Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 9, No. 1, 2024

The Sustainable Technology Research on High-Efficiency Conversion and Utilization of Biomass-Based Energy

Baoyi Wu[1, *]

[1]Monash University Malaysia, Malaysia
[*] Corresponding author: Email: bwuu0039@student.monash.edu

Abstract: This study delves into the sustainability of biomass-based energy as an alternative energy source, its technical conversion methods, and its environmental and economic impacts. Biomass resources, including plants, agricultural residues, and forestry residues, are not only widely distributed and renewable but also exhibit significant potential in reducing greenhouse gas emissions and combating climate change. The research focuses on three primary conversion technologies for biomass energy: physical conversion, chemical conversion, and biological conversion. It further explores key technologies for enhancing the sustainability of biomass-based energy, including biomass pretreatment, optimization techniques, and the integration of efficient energy conversion systems. The results indicate that, despite challenges, with continuous technological innovation and improvement, biomass energy can become a more sustainable energy option.

Keywords: Biomass-based energy, Sustainability, Conversion technologies.

1. Introduction

With the continuous growth of global energy demand and increasing concern for environmental sustainability, biomass-based energy has emerged as a highly promising alternative energy source. Biomass resources, including plants, agricultural waste, and forestry residues, possess abundant renewability and widespread distribution, making them a potentially valuable source of energy. Compared to fossil fuels, biomass energy holds significant potential in reducing greenhouse gas emissions and mitigating climate change. The carbon dioxide released through the combustion of biomass energy can be reabsorbed by biomass, forming a sustainable and recyclable ecosystem.

To achieve the efficient conversion and utilization of biomass-based energy, a series of technical challenges and sustainability considerations must be addressed. This study aims to explore sustainable technological research on biomass-based energy to facilitate its broader application and enhance energy efficiency. By improving technologies related to biomass harvesting, storage, pretreatment, conversion, and utilization, it is possible to maximize the sustainability of biomass energy while reducing environmental and social impacts. This research offers the prospect of better harnessing biomass resources to achieve a clean and sustainable energy future.

2. Biomass Energy Conversion Technologies

2.1. Physical Conversion Methods

Physical conversion methods, as a crucial step in biomass resource pretreatment, encompass processes like compression and drying. These processes enhance the physical properties of biomass to meet the requirements of energy production and storage. Compression techniques involve applying appropriate force and temperature to compact biomass materials, reducing their volume, saving storage space, and lowering transportation costs, thereby improving the economic viability of biomass resources. Effective compression optimizes the utilization of biomass resources and reduces resource wastage during energy production. Drying is used to remove moisture from biomass materials. Reducing moisture content is essential for enhancing the stability of biomass and extending its shelf life. High humidity environments can lead to biomass decay and quality loss, while drying effectively reduces humidity, improving biomass quality and storability.

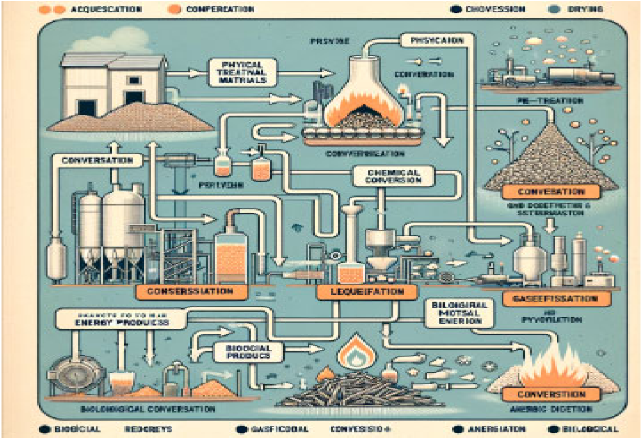

Figure 1. Biomass Energy Conversion Process

Figure 1 illustrates the overall biomass energy conversion process, from raw material acquisition, pretreatment, conversion methods to the final energy products. It clearly depicts how various stages and methods (physical conversion, chemical conversion, and biological conversion) interact and contribute to the final energy output.

2.2. Chemical Conversion Methods

Chemical conversion methods represent a range of critical engineering processes aimed at converting biomass resources into various energy products. This includes methods such as gasification, liquefaction, and pyrolysis, which provide essential support for the efficient utilization of biomass resources. Gasification converts biomass materials into synthesis gas (mainly composed of carbon monoxide and hydrogen) in a high-temperature, oxygen-deficient environment. Synthesis gas finds wide applications in energy production, chemical industries, and electricity generation, efficiently converting biomass resources into valuable energy products, reducing dependence on traditional fossil fuels. Liquefaction is the process of converting biomass materials into liquid fuels, including biodiesel and bioethanol. Liquid fuels have broad applications in transportation and thermal energy, helping reduce the demand for fossil fuels. In biomass liquefaction, compounds like polysaccharides and cellulose are broken down into combustible liquid fuels, yielding high-quality biomass liquid fuels through proper treatment and catalytic reactions, enhancing energy efficiency. Pyrolysis involves converting biomass into carbon and gas through high-temperature decomposition. In the pyrolysis process, biomass materials are exposed to high temperatures, breaking down into solid charcoal, liquid, and gas products. Biomass charcoal has various applications, including soil improvement and adsorbents. By optimizing pyrolysis parameters and reaction conditions, efficient utilization of biomass resources can be achieved, while valuable by-products are generated.

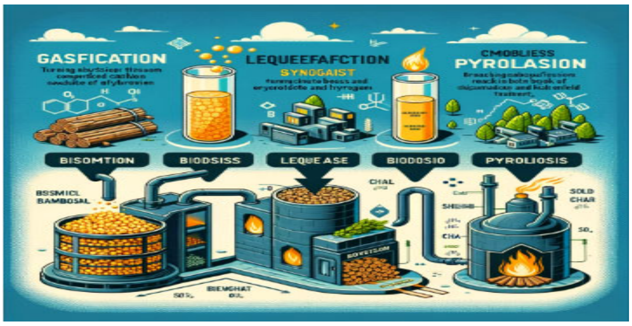

Figure 2. Chemical Conversion Processes of Biomass Energy

Figure 2 illustrates the three primary chemical conversion processes of biomass energy. The gasification process converts biomass into synthesis gas containing carbon monoxide and hydrogen, widely used in energy production and chemical industries. Liquefaction processes transform biomass materials into liquid fuels such as biodiesel and bioethanol, used in transportation and thermal energy applications. Pyrolysis involves high-temperature decomposition of biomass, generating solid charcoal, liquid, and gas products, with various applications. The figure clearly indicates the biomass inputs and different output products for each process, providing an intuitive presentation of chemical conversion methods for biomass energy.

2.3. Biological Conversion Methods

Biological conversion methods, as a significant component of biomass energy, utilize microorganisms (such as bacteria and yeast) or enzymes to convert biomass resources into biofuels or chemicals, offering substantial application potential. Fermentation is a biological conversion method based on metabolic activities of organisms, primarily converting carbohydrates in biomass into organic compounds like alcohols or other biofuels. Fermentation processes typically involve specific microorganisms or yeast strains that metabolize carbon sources in biomass into usable biofuels. Anaerobic digestion is a biological conversion process where organic waste is decomposed into biogas and organic fertilizers under anaerobic conditions. During anaerobic digestion, microbial communities break down organic waste to produce biogas, primarily composed of methane and carbon dioxide, which can be used for power generation or heating. Anaerobic digestion also produces organic fertilizers for soil improvement and agricultural production, achieving the recycling of waste resources.

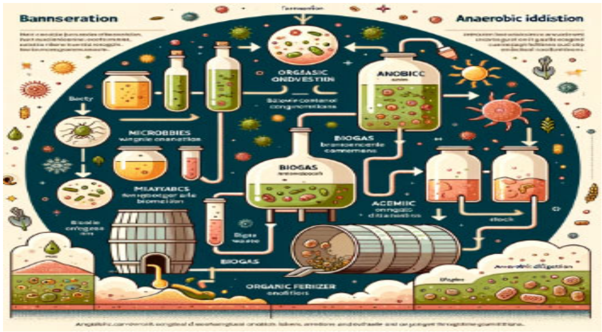

Figure 3. Biological Conversion Processes of Biomass Energy

Figure 3 vividly illustrates the biological conversion processes of biomass energy, comprising two major parts: fermentation and anaerobic digestion. In the fermentation section, microorganisms such as bacteria and yeast convert biomass into organic compounds (such as alcohol and other biofuels), relying on microbial metabolic activities. The anaerobic digestion portion depicts the process of converting organic waste into biogas (mainly composed of methane and carbon dioxide) and organic fertilizers under anaerobic conditions. The figure meticulously labels elements such as biomass, microorganisms, fermentation, biogas, and organic fertilizers, providing an intuitive explanation of the biological conversion methods of biomass energy and their products.

3. Development of Sustainable Technologies

3.1. Biomass Pretreatment and Optimization

Biomass pretreatment and optimization technologies aim to enhance the usability and efficiency of biomass, making it a vital source for renewable energy and sustainable chemicals. Key technologies include physical pretreatment, which improves the processability of biomass through methods like grinding, milling, and classification; chemical pretreatment, which enhances the degradability of biomass through acid-base treatments, steam explosion, and oxidation; biological pretreatment, which utilizes biological methods like microbial fermentation and enzymatic hydrolysis to break down complex compounds; biomass pelletization, which compresses biomass into pellet forms for ease of storage and combustion; and gasification and liquefaction technologies, which convert biomass into synthesis gas or liquid fuels. Waste reduction techniques also help reduce waste and emissions in the biomass processing process, achieving more environmentally friendly production. Ongoing improvements and innovations in these technologies contribute to increased sustainability and efficiency of biomass resources, driving the development of renewable energy, reducing reliance on fossil fuels, and promoting sustainable development.

3.2. Integration of High-Efficiency Energy Conversion Systems

Integration technologies for high-efficiency energy conversion systems effectively coordinate and integrate various types of energy conversion systems to enhance energy conversion efficiency, reliability, and controllability. The application of intelligent control systems allows real-time monitoring and optimization of subsystems through sensors and feedback mechanisms to ensure optimal performance. Computer simulation and optimization tools are used to model and analyze various components of energy systems, determining optimal configurations and operating parameters to improve efficiency. Multi-energy system integration technology requires coordinated inverters, energy storage, and energy conversion devices to achieve effective integration of different energy sources. Integration of energy storage and distribution technologies is also crucial to balance differences between energy supply and demand and includes battery technology, supercapacitors, energy storage systems, and smart grid technology. Integration technologies for high-efficiency energy conversion systems help maximize the use of renewable energy, reduce reliance on traditional energy sources, promote sustainability, and move towards a more environmentally friendly and sustainable energy future.

3.3. Energy Storage and Distribution Technologies

The efficient conversion and utilization of biomass-based energy rely on advanced energy storage and distribution technologies. Batteries, compressed air energy storage, and thermal storage technologies can be employed to store excess energy during periods of high energy production and release it during peak demand. Additionally, efficient distribution and transmission systems are crucial to ensuring that biomass-based energy can be effectively distributed to various locations and applications. Power system integration technologies allow different types of energy conversion systems to work together, while optimizing the energy supply chain can reduce the costs of energy production and distribution and enhance resource utilization efficiency. Modernizing the grid, including the implementation of smart meters, remote monitoring, and power line communication, is also essential to improve grid efficiency and reliability, support the integration of biomass-based energy, and facilitate continuous improvement and innovation in energy storage and distribution technologies. These advancements in energy storage and distribution technologies contribute to ensuring the sustainability of biomass-based energy, promoting the widespread use of clean energy, reducing reliance on traditional fossil fuels, and laying the foundation for a sustainable energy future.

4. Sustainable Technology Assessment

4.1. Environmental Impact Assessment

In the development and application of sustainable technologies, the implementation of Environmental Impact Assessment (EIA) is a critical engineering step aimed at quantifying and assessing environmental effects throughout the entire lifecycle of the technology. Life Cycle Assessment (LCA), as a systematic engineering method, conducts comprehensive environmental impact analysis of technology, covering key environmental parameters such as resource consumption, greenhouse gas emissions, water and soil pollution, from raw material extraction, production, use, to disposal, to ensure a comprehensive assessment of the technology's environmental footprint. LCA evaluates the environmental impact of technology from resource extraction to disposal using the following basic formula:

$$\mathrm{LCA} = \sum(\mathrm{I} \times \mathrm{EFi}) + \sum(\mathrm{O} \times \mathrm{EFo}) \qquad (1)$$

Biodiversity assessment evaluates the impact of technology on local ecosystems and biodiversity from an ecological engineering perspective. It focuses on potential disruptions to community structure and functionality caused by the implementation of technology, aiming to ensure that technology deployment does not lead to irreversible loss of biodiversity.

Climate impact assessment focuses on quantifying the impact of technology on climate change using numerical models and emission scenario analysis. This assessment, especially in the energy sector, evaluates greenhouse gas emissions and carbon footprints, playing an important role in understanding the potential role of technology in mitigating or adapting to global climate change. It typically involves calculating the total greenhouse gas emissions generated by the technology, using the formula:

$$\mathrm{CF} = \sum(\mathrm{GHG\ E} \times \mathrm{GWP}) \qquad (2)$$

Table 1. Environmental Impact Assessment

Technology Name	Resource Consumption (tons)	Greenhouse Gas Emissions (tons CO2 equivalent)	Biodiversity Assessment (index)
BGT	500	1000	0.85
BFT	600	1200	0.88
BPT	550	1100	0.82

Table 1 data indicates that biomass gasification technology is relatively more sustainable in terms of environmental impact, while biomass pyrolysis technology may require more environmental management and emissions reduction measures to mitigate its negative effects.

4.2. Energy Efficiency Analysis

In the assessment of sustainable technologies, energy efficiency analysis is a crucial component to ensure the economic viability and environmental sustainability of the technology. It mainly covers three key aspects: energy input-output comparison, energy conversion loss analysis, and energy benefit assessment.

Energy input-output comparison is done by accurately measuring the energy consumption and production of the technology during operation to determine its energy efficiency level. It relies on systematically collecting and analyzing energy data, such as energy types, quantities, and usage efficiency. Energy efficiency ratio (EER) can be calculated using the following formula:

$$\mathrm{EER} = \frac{\mathrm{EO}}{\mathrm{E\,I}} \qquad (3)$$

Energy conversion loss analysis aims to identify and quantify energy conversion efficiency losses in the technology's processes. This is achieved by analyzing thermodynamic and physical parameters, such as heat losses, friction losses, and resistance losses, in the energy conversion process. The goal is to discover and implement measures to improve energy efficiency, thereby reducing energy waste and enhancing overall energy efficiency. Energy conversion efficiency is typically calculated using the following formula:

$$\mathrm{ECE} = 1 - \frac{\mathrm{EL}}{\mathrm{EI}} \tag{4}$$

Energy benefit assessment focuses on quantifying the energy benefits of the technology in providing the desired services. This often involves calculating work output or service provision under unit energy input and evaluating the energy efficiency performance of the technology in practical applications, providing data support for optimization in design and operation.

Table 2. Energy Efficiency Analysis

Technology Name	Energy Input (kWh)	Useful Energy Output (kWh)	Energy Efficiency Ratio
BGT	1300	1000	0.77
BFT	1600	1200	0.75
BPT	1100	900	0.82

Table 2 shows that biomass pyrolysis technology performs well in terms of energy conversion efficiency, while biomass gasification technology and biomass fermentation technology have slightly lower energy efficiency.

4.3. Economic Feasibility Assessment

In the development process of sustainable technologies, economic feasibility assessment is a key analytical task aimed at quantitatively evaluating the commercial potential and investment value of the technology. This assessment covers cost-benefit analysis, payback period calculation, return on investment (ROI) calculation, and market analysis.

Cost-benefit analysis is conducted by comparing the total costs of implementing the technology with its expected benefits. Total costs typically include initial investment costs, operating costs, and long-term maintenance and update costs. Expected benefits consider both the direct economic benefits, such as increased production efficiency, energy cost savings, and indirect benefits, such as enhanced brand value and increased market competitiveness. The cost-benefit ratio (CER) can be expressed using the following formula:

$$\mathrm{CER} = \frac{\mathrm{TB}}{\mathrm{TC}} \tag{4}$$

Payback period and ROI calculations are crucial for evaluating the short-term and long-term economic viability of the technology. Payback period (PBP) refers to the time required for project investment costs to be recovered from expected benefits, while ROI is a key indicator measuring the profitability of investments, expressed as the ratio of investment returns to investment costs. The formulas for calculating payback period and ROI are as follows:

$$\mathrm{PBP} = \frac{\mathrm{II}}{\mathrm{AC}} \tag{5}$$

Market analysis involves comprehensive research into the target market's demand, competitive landscape, and market acceptance of the technology. This includes estimating market size, analyzing target customer groups, competitor analysis, and market trend forecasting. It helps identify the market potential of the technology and provides data support for pricing strategies, market entry strategies, and marketing activities.

Table 3. Economic Feasibility Assessment

Technology Name	Initial Investment Cost (thousands of yuan)	Annual Operating Cost (thousands of yuan/year)	Average Annual Income (thousands of yuan/year)	Payback Period (years)
BGT	200	15	35	6
BFT	250	18	40	7
BPT	180	12	30	6

Table 3 indicates that biomass gasification technology and biomass pyrolysis technology perform well in economic terms, with relatively short payback periods and moderate return on investment rates. Although biomass fermentation technology has a higher initial investment cost, it still demonstrates good economic feasibility.

5. Conclusion

Biomass-based energy, as a sustainable energy solution, holds significant potential to meet the growing global energy demand while mitigating environmental pressures. Through an in-depth analysis of physical, chemical, and biological conversion technologies, this study has shown that effective preprocessing and conversion methods can enhance the energy efficiency and utilization of biomass while reducing environmental impacts. Technologies such as biomass pellet preparation, pyrolysis, gasification, and fermentation have been proven effective in converting biomass into useful energy, supporting energy diversification. Environmental impact assessments and energy efficiency analyses further demonstrate that, despite challenges, biomass energy can become a more sustainable energy production method through technological innovation and improvements.

References

[1] Zhang L , Rao T U , Wang J ,et al.A review of thermal catalytic and electrochemical hydrogenation approaches for converting biomass-derived compounds to high-value chemicals and fuels.Fuel Processing Technology, 2022, 226:107.

[2] Chan Y H , Lock S S M , Chin B L F ,et al.Progress in thermochemical co-processing of biomass and sludge for sustainable energy, value-added products and circular economy.Bioresource Technology: Biomass, Bioenergy, Biowastes, Conversion Technologies, Biotransformations, Production Technologies, 2023.B. Smith, “An approach to graphs of linear forms (Unpublished work style),” unpublished.

[3] Zhu, Pengfei, et al. "Achieving high-efficiency conversion and poly-generation of cooling, heating, and power based on biomass-fueled SOFC hybrid system: performance assessment

and multi-objective optimization." Energy Conversion and Management 240 (2021): 114245.

[4] Liang, Wenxing, et al. "High-efficiency utilization of biomass and seawater resources based on a distributed system with SOFC-assisted CO2 capture: Feasibility analysis and optimization." Energy Conversion and Management 296 (2023): 117675.

[5] Hoang, Anh Tuan, et al. "Insight into the recent advances of microwave pretreatment technologies for the conversion of lignocellulosic biomass into sustainable biofuel." Chemosphere 281 (2021): 130878.

[6] Saxena, R. C., D. K. Adhikari, and H. B. Goyal. "Biomass-based energy fuel through biochemical routes: A review." Renewable and sustainable energy reviews 13.1 (2009): 167-178.

[7] Yang, Hui, et al. "High-Efficiency Utilization of Waste Tobacco Stems to Synthesize Novel Biomass-Based Carbon Dots for Precise Detection of Tetracycline Antibiotic Residues." Nanomaterials 12.18 (2022): 3241.

[8] Yang, Xiaomin, et al. "Fabrication of biomass-based functional carbon materials for energy conversion and storage." Materials Science and Engineering: R: Reports 154 (2023): 100736.

[9] Yurtay, Aygül, and Murat Kılıç. "Biomass-based activated carbon by flash heating as a novel preparation route and its application in high efficiency adsorption of metronidazole." Diamond and Related Materials 131 (2023): 109603.

[10] Jin, Chengbin, et al. "Biomass-based materials for green lithium secondary batteries." Energy & Environmental Science 14.3 (2021): 1326-1379.

[11] Lee, Jechan, et al. "Bioenergy generation from thermochemical conversion of lignocellulosic biomass-based integrated renewable energy systems." Renewable and Sustainable Energy Reviews 178 (2023): 113240.

[12] Reddy, B. V., and T. Srinivas. "Biomass based energy systems to meet the growing energy demand with reduced global warming: role of energy and exergy analyses." 2013 International Conference on Energy Efficient Technologies for Sustainability. IEEE, 2013.

[13] Hosseini, Seyed Ehsan, et al. "A review on biomass-based hydrogen production for renewable energy supply." International journal of energy research 39.12 (2015): 1597-1615.