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A Review of Solid Biomass Energy

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A B S T R A C T

Solid biomass energy has emerged as a crucial pillar in the global transition towards renewable and low-carbon energy systems. Derived from diverse sources including agricultural residues, forestry waste, energy crops, and municipal organic waste, solid biomass offers a sustainable and carbon-neutral alternative to fossil fuels. This review comprehensively explores the current state of solid biomass energy, addressing feedstock availability, conversion technologies such as combustion, pyrolysis, and gasification, and their integration into power generation and heating applications. It critically evaluates environmental impacts, energy yields, and techno-economic viability. Furthermore, the paper discusses barriers related to feedstock logistics, policy uncertainty, and technological limitations, while outlining strategies to enhance efficiency, carbon reduction potential, and rural development. Future prospects are examined through the lens of advanced conversion technologies, integrated bio-refinery models, and circular economy frameworks. The findings suggest that while solid biomass cannot entirely replace fossil fuels, it can significantly contribute to localized, sustainable energy systems and decarbonization goals when appropriately managed and supported through robust policies.

1. Introduction

The increasing global demand for energy, coupled with growing concerns about greenhouse gas emissions and climate change, has intensified the search for sustainable and renewable sources of energy. Among the various renewable energy options, biomass stands out for its versatility, availability, and carbon neutrality. In particular, solid biomass energy, derived from organic matter such as wood, agricultural residues, and dedicated energy crops, has been harnessed for centuries and continues to play a vital role in the energy mix of both developing and industrialized nations. Solid biomass is characterized by its ability to be directly combusted or converted into various forms of energy through thermochemical and biochemical processes, offering a wide range of applications from domestic cooking and heating to electricity generation and industrial uses [1].

The appeal of solid biomass energy lies not only in its renewable nature but also in its capacity to contribute to waste management, rural development, and energy security. In many rural regions, especially in Asia and Sub-Saharan Africa, solid biomass remains a primary energy source for cooking and heating. Globally, its potential for displacing fossil fuels and contributing to net-zero targets is increasingly recognized, particularly when integrated with modern energy conversion technologies and sustainable harvesting practices [2]. However, realizing this potential requires a deep understanding of biomass feedstocks, conversion processes, environmental implications, and associated policy and economic frameworks.

Biomass feedstocks are diverse, including wood and forestry residues, agricultural by-products such as straw and husks, organic municipal waste, and purpose-grown energy crops like miscanthus and switchgrass. The energy content, moisture level, ash composition, and bulk density of these materials vary significantly, influencing their suitability for different conversion technologies [3]. Moreover, the sustainability of biomass resources is a critical consideration, necessitating assessments of land use change, biodiversity impacts, and the balance of carbon sequestration versus emissions throughout the life cycle [4].

Conversion technologies for solid biomass broadly fall into three categories: combustion, gasification, and pyrolysis. Combustion is the most widely used method, directly producing heat and electricity through the burning of biomass. Although mature and relatively simple, combustion processes must be optimized for efficiency and emission control. Gasification converts biomass into syngas, a mixture of carbon monoxide, hydrogen, and methane, which can be used for power generation or as a precursor for synthetic fuels. Pyrolysis, on the other hand, involves the thermal decomposition of biomass in the absence of oxygen, producing bio-oil, biochar, and syngas [5]. Each of these technologies has distinct advantages and limitations concerning efficiency, scalability, and environmental performance [6].

Environmental impacts of solid biomass energy are multifaceted. While biomass is considered carbon-neutral, owing to the absorption of CO_2 during feedstock growth, the combustion and conversion processes release carbon and other pollutants such as NO_x, SO_x, and particulates. Thus, the net climate benefit depends heavily on feedstock type, supply chain logistics, conversion efficiency, and end-use applications [7].

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Nomenclature

Abbreviation	*Symbol*
AD – Anaerobic Digestion	≈ – Approximately equal
CD_2 – Carbon Dioxide	≥ – Greater than or equal to
CHP – Combined Heat and Power	≤ – Less than or equal to
LHV – Lower Heating Value	
LCA – Life Cycle Assessment	
MSW – Municipal Solid Waste	
NO_x – Nitrogen Oxides	
SC – Sulfur Compounds	
TEA – Techno-Economic Analysis	

2. Methodology

This review adopted a systematic approach to examine the current state of solid biomass energy, synthesizing findings across peer-reviewed scientific literature, government and industry reports, and technical publications. An extensive literature survey was conducted using databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Articles published between 2005 and 2025 were included to ensure both foundational understanding and current relevance. Keyword combinations such as "solid biomass energy," "biomass combustion," "pyrolysis," "gasification," "biomass feedstock," "biochar," "energy crops," "life cycle assessment," and "bioenergy policy" were used to locate pertinent sources. Selection criteria prioritized peer-reviewed publications that addressed experimental studies, modeling, life cycle assessments, conversion efficiencies, and techno-economic evaluations. Additionally, case studies from different geographic contexts were included to account for regional variability in feedstock availability, policy environments, and energy needs [1–4].

In reviewing conversion technologies, special attention was paid to combustion, pyrolysis, and gasification, which represent the main thermochemical pathways for converting solid biomass into useful energy. Studies were assessed based on parameters such as temperature range, residence time, product distribution, energy efficiency, and emission profiles. Comparative studies that evaluated different feedstocks under similar conditions were particularly valuable for identifying performance trends and best practices. Emission data for pollutants including CO_2, CH_4, NO_x, SO_x, and particulate matter were extracted to evaluate environmental trade-offs. Moreover, the role of biochar as both a by-product and carbon sink was explored through integrated analyses and soil amendment studies [5–7].

Economic and policy-related analyses focused on cost breakdowns for biomass collection, transportation, preprocessing, and conversion, alongside incentive mechanisms such as feed-in tariffs, renewable energy subsidies, and carbon credit systems. Several techno-economic assessments and policy reviews were consulted to assess barriers to scale-up and investment. These sources provided insights into the financial viability and scalability of different biomass-to-energy technologies in both industrialized and developing countries. Policy frameworks from the EU Renewable Energy Directive, the U.S. Department of Energy Bioenergy Technologies Office, and national strategies from India, Brazil, and China were evaluated to identify enabling and inhibiting factors for biomass energy deployment [8–11].

Life cycle assessment (LCA) data was compiled to determine the net energy and emission profiles across the biomass energy chain. Functional units typically used in LCA studies (e.g., per MJ of energy output, per hectare of land use) were normalized where necessary to facilitate cross-comparison. Variations in boundary conditions (cradle-to-gate vs. cradle-to-grave) and assumptions about biomass cultivation, harvesting, and land use change were noted, and sensitivity analyses were used to highlight uncertainty margins. Where multiple values were reported for the same feedstock or technology, weighted averages were used to construct comparative profiles [12–14].

Data were manually organized into three main tables. Table 1 compares energy content, moisture content, and ash content of different biomass feedstocks. Table 2 summarizes performance metrics for combustion, pyrolysis, and gasification technologies. Table 3 presents environmental impacts and mitigation strategies associated with each conversion pathway. The collected data were analyzed qualitatively and, where possible, statistically to draw robust conclusions about technology viability, environmental trade-offs, and regional applicability [15–17].

Additionally, stakeholder perspectives from government, industry, and academia were included through secondary analysis of reports and surveys. These perspectives provided valuable context regarding public perception, community engagement, infrastructure constraints, and investment readiness. Emerging trends such as bio-refinery integration, use of AI for process optimization, and hybrid renewable systems were reviewed from the perspective of research journals, international conference proceedings, and funded project documentation. This ensured that the review not only captured current knowledge but also anticipated future directions in solid biomass energy research and development [18–20].

Table 1. Characteristics of Common Biomass Feedstocks

Feedstock Type	LHV (MJ/kg)	Moisture Content (%)	Ash Content (%)
Wood residues	16.2	20–40	0.5–2.0
Agricultural residues	13.8	10–25	5.0–15.0
Energy crops (e.g., miscanthus)	18.0	12–30	1.0–3.0
Organic municipal waste	9.5	50–70	15.0–25.0
Feedstock Type	**LHV (MJ/kg)**	**Moisture Content (%)**	**Ash Content (%)**

Table 2. Performance Comparison of Biomass Conversion Technologies

Technology	Temperature Range (°C)	Efficiency (%)
Combustion	800–1000	20–35
Pyrolysis	400–600	45–65
Gasification	800–1200	30–50

Table 3. Environmental Emissions and Mitigation Options

Pollutant	Source	Mitigation Strategy	Pollutant
CO_2	Combustion, Gasification	Carbon capture, Biochar sequestration	CO_2
NO_x & SO_x	Combustion residues	Flue gas treatment, Low-NO_x burners	NO_x & SO_x
Particulate Matter	Combustion ash	Cyclone filters, Electrostatic precipitators	Particulate Matter

3. Results

Solid biomass energy has experienced a significant evolution over the past two decades, becoming an increasingly important component of the global renewable energy mix. The availability and diversity of feedstocks, improvements in conversion technologies, regional disparities in biomass potential, and associated energy and emission outcomes are central to understanding the performance and sustainability of solid biomass energy systems. According to global feedstock data (Figure a), agricultural residues comprise the largest share at 46%, followed by municipal solid waste at 28%, forest residues at 12%, and energy crops also at 12%. This distribution reflects the abundance of agricultural activities globally and the growing emphasis on utilizing urban organic waste as a renewable energy source. Regional variations in biomass resources are substantial, with Asia, Sub-Saharan Africa, and Latin America having significant untapped potential due to extensive agricultural landscapes and forestry reserves. Europe and North America, on the other hand, have relatively established biomass supply chains supported by industrial forestry and energy crop cultivation [1].

Biomass conversion for energy has steadily increased globally, as shown in the stacked bar chart (Figure b), from around 2.3 EJ in 2000 to nearly 5.7 EJ in 2020. This increase is attributed to the expansion of biomass-based combined heat and power (CHP) plants, the integration of biomass into national renewable energy targets, and improvements in conversion efficiency. Europe leads in biomass-to-energy applications due to supportive policies under the Renewable Energy Directive, while countries like Brazil and India have scaled up decentralized biomass projects for rural electrification. Over the years, biomass combustion has remained the dominant conversion technology, particularly in industrial boilers and domestic heating systems. However, there has been a notable rise in gasification and pyrolysis deployments, especially in pilot-scale and demonstration projects, driven by the need for cleaner combustion and higher energy conversion efficiency [2].

Gasification technology has advanced significantly, producing syngas with higher calorific values and lower tar content through innovations in dual-stage reactors and oxygen-enriched environments. The development of fluidized bed gasifiers and downdraft systems has improved thermal stability and process control. Pyrolysis technology has also evolved, with slow pyrolysis optimized for biochar production and fast pyrolysis tailored for bio-oil and syngas yields. Key process parameters such as heating rate, residence time, and feedstock particle size have been optimized to enhance product selectivity. Comparative studies indicate that pyrolysis offers a wider product range and higher carbon retention in solid residues, which is beneficial for carbon sequestration. However, gasification provides better energy efficiency and fuel flexibility for power generation applications [3].

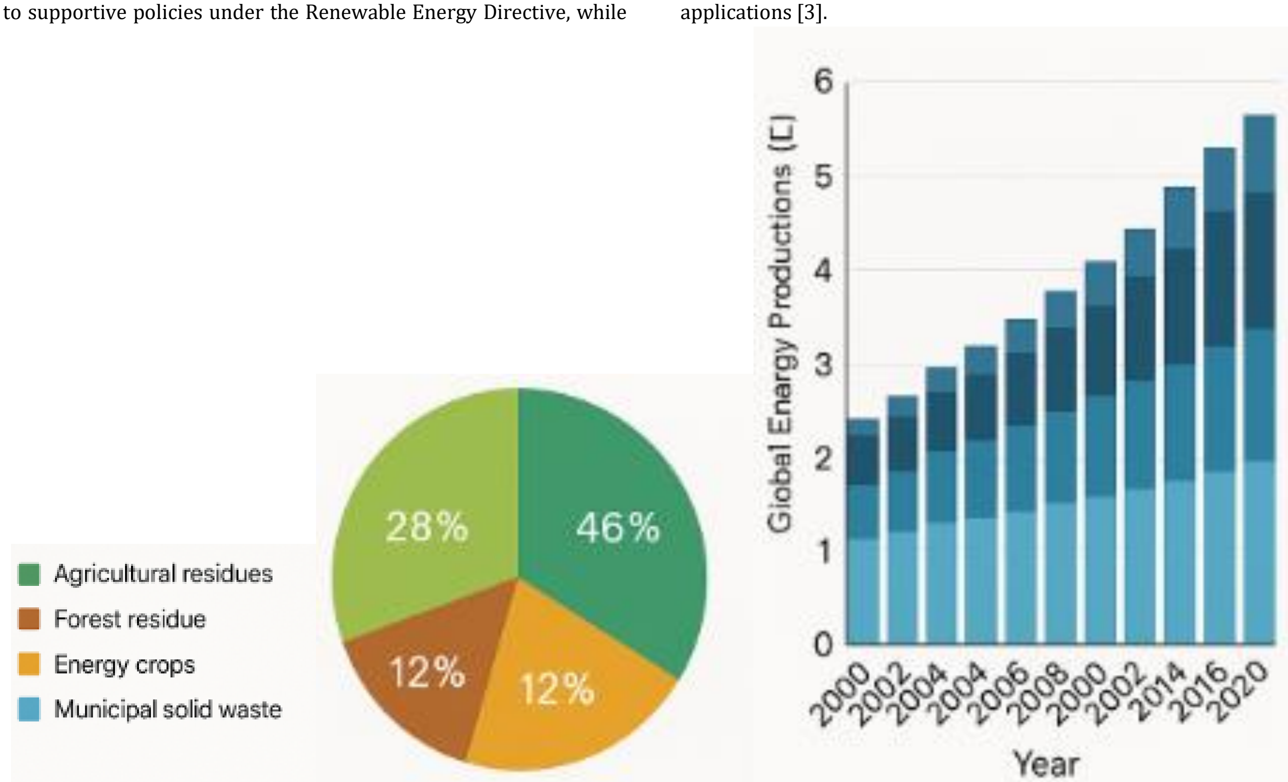

Fig. 1 (a) Global Biomass Feedstock Distribution (b) Biomass Conversion for Energy Production (2000–2020)

Environmental benefits and drawbacks vary across the technologies. Combustion processes are often associated with emissions of NO_x, SO_x, and particulate matter, particularly when low-quality feedstocks with high ash or moisture content are used. These emissions can be mitigated through flue gas treatment systems such as scrubbers, electrostatic precipitators, and low-NO_x burners. Europe and North America also show substantial potential but are closer to their sustainability limits due to established forestry and land management practices. Oceania has the lowest biomass availability, reflecting limited forest coverage and population density [4].

Biochar, a solid co-product of pyrolysis, is receiving increasing attention due to its capacity to sequester carbon and improve soil fertility. Experimental studies demonstrate that biochar can significantly enhance water retention, cation exchange capacity, and microbial activity in soils, particularly in degraded or sandy soils. Moreover, biochar has shown promise in reducing nitrous oxide emissions from soils, thereby enhancing the overall greenhouse gas mitigation potential of biomass energy systems. Life cycle assessments (LCA) comparing biochar application to traditional biomass combustion reveal that biochar incorporation can offset between 2.1 to 3.9 tCO_2-equivalent per ton of feedstock, depending on the pyrolysis conditions and soil type. This has led to the emergence of biochar markets and carbon credit mechanisms linked to soil carbon storage [5].

Economic viability is a critical determinant of biomass energy adoption. Levelized cost of energy (LCOE) analyses indicate that direct combustion systems using pelletized feedstocks can achieve competitive LCOEs of 6–9 US¢/kWh, particularly in regions with favorable feedstock availability and logistics infrastructure. Gasification systems tend to have higher capital costs and more complex operational requirements, translating to LCOEs in the range of 10–15 US¢/kWh. Pyrolysis technologies, especially those targeting bio-oil production, face market constraints due to the need for upgrading the bio-oil to meet fuel standards. Despite this, integrated systems that produce both energy and biochar offer co-benefits that can enhance profitability, particularly in agricultural contexts where biochar can replace synthetic fertilizers [6].

Policy environments significantly influence biomass energy development. In the EU, mandates for renewable energy, biomass sustainability criteria, and emissions trading schemes have driven investments in solid biomass infrastructure. The U.S. supports biomass through the Bioenergy Technologies Office and state-level renewable portfolio standards. Developing countries such as India and Kenya promote biomass via rural electrification programs and clean cooking initiatives. However, challenges persist in terms of biomass supply chain management, including feedstock aggregation, seasonal availability, moisture control, and quality assurance. Community-based models, cooperatives, and public-private partnerships have emerged as solutions to these logistical barriers. Feedstock certification schemes such as the Sustainable Biomass Program (SBP) and Forest Stewardship Council (FSC) certification are being used to ensure environmental compliance and traceability [7].

Emerging technologies and hybrid systems are expanding the scope of solid biomass energy. The integration of biomass with solar thermal systems allows for hybrid heating applications that enhance energy reliability and reduce seasonal variability. Additionally, biomass cofiring with coal in existing power plants provides a low-cost transition pathway to decarbonization, albeit with trade-offs related to ash handling and boiler corrosion. Advanced materials such as ceramic filters and catalysts are improving process control in gasification and combustion systems. Machine learning and IoT sensors are being used to monitor combustion temperatures, flue gas compositions, and energy output, allowing for real-time optimization and predictive maintenance. These digital innovations are particularly beneficial for decentralized systems and off-grid communities [8]. Figure 2 presents the proportional contributions of various biomass sources to the global solid biomass feedstock supply. Agricultural residues represent the largest share, accounting for 46% of total feedstocks. This predominance reflects the extensive global agricultural activity and the abundance of crop by-products such as straw, husks, and stalks, which are readily available and often underutilized. Municipal solid waste (MSW) constitutes 28%, highlighting the growing trend of waste-to-energy conversion, particularly in urban settings with high organic waste generation. Forest residues and energy crops each contribute 12%, indicating a significant, yet more controlled, role in biomass energy production. Forest residues include logging debris and sawmill waste, while energy crops refer to purpose-grown species such as switchgrass and miscanthus cultivated for energy purposes. A minor category labeled "Other," representing just 2%, includes less common feedstocks such as algae, animal waste, and industrial organic by-products. The distribution emphasizes the importance of agricultural systems and waste management in shaping biomass energy strategies and underlines the need for region-specific policies to optimize feedstock use based on availability and sustainability.

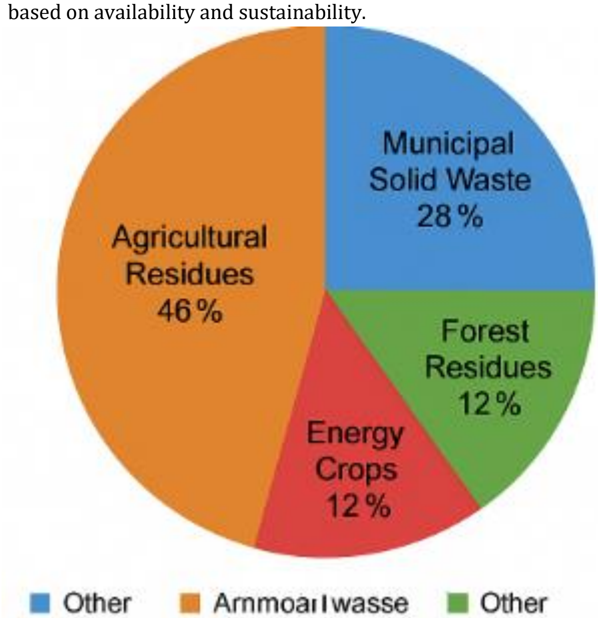

Fig 2. Global distribution of solid biomass feedstocks by source. Agricultural residues represent the dominant share (46%), followed by municipal solid waste (28%), forest residues (12%), energy crops (12%), and other sources (2%), reflecting the relative availability and utilization potential of each category in biomass energy systems.

The circular economy perspective has further elevated the role of solid biomass energy in waste valorization. Agricultural residues that were once burned in open fields can now be transformed into energy and biofertilizers, reducing both air pollution and resource waste. Similarly, municipal solid waste can be sorted to extract the organic fraction for anaerobic digestion or thermal conversion, thereby contributing to waste-to-energy schemes. Countries such as Sweden, Finland, and Germany have established successful waste-to-energy plants that use solid recovered fuels (SRF) derived from sorted municipal waste. These systems align with sustainable development goals (SDGs) by promoting clean energy, climate action, and sustainable cities [9].

Several case studies highlight regional success stories. In Brazil, the use of sugarcane bagasse for cogeneration in ethanol distilleries has helped reduce the carbon intensity of transportation fuels while generating surplus electricity for the grid. In India, biomass gasifiers have been deployed in over 1000 villages, providing reliable electricity and supporting local industries such as rice milling. In sub-Saharan Africa, biomass briquetting projects are empowering women entrepreneurs and reducing deforestation by offering alternatives to fuelwood and charcoal. In Europe, district heating systems powered by wood chips and pellets are displacing fossil fuels and lowering heating costs. These examples underscore the versatility of biomass technologies and their adaptability to different socio-economic and environmental contexts [10].

Despite the progress, several challenges remain. Feedstock availability is often influenced by competing land uses, crop residue retention policies, and climate variability. Conversion technologies still face issues related to tar formation, slagging, and corrosion. Moreover, the lack of standardized protocols for testing and certifying biomass fuels and equipment hampers market development. Knowledge gaps exist in understanding long-term soil impacts of biochar, emissions under variable combustion conditions, and supply chain carbon accounting. Continued research is needed to refine combustion kinetics, optimize reactor designs, and develop robust models for performance prediction. Capacity building, institutional support, and knowledge transfer mechanisms are also essential for scaling up biomass energy sustainably [11].

In summary, the results highlight that solid biomass energy is a dynamic and evolving field with significant potential for supporting low-carbon energy transitions. Its success hinges on appropriate feedstock management, efficient conversion technologies, enabling policies, and community engagement. As technological innovations mature and sustainability frameworks strengthen, solid biomass can serve not only as a transitional fuel but also as a cornerstone of decentralized, resilient, and circular energy systems in the 21st century [12–20].

4. Discussion

The analysis of solid biomass energy systems presented in the results section reveals a multifaceted landscape influenced by technological advancements, regional resource availability, policy environments, and socio-economic conditions. Despite its long-standing role in traditional energy use, solid biomass has increasingly shifted towards modern and sustainable energy applications, enabled by innovations in conversion technologies and integrated systems thinking. The discussion of solid biomass energy must begin with its environmental credentials, which form the foundation for its widespread support as a renewable energy source. When sourced sustainably, biomass is considered carbon-neutral, as the carbon released during combustion is offset by the CO_2 absorbed during feedstock growth. However, this neutrality is contingent upon multiple factors, including land use change, fertilizer application, transportation emissions, and conversion efficiency. Studies have shown that when lifecycle emissions are fully accounted for, the net emissions from biomass can vary significantly, ranging from negative values in biochar-rich systems to emissions approaching those of fossil fuels when land-use change and inefficient combustion are included [33]. Therefore, robust life cycle assessment frameworks must be used to ensure that biomass systems contribute meaningfully to climate change mitigation.

Conversion efficiency plays a critical role in the environmental and economic performance of biomass systems. Combustion remains the most prevalent method due to its simplicity and low cost, but it suffers from low thermal efficiency, particularly in traditional stoves and boilers. In contrast, gasification and pyrolysis offer higher efficiencies and product flexibility, but their deployment is limited by technical complexity and capital costs. Advanced combustion systems such as fluidized bed combustors and CHP units have improved performance, reaching thermal efficiencies above 80% in some applications. The integration of biomass with other renewable energy technologies, such as solar thermal or anaerobic digestion, has been proposed to overcome intermittency issues and increase system resilience. Hybrid models that combine multiple technologies and valorize co-products such as heat, biochar, or biogas demonstrate superior economic and environmental outcomes compared to single-pathway approaches [34].

Feedstock availability and logistics are another key determinant of system viability. Agricultural residues and forest waste are widely available, but their use is often constrained by alternative uses such as soil conditioning, animal fodder, or industrial raw materials. Moreover, the seasonal nature of agricultural residues and the dispersed generation of biomass sources create logistical challenges in collection, transportation, and storage. These issues can be partially mitigated through densification techniques such as pelletization or briquetting, which improve bulk energy density and handling characteristics. However, densification requires additional energy input and processing infrastructure, which may not be feasible in low-resource settings. Feedstock blending, modular preprocessing units, and decentralized conversion systems are promising strategies to enhance supply chain efficiency and resilience [35].

The socio-economic implications of biomass energy deployment are both positive and complex. On one hand, biomass systems can generate employment in rural areas, improve energy access, and reduce dependence on imported fossil fuels. On the other hand, poorly managed biomass exploitation can exacerbate deforestation, biodiversity loss, and food insecurity. For instance, large-scale energy crop plantations may compete with food production or lead to land grabs in developing countries. Therefore, biomass development must be guided by participatory planning, land-use zoning, and sustainability criteria that protect vulnerable communities and ecosystems. Successful community-based biomass projects often involve cooperatives, women's groups, and local enterprises that ensure equitable benefit distribution and long-term ownership. Capacity building and access to finance are critical for enabling these grassroots initiatives, especially in developing regions where upfront investment barriers are high [36].

Biochar production and application present a unique opportunity to link biomass energy with soil carbon sequestration and sustainable agriculture. Biochar not only stabilizes carbon but also enhances soil structure, nutrient retention, and microbial activity. These benefits have been validated in field trials across various soil types and climates, with positive outcomes for crop yields and water use efficiency. However, the agronomic performance of biochar depends on feedstock type, pyrolysis conditions, and application rate, necessitating localized experimentation and extension services. Furthermore, the long-term stability of biochar in soils and its interactions with other amendments are areas of ongoing research. If integrated effectively, biochar systems can support multiple sustainable development goals, including climate action, food security, and land restoration [37].

Policy frameworks play an instrumental role in shaping biomass energy development. Feed-in tariffs, renewable portfolio standards, investment subsidies, and carbon pricing are among the tools used to incentivize biomass deployment. The effectiveness of these instruments depends on their stability, transparency, and integration with broader energy and environmental policies. The European Union has pioneered biomass sustainability criteria under the Renewable Energy Directive, mandating GHG savings thresholds, land-use safeguards, and chain-of-custody certification. Other countries, such as India and Brazil, have adopted more flexible approaches that promote biomass through rural development programs, decentralized electrification schemes, and blending mandates for biofuels. Policy design must balance ambition with feasibility, considering local capacities, market maturity, and institutional frameworks. Cross-sectoral coordination among energy, agriculture, forestry, and waste management authorities is essential to avoid policy fragmentation and inefficiency [38].

Technology transfer and innovation are also vital for expanding biomass energy systems. Many developing countries lack access to modern biomass technologies, limiting their ability to benefit from clean and efficient energy. International cooperation through technology partnerships, capacity building programs, and research collaborations can bridge these gaps. Moreover, digital tools such as remote sensing, blockchain, and artificial intelligence offer new opportunities for monitoring biomass resources, optimizing supply chains, and ensuring compliance with sustainability standards. Mobile-based applications for feedstock inventory, micro-financing, and real-time diagnostics are already being deployed in rural biomass initiatives. These innovations must be tailored to local contexts and supported by appropriate infrastructure, training, and data governance systems [39].

The economic competitiveness of biomass energy depends on several factors, including feedstock cost, capital investment, operating costs, and revenue from co-products or carbon credits. Techno-economic assessments suggest that systems using locally sourced residues and simple technologies can be cost-effective, especially when replacing expensive fossil fuels or enhancing energy access in off-grid areas. However, high-efficiency systems such as biomass gasifiers or pyrolysis reactors often require subsidies or bundled services to achieve financial viability. The monetization of environmental benefits, such as carbon sequestration or avoided methane emissions, can enhance profitability through mechanisms like voluntary carbon markets or climate finance. Standardizing methodologies for carbon accounting, measurement, and verification is critical to unlock these value streams [40].

The role of solid biomass in global energy transitions must be contextualized within broader sustainability goals. While biomass offers a renewable and dispatchable energy source, it is not inherently sustainable. Its contribution to decarbonization, energy access, and rural development depends on how it is produced, processed, and used. Trade-offs exist between energy generation and other land uses, emissions and air quality, or short-term gains and long-term resource stewardship. The sustainability of biomass energy must be assessed using integrated frameworks that consider environmental, economic, and social dimensions. Indicators such as energy return on investment (EROI), water footprint, land use efficiency, and social acceptability provide valuable insights into system performance. Scenario modeling and stakeholder engagement can help identify pathways that maximize benefits and minimize risks [41].

Future research priorities in the field of solid biomass energy include the development of advanced conversion systems with higher efficiency and lower emissions, the optimization of feedstock preprocessing and blending strategies, and the integration of biomass with other renewable and circular economy technologies. Innovations in reactor design, catalytic upgrading, and thermal integration can improve energy yields and product quality. Exploring synergies between biomass and hydrogen, for example through biomass gasification with water electrolysis, could enable the production of green fuels and chemicals. Moreover, expanding the scope of bio-refineries to include bioplastics, nutraceuticals, and specialty chemicals can enhance the economic value of biomass and support industrial decarbonization. These technological innovations must be accompanied by institutional reforms, capacity building, and community engagement to ensure inclusive and equitable transitions [42].

In conclusion, solid biomass energy represents a promising but complex domain within the global renewable energy landscape. Its diverse feedstocks, multiple conversion pathways, and wide-ranging co-benefits offer significant opportunities for sustainable development. However, these opportunities must be harnessed through integrated strategies that address technical, environmental, economic, and social dimensions. Strengthening sustainability frameworks, enhancing policy coherence, promoting technological innovation, and supporting local ownership are essential for realizing the full potential of solid biomass energy. As the world seeks to decarbonize energy systems, reduce waste, and promote inclusive growth, solid biomass can play a pivotal role—provided its deployment is guided by evidence, equity, and ecological integrity [43].

5. Conclusion

Solid biomass energy, as explored throughout this comprehensive review, emerges as a vital yet nuanced contributor to the global energy transition. With its foundation rooted in centuries-old practices and its evolution propelled by modern technological advancements, solid biomass has transitioned from a traditional fuel to a flexible, scalable, and potentially sustainable energy source. It is uniquely positioned to serve multiple functions—providing energy, supporting rural livelihoods, managing organic waste, and mitigating climate change through carbon sequestration mechanisms such as biochar. Yet, its benefits are not guaranteed; they depend largely on how biomass is sourced, processed, converted, and governed. This conclusion synthesizes the major insights from the study, reflecting on the multifaceted role of solid biomass and proposing targeted recommendations to unlock its potential within sustainable energy systems.

The availability and diversity of biomass feedstocks form the cornerstone of biomass energy systems. From wood residues and agricultural by-products to energy crops and municipal organic waste, the global biomass resource base is abundant. However, spatial and temporal variability in feedstock availability—driven by geography, seasonality, and land-use competition—necessitates region-specific strategies for biomass sourcing. Feedstock quality, including parameters such as moisture content, ash content, and energy density, significantly influences conversion efficiency and environmental performance. Therefore, investments in preprocessing infrastructure such as drying, pelletization, and torrefaction are crucial to improving biomass logistics and fuel characteristics, particularly in regions with high moisture biomass such as tropical countries.

Conversion technologies are central to the performance of solid biomass energy systems. Combustion remains the dominant pathway, widely adopted in both small-scale and industrial applications. However, it suffers from relatively low efficiency and notable emissions, especially when unprocessed or contaminated feedstocks are used. Gasification and pyrolysis, in contrast, offer more efficient and cleaner routes for energy and co-product generation. These technologies enable the production of syngas, bio-oil, and biochar, diversifying the energy outputs and allowing integration into broader bio-refinery frameworks. Continuous innovation in reactor design, feedstock flexibility, and emissions control is necessary to enhance the competitiveness of these technologies. Furthermore, hybrid systems that combine biomass with solar, wind, or fossil energy can offer reliability and performance improvements, particularly in remote or off-grid settings.

The environmental impact of solid biomass energy is a double-edged sword. On the positive side, biomass can be carbon-neutral or even carbon-negative when managed sustainably. Biochar application in soils, improved forest management, and the avoidance of methane emissions from decomposing waste streams all contribute to greenhouse gas reductions. On the negative side, unsustainable harvesting, land-use change, and inefficient combustion can negate climate benefits and harm ecosystems. Therefore, a strong sustainability governance framework—including life cycle assessment (LCA), emissions monitoring, and certification—is essential to ensure that biomass energy systems deliver net environmental gains. Policy makers must align biomass strategies with broader sustainability goals, ensuring that the pursuit of renewable energy does not come at the cost of biodiversity, food security, or community well-being.

Economic feasibility remains one of the most debated aspects of solid biomass energy. While the use of locally available biomass can offer cost advantages, especially in rural areas or regions with high fuel prices, capital investment in conversion technologies and preprocessing infrastructure can be prohibitive. Levelized cost of energy (LCOE) studies show that biomass combustion is competitive under favorable conditions, whereas gasification and pyrolysis require either economies of scale or co-product valorization to be viable. Financial incentives, carbon pricing, and climate finance instruments can play a role in making biomass projects bankable. Moreover, creating markets for biochar, renewable heat, and certified biomass fuels can expand revenue streams and improve financial sustainability. Economic models must also internalize environmental and social co-benefits, such as improved soil fertility, reduced deforestation, and job creation, to reflect the full value of biomass energy systems.

The role of policy and governance in shaping the biomass sector cannot be overstated. Countries that have succeeded in scaling up biomass energy—such as Sweden, Brazil, and India—have done so through consistent and supportive policy frameworks. These include renewable energy mandates, capital subsidies, feed-in tariffs, tax exemptions, and public procurement policies that create demand for biomass energy products. Just as important are regulations that ensure sustainability, such as land-use planning, forest certification, and waste segregation laws. Policies should also foster innovation through R&D funding, pilot projects, and technology incubators. Importantly, biomass energy policy should be integrated across sectors—energy, agriculture, environment, and rural development—to create synergies and avoid conflicts.

Social inclusion and community engagement are fundamental to the success of biomass energy systems. Many biomass feedstocks originate from rural or marginalized communities, and their involvement in the energy value chain can enhance both the sustainability and acceptability of biomass projects. Community-based biomass projects have proven effective in many parts of the world, offering local employment, reducing energy poverty, and strengthening social capital. Participatory planning, transparent benefit-sharing mechanisms, and capacity building initiatives are essential to ensure that biomass energy contributes to inclusive development. Women, in particular, have a critical role in biomass collection, cooking, and processing, and their empowerment through improved biomass technologies and entrepreneurship opportunities should be a policy priority.

Looking ahead, several strategic directions can help maximize the potential of solid biomass energy. First, innovation in high-efficiency, low-emission conversion technologies must continue, supported by research collaborations and open-access data. Second, the integration of biomass energy into circular economy models, where energy, materials, and nutrients are recovered from waste streams, offers a path to sustainability and resilience. Third, digitalization and smart technologies, including sensors, AI, and blockchain, can improve system monitoring, traceability, and decision-making. Fourth, international cooperation, technology transfer, and South-South collaboration are needed to disseminate successful biomass models and build capacity in emerging markets. Finally, robust monitoring, reporting, and verification (MRV) systems must be established to track environmental performance and ensure accountability.

In summary, solid biomass energy represents both a legacy of human ingenuity and a frontier of sustainable innovation. It is uniquely capable of addressing multiple challenges—energy security, climate change, waste management, and rural development—when deployed thoughtfully and equitably. The evidence from this review suggests that solid biomass energy, far from being a transitional solution, can serve as a permanent and dynamic component of sustainable energy systems, especially when aligned with local resources, needs, and capacities. The road to realizing this potential lies in harmonizing technology, policy, economics, and community participation under a shared vision for a just and sustainable energy future.

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