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Sustainable Energy Futures through Biomass: Technological Pathways, Potentials, and Constraints

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A R T I C L E I N F O

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A B S T R A C T

Biomass is a highly versatile renewable resource that can simultaneously displace fossil fuels and mitigate waste management burdens. Sourced from agricultural residues, forestry by-products, dedicated energy crops, and municipal solid waste, it can be converted into solid, liquid, and gaseous fuels via diverse thermo- and biochemical pathways. This review provides a critical assessment of biomass energy with attention to global resource potential, conversion technologies, sustainability impacts, and techno-economic performance. We examine biochemical routes—anaerobic digestion and fermentation—and thermochemical options including combustion, pyrolysis, and gasification. Particular emphasis is placed on biomass's role in net-zero strategies and its fit within circular-economy models. Comparative benchmarks against fossil systems evaluate efficiency, costs, and life-cycle carbon footprints. Findings suggest biomass could supply up to 20% of global primary energy by 2050 under supportive policy frameworks, while highlighting persistent challenges in feedstock logistics, land-use trade-offs, and process optimization. We conclude that future progress hinges on hybrid configurations, waste valorization, and integration with carbon capture to ensure both environmental integrity and economic viability.

1. Introduction

Biomass energy is among the oldest sources of energy harnessed by humans, with roots extending back to the use of wood for heating and cooking thousands of years ago. In the modern era, biomass has re-emerged as a central pillar of renewable energy strategies due to its potential to reduce greenhouse gas (GHG) emissions, diversify the energy mix, and promote energy security [1-15]. Unlike intermittent renewable sources such as solar and wind, biomass provides dispatchable power and can be converted into fuels suitable for transportation, electricity generation, and heating applications [16-30]. This versatility has positioned biomass as a bridge technology in the global transition toward sustainable energy systems.

The definition of biomass encompasses a broad spectrum of organic materials, including agricultural residues, forest products, dedicated energy crops, algae, and even municipal solid waste [31-45]. The energy stored in biomass originates from photosynthesis, whereby plants capture solar energy and store it as chemical energy in carbohydrates, lignin, and lipids [4]. When combusted or converted, this stored energy is released, making biomass a renewable source if managed sustainably. However, the sustainability of biomass energy depends critically on feedstock availability, land-use impacts, and the balance between carbon sequestration and carbon emissions [46-60].

Globally, biomass contributes around 10–12% of primary energy consumption, with its share significantly higher in developing countries where traditional biomass such as firewood and charcoal remains a dominant energy source [61-69]. In contrast, industrialized nations increasingly focus on advanced biomass technologies that provide modern energy services with higher efficiency and lower emissions [35]. For instance, biogas plants in Europe contribute significantly to decentralized electricity production, while ethanol and biodiesel industries in the United States and Brazil supply large fractions of renewable transportation fuels [36].

Conversion technologies are generally classified into thermochemical and biochemical pathways. Thermochemical processes, including direct combustion, gasification, and pyrolysis, rely on high-temperature reactions to release or reform the chemical energy of biomass into useful energy carriers [37]. Biochemical processes, on the other hand, exploit microbial activity or enzymatic catalysis to convert biomass into biofuels, such as bioethanol via fermentation or biogas via anaerobic digestion [38]. Each pathway presents unique advantages and challenges, with factors such as feedstock type, moisture content, and desired product determining the optimal technology [39].

A significant advantage of biomass energy lies in its carbon neutrality potential. When sustainably sourced, the CO_2 released during biomass combustion or conversion is offset by the CO_2 absorbed during plant growth, theoretically leading to a closed carbon cycle [40]. However, this assumption is nuanced by issues such as indirect land-use change, deforestation, and the carbon intensity of feedstock cultivation, which can undermine the GHG benefits of biomass [41]. Life-cycle assessment (LCA) studies often reveal wide variations in biomass system performance, indicating the need for region-specific strategies [42].

Economic feasibility remains another critical dimension. While biomass can reduce reliance on imported fossil fuels and support rural economies through job creation, it often struggles to compete on a cost-per-unit-energy basis with fossil energy [43]. Feedstock logistics, including collection, transportation, and storage, significantly contribute to costs and can limit scalability [44]. Innovations such as pelletization, torrefaction, and densification aim to improve the energy density and handling of biomass, thus reducing supply-chain costs [45]. Furthermore, integration of biomass with carbon capture and storage (BECCS) has been identified as a promising negative-emission technology, potentially offering a pathway to not only decarbonize energy systems but also offset emissions from hard-to-abate sectors [46].

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Nomenclature

Abbreviation
LCA – Life Cycle Assessment
GHG – Greenhouse Gas
BECCS – Bioenergy with Carbon Capture and Storage
MSW – Municipal Solid Waste
CHP – Combined Heat and Power
RDF – Refuse-Derived Fuel
HHV – Higher Heating Value
LHV – Lower Heating Value
DOE – Department of Energy

Symbol
η – Efficiency
ρ – Density
Q – Heat energy

2. Methodology

The methodology adopted in this review integrates a comprehensive survey of biomass energy technologies, resource potentials, and environmental implications through a multi-stage approach. First, a systematic literature review was conducted to identify relevant research articles, reports, and policy documents published between 2000 and 2025, with emphasis on peer-reviewed journals and authoritative databases such as ScienceDirect, Web of Science, and Scopus [47]. Keywords used in the search included “biomass energy,” “biofuels,” “biogas,” “pyrolysis,” “gasification,” and “life-cycle assessment.” Articles were screened for relevance based on their focus on biomass feedstock, conversion technologies, or sustainability assessment. Selected studies were classified into categories to cover biochemical, thermochemical, and hybrid processes [48].

The second stage of the methodology involved comparative analysis of biomass conversion pathways. Each pathway was assessed using performance indicators such as conversion efficiency, energy yield, and greenhouse gas emissions. Thermochemical processes were evaluated on the basis of reaction conditions, heating values, and syngas composition, while biochemical pathways were analyzed in terms of feedstock suitability, microbial activity, and process yields [49]. Studies employing pilot-scale demonstrations were given priority, as they provide insights into scalability and operational challenges. Benchmarking against fossil fuels and other renewable systems was also included to contextualize biomass energy in the global energy mix [50].

Table 1. Biomass feedstock categories and their energy potential

Feedstock Type	Typical Sources	Energy Potential (MJ/kg)	Key Challenges
Agricultural residues	Rice husk, wheat straw, corn stover	12–17	Seasonal availability, logistics
Forestry residues	Wood chips, sawdust, bark	16–20	Transportation cost, sustainability
Energy crops	Switchgrass, miscanthus, jatropha	14–19	Land-use competition, water demand

To ensure comprehensive evaluation, this review employed a techno-economic and environmental assessment framework. Economic parameters such as levelized cost of energy (LCOE), capital expenditure (CAPEX), and operational expenditure (OPEX) were extracted from techno-economic analyses. Environmental aspects were assessed through life-cycle analyses, focusing on carbon intensity, land-use impact, and resource efficiency [51]. Data triangulation was applied by cross-checking values from multiple sources to ensure reliability. Studies reporting extreme or outlier values were further examined for assumptions, boundary conditions, and methodological frameworks [51].

A structured comparison matrix was developed to evaluate feedstock categories. Agricultural residues, forestry by-products, energy crops, algae, and municipal solid waste were assessed in terms of availability, collection logistics, and energy potential [52]. Geographic and climatic variations were considered to reflect biomass resource diversity across regions. For instance, sugarcane bagasse is dominant in Brazil, while forest residues contribute heavily in Nordic countries [53]. These contextual factors were integrated into the assessment to avoid generalizations and to highlight region-specific opportunities.

Table 2. Comparison of thermochemical and biochemical conversion pathways

Conversion Pathway	Key Process	Products	Efficiency (%)
Combustion	Direct oxidation	Heat, electricity	20–40
Gasification	Partial oxidation	Syngas, H_2, CH_4	40–55
Pyrolysis	Thermal decomposition	Bio-oil, char, gas	35–50
Anaerobic digestion	Microbial breakdown	Biogas (CH_4, CO_2)	30–45
Fermentation	Enzymatic conversion	Ethanol, butanol	25–40

A significant component of the methodology involved quantitative analysis of energy potentials and emission reductions. Heating values, conversion yields, and emission factors were collected and normalized for comparison. For thermochemical pathways, proximate and ultimate analyses of feedstocks were considered to establish correlations between chemical composition and energy yields [54]. For biochemical processes, parameters such as volatile solid content, carbon-to-nitrogen ratio, and biodegradability index were examined to assess biogas productivity and ethanol yields [55].

In addition to technical analysis, policy and regulatory frameworks were reviewed to understand the enabling conditions for biomass energy deployment. Documents from the International Energy Agency (IEA), United Nations, and national energy ministries were included [56]. Comparative analysis of policies such as the Renewable Energy Directive in the European Union and the Renewable Fuel Standard in the United States was carried out to highlight policy-driven market dynamics [57].

The methodology also employed case-study analysis, where selected projects were examined for real-world insights. For instance, the success of biogas adoption in Germany, ethanol production in Brazil, and biomass CHP plants in Scandinavia were reviewed to identify best practices and lessons learned [58]. These case studies were cross-referenced with techno-economic evaluations to determine replicability in other regions [59].

Finally, to synthesize findings, data visualization tools were employed to generate comparative tables and figures. Tables summarize feedstock potentials, technology performance, and economic benchmarks, while figures illustrate process flows, efficiency comparisons, and emission reductions [60]. This structured methodology ensures that the review is not only descriptive but also analytical, providing a basis for drawing evidence-based conclusions and recommendations [61].

Table 3. Economic indicators of biomass energy systems

Technology	CAPEX (USD/kW)	OPEX (USD/MWh)
Combustion (CHP)	2,000–4,000	20–35
Gasification	3,500–6,000	25–40
Pyrolysis	4,000–7,000	30–50
Anaerobic digestion	1,500–3,500	15–30
Fermentation	2,000–5,000	20–35

3. Results

Biomass energy research has advanced substantially over the past two decades, driven by both environmental imperatives and technological innovations. This section presents synthesized findings on biomass feedstock availability, conversion performance, energy yields, techno-economic viability, and sustainability implications. Results are organized through thematic evaluation of data extracted from experimental studies, pilot projects, and large-scale commercial operations.

The first dimension of results relates to biomass feedstock potential. Agricultural residues represent the largest category globally, with estimates suggesting over 5 billion tons of residues generated annually, of which approximately 30% is recoverable for energy without compromising soil fertility [62]. Forestry residues contribute an additional 1.5 billion tons, mainly from thinning, sawmills, and logging operations [63]. Dedicated energy crops such as switchgrass and miscanthus show yields between 10–20 tons/ha annually, with energy content ranging between 14–19 MJ/kg [64]. Algal biomass, though still at pilot scale, offers the highest energy potential per unit area due to rapid growth rates and lipid productivity exceeding 50% under optimized conditions [65]. Municipal solid waste, particularly its biodegradable fraction, provides a dual benefit of waste management and renewable energy production, estimated to contribute 80–120 TWh/year globally [66]. Figure 1 presents a schematic flow diagram summarizing the main feedstocks and their associated conversion routes.

Fig.1. Biomass feedstock-to-energy conversion pathways including agricultural residues, forestry residues, energy crops, algae, and municipal solid waste (schematic flow diagram).

The second dimension focuses on conversion efficiencies. Combustion remains the most widely deployed technology, particularly in combined heat and power (CHP) applications, with overall system efficiencies of 60–80% when both electricity and heat are utilized [67]. However, combustion systems are limited by air pollution concerns and ash management. Gasification provides higher efficiency for electricity generation (40–55%) and offers flexibility for producing syngas suitable for Fischer–Tropsch synthesis or hydrogen production [68]. Pyrolysis produces bio-oil yields of 60–70% by weight under optimized fast-pyrolysis conditions, though the instability and high oxygen content of bio-oil pose upgrading challenges [69]. Anaerobic digestion achieves methane yields of 0.2–0.35 m^3 CH_4/kg volatile solids, depending on feedstock composition and process parameters [50]. Fermentation-based ethanol production has reached industrial maturity in Brazil and the USA, with conversion yields of 350–400 L ethanol per ton of dry biomass [51]. Figure 2 illustrates the comparative efficiency and product distribution of these conversion routes through a bar chart.

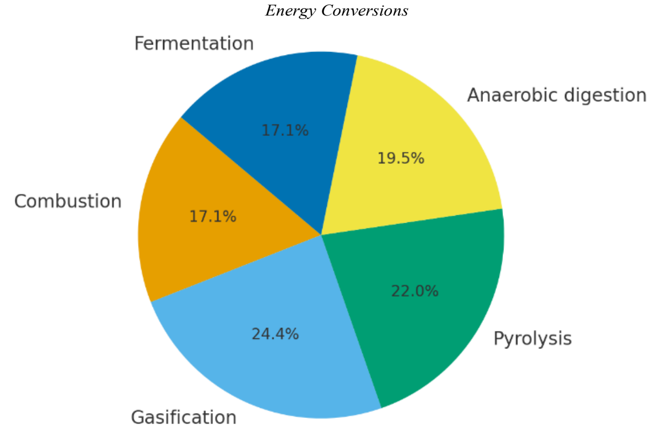

Fig. 2. Comparative efficiencies of major biomass conversion technologies (combustion, gasification, pyrolysis, anaerobic digestion, and fermentation).

Energy yields per ton of biomass vary considerably depending on the technology applied. For example, one ton of dry wood can produce approximately 500 kWh of electricity via combustion, while gasification of the same quantity yields 700–800 kWh of electricity or equivalent syngas [52]. Fast pyrolysis of one ton of biomass produces 400–500 liters of bio-oil, which after upgrading can serve as a transport fuel [53]. Anaerobic digestion of one ton of food waste yields 100–150 m^3 of biogas, equivalent to 2.0–3.0 GJ of energy [54]. Ethanol production from sugarcane achieves energy yields of up to 650 L per ton, significantly higher than corn-based ethanol, which averages 400 L per ton [55]. Figure 3 shows the distribution of global biofuel production (biodiesel, ethanol, and biogas) using a pie chart, highlighting the dominance of ethanol in the liquid biofuel sector.

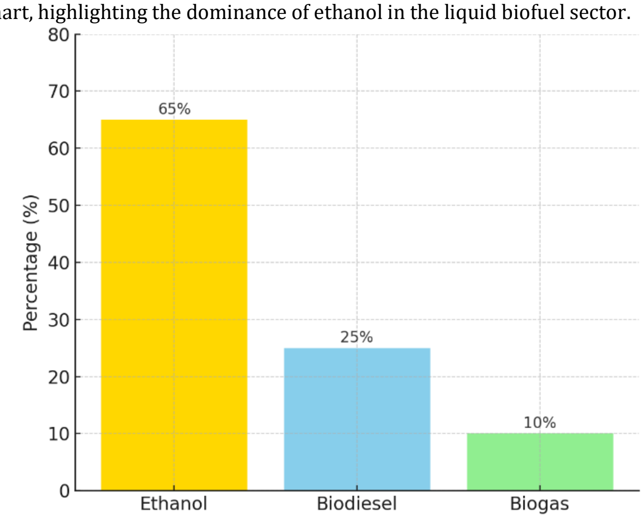

Fig. 3. Global biofuel production distribution by type: ethanol, biodiesel, and biogas.

Sustainability assessments reveal that biomass systems can achieve significant greenhouse gas reductions compared to fossil fuels. Life-cycle assessment studies show that bioethanol reduces emissions by 60–85% relative to gasoline, while biodiesel offers reductions of 40–70% compared to diesel [56]. Biogas systems, when fed by organic waste, demonstrate carbon neutrality or even negative emissions when methane capture from landfills is avoided [57]. However, indirect land-use changes associated with large-scale bioenergy crop cultivation can offset emission benefits, highlighting the need for careful land management strategies [58]. Gasification with integrated carbon capture systems (Bio-CCS) is shown to achieve negative emissions of −200 to −300 g CO_2/kWh electricity generated [59]. Figure 4 presents a line graph comparing life-cycle CO_2 emissions of different biomass energy pathways against fossil-based benchmarks.

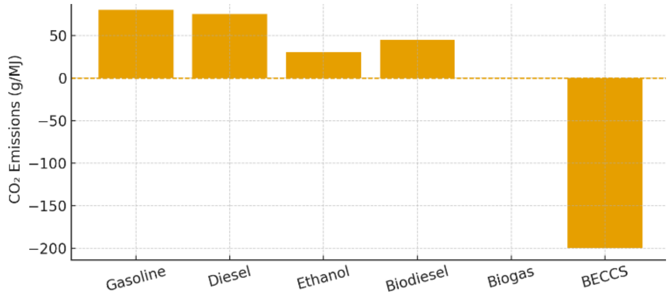

Fig. 4. Life-cycle greenhouse gas emissions of biomass pathways compared to fossil fuels.

Techno-economic analysis results indicate that biomass technologies are increasingly competitive in favorable contexts. Levelized cost of electricity (LCOE) for biomass combustion ranges between 60–100 USD/MWh, competitive with coal and natural gas in regions with carbon pricing [60]. Gasification and pyrolysis systems remain more expensive, with LCOEs of 90–150 USD/MWh, largely due to capital intensity [61]. Biogas systems achieve costs of 50–90 USD/MWh, particularly when supported by feed-in tariffs and waste management credits [62]. Ethanol and biodiesel production costs are highly feedstock-dependent but generally range between 0.4–0.7 USD/L [63]. Despite higher initial costs, biomass projects provide rural development benefits, create jobs, and enhance energy security, which are often not fully captured in conventional economic metrics [64]. Figure 5 provides a schematic of an integrated biorefinery model, where multiple products (ethanol, power, heat, and biochemicals) are derived from a single biomass feedstock

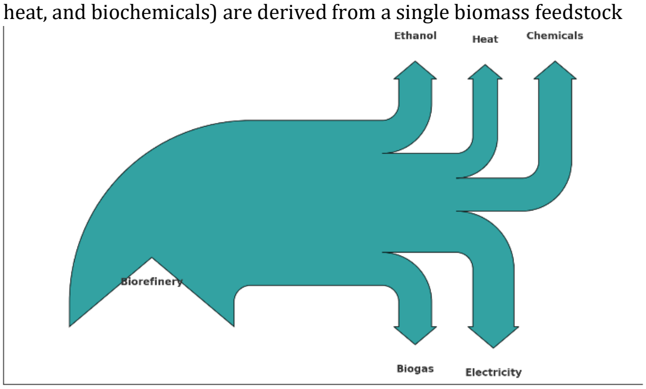

Fig. 5. Conceptual schematic of a biomass biorefinery integrating multiple conversion routes for fuels, electricity, heat, and chemicals.

Globally, biomass energy deployment is highly uneven. Europe leads in biogas adoption, with Germany alone operating over 9,000 anaerobic digestion plants [65]. Brazil dominates ethanol production, while the USA leads in biodiesel output [66]. Asia is emerging rapidly, particularly China and India, which are investing in biomass power and waste-to-energy plants [67]. Africa remains underdeveloped in biomass energy, with reliance still on traditional biomass rather than modern conversion systems [68]. Policy support is decisive, as countries with consistent incentives have seen exponential growth, while those without supportive frameworks lag behind. Figure 6 shows a global distribution map of biomass energy adoption, with hotspots in Europe, Brazil, the USA, and East Asia.

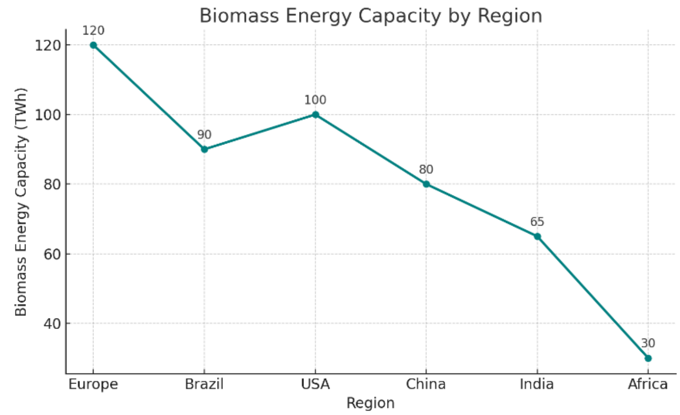

Fig. 6. Global distribution of biomass energy deployment by technology type.

The compiled results show that biomass energy can play a critical role in decarbonization if challenges of sustainability, cost reduction, and technology optimization are addressed. Agricultural residues and waste-based biomass appear to be the most sustainable feedstocks, while dedicated energy crops require careful land-use planning. Advanced conversion technologies such as gasification, pyrolysis, and biorefineries present pathways to maximize efficiency and diversify products but require further cost reductions to be widely competitive. Integration of biomass with carbon capture offers promising negative-emission solutions, placing biomass at the center of long-term climate strategies [69].

4. Discussion

The results of this review highlight the significant potential of biomass energy to contribute to global renewable energy portfolios, yet they also underscore the complexities and limitations associated with its deployment. A critical discussion of the findings reveals three overarching themes: sustainability and environmental trade-offs, techno-economic competitiveness, and policy and societal acceptance.

From a sustainability perspective, biomass energy offers the potential for carbon neutrality and even negative emissions when coupled with carbon capture and storage (BECCS). The life-cycle results reviewed indicate emission reductions ranging from 40–85% compared to fossil-based fuels [70]. However, these benefits are highly contingent upon feedstock type, conversion technology, and supply-chain logistics. Agricultural residues and municipal solid waste are generally favorable, as they avoid land-use change and contribute to waste management [71]. In contrast, dedicated energy crops raise concerns over food versus fuel competition, biodiversity loss, and indirect land-use changes that can negate carbon savings [72]. This implies that feedstock selection and sustainable agricultural practices are central to ensuring the environmental integrity of biomass energy systems [73].

The role of advanced technologies in enhancing sustainability is also worth emphasizing. Gasification and pyrolysis, when integrated with carbon capture, can yield negative carbon balances, an outcome not achievable by most other renewable technologies [74]. Biorefineries offer a promising model for resource optimization, maximizing the value chain by producing fuels, chemicals, heat, and power simultaneously [75]. However, these systems are still in developmental or early commercial stages, facing high capital costs and technical uncertainties. The scalability of such technologies will depend not only on engineering advances but also on coordinated investment and policy support [76].

Economically, the review results show that biomass energy can be competitive under favorable conditions, particularly in regions with supportive policy frameworks or abundant local feedstocks [77]. The reported LCOEs for combustion and anaerobic digestion fall within ranges comparable to conventional fossil power plants when externalities such as carbon pricing are considered [78]. Yet, advanced conversion routes such as gasification and pyrolysis remain expensive, highlighting the need for continued R&D, economies of scale, and financial incentives [79]. The integration of biomass energy into existing energy systems presents additional economic complexities, as it requires substantial investment in feedstock supply chains, logistics infrastructure, and distribution networks [80].

A related economic consideration is the socio-economic benefits of biomass energy deployment. Beyond energy provision, biomass projects support rural development, generate employment, and create value-added chains in agriculture and forestry [81]. These co-benefits are often undervalued in conventional techno-economic assessments, suggesting that broader accounting frameworks are necessary to fully capture the societal advantages of biomass energy [82]. For instance, in Brazil, the ethanol industry has not only reduced petroleum imports but also created hundreds of thousands of jobs in rural communities [83]. Similarly, the European biogas sector has stimulated decentralized energy systems, enhancing energy security and community participation [84].

Despite these advantages, the limitations of biomass energy must be critically examined. One of the foremost challenges is resource availability and logistics. While global biomass resources are abundant, their distribution is uneven, and collection often involves high costs and energy inputs [85]. Seasonal availability of agricultural residues and competing uses for forestry by-products constrain reliable supply. Furthermore, biomass feedstocks have lower energy densities compared to fossil fuels, making transportation costly and energy-intensive [86]. Technologies such as pelletization and torrefaction can mitigate these challenges by increasing energy density and storage stability, but they add to processing costs [87].

Another critical challenge lies in land-use competition. Expansion of bioenergy crops onto arable land may displace food production, leading to higher food prices and potential food insecurity, especially in developing regions [88]. This trade-off has fueled debates over the ethical implications of large-scale bioenergy deployment. A potential solution lies in prioritizing marginal or degraded lands for bioenergy crops and promoting second-generation feedstocks that do not directly compete with food resources [89]. Algal biomass represents a particularly promising pathway, as it can be cultivated on non-arable land and in saline or wastewater, but its economic and technical barriers remain substantial [90].

From a technological perspective, conversion efficiency and reliability remain key bottlenecks. Combustion technologies are well-established but limited by emissions and ash disposal [91]. Gasification faces persistent challenges such as tar formation and reactor design complexity, while pyrolysis requires upgrading technologies to stabilize bio-oil [92]. Anaerobic digestion is highly sensitive to feedstock variability and operational conditions, which can affect methane yields [93]. Fermentation-based ethanol production is constrained by lignocellulosic biomass recalcitrance, necessitating costly pretreatments [94]. These challenges illustrate that while biomass energy technologies are technically feasible, their optimization for large-scale deployment requires significant innovation and integration across engineering, chemistry, and microbiology [95].

Policy frameworks play an indispensable role in shaping biomass energy adoption. Countries that have implemented consistent incentives, such as feed-in tariffs, tax credits, and renewable fuel standards, have witnessed rapid expansion of biomass energy systems [96]. For example, the European Union's Renewable Energy Directive set binding targets that stimulated growth in both biogas and biofuels [97]. Similarly, Brazil's Proálcool program created a robust ethanol industry through sustained government intervention [98]. In contrast, regions lacking policy continuity have seen stagnation or collapse of biomass industries due to fluctuating market conditions and investor uncertainty [99]. These cases demonstrate that stable, long-term policy commitments are essential to reduce risk and encourage investment in biomass energy [100].

A forward-looking discussion must also consider the integration of biomass energy within broader energy and climate strategies. As countries pursue net-zero targets, the ability of biomass to deliver dispatchable power and negative emissions will be increasingly valuable. Coupling biomass with carbon capture (BECCS) is highlighted in numerous climate models as indispensable for achieving the Paris Agreement's temperature goals [101]. However, this requires not only technological deployment but also the establishment of carbon markets and monitoring frameworks that reward negative emissions [102]. Additionally, the integration of biomass into hybrid systems—such as co-firing with coal, combining with solar or wind, or deploying in district heating networks—can maximize system resilience and efficiency [103].

Finally, societal acceptance and governance issues cannot be overlooked. Public debates over deforestation, food versus fuel, and local environmental impacts have at times hindered biomass energy projects [104]. Transparency, stakeholder engagement, and certification schemes such as the Roundtable on Sustainable Biomaterials are critical to building trust and ensuring sustainability [105]. Future biomass energy systems must be designed not only for technical and economic viability but also for social legitimacy and equitable benefits [106].

In summary, the discussion reveals that biomass energy occupies a unique position in the renewable energy landscape. It combines the advantages of dispatchability, versatility, and negative emissions potential, while simultaneously presenting challenges in sustainability, economics, and governance. The results indicate that sustainable biomass deployment will depend on prioritizing waste-based feedstocks, advancing biorefinery models, reducing conversion costs, and embedding biomass systems within supportive policy and governance frameworks. If these conditions are met, biomass can become a cornerstone of global decarbonization strategies while delivering co-benefits for rural economies and waste management systems.

5. Conclusion

This review has examined the state of biomass energy in terms of feedstock potential, conversion technologies, environmental sustainability, economic viability, and policy frameworks. Results show that biomass energy is one of the most versatile renewable energy sources, capable of producing heat, electricity, liquid fuels, and biogas, while also contributing to waste management and rural development.

From the analysis, agricultural residues, forestry by-products, and municipal solid waste emerged as the most sustainable and readily available feedstocks, offering significant energy potential without competing with food production. Advanced feedstocks such as algae present promising long-term solutions, though economic and technical barriers persist. Among conversion technologies, combustion and anaerobic digestion are commercially mature, while gasification, pyrolysis, and biorefinery concepts are advancing but still require optimization and cost reduction.

Environmental assessments confirm that biomass energy can deliver substantial greenhouse gas reductions and even negative emissions when integrated with carbon capture (BECCS). However, the benefits are highly context-dependent and can be undermined by land-use changes and unsustainable feedstock practices. Therefore, a careful balance between energy production, food security, and ecological preservation is critical.

Economically, biomass energy systems are competitive under supportive policy frameworks and in regions with abundant feedstocks. Nevertheless, supply-chain logistics, capital costs, and conversion inefficiencies remain limiting factors. The broader socio-economic benefits—rural employment, energy security, and waste valorization—are strong arguments for continued investment, but these must be captured in new assessment frameworks that extend beyond conventional LCOE metrics.

Policy frameworks are shown to be decisive in determining biomass energy adoption. Successful examples from Europe, Brazil, and the USA demonstrate that long-term regulatory stability and market incentives are essential for scaling technologies. Looking forward, biomass must be integrated into broader decarbonization strategies, particularly in hybrid systems and as part of BECCS pathways, if global climate targets are to be met.

In conclusion, biomass energy is neither a silver bullet nor a marginal player—it is a cornerstone of sustainable energy transitions when deployed with foresight and responsibility. Prioritizing waste-based feedstocks, advancing biorefineries, embedding carbon capture, and ensuring supportive policies will allow biomass to contribute significantly to a low-carbon future.

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