Biomass: A Sustainable Vector for Next-Generation Renewable Energy Systems

Dr Mousumi Bhattacharjee James
Assistant Professor, New Horizon Institute of Technology and Management, Thane

***Abstract*—Renewable energy has moved from being a choice to becoming imperative for our planet's survival. This was once optional, but it is now essential—clean energy is the cornerstone of a sustainable future. In today's climate reality, renewables aren't optional—they're indispensable.The shift to renewable energy is no longer a trend; it's a global obligation. As the planet faces mounting climate pressures, resource depletion, and energy inequities, transitioning to clean sources is the only path forward that balances economic growth, environmental preservation, and social well-being. In a world increasingly defined by its energy choices, renewable energy offers a rare intersection of innovation, sustainability, and equity. It is not just about power—it is about empowerment, better and smarter options. Biomass stands out as a versatile and sustainable renewable energy source that bridges the gap between waste management and clean energy production. Its ability to convert organic residues—ranging from agricultural by-products to municipal waste—into electricity, heat, and biofuels makes it a practical solution for both rural and urban energy needs.Though choices are multiple, the current review discusses biomass energy as an option fueling the next generation of green innovation. The various aspects of the same will be discussed here and why it can be considered as powering a sustainable tomorrow, to bring about a renewable revolution.The history of biomass, Biomass as a promising renewable energy option, the environmental impacts of biomass and much more is reviewed**.

***Index Terms*—Biomass, Environment, Fuel, Renewable energy, Sustainable**.

I. INTRODUCTION

Renewable energy isn't just a smart option anymore; it's now a global necessity. As the planet faces mounting climate pressures, resource depletion, and energy inequities, transitioning to clean sources is the only path forward that balances economic growth, environmental preservation, and social well-being. In a world increasingly defined by its energy choices, renewables offer a rare intersection of innovation, sustainability, and equity. They are not just about power—they're about empowerment, better and smarter options. Researchers working on environmental aspects have stated that renewable energy is imperative to fight climate change and global warming. The use of clean energy and renewable energy resources originates in early human history; how the world has harnessed power from these resources to meet its energy needs has evolved over time. Today, this urgent need for research and reviewing options in renewable energy resources have found a unanimous voice.There is an array of options like solar energy, wind energy, hydro power, biomass, tidal energy, geothermal energy and the emerging green hydrogen energy. Though choices are multiple, the current review discusses biomass energy as an option fueling the next generation of green innovation. The various aspects of the same will be discussed and why it can be considered as powering a sustainable tomorrow, to bring about a renewable revolution.

Biomass energy is gaining serious traction as a versatile and sustainable contender in the future of renewables. As the global perspective races toward clean energy solutions, biomass stands out as a powerhouse rooted in nature and innovation. By transforming agricultural residue, forestry byproducts, and organic waste into reliable energy, biomass bridges the gap between rural abundance and urban demand. It not only fuels industries and households—it fuels livelihoods, resilience, and circular economies. Biomass is continuously reducing carbon footprints while empowering communities. Biomass is not an alternate energy source—it can rather be stated as the fuel source for shaping a sustainable and more inclusive tomorrow.

Biomass, as defined by recent sources (1), is any organic matter that can be used as an energy source. Wood, crops, yard, and animal waste are examples of biomass. People have used biomass longer than any other energy source. For thousands of years, people have burned wood to heat their homes and cook their food. Biomass gets its energy from the sun. Sunlight is absorbed by plants by a process called photosynthesis. Plants make carbohydrates from sunlight, air, water, and nutrients from the soil. As human civilization expands, resulting in the substantial growth of the economy globally, resource and environmental issues become extremely essential, posing the two most significant challenges to global growth. Newer energy systems and renewable energy concepts have been considered as the focus of a newer industrial trend and development. All countries across the globe are looking for new types of energy that are sustainable and clean and can replace conventional fossil fuels, and the development of new energy and renewable energy has been regarded as the focus of a new trend of industry promotion and development. Biomass energy is a renewable resource that can be converted into three stages of fuel: gas, liquid, and solid (2, 3).

II. HISTORY OF BIOMASS ENERGY

As rightly stated in one of the research papers, Biomass is the first-ever fuel used by humankind and is also the fuel that was the mainstay of the global fuel economy till the middle of the 18th century. Later, fossil fuels gained importance as they were not only more abundant and denser in their energy content, but also caused less pollution when they were burned. In recent years, there has been a resurgence of interest in biomass energy because biomass is perceived as a carbon-neutral source of energy (4). The history of Biomass energy goes long before the term "renewable energy" was even coined. In the primitive era, humans used wood fires for cooking and warmth, making biomass one of the first energy sources ever utilized. Over time, biomass evolved beyond simple burning. Early civilizations (e.g., Mesopotamia, Indus Valley, ancient China) used firewood as their main source of energy. Until the Industrial Revolution, biomass was the dominant source of energy across the world. In rural areas, people used charcoal, peat, and agricultural waste in addition to wood. In medieval Europe, deforestation due to the overuse of wood led to increased use of coal. By the 19th century, people were experimenting with ethanol and vegetable oil as fuel sources. Today, biomass includes everything from crop residues to organic waste, helping to reduce reliance on fossil fuels. In the 18th and 19th centuries, coal and later oil replaced biomass as the primary energy sources in industrialized countries. Biomass continued to be widely used in less developed regions for household energy needs.

By the mid-1800s, wood contributed to 90 percent of the energy Americans used. Biomass is currently the most frequent form of renewable energy, and its usage is further increasing due to the devastating impacts of fossil fuel consumption. People have used biomass for energy from living things since the earliest Homo sapiens first lit up wood fires for cooking or keeping themselves warm. Today, biomass is being used to fuel a large number of machines. Research enumerates the global status of biomass vs. other renewable energies (5). Similarly, another such study (6) stated that this mainly addresses biodiesel, biogas, biohydrogen, biofuel cell, and so on. By identifying global hotspots in biomass energy research, this study is beneficial for researchers, e.g., the selection of future research topics. Similarly, policymakers will learn from the findings of this analysis with a good understanding of the status quo of biomass energy development. Modern bioenergy research paved the way for alternative sources of energy. After the oil crises of the 1970s, interest in renewable energy, including biomass, grew. Scientists began to explore ways to convert biomass into biofuels (e.g., ethanol from corn or sugarcane, biodiesel from vegetable oils). In the 21st century, the grave concerns about sustainability urged scientists and researchers to move away from the comforts of fossil fuels to alternative energy sources. Biomass re-emerged as part of the global push for sustainable energy and climate change mitigation. Technologies like biogas plants, wood pellet stoves, waste-to-energy systems, and advanced biofuels are now being used worldwide. Today, biomass contributes to renewable energy targets in many countries. A study mentions (7). In their study of the need for biogas for global sustainability, they concluded that a need for research into processes for production should be initiated so that efficient anaerobic biodegradation of these resources could be facilitated.

III. LITERATURE REVIEW

A critical review on the environmental impacts of renewable energy systems (8). This study provides an in-depth discussion of various renewable energy systems. The Environmental impact of renewable systems is analysed. Further, they also evaluated the prospects of renewable technology. The Limitation of renewable systems was also presented. A very recent study laid down (9) This study expressed the growing awareness of and the importance of transitioning to sustainable energy sources from conventional energy, further they emphasized the necessity of fostering business optimism toward renewable energy, as businesses wield significant need of transitioning to long term renewable energy sources, as business confidence and energy consumption dynamics influence renewable energy development.

A study discussed the composition of biomass, which is one of the many studies done on this subject (10). Their findings showed that the chemical composition of biomass is quite variable, as was determined by proximate, ultimate, and ash analyses. An important research study established (11). The study analysed the environmental impacts of bioenergy systems based on the objectives of the European Union (EU) policy agenda to reduce greenhouse gas emissions and to decrease the dependence on fossil fuel sources. As a result, the number of biomass power plants has increased to achieve these policy objectives over the last decades. One such research enumerates (12) that biomass contributes a large amount of renewable energy, and further, there is considerable scope to modernize biomass energy production delivery systems to provide varied energy carriers such as electricity, liquid fuels, and gases. Successful case studies for traditional and modern biofuels in a number of countries are presented. Economic, social, and environmental issues could be examined over the whole biomass energy spectrum.

A study mentioned earlier in this article (4) took stock of the various sources of biomass and the possible ways in which it can be utilized for generating energy. After this, it examines the environmental impacts, like greenhouse gas emissions, of different biomass energy generation–utilization options. Another article (13) stated that Biomass accounts for 35% of primary energy consumption in developing countries. They further stated that in the future, biomass can provide an economical and sustainable alternative energy, while at the same time aiding countries in meeting their greenhouse gas reduction targets. By the year 2050, it is estimated that 90% of the world population will live in developing countries, and hence, the need for the utilization of biomass energy will escalate.

An overview of biomass usage in the US (14) summarizes reports prepared for the U.S. Environmental Protection Agency (EPA) by researchers at the U.S. Department of Energy's (DOE) Oak Ridge National Laboratory (ORNL). The conclusions drawn from a Biomass Energy Strategies Workshop conducted at ORNL, the Biofuels Feedstock Development Program (BFDP), have largely concentrated on the development of dedicated biomass feedstocks, referred to as energy crops. Two common types of energy crops have gained the maximum attention: short-rotation woody crops and herbaceous energy crops. These cropping systems use traditional food production technologies as a means of maximizing the production of biomass per unit of land.

On the other hand, there are certain studies which emphasize the cons of biomass energy. One such study stated that the global potential for biomass energy production is large in absolute terms, but it is not enough to replace more than a few percent of current fossil fuel usage. Increasing biomass energy production beyond this level would probably reduce food security and initiate the process of climate change (15).

Recently, a study (16) showed that recent advances in ANN (Advancements in artificial neural networks) applied to biomass fast pyrolysis under the convergence of ML with bioenergy production. Bibliometric analysis shows that the growth of research activity has accelerated from an average of 2.05 publications per year for the period 1994–2013 to 24.4 publications per year for the period 2014–2023. Key findings show that ANN models are able to predict pyrolysis results with a high degree of accuracy. Earlier, a study (17) laid down that while biomass is attractive as a renewable, low-sulfur fuel, the utilization of biomass as an energy resource is not without potential environmental impacts. They further stated that the environmental impacts from biomass

production and conversion can be minimized if more careful planning and conservation practices are implemented, appropriate environmental control technology is employed, and better utilization of any by-products produced is done. A very detailed study (18) laid down the basis of biomass production through the process of photosynthesis and its resulting composition and characterization that determine the different biomass types and classification. This chapter provides a detailed review of the different biological resources at a larger scale, focusing on their integral characteristics, systems of production, actual use, and suitability for bioenergy purposes. Primary biomass from the agricultural and forestry sector, algae biomass, as well as residual biomass and wastes, as sources of energy, are addressed.

The pertinence of renewable energy is gaining limelight as the use of renewable energy sources is becoming increasingly necessary, if we are to achieve the changes required to address the impacts of global warming, a study emphasized (19) that the use of biomass, as a conventional energy source for the third world, can play a important role in helping the developed world reduce the environmental impact of burning fossil fuels to produce energy but only if related areas of replanting were implemented immediately. Biomass is recognized as a legitimate renewable energy source and is regarded as a viable strategy for mitigating global warming by substituting for fossil fuel consumption. An important literature recently published (20) stated that Biomass has become a key contender in the race to find sustainable energy options, as we move toward a more environmentally friendly future. This extensive assessment explores the potential of biomass to transform the global energy landscape. They highlighted the adaptability of biomass for the production of energy, heat, and biofuels. Furthermore, they evaluated the socioeconomic and environmental impacts of biomass, including greenhouse gas emissions, land use, and community effects. They stated that, to increase the potential of biomass as a renewable energy source, it is essential to understand how these three factors interact. To maximize energy production while curtailing environmental problems, this review examines obstacles, ongoing research, and recent developments in effective biomass-based energy systems.

IV. BIOMASS FEEDSTOCK

Biomass comes from a wide variety of organic materials—essentially anything recently living that can be used as fuel. They can be enumerated as Wood and wood residues like firewood, wood chips, sawdust, and by-products from lumber and paper industries, like black liquor. Crops and residues such as Corn, sugarcane, soybeans, switchgrass, and crop leftovers like husks and stalks are commonly used for biofuel production. Dedicated energy crops can also serve as biomass feedstock. Fast-growing plants like miscanthus, bamboo, and hybrid poplar are cultivated specifically for energy use, often on marginal land. Municipal solid waste (MSW) with Biodegradable components of household and industrial waste—like food scraps, paper, and yard trimmings—can be converted into energy. Animal manure and sewage are used in anaerobic digesters to produce biogas, a renewable form of natural gas. Algae are a promising source due to their rapid growth and high oil content; algae can be used to produce biodiesel and other biofuels. A review discusses the Significance and Challenges of Biomass as a Suitable Feedstock for Bioenergy and Biochemical Production (21)

V. BIOMASS POWERING A SUSTAINABLE TOMORROW

Biomass holds immense potential as a sustainable energy source because it bridges the gap between waste management, energy security, and climate action. Biomass energy plays a vital role in the transition towards a cleaner, greener, and more sustainable future. As a renewable energy source derived from organic materials such as plant residues, agricultural waste, forestry byproducts, and even animal waste, biomass offers immense potential to meet growing energy demands while minimizing environmental impact.

There are abundant reasons why Biomass is Key to Sustainability. First and foremost, it is Renewable and Abundant that Biomass can be continuously replenished through sustainable agricultural and forestry practices. Next and very importantly, Biomass has Carbon Neutrality, which implies that when managed properly, the carbon dioxide released during biomass combustion is offset by the carbon absorbed during plant growth, contributing to a balanced carbon

cycle. Furthermore, it effectively converts Waste to energy, which means Biomass utilizes waste materials that would otherwise contribute to pollution or landfill burden, turning them into valuable energy. It can effectively promote rural Development because Biomass energy promotes local economies, providing jobs and supporting farmers and forest communities. More importantly, foreseeing a brighter tomorrow, it can cause a Reduction of Greenhouse Gas Emissions, which means Biomass helps combat climate change by lowering reliance on coal, oil, and natural gas. It can give Energy Security by diversifying the energy mix, and biomass enhances energy independence. Advancements in biomass technology, such as gasification, anaerobic digestion, and second-generation biofuels, are making biomass energy cleaner and more efficient. Integrating biomass with other renewables (like solar and wind) and smart grids will further enhance its role in achieving global sustainability goals. Depletion of conventional fuel resources and environmental concerns have become the driving force to explore an environmentally friendly, renewable, economical, and sustainable alternative energy source. In this context, a research paper discussed the possibility of utilizing agricultural biomass as a renewable energy source for the future (22). Such studies will be beneficial to help stakeholders, energy managers, and decision makers working in the sustainable and renewable energy sectors to consider agricultural biomass for energy production at a larger scale.

Another such study (23) establishes a lot about why Biomass holds potential for a sustainable future. They stated that analyzing the amount of existing research, it was found that about 50% renewable energy records available were bioenergy records. Further, they stated that the publications on each of the four main sources of biomass (agriculture, forest, wast,e and other) represent about one quarter of bioenergy records retrieved. Biomass – the fourth largest energy source after coal, oil, and natural gas - is the largest and most important renewable energy option at present and can be used to produce different forms of energy. An in-depth study focuses on how biomass is a promising renewable energy option (24). They stated that the world's population continues to grow at a high rate, such that today's population is twice that of 1960, and is projected to increase further to 9 billion by 2050. As a result, a situation arises in which the percentage of global energy being used by cities is quite high. Biomass is a resource that is present in a variety of different materials such as wood, sawdust, straw, seed waste, manure, paper waste, household waste, wastewater, etc. The economic potential of biomass is the reason behind its usage conventionally and gaining importance, the annual volumes of agricultural production, whose by-products can be used as a source of energy and are even being promoted as so-called energy crops, specifically for this purpose. The bibliometric analysis concluded that the main countries investigating the subject of biomass as renewable energy production are the United States, followed by China, India, Germany, and Italy, as large countries in number of inhabitants are interested in the use of new renewable energy sources such as the use of biomass.

VI. BIOMASS ENERGY AND ECOLOGICAL IMPACT

Biomass and the environment are deeply interconnected, offering both opportunities and challenges for sustainability. The Positive impacts are that Biomass is a renewable energy source, often considered carbon-neutral because the CO_2 released during combustion is roughly offset by the CO_2 absorbed during plant growth. (25) . Secondly, it can reduce dependence on fossil fuels and help manage organic waste through energy recovery (26). The net flow of CO2 to the atmosphere could be effectively reduced by replacing fossil fuels with sustainably produced biomass. Though there are certain environmental concerns, like burning biomass can still release pollutants like carbon monoxide and particulate matter, especially if not properly managed. Further unsustainable harvesting may lead to deforestation, soil degradation, and biodiversity loss.

VII. CONCLUSION

Biomass stands out as a versatile and sustainable renewable energy source that bridges the gap between waste management and clean energy production. Its ability to convert organic residues—ranging from agricultural by-products to municipal waste—into electricity, heat, and biofuels makes it a practical solution for both rural and urban energy needs. When managed responsibly, biomass can be nearly carbon-

neutral, as the carbon dioxide released during combustion is offset by the carbon absorbed during the growth of the biomass itself. Moreover, it supports energy diversification, reduces reliance on fossil fuels, and promotes circular economy principles by turning waste into value. However, its long-term viability hinges on sustainable sourcing, efficient conversion technologies, and robust policy support. With continued innovation and environmental safeguards, biomass can play a pivotal role in the global transition to a low-carbon energy future. Moreover, more and more research is required to develop the technology of production, refining, sourcing, and even transportation of this fuel so that biomass can be seen powering the global future of renewable energy.

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REFERENCES

[1] Elliot Clark, what is Biomass? Energy Theory,November 17, 2023

[2] M. E. Bildirici, “Relationship between biomass energy and economic growth in transition countries: Panel ARDL approach,” GCB Bioenergy, 2014.

[3] From The Past to the Future, Research on Biomass Energy and the Environment, Santosh Kumar Singh, JETIR November 2018, Volume 5, Issue 11.

[4] Tasneem Abbasi, S.A. Abbasi, Biomass energy and the environmental impacts associated with its production and utilization, Renewable and Sustainable Energy Reviews, Volume 14, Issue 3, April 2010, Pages 919-937.

[5] A review on biomass: Importance, chemistry, classification, and conversion, June 2019, Biofuel Research Journal 6(2):962-97

[6] Guozhu Mao, Hongyang Zou, Guanyi Chen, Huibin Du, Jian Zuo, Past, current and future of biomass energy research: A bibliometric analysis, Renewable and Sustainable Energy Reviews, Volume 52,2015, Pages 1823-1833, ISSN 1364-0321.

[7] Bond, Tom & Templeton, Michael. (2011). History and future of domestic biogas plants in the developing world. Energy for Sustainable Development. 15. 347–354.

[8] A critical review on environmental impacts of renewable energy systems and mitigation strategies: Wind, hydro, biomass and geothermal, Enas Taha Sayed, Tabbi Wilberforce, Khaled Elsaid, Malek Kamal Hussien Rabaia, Mohammad Ali Abdelkareem, Kyu-Jung Chae, Science of The Total Environment Volume 766, 20 April 2021, 144505.

[9] Irsan Hardi, Ghalieb Mutig Idroes, Yoshihiro Hamaguchi, Muhlis Can, Teuku Rizky Noviandy, Rinaldi Idroes, Business confidence in the shift to renewable energy: A country-specific assessment in major Asian economies, Journal of Economy and Technology, 3, (44-68), (2025).

[10] An overview of the chemical composition of biomass, Stanislav V. Vassilev, David Baxter, Lars K. Andersen, Christina G. Vassileva, Fuel Volume 89, Issue 5, May 2010, Pages 913-933.

[11] Assessment of environmental impact of biomass power plants to increase the social acceptance of renewable energy technologies, Paletto, Alessandro et al., Heliyon, Volume 5, Issue 7, e02070, July 2019.

[12] D.O. Hall, Biomass energy, Energy Policy, Volume 19, Issue 8, October 1991, Pages 711-737.

[13] Mustafa Balat & Günhan Ayar, Biomass Energy in the World, Use of Biomass and Potential Trends, Energy Sources, Volume 27, 2005 - Issue 10.

[14] William G. Hohenstein, Lynn L. Wright, Biomass energy production in the United States: an overview, Biomass and Bioenergy, Volume 6, Issue 3, 1994, Pages 161-173.

[15] Biomass energy: the scale of the potential resource, Field, Christopher B. et al., Trends in Ecology & Evolution, Volume 23, Issue 2, 65 - 72.

[16] Khaoula Laouidi a, Sanae Habchi b, Casimir Kalibe Fanezoune b, Brahim Sallek a, Nataliia Kussul c, Hassan El Bari , Advancements in artificial neural networks and fast pyrolysis of biomass processing: A comprehensive review and a bibliometric analysis, Journal of Analytical and Applied Pyrolysis, Volume 189, August 2025, 107098.

[17] Judy L. Trimble, Robert I. Van Hook, A. Gray Folger, Biomass for energy: the environmental issues, Biomass, Volume 6, Issues 1–2, 1984, Pages 3-13.

[18] Javier Sánchez, María Dolores Curt, Nicolas Robert, Jesús Fernández, Chapter Two - Biomass Resources, The Role of Bioenergy in the Bioeconomy, Resources, Technologies, Sustainability and Policy, 2019, Pages 25-111.

[19] Peter McKendry, Energy production from biomass (part 1): overview of biomass, Bioresource Technology, Volume 83, Issue 1, May 2002, Pages 37-46.

[20] Farhad Ali, Asadullah Dawood, Akbar Hussain, M Hisham Alnasir, Muhammad Asad Khan, Tehmeena Maryum Butt, Naveed Kausar Janjua & Anum Hamid, Fueling the future: biomass applications for green and sustainable energy, Published: 17 July 2024, Volume 5, article number 156, (2024).

[21] Richard Ahorsu,Francesc Medina, Magda Constantí, Significance and Challenges of Biomass as a Suitable Feedstock for Bioenergy and Biochemical Production: A Review, Departament d'Enginyeria Química, Universitat Rovira i Virgili, 43007 Tarragona, Spain, Energies 2018, 11(12), 3366)

[22] Saleem, Muhammad, Possibility of utilizing agricultural biomass as a renewable and sustainable future energy source, Heliyon, Volume 8, Issue 2, e08905, February 2022.

[23] Global Potential of Sustainable Biomass for Energy, Svetlana Ladanai Johan Vinterbäck, SLU, Swedish University of Agricultural Sciences Department of Energy and Technology, Rapport, Institutionen för energi och teknik, SLU, Report 2009.

[24] Biomass as Renewable Energy: Worldwide Research Trends, Miguel-Angel Perea-Moreno, Esther Samerón-Manzano, Alberto-Jesus Perea-Moreno, Sustainability 2019, 11(3), 863.

[25] Roadmap to sustainable carbon-neutral energy and environment: Can we cross the barrier of biomass productivity?Pankaj Kumar Maurya, Soumila Mondal, Vinod Kumar & Shailendra Pratap Singh, Environmental Science and Pollution Research, Volume 28, pages 49327–49342, (2021).

[26] Leif Gustavsson, Pal Borjesson, Bengt Johansson, Per Svenningsson, Reducing CO2 emissions by substituting biomass for fossil fuels, Leif Gustavsson, Pal Borjesson, Bengt Johansson, Per Svenningsson, Energy, Volume 20, Issue 11, 1995, Pages 1097-1113)