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REVIEW

Biomass for a Circular Economy from Traditional Sectors: Mini Review

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ABSTRACT

Sustainable alternatives have grown more prevalent due to an urgent need to address climate change, environmental degradation, and the depletion of non-renewable resources. As an inexhaustible and renewable resource, biomass has become an attractive option for energy production within the framework of a circular economy that emphasizes resource efficiency and environmental sustainability. Various kinds and sources of biomass, from forestry waste and agricultural residue to animal dung and microalgae, are fully explored in this mini review, along with their potential for biofuel production in both developed and developing countries. The processes for thermochemical and biochemical conversion, the sustainability of using biomass, and the socioeconomic advantages, especially for African countries, are highlighted. Key case studies demonstrating the value and potential of biomass waste in promoting sustainable energy transitions worldwide are also discussed in this review. Despite its potential, the use of biomass is restricted due to challenges including low conversion efficiency, high transportation costs, seasonal variability, and insufficient advancements in technology. Nonetheless, biomass offers an innovative approach for developing an environmentally friendly, efficient, and low-carbon economy that promotes sustainable development and energy security. Holistic approaches, such as increased regional cooperation, capacity building, technical innovation, and policy reform, must be implemented to address existing challenges.

Keywords: Biomass; Circular Economy; Renewable Energy; Environmental Sustainability

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1. Introduction

Due to societal reform and rapid industrialization, the demand for renewable energy is increasing rapidly in developed and third-world developing countries [1,2]. The world's population was estimated at 2.6 billion in 1950. The world's population today exceeds 7.7 billion, and by 2050, it is expected to reach 9.7 billion, and 10.9 billion by 2100 [3,4]. Currently, the global generation of waste is estimated at 3.5 million Mg per day, which is expected to double by 2050 and triple by 2100 [5]. Therefore, the gap between environmental sustainability and economic growth is growing [6]. This means the linear "take-make-dispose" model is no longer sustainable [7]. It is crucial to develop a sustainable approach to managing waste, reducing waste, and improving human and environmental health by utilizing waste and bio-feedstock as inputs for industry [8–10]. Recycling and the utilization of biomass elements have proved to be the major aspects of executing the idea of a circular economy (**Figure 1**) [11]. The use of renewable energy, such as hydro, wind, solar, and biomass, has received great attention [12]. Among these renewable energies, biomass stands out. This is due to its abundance, low cost, and reduction of atmospheric carbon dioxide, which can degrade thermally into several types of fuels [13]. It is crucial to replace fossil fuels with non-fossil fuels to reduce carbon emissions due to climate change [14]. Biomass energy has been a main source of cooking and electricity, mostly in rural areas. However, most of the agricultural and industrial sectors do not know how to manage biomass waste well. As a result, poor biomass waste disposal produces foul smells and pollutes the air, water, and land, making it easy for parasitic insects like flies and mosquitoes to spread diseases like cholera and malaria. Furthermore, burning biomass enhances the risk of infections, leads to respiratory disorders like asthma and chronic obstructive lung disease, as well as releases greenhouse gases like methane, which are a threat to both human and environmental health [15–17].

To manage the waste, converting it to biofuel energy using the circular economy concept might be the required solution. This review aims to look at various agricultural, animal waste, forestry, and microalgae biomass as potential for renewable energy application in the world, particularly in Africa. It will explore how sustainable and economical biofuel energy is, as well as the amount of energy that can be generated from biomass waste. The review will further discuss the effect of biomass energy on human and environmental health. Lastly, the challenges that come with the use of biomass biofuel and the prospects will be investigated.

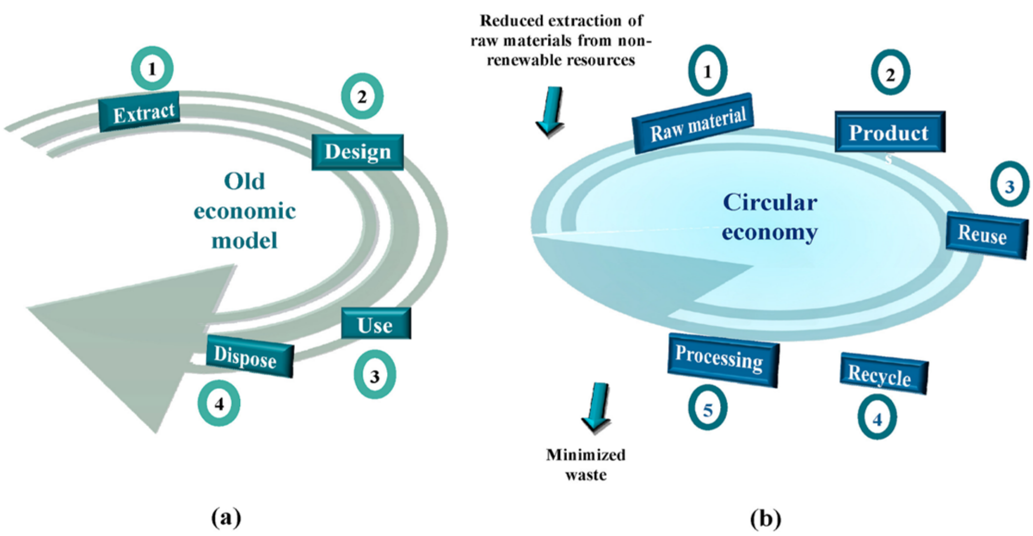

Figure 1. (**a**) Old economic model based on the "take-make-use-throw" method. (**b**) The rising concept of the circular economy [13].

1.1. Biomass

Biomass is defined as a vegetal (agricultural wastes, crops, algae) or animal (manure) biological residue [18]. It is the most abundant renewable resource on earth, with a production of nearly 20×10^{10} tonnes per year [19]. Woody plants, grasses, herbaceous plants, manures, and aquatic plants are the most common kinds of biomass [20]. Biomass accounts for 8% to 15% of the world's supply of energy, electricity, and transportation fuels[21]. It has the potential to supply 33–50% of the world's primary energy needs by the year 2050[22]. It is crucial to replace fossil fuels with non-fossil fuels to reduce carbon emissions, which might result in environmental challenges such as acid rain, climate change, global warming, human health, and biodiversity damage[23].

Moreover, in contrast to fossil fuels like coal, petroleum, and natural gas, biomass offers a steady supply of feedstock[24]. Various methods are employed to convert biomass into energy, including burning solid waste, growing crops, generating biofuel from landfill gas, and producing bio-oil[25].

1.2. Circular Economy

The circular economy (CE) began as an initiative in the face of global resource depletion and climate change challenges, attempting to change how the whole economic system operates from linear to circular flows[26]. CE is viewed as a new business model that is likely to bring about a more sustainable and peaceful society[27]. This idea was promoted in the 1990s in China in response to economic growth and natural resource limitations[28]. It is believed to be the solution to resource scarcity, waste, economic development, and environmental challenges[29]. Numerous CE definitions have been proposed over the years. According to Kirchher, Reike, and Hekkert, the concept of *end of life* is replaced in the CE economic system by reducing, reusing, recycling, and recovering resources throughout the processes of production, distribution, and consumption (**Figure 2**). It works to achieve sustainable development, benefiting the present and future generations by concurrently fostering social justice, economic success, and environmental quality. It is made possible by innovative company strategies and conscientious customers[30]. It is based on 5R values, which are reuse, recycle, reduce, repurpose, and recover[31]. The three primary values of the CE concept are to design, minimize waste, sustain products in use, and restore the environment[32].

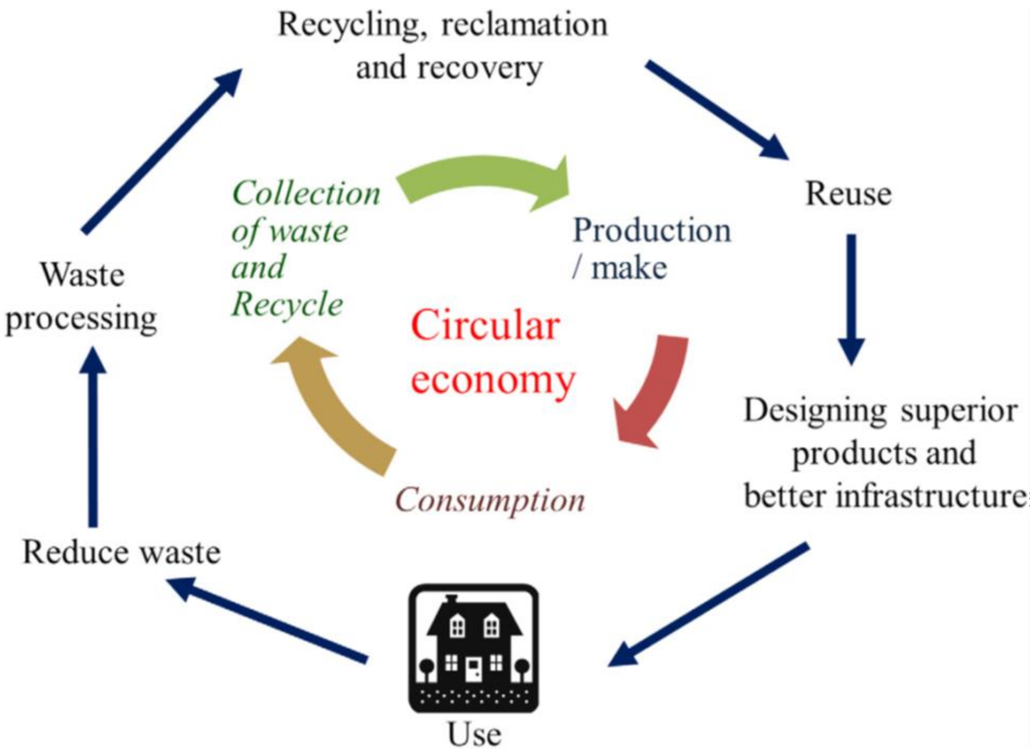

Figure 2. The conceptual cycle exhibits a circular economy system[23].

2. Biomass to Biofuels

The conversion of biomass into biofuels is typically achieved using thermochemical or biochemical reactions to produce different bioproducts (**Figure 3**)[33,34]. The nature and amount of biomass feedstock, as well as the preferred energy source, determine the biomass conversion method[35]. Thermochemical processes comprise combustion, pyrolysis, gasification, and activation, whilst biochemical methods comprise hydrolysis and extraction[36,37]. In general, the two methods have proven to be economically equal. Nonetheless, according to life cycle analysis, biochemical conversion might be superior to the energy balance and the amount of greenhouse emissions[20].

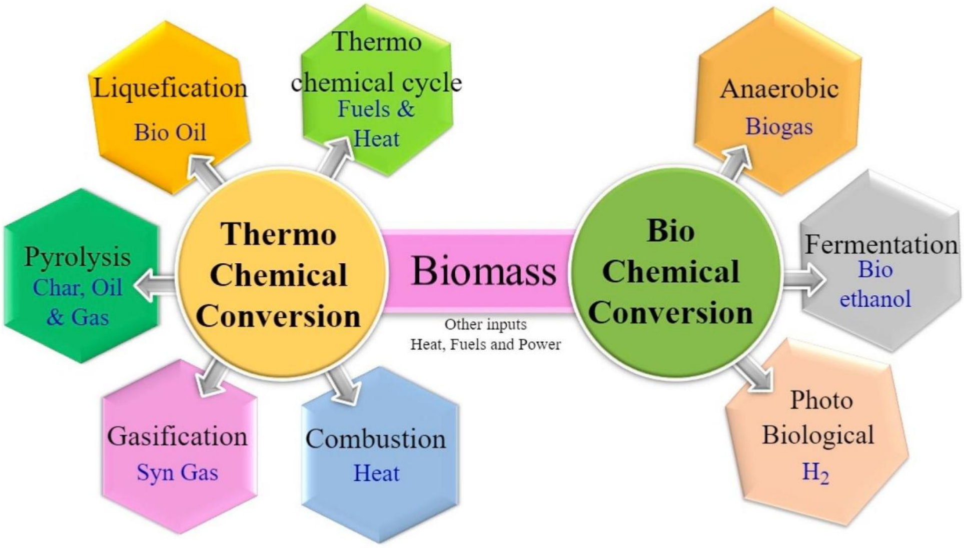

Figure 3. Pathway for biomass conversion- thermo and biochemical conversion[20].

3. Types of Biomass Waste

3.1. Lignocellulose Waste

Lignocellulosic biomass is studied worldwide as a source of liquid fuels and chemicals because of its abundance and renewability[38,39]. The dry plant material known as lignocellulosic biomass consists of cellulose (25–50 wt%), hemicellulose (15–40 wt%), lignin (10–40 wt%), extractives (0–15 wt%), and usually some inorganic mineral materials (**Figure 4**)[40]. Most lignocellulosic biomass feedstocks used in energy production come from the forestry, industrial, and agricultural sectors (**Table 1**)[41].

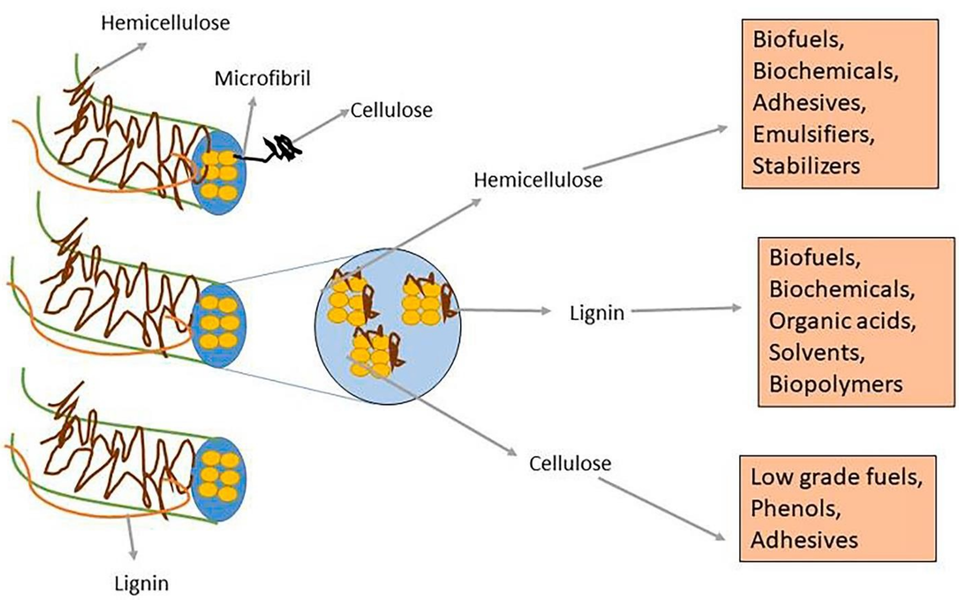

Figure 4. Structure of lignocellulosic biomass and the products[12].

Table 1. Energy-producing lignocellulosic biomass feedstocks [41].

Supply Sector	Type	Examples
Agriculture	Lignocellulosic energy crops	Herbaceous crops: reed, miscanthus, and switchgrass.
	Crop residues	Straw crops (rice, wheat, corn, and cotton stalks).
	Energy crops that include sugar, oil, and starch	Sugarcane; Corn; Rape Seed.
Forestry	Dedicated forestry	Plantations with a short rotation (eucalyptus, poplar, and willow).
	Forestry by-products	Barks; wood blocks; thinning wood chips; wood chips from tips and branches; thinning logs.
Industry	Lignocellulosic agro-industrial residues	Corn cob, rice husk, and sugarcane bagasse.
	Wood industry residues	Sawdust and wood debris from sawmills.
Other	Lignocellulosic waste	Residues of lignocellulosic materials from gardens and parks (grass, trimming).

3.1.1. Agricultural Crop Residues

As a by-product of agricultural post-harvest operations or through industrial crop processing, biomass is produced from agricultural crop waste [42].

Maize stover and wheat straw are the major crop productions in South Africa (SA), which results in them potentially contributing the largest residue in the country. Annually, almost 14.4 million tonnes are estimated from maize and wheat crop residues (**Table 2**). However, only 6 million tonnes can be sustainably harvested from the fields. Batidzirai and co-authors investigated the technical, financial, and environmental viability of the maize stover and wheat straw crop residues for energy from biomass production [43]. They reported that farmers should move from traditional tillage to no-till farming to have high volumes of crop residues and sustainability. They recommended that more studies should be conducted to explore several fundamentals of the supply chain, such as stakeholder organization, risk assessment, and potential technical issues at the conversion end.

Table 2. Prospects for sustainable maize and wheat residue in South Africa (base case) [43].

Region	Maize Stover (Mt)^a	Wheat Straw (Mt)^a	Total Residues (Mt)	Total Crop Residues (PJ)^b
Western Cape	0.01	0.002	0.01	0.2
Northern Cape	1.33	0.385	1.71	31.0
Free State	1.65	0.009	1.66	30.1
Eastern Cape	0.03	0.003	0.03	0.5
KwaZulu-Natal	0.31	0.025	0.34	6.1
Mpumalanga	1.58	0.099	0.11	29.0
Limpopo	0.01	0.099	0.11	1.9
Gauteng	0.24	0.005	0.24	4.4
North West	0.011	0.055	0.06	1.1
Total	5.15	0.603	5.75	104.5

Note: ^{a} It is assumed that for both wheat and maize, the average residue-to-product ratio is 1:1; ^{b} The predicted HHV for the leftover wheat and maize is 17.8 GJ t_1 and 18.2 GJ t_1, respectively.

Chang and friends looked at bioenergy production in Taiwan by using waste biomass from the forest and rice fields. The residues from rice paddy fields consist of rough rice, rice husk, and rice straw. Almost 60% of Taiwan's regions are enclosed forests, whereby rice paddy and forest cover most of the land, as seen in **Figure 5**. Their results showed that biomass bioenergy had the potential to displace gasoline by producing bioethanol and burning leftover fuel. Rice paddies' biomass and the forest sector's biomass may produce 40.15 and 206.77 PJ yearly, respectively [44].

Crop residue biomass was used as a potential source for second-generation biofuel production by Ayamga et al. in the Ghana Lawra-Nandom district (**Figure 6**). The agricultural feedstocks used included millet, sorghum, maize, and groundnut residues. Their study was conducted using interviews, surveys, field, and laboratory experiments. From their findings, the district's annual crop residue production amounted to 272.000t. About other crops, sorghum generated the highest number of residues, with 59% of total residues. They further reported that the biofuel production process's net energy balance was 1718.7 MJ, with an energy output-to-input ratio of 1.31. They advised the Ghana government to invest in the research of second-generation biofuels using crop residues due to their benefits [45].

In Andalusia, Spain, Marquina and their friend explored the economic potential of biomass from the olive sector for thermal and electrical energy uses. Spain is the number one country in olive oil production globally and in Europe (EU), with roughly 45% worldwide and 60% of EU production. In their study, they estimated the maximum amount of electrical and thermal energy that can be obtained from the remnants of the olive sector, the amount of biomass that can be obtained from them, and the economic value of using these energies. In their results, they found that many olive sector residues for power were wasted by 69.23%. That resulted in lower electrical and thermal energy generation. That could have resulted in the full use of 83.9% and 64.9% greater generation of electrical and thermal energy, respectively. It was also found that the olive sector's biomass economic value was higher than the market price value (**Figure 7**) [46].

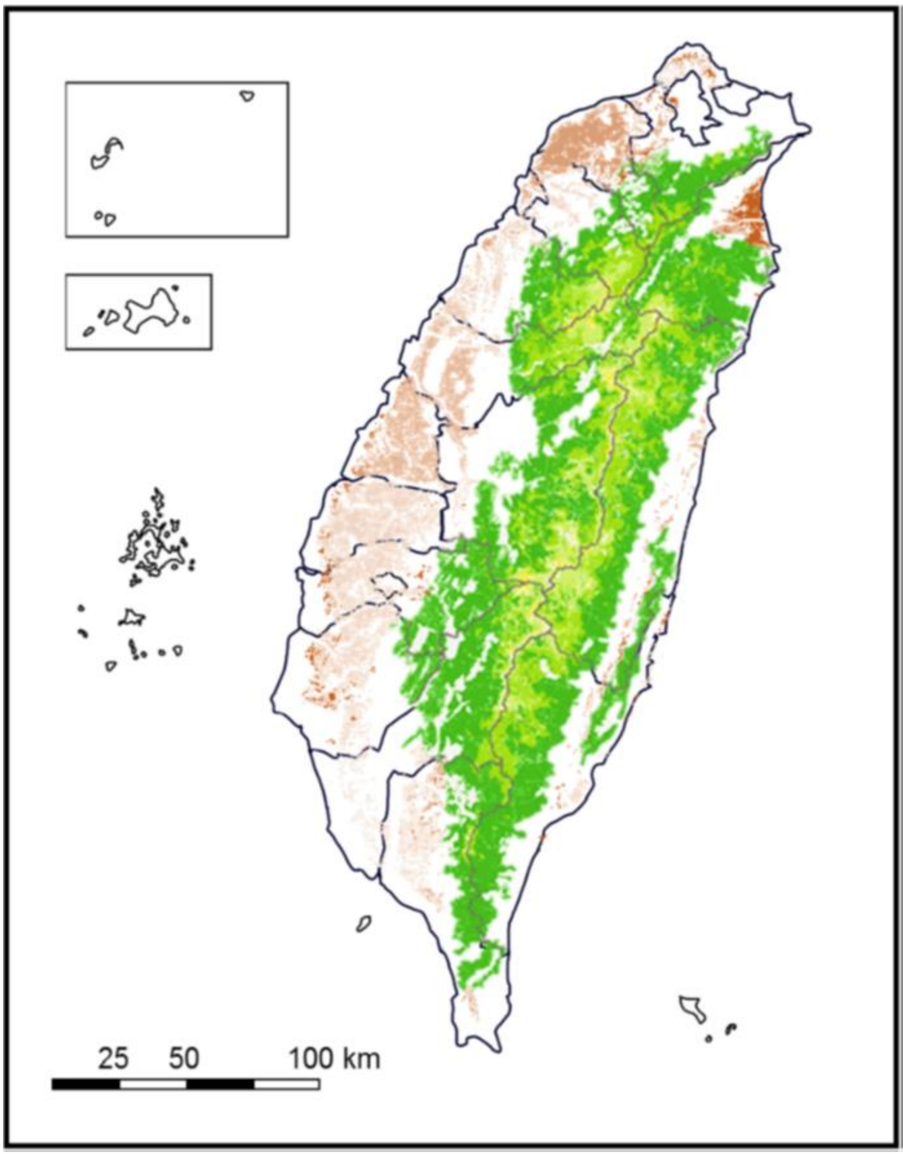

Figure 5. Taiwan map. The forest and regions of rice paddies are light gray. Legends: yellow sub-alpine softwood woods; temperate hardwood/softwood mixed woodlands; rice paddies (light brown); and cold temperate softwood forests (mid-green) [44].

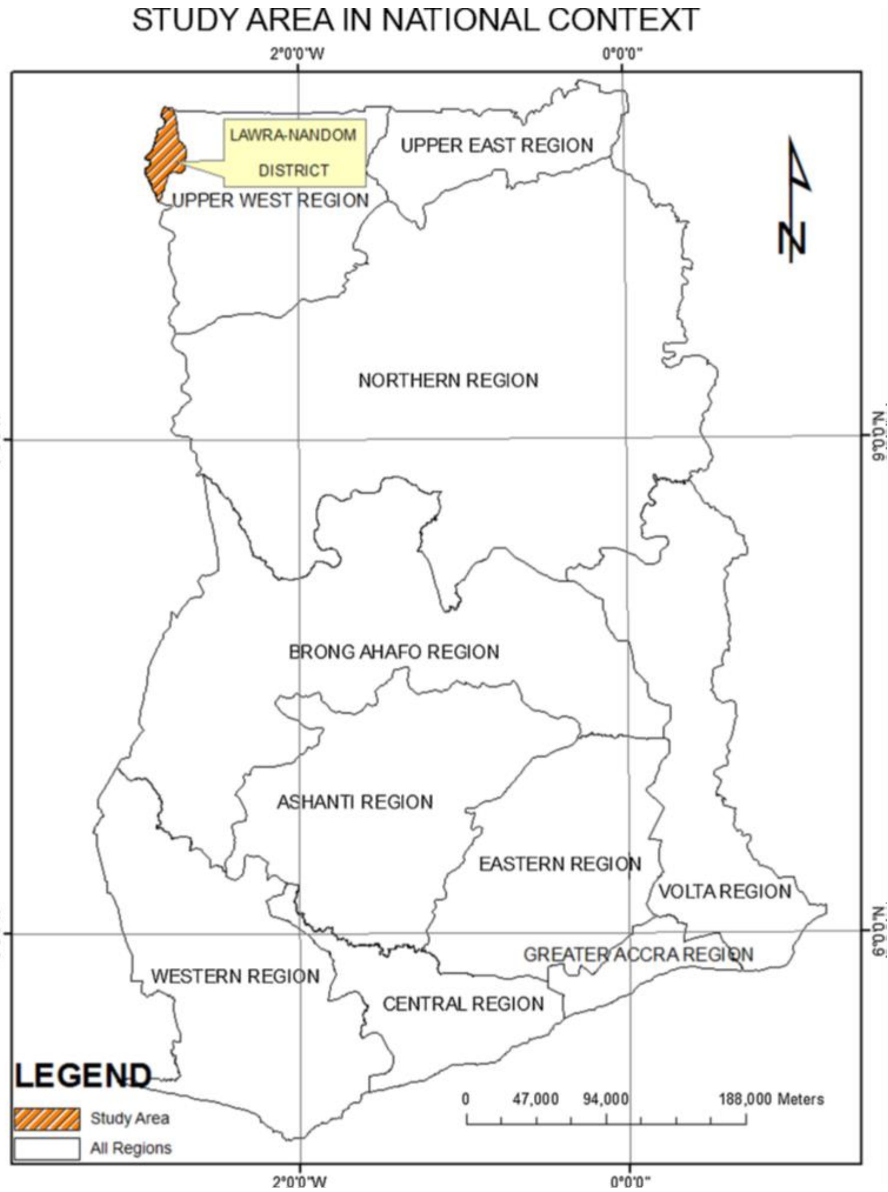

Figure 6. Ghanaian map displaying the Lawra-Nandom district [45].

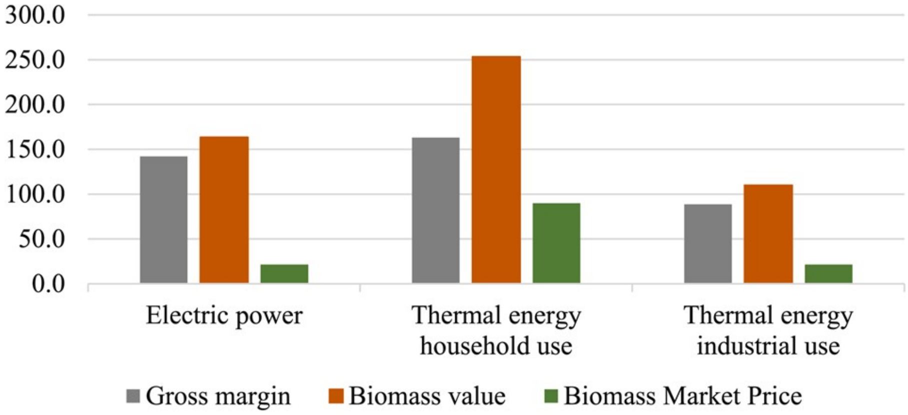

Figure 7. The margin of the biomass economic value over its market price (Unit: €/t) [46].

In 13 years, Uzoagba et al. studied the possibility of turning crop residuals from 25 energy crops in Africa and 15 chosen countries into solid biofuel, biogas, and bioethanol. They reported that Africa has the potential to produce 139.79 million tonnes of oil Equivalent (Mtoe) of solid biofuel, 82.62 Mtoe of bioethanol, and 83.05 Mtoe of biomethane each year on average. The crops with the most potential for bioenergy were sorghum, cassava, and maize. Namibia and the Central African Republic had the lowest national potential, while South Africa and Nigeria had the highest [47].

In Mexico, where 3.6 million tons of corn cob residue are produced yearly, Manzini and others investigated the low-carbon technique of corn cob gasification for the corn flour industry. According to the study, using a small-scale gasifier cogeneration system produces power and heat while reducing CO_2 emissions by 51.7%. Biochar, which is beneficial for restoring soil, was also produced by this method. They further reported savings of USD 85,401 for a medium-sized business that produced 1,039 tons of maize flour a year [48].

Same and friends examined how agricultural waste, such as straws, husks, shells, stalks, fibers, and peels, may be strategically used to produce bioenergy in West Africa. The best residue type was found to be cereal straws through multicriteria decision analysis. Approximately 402 million metric tons of biomass with an energy content of 6,960 PJ may be produced yearly in the region, according to the study. This would be enough to supply 20.13% of West Africa's overall energy needs [49].

3.1.2. Forestry Biomass

Bildrici et al. studied the association between the consumption of woody biomass energy and economic growth in several sub-Saharan African nations. The study was conducted in some countries, including South Africa, Angola, Guinea-Bissau, Mauritania, Niger, Nigeria, and the Seychelles. They used the Autoregressive-Distributed Lag (ARDL) model and the traditional Granger causality procedure to study the short and long-run relationship between economic growth and woody biomass consumption. They found a unidirectional causal relationship between economic growth and the amount of woody biomass energy consumed in Angola, Guinea-Bissau, and Niger. However, it was bidirectional for South Africa, Nigeria, Mauritania, and Benin [50]. Another study was done in Sub-Saharan Africa (SSA) by Dasappa et al. to assess the economic analysis using biomass gasification for power generation. They estimated a possible power of about 10,000 MW and 5,000 MW generation by using 10% of forest residues and 30% of agro-processing residues, respectively, from the wood processing industry. It was then concluded that effective use of biomass in Africa can meet the electricity and cooking generation necessities. Moreover, the electricity demand could be met through gasification power generation technology [51].

Manyele and friends used pyrolysis technology to assess the lifecycle of the production of biofuel from wood biomass. In Tanzania, 91% of the total energy comes from biomass, about 8% is imported, and the remaining 1% comes from electricity. It was established that during its lifecycle, biofuel had a slightly adverse impact on human health and the environment. Furthermore, biofuel showed superior performance in the combustion facilities. As compared to petroleum fuels, biofuels showed lower emission levels, which were below the standard limits [52].

Salam et al. examined how Bangladesh uses forest, agricultural, and municipal solid waste as key biomass feedstocks for hydrogen energy. The country's biomass potential, comprised of agricultural waste, is 47.7 million tons of oil equivalent (MTOE). Gasification yields of hydrogen varied from 10% to 25%, with improved systems achieving up to 12.8%. According to the study, purification procedures such as water-gas shift and pressure swing adsorption, along with temperature and gasifying agents, were important process variables. An anticipated energy cost of USD 0.1116/kWh indicated that biomass gasification was economically viable [53].

3.1.3. Agro-Industrial Biomass

Schemer and colleagues explored corn cobs as a potential bioenergy feedstock for both the production of combined heat and power (CHP) and biofuel [54]. They wanted to study the availability of corn cobs from the North Central United States (North Dakota, South Dakota, and Minnesota), where they employed the corn grain ethanol plants that are currently in place as a stand-in for prospective co-located cellulosic ethanol plants in the future. They found out that the greenhouse gas emissions were reduced by 60–65% when using CHP from cobs residues. The supply limitations for corn for the mature biofuel business were thought to be feasible because of the radius area overlap between the existing corn grain ethanol plants (**Figure 8**). It was suggested that to satisfy multiple customers' renewable energy needs, a multi-feedstock approach was needed.

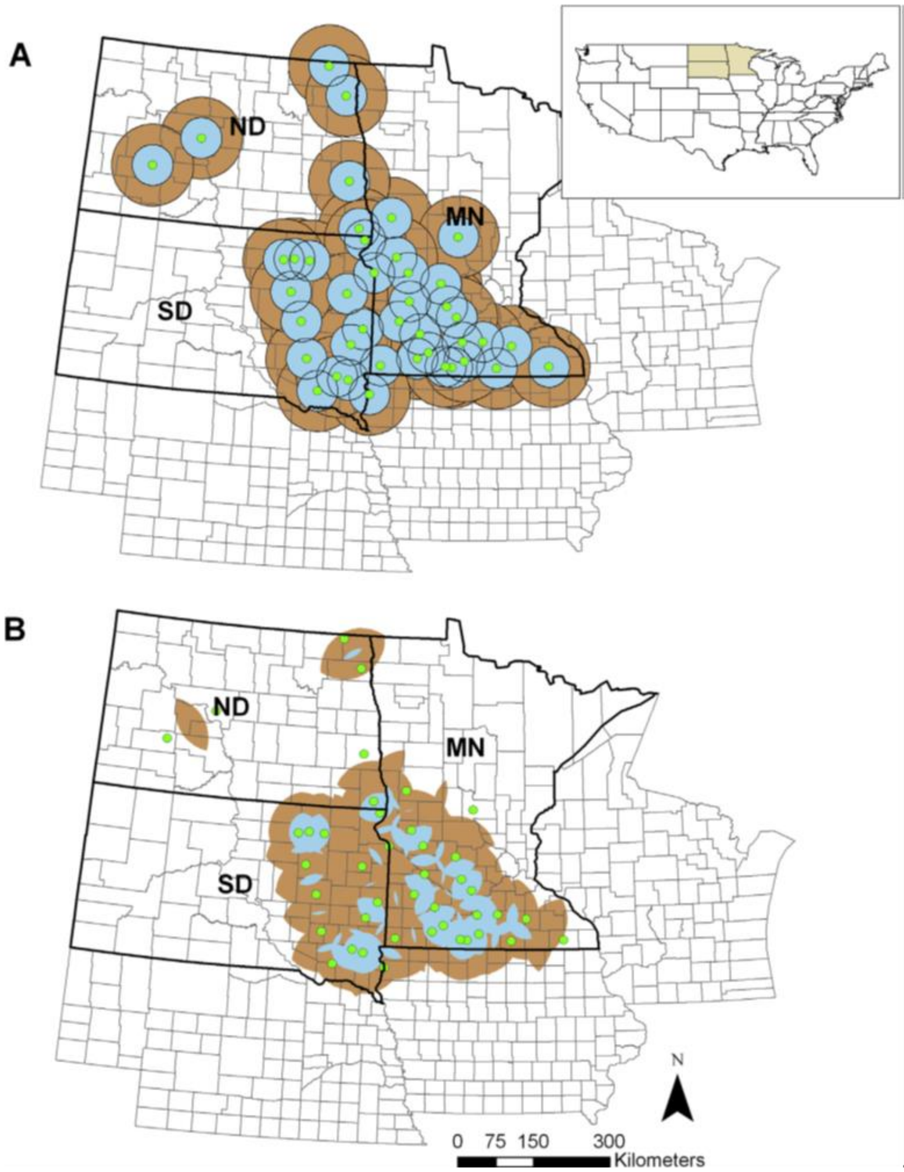

Figure 8. Locations of corn grain ethanol plants (green) in Minnesota (MN), North Dakota (ND), and South Dakota (SD) with matching radius areas (A) of 40 km (blue) and 80 km (brown) and overlaps in radius areas for the 40 km (blue) and 80 km (brown) radius distances [54].

Barry et al. evaluated the availability of residues for gasification in Burkina Faso. Burkina Faso is a landlocked country that is dependent on importing fossil fuels to meet the national energy demand. About 90% of their households' energy sources are from biomass, including wood, charcoal, and agricultural and agro-industrial residues. Their primary source of data was information on annual production rates and agricultural areas, which they obtained from statistical data provided by Burkina Faso's National Institute of Statistics and Demography. They also gathered their data from agricultural and agro-industrial residues. Their findings showed that only rice husks and cotton stalks could be recovered at rates of 75% and 20%, respectively, and that these materials have mobilizable potential for bioenergy of 6,497 and 723,260 tons.

Furthermore, the residues had an energy potential of 44,638 toes and 253 toes. They concluded that by using these agricultural biomass resources extensively, Burkina

Faso's agro-industries can have better energy conditions by importing less energy [55].

Olupot and colleagues conducted a study on the characteristics of 10 specific kinds of rice husk in Uganda. They also evaluated the financial advantages of generating power from rice husks with diesel engine generators. Their results showed that husks have the potential to generate electricity of 15,310 MWh per year. Thus, resulting in US$4,903,636 in diesel savings annually and 14.045 t CO_2/year in CO_2 emission savings. On the other hand, a 250 kW generator running for 8 hours a day, 350 days a year, requires 5.8 t of husk each day to generate 700 MW h/year. Therefore, about US$98,000 is saved compared to the diesel plant, with a 2.5-year payback period [56].

The potential of sugarcane waste generated by small-scale farmers in South Africa as a biomass feedstock to produce bioenergy was examined by Chipfupa et al. According to their research, the fields currently burn more than 90% of the debris from sugarcane, mostly leaves and tops, which increases greenhouse gas emissions. With an estimated 2.7 million tons of sugarcane waste available each year, the analysis shows that, with a 50% recovery rate and 36% energy conversion efficiency, 150,323 MWh of electricity could be produced annually. These findings show the importance of improved waste management practices in reducing emissions and increasing the rate of renewable energy [57].

In the southeast and midwestern regions of Mexico, Rincon and friends studied sugar cane bagasse as the primary feedstock for fired cogeneration systems. Biomass-integrated gasification combined cycle (BIGCC) and biomass steam turbines were the two cogeneration systems that were examined. The BIGCC system was found to be the most effective, meeting heat demands while generating excess electricity, which could reduce the cost of producing ethanol by about 18% [58].

3.2. Animal Waste

Anaerobic digestion (AD) and gasification in a cascade flow of materials were studied in conjunction by Antoniou et al. They investigated the gasification of the dry solid digested by-product of mixed agricultural wastes, which included cereal bran (12%), cow manure (20%), maize and triticale silages (25%), and pig manure (43%). From their findings, they revealed that the gas was categorized as medium heating value fuel, which was suitable to generate 971 kWh of electricity per day to improve the economic feasibility of the AD plant. The dual system demonstrated the ability to generate carbonaceous material for agronomic uses and to improve the efficiency of renewable energy. Additionally, it demonstrated concrete opportunities for later use, which will eventually support an ongoing flow of resources [59].

In Uganda, Okello estimated the animal residue potential for energy using cattle, pigs, goats, sheep, poultry, and humans. The energy potential was estimated using the daily production of volatile solids per animal and the biogas yield per kilogram of volatile solids. Their findings showed that cattle manure showed the highest energy potential, followed by goats (**Table 3**). According to their report, the use of biomass residues for energy is quite limited in Uganda. The country needs to overcome several technical, environmental, social, and economic restrictions [60].

Table 3. Potential energy in theory for animal manure [60].

Animal Category	Population (millions)	VS[a] (kg d^{-1})	B 3–1 B_o (m kg)	Potential (PJ y^{-1})
Cattle	11.71	2.67	0.20	45.56
Goats	12.29	0.33	0.31	9.18
Sheep	3.58	0.30	0.31	2.43
Pigs	3.18	0.59	0.31	4.25
Chicken	37.58	0.02	0.18	0.99
Ducks	1.47	0.02	0.22	0.05
Human	30.66	0.06	0.20	2.69
Total				65.23

Note: [a] Volatile solid per animal; [b] Biochemical methane potential.

Using animal waste that contains rumen, blood, and manure, Khalil and friends investigated the possibility of producing biogas in Indonesia. They estimated that the biogas generated from animal waste was up to 9,597.4 Mm^3 per year, which could be converted to 1.7×10^2 kWh of electricity. However, the application of small and large-scale operations, political, technical, social, and institutional, is still a challenge for the implementation of biogas energy in Indonesia [61].

In rural Tanzania, the study conducted by Mwakitalima and colleagues combined solar photovoltaic and biogas systems with cattle manure as a feedstock. With a home load of 30 kW, it aimed to fulfill a peak electrical demand of 63.41 kW. The system displayed a levelized cost of energy (LCOE) of USD 0.1109/kWh and a net current cost of USD 85,107. In different circumstances of reliability, the LCOE fell to as low as USD 0.0887/kWh. The hybrid solution proved to be both economical and appropriate for rural off-grid electricity [62].

3.3. Microalgae

Microalgae have gained popularity as a substitute feedstock for biodiesel among scientists, business owners, and the public in the past few years. Bulky and varied, microalgae are eukaryotes that are photosynthetic and have a basic cellular structure. Microalgae feedstock can be unicellular or multicellular and has less competition with other oil crops for land availability [63,64]. Microalgae can be cultivated from aquatic environments for triglyceride production, which can be used to produce third-generation biofuel [65]. Biofuel production from microalgae has great advantages, such as using minimal water, not needing extra land, being economical, and improving the quality of air by absorbing atmospheric CO_2 [66].

To generate bioethanol for Malaysia's transportation sector, Szulczyk et al. evaluated the economic viability and sustainability of using microalgae (*Chlorella vulgaris*) as well as the mitigation of greenhouse gas emissions. The algae farms are expected to yield 47.38 million liters of bioethanol in 2024, with a peak production of 163.67 million liters in 2044, for $0.65 per liter. Their results also showed that bioethanol mitigated CO_2 emissions significantly, and it reduces the pollution from gasoline-powered engines' exhaust. The flue gas from coal and natural gas electric power plants contains CO_2, which the Chlorella vulgaris bacteria convert into oxygen [67].

In another study, *Chlorella vulgaris* (FWM-CV) was used by Al-lwayzy and friends to conduct lab-scale research on freshwater microalgae as a source of biofuels for diesel engines. They also investigated the impact of growth circumstances on the characteristics of the biodiesel made from FWM-CV. It was observed that the physical properties of FWM-CV biodiesel and conventional diesel are almost the same. As compared to the cottonseed biodiesel (CS-E20), an increase in engine power by 8.93% and fuel properties of the CS-ME20 after the addition of FWM-CV were observed [68].

Chlorella vulgaris was used again in a different study by Thirugnanasambantham and others to assess the *Chlorella vulgaris* sp. microalgae as a possible source material to produce biodiesel [69]. In their study, they also identified the biodiesel production strains of microalgae.

Chlorella vulgaris is found to have immense potential to produce biodiesel based on biomass yield and quality of lipid production. They suggested that when selecting algal biomass as feedstock for lipid-based algal biofuel, the biomass yield, lipid material, and its fatty acid structure must be considered for the choice of a specific microalgae strain.

4. Challenges and Sustainability

The use of biomass in the energy field is growing worldwide. However, climate change, an increase in environmental restrictions, and widespread extinction of plant and animal species are putting biomass sources at risk [70]. Despite several biomass applications, the amount of biomass generated is insufficient to support its varied uses. Furthermore, low conversion efficiencies and logistic restraints result in high production costs, making it uneconomical to generate energy from biomass [71].

Several difficulties contribute to these challenges. For instance, high moisture content in biomass, low bulk density, and insufficient time for field preparation for the next crop hinder effective biomass utilization [72]. Moreover, the collection process of animal waste can be challenging during rainfall and grazing periods, as the waste to be collected may vary [73]. Adding to these complications, the collection, transportation, and storage of biomass feedstocks present logistical challenges, as they can be costly and energy-intensive, especially in remote or rural areas [28]. Consequently, the development of biomass conversion plants and supply chains requires significant initial investment, demanding effective economic management and economic incentives [28].

In addition to logistical constraints, technological advancements are necessary to optimize conversion processes, such as thermochemical and biochemical methods, for various biomass types, since their efficiencies vary [6].

Economic factors also pose significant challenges. Presently, the main drawback of biomass energy is its lack of economic competitiveness when compared to petroleum [74]. To address this issue, the marketability of biomass goods and environmental certification will highlight their economic significance, establish a biomass product supply chain that can easily sustain production, and enhance consumer perception of biofuel products [5,75]. Furthermore, it is possible to combine biofuel generation with the treatment of CO_2-rich flue gas and nitrogen-rich municipal wastewater to make this process profitable and sustainable [76].

Beyond economic and technological issues, human capital presents another obstacle. One of the fundamental issues facing the renewable energy industry is the lack of knowledge and specialized skills among professionals. Due to significant differences from conventional systems, current experts frequently lack the qualifications required for renewable technology. Therefore, specialized degrees and focused training programs are needed to bridge this gap, as integrated modules in conventional engineering courses can be insufficient [77]. Despite abundant resources, modern biomass technologies, such as gasifiers, anaerobic digesters, and pelletizers, remain underutilized due to their excessive costs, limited technical expertise, and restricted local manufacturing capacity. Investments in local production, skills development, and supportive policies are essential to overcome these challenges [78].

Finally, a major challenge to the sustainable use of biomass energy lies in the widespread use of low-thermal-efficiency, typical wood-burning cookstoves. These inefficient systems emit substantial amounts of particulate matter and carbon monoxide, posing significant health and environmental problems associated with traditional biomass technologies. As a result, they contribute notably to indoor air pollution and deforestation [79].

5. Prospects

5.1. Biomass Sustainability

Plant-based biomass energy is vulnerable to depletion if it is not extracted and used sustainably. Restoring plant cover is therefore essential. Energy trees and crops should be encouraged to be grown on farms, not just in rural areas, but also in towns and cities [80].

To encourage sustainability and reduce reliance on fossil fuels, policymakers ought to give renewable energy sources like wind and solar top priority. The promotion of conservation techniques, increasing public awareness, and improving energy efficiency constitute key approaches. To promote cleaner technologies and a low-carbon transition, it is urged that carbon pricing mechanisms, such as taxes or emissions trading, be put in place to lower CO_2 emissions. Furthermore, economic planning should incorporate sustainable development to ensure fair, environmentally friendly advancement and align growth with climate goals [81].

5.2. Community Engagement and Empowerment

Communities and local stakeholders should be given opportunities to participate in supply chain activities and be actively involved in the design of business models and decision-making processes. Based on the viewpoint of significant participants and beneficiaries, this inclusive approach makes it easier to share experiences and knowledge [82].

Capacity-building initiatives, such as training for local staff, business owners, and end users, as well as awareness campaigns that promote adoption and change public opinion, are necessary to support the deployment of bioenergy technologies [83].

Through efficient dissemination, institutional coordination, and stakeholder engagement, governments should enable the implementation of bioenergy projects by giving farmers, investors, lenders, planners, forest owners, and local communities access to information and resources, including business models and financing options [84].

5.3. Research and Innovation

To improve the efficiency, affordability, and adaptability of biomass conversion technologies, research has lately focused on combined pretreatment methods that tackle the high energy requirements and environmental challenges of conventional single-step processes. Torrefaction and densification are two major feedstock processing developments in this area. Torrefaction improves energy density, water resistance, and storage stability by removing moisture and volatile chemicals. The processed biomass is then compressed into dense, uniform pellets through pelletization, which enhances handling, transportation safety, and combustibility. Thus, the sustainability and economic viability of biomass supply chains are improved by these processes [34,85–87].

5.4. Collaboration and Partnerships

To develop biomass value chains that improve energy access and promote the goals of the circular economy, various countries are now working together. For example, the EU promotes the development of biomass through public-private partnerships like the Circular Bio-based Europe Joint Undertaking (CBE JU) and the Bio-based Industries Joint Undertaking (BBI JU), which link industry, research institutions, policymakers, and primary producers to ensure sustainable sourcing and scaling of bio-based innovations [88].

In Kenya, Eni Kenya secured support from the Italian Climate Fund and the International Finance Corporation (IFC) to establish advanced biofuel and agri-processing facilities. This will connect smallholder oilseed producers, industry, and finance to improve feedstock supply chains and increase rural incomes (IFC press release, 2024).

Moving forward, initiative-taking efforts should be made to expand cooperation with current regional climate mitigation initiatives and take advantage of opportunities under the Sustainable Energy for All initiative. Furthermore, both new and existing regional frameworks for trade and investment cooperation can help improve access to energy [89].

Promoting regional alliances and international trade is a key strategy for developing bioenergy. Efficiency and scalability can be increased by standardizing bioenergy rules and exchanging best practices. This kind of cooperation promotes a sustainable regional bioenergy market and improves technological transfer in [90].

6. Conclusions

Shifting from a linear to a circular economy is crucial to solving the challenges caused by environmental degradation and dependency on fossil fuels. In this mini-review, biomass resources, including forestry, animal, microalgae, and agricultural wastes, have demonstrated a wide range of potential as renewable energy sources. Global studies provide evidence of the advantages of biomass energy, including lower greenhouse gas emissions, economic feasibility, and environmental sustainability. However, overcoming logistical, technological, and financial obstacles is necessary to realize the potential of biomass-based energy systems. The establishment of sustainable biomass supply chains and the development of these technologies depend significantly on public-private collaborations, governmental laws, and research funding. With sustained innovation and the involvement of stakeholders, biomass has the potential to transform the development of a resilient, low-carbon, and circular economy. Furthermore, integrating biomass with other renewable energy sources, like solar and geothermal sources, and coordinating its application with more general objectives in energy legal services, rural development, and climate action are also essential for future advancement. In the long term, biomass could be presented as an essential component of its long-term sustainability and renewable energy potential through a comprehensive and inclusive approach.

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Conflicts of Interest

The authors declare no conflict of interest.

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