WASTE

3.1 Thermochemical Conversion Technologies

Thermochemical conversion technologies have been extensively used to convert waste biomass to renewable energy using high-temperature process. The most mature technology for producing heat and electricity from biomass is combustion, in which biomass is directly oxidized, while gasification produces a syngas with hydrogen, carbon monoxide and methane which can be used for power generation and chemical synthesis. Pyrolysis is carried out under oxygen-deficient conditions to generate bio-oil, biochar and combustible gases, which could be used to produce renewable fuels and carbon sequestration. Hydrothermal liquefaction (HTL) has shown to be a highly effective process for transforming wet biomass to energy-dense bio-crude without lengthy drying, thus optimizing the energy recovery potential of high moisture feedstocks. Recent developments are concerned with increasing conversion efficiency, product selectivity and integration with downstream biorefinery processes for maximum utilization of resources (Pandey & Sharma, 2024).

3.2 Biochemical Conversion Technologies

Biochemical conversion uses microorganisms and enzymes to convert biodegradable biomass to renewable fuel at relatively mild operating conditions. The technology to produce biomethane from organic waste and the production of rich digestate for agricultural uses is still one of the most developed and advanced ones. Lignocellulosic sugars are subjected to fermentation processes to produce bioethanol which plays a major role in the production of sustainable liquid transportation fuels. Biohydrogen production has been rising in significance since hydrogen is a clean-energy carrier with high energy content and no carbon emissions are produced on utilization. Dark fermentation has shown great potential among the several methods due to its capacity to convert broad spectrum of biomass feedstocks to hydrogen without the need for light energy. Pre-treatment methods that improve the availability of carbohydrates and hydrogen, microbial inocula, and substrate properties are key factors affecting the performance of the process (Albuquerque et al., 2024; Gbiete et al., 2024). In addition, photo-fermentation can also be used in conjunction with dark fermentation, which makes use of the organic acids produced during the first step, thereby enhancing the biomass conversion efficiency (Mishra et al., 2019) and total hydrogen generation.

3.3 Hybrid and Integrated Biorefinery Approaches

Hybrid conversion systems involve a combination of different biological and thermochemical technologies in order to achieve the highest possible use of biomass with the lowest possible generation of wastes. In this regard, integrated dark-photo fermentation is one of the most suitable methods to improve biohydrogen production as it utilizes intermediate products from dark fermentation processes as feed for the photo-fermentation process. Likewise, dark fermentation and anaerobic digestion can be integrated to generate hydrogen and methane simultaneously, bringing the overall energy recovery from biomass resources up to a high level (Phanduang et al., 2019). The modern integrated biorefineries take this concept one step further by processing biofuels, bioenergy, platform chemicals, biomaterials, and biofertilizers simultaneously from one biomass feedstock, with the processing steps being interconnected. These systems boost the efficiency of the use of resources, minimize environmental effects and enhance the economic sustainability of biomass valorization. Advanced pretreatment techniques, integration, digital monitoring, and circular bioeconomy principles have been highlighted in recent times to boost productivity and commercialization scope, making integrated biorefineries a centerpiece for the sustainable bioenergy production of the future (Pandey and Sharma, 2024).

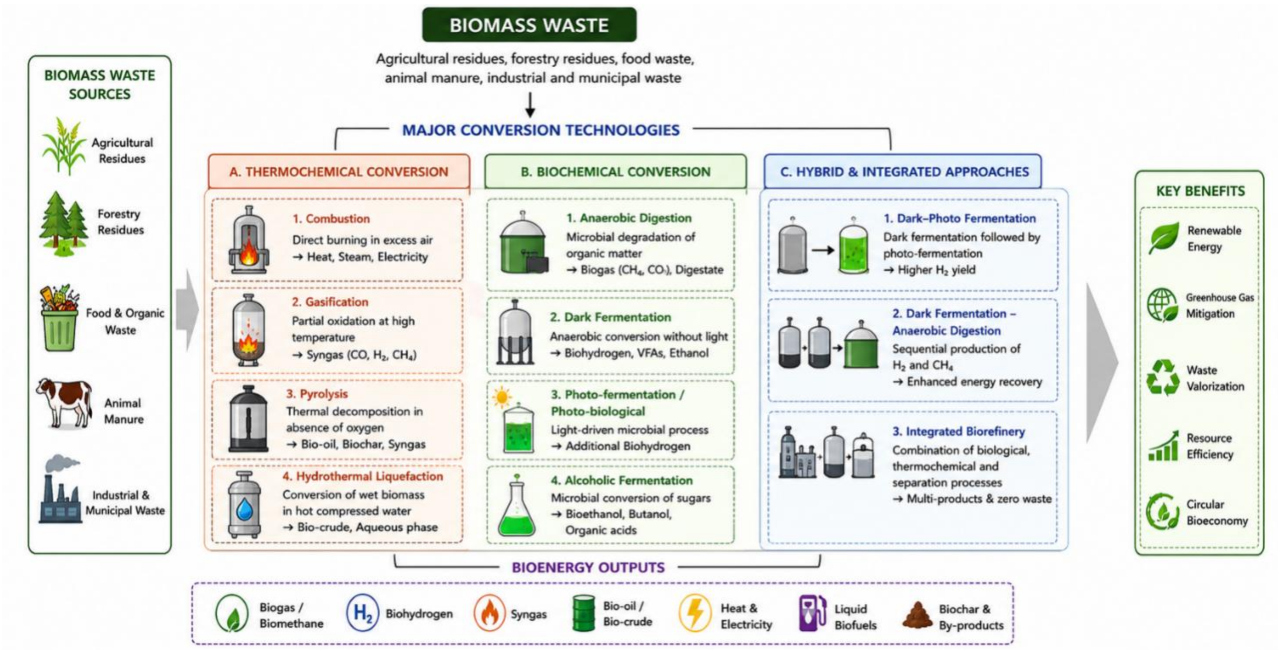

Figure 1. Major biomass conversion technologies for bioenergy production. Thermochemical, biochemical, and integrated approaches convert diverse biomass waste streams into a range of bioenergy outputs while supporting circular bioeconomy and environmental sustainability.

4. BIOMASS-DERIVED VALUE-ADDED BIOPRODUCTS

4.1 Bio-Based Chemicals and Platform Molecules

In addition to the production of renewable energy, biomass valorization can also lead to the production of high-value chemicals which could be used to replace chemicals derived from petroleum. Biomass-derived platform molecules such as organic acids, alcohols, furfural and 5-hydroxymethylfurfural (HMF) are significant molecules in the production of fuels, pharmaceuticals, polymers, solvents and specialty chemicals. The efficiency of biomass intermediate conversion to valuable chemicals via selective electrocatalytic upgrading and heterogeneous catalytic processes has recently been improved to great extent. Bio-based ethylene, for example, is a platform chemical with many applications for the industrial sector, and HMF is a platform molecule that can be used to make sustainable polymers and fine chemicals via environmentally friendly catalytic routes (Li & Sun, 2018; Hulea, 2018; Messori et al., 2022).

4.2 Biopolymers and Bioplastics

With the growing awareness of plastic pollution, biodegradable polymers from renewable biomass resources are gaining momentum. Some of the most widely researched bioplastics are polyhydroxyalkanoates (PHA) and polylactic acid (PLA) due to their biodegradability, biocompatibility, and versatility in use across a variety of industries. Recently, it has been proven that cellulose microfibers derived from biomass waste can be used to effectively strengthen PHA and PLA composites, enhancing their mechanical strength, thermal stability, and durability, without compromising the environment. These are bio-based options to replace traditional petroleum-based plastics and promote sustainable production and circular material use (Mármol et al., 2020).

4.3 Biochar, Activated Carbon, and Functional Carbon Materials

Biochar and functional carbon materials with high value in the environment and industry are also obtained by the thermochemical conversion of biomass. The porous structure and high adsorption capacity of biochar make it useful in various applications, including soil improvement, carbon sequestration, wastewater treatment, and environmental remediation. In recent years, activated carbon from biomass and advanced functional carbon materials have become increasingly interesting and promising materials for use in catalysis, energy storage, gas adsorption, and electrochemical devices. They are renewable sources, tunable surface chemistry, and favourable physicochemical properties, making them interesting substitutes for conventional carbon material, which also leads to waste minimisation and sustainable material production (Rodriguez Correa & Kruse, 2018).

4.4 High-Value Products

The biomass waste is also an important precursor for generating various high value bioproducts through microbial and biotechnological processes. Microbial fermentation derived enzymes are widely used in the food industry, pharmaceutical industry, biofuel industry and environmental biotechnology. Additionally, biomass-based substrates can be used to produce microbial proteins, biosurfactants, biofertilizers, nutraceuticals and other secondary metabolites, which have a wide range of applications in agriculture, healthcare and industrial manufacturing. These products offer not only higher economic returns than traditional biofuels but also make integrated biorefineries more profitable through fully utilizing biomass resources. Therefore, valorization of biomass in a simultaneous production of bioenergy and value-added bioproducts is one of the most promising approaches to increase the commercial sustainability of valorization biomass systems and strengthen the circular bioeconomy (Dabbagh et al., 2019).

Table 2. Major Biomass-Derived Value-Added Bioproducts and Their Applications

Bioproduct	Production Route	Major Applications	References
Platform chemicals (HMF, furfural, organic acids)	Catalytic conversion	Chemicals, fuels, polymers	Li & Sun (2018); Messori et al. (2022)
Bioplastics (PHA, PLA)	Microbial fermentation	Packaging, biomedical materials	Mármol et al. (2020)
Biochar & activated carbon	Pyrolysis/carbonization	Soil amendment, adsorption, energy storage	Rodriguez Correa & Kruse (2018)
Enzymes & microbial proteins	Fermentation	Food, pharmaceuticals, biotechnology	Dabbagh et al. (2019)
Biofertilizers	Anaerobic digestion	Sustainable agriculture	Dabbagh et al. (2019)

5. Sustainability Assessment and Circular Bioeconomy Perspectives

5.1 Environmental Benefits

The valorisation of biomass wastes is crucial for environmental sustainability by converting the organic waste into renewable energy and value-added products and minimizing the reliance on fossil resources. Transitions towards circular bioeconomy principles reduce waste production by recovering waste and maximising the continuous use of renewable biological resources. Through this, landfill disposal is cut down while simultaneously increasing the efficiency of the use of resources, as waste is converted into fuels, chemicals, fertilizers and biomaterials (Carus & Dammer, 2018). In addition, switching to bioenergy from fossil-based energy helps reduce greenhouse gas (GHG) emissions, and the use of biochar provides extra benefits by sequestering carbon over the long-term and enhancing soil quality. Effective biomass utilization, thus climate change mitigation and sustainable resources management. To achieve the same environmental benefits, however, there needs to be a balance of biomass production and biodiversity conservation, so that circular bioeconomy strategies do not have a negative effect on natural ecosystems (Stephenson & Damerell, 2022). The integration of efficient waste management and low carbon technologies have also been highlighted in recent studies as critical enabling technologies for biomass-based renewable energy systems to play significant roles in global GHG reduction efforts (Filonchyk et al., 2024).

5.2 Economic and Techno-Economic Considerations

Technological efficiency, production costs, market demand and scalability of the industry are key to the commercial application of biomass valorization. Integrated biorefineries can boost economic performance by producing several revenue streams based on simultaneous production of bioenergy, biofuels, chemicals and high value bioproducts. The optimization of the process, new conversion technologies and an efficient supply chain have made biomass derived products more cost effective and competitive. Additionally, the increasing demand for renewable fuels, green chemicals and sustainable materials opens new business opportunities within the bioeconomy. However, significant commercialization efforts will need to be undertaken to address issues of feedstock logistics and processing costs through ongoing investments in infrastructure, technological advancement, and financial support. Even though Bioenergy is not established, techno-economic evaluations are still relevant for assessing efficiency in production, scalability and long-term profitability, especially for new systems like renewable hydrogen production (Curcio, 2025).

5.3 Social and Policy Dimensions

The valorisation of biomass can be considered as a tool for sustainable socio-economic development, both because it generates jobs and because it supports rural economies and ensures energy security. Agricultural and forestry residues offer alternative sources of income to farmers and promote the development of decentralized biomass processing units in rural areas. Efficient use of biomass resources increases the use of the available natural resources near where they are needed, which in turn decreases reliance on imported fossil fuels and strengthens national energy security. Key government policies that can drive biomass-based industrial development and spur private sector investment involve renewable energy goals, financial incentives, carbon pricing and investment support. Effective policy frameworks that integrate environmental protection, technological innovation, and economic development are essential for promoting sustainable bioenergy transitions, particularly in developing countries (Falcone, 2023).

5.4 Life Cycle Assessment (LCA) and Sustainability Indicators

Life Cycle Assessment (LCA) is a comprehensive tool for studying the environmental, economic and social implications of biomass valorization across the whole production chain, from the collection of the biomass to the end-product use. LCA helps to identify resource use, energy efficiency, emissions and environmental hotspots, supporting evidence-based decision making and optimizing processes. The incorporation of sustainability indicators corresponding to the UN Sustainable Development Goals (SDGs) adds to the assessment of biomass conversion systems by integrating environmental protection, economic performance and social well-being in a single valuation approach (Wulf et al., 2018). Recently, Life Cycle Sustainability Assessment (LCSA) has extended the boundaries of LCA by combining environmental, economic and social aspects, offering a holistic method for assessing the sustainable potential of biomass-based technologies and their contribution to the 2030 SD Agenda (Backes & Traverso, 2022).

6. Challenges, Emerging Innovations, and Future Research Directions

The valorization of biomass waste has made great strides in the last ten years, but there are still some technical, economic and operational limitations to overcome that prevent the widespread commercialization of technology. The first and most important constraint is the moisture content, seasonable availability and heterogeneity of biomass sources in terms of their lignocellulosic composition and ash content. This variability affects the efficiency of the pretreatment, the conversion performance and the consistency of the products, that makes process standardization difficult. Pretreatment is another key challenge as conventional physical, chemical, and biological pretreatment processes are high energy-consuming, high chemical consumption, and lengthy processing. Moreover, a lot of biomass conversion technologies are not achieving optimal recovery of the energy from the biomass and are still not fully utilizing biomass fractions, which lowers biomass conversion efficiencies. The downstream purification of products such as biofuels, platform chemicals and specialty bioproducts also significantly increases production costs, decreasing the economic competitiveness of biomass-derived products. The challenges underscore the necessity of developing more efficient conversion technologies, optimizing feedstock management, and optimizing the processes at an integrated level to realize sustainable biomass utilization at an industrial scale.

New technologies, which are emerging, are offering new opportunities to break these limitations and optimise the function of biomass valorization systems. Artificial Intelligence (AI) and Machine Learning (ML) are now being used to optimize the selection of feedstock materials, predict properties of biomass materials, monitor the performance of the reactor and optimize the operation of the reactor to maximize the yield of products. With digitized biorefineries, which feature sensors, automation, IoT, and real-time monitoring, process control, predictive maintenance, and enhanced operational efficiency are achieved. Meanwhile, synthetic biology has helped to create a new generation of engineered microorganisms to produce higher amounts of biofuels, enzymes, organic acids and other value-added biochemicals. Advances in catalyst design have helped to improve the selectivity and efficiency of thermochemical and catalytic conversion processes and reduce energy inputs. Nanotechnology has also helped in the development of nanocatalysts and advanced adsorbents for better biomass pretreatment, catalytic performance, and purification of products. Furthermore, carbon capture technologies can be combined with biomass conversion technologies to produce carbon negative bioenergy systems, which also produce renewable energy and reduce the amount of carbon dioxide in the atmosphere.

The future needs of flexible multi-feedstock biorefineries to process various biomass resources efficiently with a constant product quality and stability is a key priority for future research. Much more attention should also be given to zero-waste processing strategies which aim to make the best use of all the biomass fractions by utilizing residual streams as renewable fuels, chemicals, fertilizers and advanced functional materials. To achieve high productivity and low production cost, process intensification methods, using integrated conversion technologies, continuous reactor systems and energy-efficient designs will be crucial. Biomass processing plants that are decentralized and modular and are set up near biomass generation sites can further reduce transportation costs, boost rural economies and increase access to resources. Moreover, detailed techno-economic analyses, common sustainability assessment methods, policy incentives, and increased research, industry and policy integration will be needed to speed up commercialization. Further innovations in these areas will allow biomass waste valorisation to contribute more to the circular bioeconomy, to lower the greenhouse gas emissions, to enhance the production of renewable energy and contribute to long-term sustainable development.

7. Conclusion

The valorization of biomass waste has become a gamechanger in the fields of sustainable waste management and renewable energy and bio-based products. Thermochemical, biochemical and hybrid conversion technologies have proven to be promising to convert a wide variety of biomass resources into biofuels, bioenergy, platform chemicals, biopolymers, functional carbon materials and other high value bioproducts, which will increase the efficiencies of biomass utilization and mitigate reliance on fossil-derived feedstocks. By using more biomass and less waste, and with fewer impacts to the environment, the adoption of integrated biorefinery concepts further strengthens the circular bioeconomy. However, there remain various challenges for the large-scale implementation, such as feedstock heterogeneity, pretreatment, process optimization, product purification and purification, and economics and supply chain management. Artificial Intelligence, digital biorefineries, synthetic biology, advanced catalysts, nanotechnology and integration of Carbon Capture are some of the emerging innovations that could enhance the efficiency of conversions, operational flexibility and commercial viability. As well as strong sustainability evaluations, enabling policy regimes, and research/industry/government partnerships to spur the deployment of technology. These biomass valorization strategies will be of greatest importance in the future: valorization on multi-feedstocks, valorization based on zero waste biorefineries, and valorization based on low carbon production systems which can become scalable for supporting the objectives of global climate change and sustainable industrial development. These developments put biomass waste valorization in a pivotal role for the future circular bioeconomy, and therefore the production of cleaner energy, resource conservation, environmental protection and long-term socio-economic sustainability.

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