



Biomass and bioenergy: Unlocking the potential for a sustainable future

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Abstract

Biomass and bioenergy are increasingly recognized as viable alternatives to fossil fuels, offering opportunities to produce renewable energy while mitigating environmental impacts. This review explores various biomass feedstocks, including wood, agricultural residues, algae, and food waste, alongside conversion technologies such as combustion, anaerobic digestion, pyrolysis, and gasification. The environmental, economic, and social benefits of bioenergy systems are examined, emphasizing greenhouse gas reduction, waste management, and community engagement. Challenges related to feedstock availability, technological readiness, economic feasibility, and policy integration are discussed, highlighting the need for integrated strategies, innovation, and sustainable practices. Overall, biomass and bioenergy hold significant potential in advancing a resilient, low-carbon, and sustainable energy future.

Keywords: Biomass, bioenergy, renewable energy, sustainable fuels, agricultural residues and algae

Introduction

Biomass and bioenergy in particular have been a focus of much research and investigation into their potential as alternative fuels to fossil fuels in the quest for sustainable energy. The use of organic materials in energy production not only provides a response to the growing issues surrounding energy security and availability, but their growth and use also offer possible environmental benefits. Biomass – such as wood, agricultural waste or dedicated energy crops – is a renewable resource that can be processed into different types of fuel using varied technologies. These renewable sources of energy present themselves as flexible enough options to allow a substitution to non-renewable energy, and this essay will examine the various classes of biomass, conversion methods, their possible ecological benefits, drawbacks, and examples, in tip-toeing the critical evolution of the role biomass and bioenergy will assume in moving towards sustainability in fuels.

Biomass Types

The main biomass feedstock can be classified based on the material type and source. The commonly used biomass types include wood, residues from agricultural products, or other types of organic wastes, which could originate from food manufacturing industries or even municipal solid waste. In agriculture-rich countries, residues from crops such as rice, corn, and other cereals can be a viable feedstock source, while wood sources still play a significant role in many conventional and developing bioenergy

markets (Nunes *et al.*, 2020) ^[9] Meanwhile, biomass waste from industrial activities and municipalities is becoming a favorable feedstock source due to their potential to reduce landfill wastage while helping achieve renewable energy goals (Yana *et al.*, 2022) ^[14]. These different available biomass feedstocks present unique characteristics in terms of calorific value, supply and logistic considerations, and local practices.

In addition to this, the abundance and regenerative potential further support wood as a biomass feedstock. This ensures the feedstock's viability in the bioenergy and biofuels production systems because of the continuity in supply. Its continuous yield from forest resources through sustainable forestry practices and adaptable growth in temperate or tropical sources establish wood as a renewable biomass feedstock across harvest cycles. Both forest and wood sources also promote strategies for sourcing depending on the ecological and economic conditions present in a certain location. Therefore, energy and fuel production would benefit from stable supply chains for wood as a feedstock. Being mainly lignocellulosic, its renewability as a biomass feedstock is further intensified by development in biomass pretreatment and conversion technologies – even with the presence of climactic shifts affecting wood growth and harvesting viability (Freitas *et al.*, 2021) ^[3]. Coupled with these characteristics, wood is continuously capable of responding to the demands required – both immediate and future – in sustainable fuel production.

Table 1: Biomass Types and Characteristics

| Biomass Type | Source/Feedstock | Calorific Value (MJ/kg) | Advantages | Limitations/Challenges |
|-----------------------|--------------------------------------|-------------------------|--|---|
| Wood | Forest residues, wood chips | 15–20 | Renewable, stable supply, high lignocellulose | Requires sustainable harvesting, seasonal variation |
| Agricultural Residues | Rice husks, wheat straw, corn stover | 12–18 | Abundant, reduces waste, low land competition | Seasonal availability, may affect soil nutrients |
| Algae | Microalgae, macroalgae | 20–25 | Fast growth, non-arable land, high lipid content | High cultivation cost, technology-intensive |
| Food Waste | Municipal, industrial | 10–15 | Reduces landfill, renewable, widely available | Heterogeneous composition, collection logistics |

Table-1 explore biomass feedstocks vary widely in their characteristics, availability, and applications. Traditional sources like wood provide a stable and renewable feedstock with high lignocellulose content, making them suitable for long-term energy production. Agricultural residues, such as rice husks or corn stover, are abundant and reduce organic waste, but their seasonal nature and potential impact on soil nutrients must be managed carefully. Emerging feedstocks like algae offer rapid growth on non-arable land and high energy potential, though cultivation remains costly and technology-intensive. Similarly, food waste presents an easily available source that simultaneously addresses waste management issues, although its heterogeneous nature can complicate processing. On top of that, agricultural residues turn out to be a particularly advantageous biomass energy feedstock due to their availability in large quantities in many geo agriculture regions, solving problems of both energy sourcing and waste disposal. Agricultural by-products, including biomass feedstocks like rice husks, wheat straws, and corn stover, are produced in large quantities, which are without major additional land use change competitions, and supplied at a constant rate due to land exploitation. Converting agrarian wastes to electricity, biochar, or even just combustion products, means they are replacing energy sources but also preventing agricultural organic waste from being treated through open burning or disposal in landfills, causing further environmental damage. Agricultural waste, while using biochar-to-fuel technologies, also abates significant carbon emission potential; but these systems can also embed environmental risks, from the hidden potential of soil acidification and eutrophication, for instance, when land use change/adoption or other input measures are introduced (Lee *et al.*, 2020) [5]. Agricultural residues improve overall sustainability of biomass energy, but their systems still require monitoring for optimal waste utilization and mitigation of further environmental consequences.

Finally, it should be noted that new sources of biomass, including algae and food waste, gain popularity due to their flexibility and potential for increasing scale. For example, algae have a high growth rate and can be cultivated on non-arable land, making it a sustainable source of biofuels that does not compete with food crops. Food waste, in turn, is one of the largest sources of organic waste, which can be successfully used to produce energy while simultaneously solving problems with excessive use of landfills. Current research activities demonstrate a shift toward alternative and nontraditional sources of biomass used to produce biofuels and other products that will help ensure energy diversity and discover new pathways for the bioenergy sector's globalization (Perea-Moreno *et al.*, 2019) [12]. Integrating these scarcely used sources of biomass into the work of a bioenergy system will allow researchers and engineers to achieve greater flexibility and resource efficiency. This factor will further strengthen the prospects for creating a low-carbon sustainable fuel.

Conversion Technologies

Equally to the variety of existing biomass feedstock, the successful recovery of energy from biomass is significantly

determined by the selection of recycling technology. The most adopted recycling process for energy recovery is combustion, which is mostly applied for energy generation in power plants and heating facilities. This is due to its simplicity and familiarity coupled with existing dependences. The main thermal processes alternative to combustion are pyrolysis, gasification and hydrothermal carbonization. These conversion processes provide the opportunity to obtain fuels, feedstock or biochar from biomass in a more controllable manner, regulating temperature, pressure and heating rate (Lewandowski *et al.*, 2020) [6]. Anaerobic digestion is a non-thermal process that involves the generation of biogas through converting any organic matter, such as agricultural residues and food wastes. Conversion via micro-organisms can play a significant role in decentralized energy systems. Nowadays, both conventional and advanced conversion processes are part of the wider conversation to increase the efficiency and scope of bioenergy in the global energy market, along with the increasing importance of flexible conversion units and CO₂ collection technologies (Sliper, 2024) [13].

More specifically, combustion has been the most widely adopted and commercially available route for biomass energy conversion to date due to its direct and established nature in contemporary energy generation systems. During biomass combustion, common organic matter including wood, agricultural residues, and select waste streams are oxidized in short time under high temperatures, releasing thermal energy, steam and flue gases that can be used to generate electricity in turbines or provide district heating. It is highly versatile from small residential stoves to large commercial power plants, with conversion efficiencies generally between 20% and 35% depending on the feedstock and specific system (Lewandowski *et al.*, 2020) [6]. Continuous improvements in boiler technology and emission regulations have resulted in steady improvements in thermal efficiency and reductions in particulates and gaseous emissions, although air quality issues continue to be a concern in urbanized areas. However, the widespread use of combustion today can be mainly explained by its simple operation, broad feasibility on diverse feedstocks and connections with existing energy generation systems. Conversion technologies transform these diverse feedstocks into usable energy forms with varying efficiency levels. Combustion, the most common method, is simple and versatile but offers moderate efficiency and potential air pollution. Anaerobic digestion converts organic matter into biogas, providing decentralized energy and effective waste management, but requires controlled conditions and time. Pyrolysis and gasification are more advanced thermal processes capable of producing bio-oil, syngas, and biochar with higher energy efficiency, though they demand higher technology investments and pre-treatment of feedstocks. Together, the selection of appropriate feedstocks and conversion methods determines the sustainability, efficiency, and environmental impact of biomass energy systems, highlighting the need for tailored solutions based on local conditions and resource availability shown in table-2.

Table 2: Biomass Conversion Technologies

| Conversion Technology | Process Type | Main Product(s) | Efficiency (%) | Advantages | Limitations |
|-----------------------|--------------|---|----------------|--|--|
| Combustion | Thermal | Heat, electricity | 20–35 | Simple, widely used, versatile feedstock | Air pollution, moderate efficiency |
| Anaerobic Digestion | Biological | Biogas (CH ₄ + CO ₂) | 30–40 | Waste management, decentralized, renewable | Requires controlled conditions, slow process |

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|--------------|-----------------------|---|-------|--|---|
| Pyrolysis | Thermal (oxygen-free) | Bio-oil, syngas, biochar | 35–50 | Flexible product output, low emissions | Technology cost, feedstock pre-treatment needed |
| Gasification | Partial oxidation | Syngas (CO + H ₂ + CO ₂) | 40–55 | High-energy yield, flexible applications | High temperature, complex technology |

Specifically, anaerobic digestion provides a biologically mediated alternative to convert organic materials, such as agricultural residues, municipal waste, and some industrial by-products, into biogas—a renewable fuel characterized by high methane and carbon dioxide contents. This process takes place in anaerobic systems characterized by the lack of oxygen, where specific microbial communities degrade complex organic residues which generates specific gases that can be used for heat, electricity, or upgraded for direct injection to natural gas pipelines. Anaerobic digestion systems not only serve to improve the diversification of energy matrixes but also contribute to a compelling environmental argument for their deployment. Indeed, anaerobic digestion can be also perceived as a viable bioenergy solution to the problems associated with solid waste management, landfilling, and the uncontrolled production of methane as a result of the uncontrolled degradation of organic matter. Biogas production contributes to comprehensive waste management approaches and the achievement of sustainability goals, particularly in scenarios with significant availability of organic residues from agricultural and municipal sources (Yana *et al.*, 2022) ^[14]. Therefore, the common potential of these technologies to address different sustainability issues proves further the need to embrace bioenergy alternatives.

Pyrolysis and gasification are also innovative techno-economic pathways that compete with traditional combustion processes for the effective transformation of biomass into viable energy carriers. In pyrolysis, an oxygen-free thermal treatment applied to the organic feedstock produces a blend of bio-oil, syngas, and biochar, which can be exploited as fuels, chemical precursors, and soil amendments (Khan *et al.*, 2022). Conversely, gasification is a partial oxidation process applied to biomass at elevated temperatures, producing a mixture of carbon monoxide, hydrogen, and carbon dioxide, a synthesis gas that may be used in combined heat and power plants or as a liquid fuel precursor. When compared to traditional biomass combustion systems, these conversion pathways are generally more controllable concerning their product yields and permeability characteristics in terms of emissions (De Jong *et al.*, 2019). They are particularly suited for the establishment of flexible and integrated bioenergy systems that can play a pivotal role in advancing the decarbonization agenda across numerous economic sectors. The report by Sliper (2024) ^[13] shows the latest global developments regarding pyrolysis and gasification technologies and how they are becoming alternatives, first to traditional conversion processes used to meet the fuel needs of the transportation sector, and second, to advance the sustainability agenda within the energy systems of the modern world.

Environmental Impacts

Aside from the technical differences resulting from the varying conversion techniques available, implementations of biomass and bioenergy offer tangible environmental benefits that set such resources apart from traditional fossil

fuels. Replacing non-renewable energy with biomass, for one, can dramatically cut greenhouse gas (GHG) emissions, given that sustainable production and harvesting methods are followed alongside sophisticated conversion technologies. As such cuts could be made through biochar-to-fuel systems using agricultural by-products, these systems have been found to reduce global warming potential. Particularly partnered with combined heat and power (CHP) systems or when boosting electricity generation that replaces fossil-based resources, the energy application has been shown to yield promising reductions (Lee *et al.*, 2020) ^[5]. Incorporation of carbon capture and storage (CCS) methods—as tested under research schemes such as BIO-CAP-UK—also allow bioenergy applications to implement negative emissions, furthering the argument for their deployment in reducing climate change impacts (Makepa & Chihobo, 2025) ^[8]. Again, these situations are contingent on optimized land use, precision agricultural practice, and continued technological development to sustain resource use while allowing for the most benefits to accrue at local and planetary levels.

Thus, the use of biomass energy is increasingly recognized as a viable climate change mitigation measure due to its reduction of the net carbon footprint of energy production. Unlike fossil fuel use, the combustion of which returns down-sequestered carbon to the atmosphere from geological timescales, energy production with biomass is based on a modern carbon cycle that draws down and re-releases current atmospheric carbon dioxide as plants grow, and that value is returned to the atmosphere when organic matter is converted to energy. Specific analyses of countries with significant biomass energy uses indicate that increasing consumption of biomass energy is associated with decreasing carbon dioxide emissions, demonstrating that biomass energy production is capable of reducing property accumulation of greenhouse gases relative to standard energy pathways (Destek *et al.*, 2021) ^[2]. Biomass energy production technologies that are appropriately used in synergy with sustainable harvesting techniques can further enhance or maintain this greenhouse gas balance due to the low or negative net emissions that many of these practices impose on biomass energy systems. Therefore, the widespread adoption of biomass energy technologies will produce benefits in the national and global climate change strategies that will reduce general emissions as a measurable objective, while also facilitating the parallel compliance of climate environmental policy objectives.

Thus, the application of biomass energy systems is instrumental in promoting sustainable and efficient resource recovery and waste management, both environmentally and economically, within a locality and on a national level. Shifting the use of organic wastes, from agricultural residues to municipal solid waste, into useful energy forms reduces their contribution to landfills, and consequently, methane emissions from uncontrolled degradation. This practice consumes resources that otherwise impose additional loads on the environment and recovers significant amounts of renewable energy, as livestock assessments in

different territories reveal (Liu & Rajagopal, 2019) [7]. In practice, maximizing the energy recovery potential of different waste feedstocks needs to account for specific regional conditions, as a way to find the most beneficial process both in terms of net energy and emissions. Therefore, the implementation of biomass systems contributes to resource loops closure, thus enhancing energy sustainability and minimizing the dependence on harmful disposal approaches.

Lastly, the sustainable practices of biomass energy system may endanger the integrity of rich and diverse ecosystems providing essential natural habitats. Energy crop cultivation and harvesting along with the use of agricultural and forest residues can be managed to minimize monoculture practices or application causing habitat destruction. Under physical conditions, well-established precision agriculture practices and soil management can develop biomass cultivation without affecting sensitive habitats or causing soil erosion, while adopting crop rotation or plantation and combined cultivation using previously degraded or barren lands (Makepa & Chihobo, 2025) [8]. In addition, developed processing and conversion technology can be adopted to create possible solutions for using non-food biomass helping to mitigate the competition between food staging and production facilities while reducing the threatening effects on existing ecosystems. Through the introduction of efficient practices in biomass energy system development, it is possible to use the productive soils of cultivated landscapes, stimulate local biodiversity, and contribute to the stability of the ecosystem required for permanent environmental resilience.

Challenges and Limitations

Despite the technical opportunities, there are interconnected barriers to the large-scale deployment of biomass energy systems. The resource availability remains a continuous barrier as climate variability and extreme weather conditions can affect the uptime and quality of lignocellulosic feedstocks. Therefore, to ensure reliable and consistent feedstock availability through adaptive harvesting and crop rotation is required. The technological barriers on the other hand affect the bioenergy economics, particularly the costs for feedstock supply, process efficiency, and logistics. Better engineering and conversion processes are still required, especially in improving the enzymatic hydrolysis of lignocellulose. In order to address and minimize these barriers biorefineries also need to consider their location and logistics. As such, emerging and continued research on climate-responsive and resilient crops, and circular bio-based production are still needed to further advance the second-generation biorefineries while meeting their current barriers, and potential impacts on food security and climate change.

Nonetheless, the dilemma of biomass resource productivity is penetrating deeper with the trade-off of bioenergy crops and food resource respectively. Using the limited arable land for growing biomass feedstocks may result in the unfortunate shift of concrete food crops-growing area, which will be a food insecurity threat as well as a rise in market fluctuation in various regions. Climatic factor enthusiasm, including drought, soaring, dropping temperatures, and land degradation will adversely affect the yield and quality of lignocellulosic biomass as well (Freitas *et al.*, 2021) [3]. Engaging agro-ecosystems to meet the needs

for biofuels and food simultaneously, will require climate-smart agriculture practices and resilient crop varieties to sustain environmental challenges without replacing basic food requirements. Therefore, sustainable land practices and crop rotation schedules must be of priority to gather a revolving supply of renewable fuel and food components thereby keeping a balance between both elements.

In summary, technological limitations are still significant obstacles to further deployment and optimization of biomass energy production systems. Conversion technologies need to mature further in terms of efficiency, feedstock flexibility and compatibility with low-cost carbon dioxide disposal methods. Moreover, current biomass operational systems present technical and economic efficiency issues when upscaling for new markets (i.e. transportation demand of high-quality renewable fuels and resilient supply chains) (Sliper, 2024) [13]. Premises for a competitive and sustainable production of bioenergy rely on investments in research and development, balanced policy frameworks to boost innovation and to allow the implementation of more flexible power systems. If those do not occur, biomass opportunities for displacing traditional fuels and contributing to sustainability goals will continue to be hindered by technological and infrastructural limitations.

In addition, economic and policy hurdles further escalate the challenges of mainstreaming biomass and bioenergy breakthrough as a mainstream energy alternative. High initial investments and operational expenditures are a deterrent for adoption at commercial scale, particularly when feedstock sourcing and logistics must be streamlined in order to secure economic viability. Often, the mismatch between policy and technology is evident in terms of timid roadmap incentives, non-harmonized regulations, and lack of support instruments to bolster economic feasibility and demand (Paul *et al.*, 2024) [11]. The progress towards second-generation biorefineries may be constrained by the lack of stable and long-term commitments on policy, alliances and development for circular bio-based production models that seek to reduce costs and environmental footprints. At this stage, the bioenergy sector is expected to flourish by not only making strides in feedstock processing efficiency improvement and resource logistics optimization, but also in devising coordinated strategies that would dissociate their positive impact on economic feasibility and supportive policy instruments.

Case studies and examples

Biomass energy applications include the use of bamboo as renewable feedstocks, which illustrate examples of innovative project development across the Asian region. A feasibility study shows that the countries of Malaysia, Indonesia, Vietnam, and Japan have developed bamboo bioenergy at various scales from off-grid to commercial power plants. Indonesia's Mentawai region has a 700 kW off-grid power plant that showcased technology using locally sourced feedstocks to deliver community-based energy solutions, while Japan has a 995 kW generation facility that used the same technology. A 4 MW bamboo power plant is in the pipeline for Malaysia, with commercialization scheduled between 2022 and 2023, illustrating scaling towards national energy demands (Ku Azman Shah *et al.*, 2021) [4]. Aside from supplying renewable electricity, the projects also have positive socioeconomic impacts, highlighting the replicability and

adaptability of biomass energy systems across various settings.

In particular, a case concerning the establishment of a community-level biomass power generation plant in rural Indonesia demonstrates the delivery of practical benefits and replicable approaches to energy provision. Agricultural waste resources, such as palm oil waste and rice husks, are used as the main feedstock in small-scale power generation facilities that can provide electricity for rural areas where energy access is limited. Community participation has been key to the feedstock collection and as stakeholder in the operation and maintenance of the facility (Yana *et al.*, 2022)^[14]. This project is a means for rural energy access, as well as waste management practices, reduced use of diesel generators, employment opportunities for local laborers. Overall, the adoption of locally available biomass resources empowers rural communities to be energy independent as well as be integrated into the larger national energy policy aims and initiatives for rural development and energy delivery.

Following this trend, large-sized bioenergy programs have been proven to significantly impact national energy supply systems and contributing a lot to decarbonization commitments. In the US case, the full exploitation of waste and biomass residues is carried out through integrated processing at industrial scale energy conversion plants. Life-cycle analysis suggests that when the most promising available wastes and residues are fully exploited through state of-the-art conversion pathways, they can supply between 3.1 and 3.8 exajoules of renewable energy with a net gain of 2.4 to 3.2 exajoules of energy (Liu & Rajagopal, 2019)^[7]. In such scenarios, industrial bioenergy facilities can effectively substitute fossil fuels and reduce emissions by 103 to 178 million tCO₂e annually. Even with those results, further improvements on feedstock selection, site location or technology implementation are possible as no solution will ever give more energy or emissions reduction than other in the wide variety of regions.

Furthermore, algae as a new biomass source is a promising feedstock due to its high growth potential and low requirement of agricultural land. Recent efforts in developing such large-scale algae biofuel projects have targeted the installation of sophisticated photobioreactors and open-pond algal production systems that convert solar energy and carbon dioxide into high-energy biomass. Also, the developed systems have the potential for carbon sequestration and contribute to life-cycle greenhouse gas emission reductions while enabling a circular economy in bioenergy innovations (Capareda, 2023)^[1]. For instance, pilot plants showed that algae bio-oil could substitute for fuel oil and gasoline derived from petroleum. Currently, research studies focus on further improving algae energy value and reducing production costs. As an algae bioenergy project continues to evolve, promising unconventional feedstocks contribute to the diversification and securing a global low-carbon fuel transition.

In summary, the case studies assessed provide significant implications for the development and implementation of future biomass energy projects. The successful projects utilized locally available feedstock, promoted community engagement, and involved the selection of appropriate technologies for the local context to sustain operations and ensure stakeholder participation. Furthermore, the Life Cycle Assessment results presented by various biomass

power plants reveal that carefully planned resource acquisition, emissions, and waste management can mitigate environmental consequences while promoting the acceptance of renewable technology in the society (Paletto *et al.*, 2019)^[10]. Therefore, such development approaches should be dependent on the environmental, social, and logistical aspects of specific contexts. Incorporation of such implications would allow future biomass projects to deliver stable renewable energy while reducing potential adverse effects, ensuring the long-term support to the industry among the local communities.

Conclusion

To conclude, bioenergy and biomass have significant potential for the development of sustainable fuel systems. The application of diverse biomass sources, from traditional wood and agricultural by-products to innovative future feedstock such as algae, biomass energy systems may help to provide renewable energy, combat waste issues, and reduce greenhouse gas emissions. At the same time, the biomass energy potential cannot be accomplished without addressing a range of challenges related to the resources availability, technology readiness, economics and financing, and policy integration. Resource efficiency, innovative technology and community engagement balanced strategies will be instrumental for the further biomass energy sector development. Further integrated policies and research will be necessary for the advancement of bioenergy and biomass towards the resilient low-carbon energy future.

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