Journal of Scientific and Technical Research
15 (1) 2025, 154-161
www.publishingindia.com/jstr

An Overview on Waste Biorefineries for Sustainable Development

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Abstract: A major part of the sustainable and regular waste management hierarchy is energy reproduction and creating the usable product through many waste capitals to support the concept of circular economies with appropriate framework and to minimize the challenges of waste originated problems of sanitation, environment, and public health. Because of limited funds and inadequate infrastructure and facilities to sustain effective and technical global standards, waste discarding of any item to landfills is usually employed approach in today's globe, especially in poor countries. Consequently, the dump-sites or non-sanitary landfills have become the main causes of greenhouse gas emissions, soil and water contamination, bad smells, leachate, and disease carrying vectors, flies, and rats. Still, if properly and sensibly controlled, trash can be a possible source of fuels, energy, and value-added goods.

Keywords: Circular bioeconomy, Green products, Biomass, Biorefineries, Waste product.

I. Introduction

The world's current population is 8.2 billion as of May 2025; nonetheless, daily numbers are increasing and by 2057 they should reach 10 billion [1]. Unprecedented problems with environmental degradation, climate change, resource depletion, and growing global waste generation define the twenty-first century. Based on the "take-make-dispose" paradigm, conventional linear economic models have produced unsustainable patterns of production and consumption with major effects on society and the ecology [2]. These difficulties have led to increasing worldwide agreement on the need of moving towards more sustainable systems. The idea of the circular bioeconomy is among the most interesting ones since it combines the ideas of circular economy and bioeconomy to support sustainable resource use, waste minimisation, and renewable bio-based manufacture [3]. Development and application of waste biorefineries integrated systems that transform several waste sources into valuable bio-based products including bioenergy, biofuels, chemicals, minerals, and fertilizers at the core of this change is Waste biorefineries, unlike conventional waste treatment plants, use a systems-thinking approach stressing the whole valorising of organic and inorganic wastes using environmentally friendly and economically feasible technology [4]. Waste management and bio-based production help to provide sustainable industrial practices and renewable energy in addition to helping to reduce waste and regulate pollution. Under this paradigm, biorefineries have drawn interest as a flexible and possible substitution for negative-valued petroleum and fossil fuel-based waste refineries where biomass of uneatable feedstock and biogenic waste as raw materials produce a variety of products including biofuel, industrial biochemicals, and biomaterials with commercially important biopolymers [5, 6].

Fig. 1 shows the evaluation instruments for the circular bio-economy including biorefineries. In turn, these worldwide challenges demand quick and significant solutions so that the human race may solve the waste spreading and waste handling problem [7] and circular bio-economy might be rather helpful in addressing these problems.

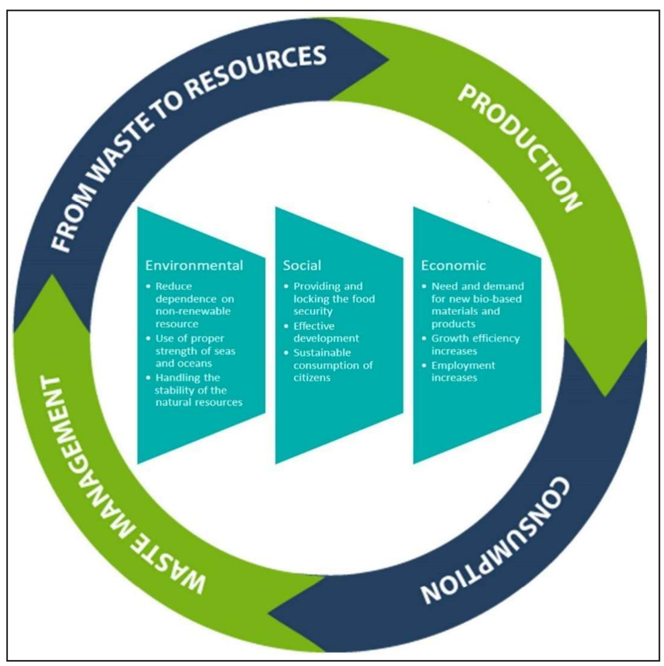

Fig. 1: Assessment Tool for Circular Bioeconomy

The circular bioeconomy, also referred to as the bio-based circular economy, is a crucial and beneficial concept in the context of the bioeconomy and circular economy. It denotes the continuous and systematic utilisation of biomass from biological resources to facilitate the growth of the economy. This circular bioeconomy enables the sustainable production of biomass, which includes waste and side streams, and reduces environmental contamination [8, 9]. The advantages of a circular bioeconomy include the following: a) reduced greenhouse gas emissions, b) the valuing of waste products and materials from a variety of sources, c) the enhancement of eco-efficiency in resources, and d) the reduction of environmental contamination. Enriquez initially proposed the concept of bioeconomy in 1998, which underscored the significance of genomics and the genome. During the early 20th century, the bioeconomy attracted significant attention and compelled Europe to adopt it as a policy that was in motion, thereby increasing awareness of sustainability [10-13]. The circular bioeconomy employs biomass as a critical component in the production of a variety of bio-products, bioenergy, bio-fuels, and biochemicals in a biorefinery, following the circular economy structural process [14, 15].

A. Concept and Scope of Waste Biorefineries

A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, heat, and value-added chemicals from biomass. When the feedstock primarily consists of waste materials — such as food waste, crop residues, lignocellulosic biomass, sewage sludge, and industrial by-products — the system is termed a waste biorefinery. The core objective is to replicate the operational model of petroleum refineries but with sustainable and circular inputs and outputs.

Integrated waste biorefineries extend this concept further by incorporating multiple technologies, feedstocks, and product streams within a single framework. Such integration facilitates:

- Enhanced process efficiency,
- Improved economics through co-product valorization,
- Reduced environmental impact through closed-loop systems,
- Decentralized and modular operations adaptable to local waste availability.

The versatility of waste biorefineries allows them to be tailored to regional conditions, enabling the production of a wide spectrum of bio-based products aligned with market demand and resource availability.

B. Role in the Circular Bioeconomy

By encouraging sustainable production and consumption of biological resources inside closed-loop systems, the circular bioeconomy seeks to divorce economic growth from environmental degradation. Three fundamental ideas—renewable resource use, waste minimisation and reuse, and regenerative systems that help to restore natural ecosystems—are underlined here. Actually realising this goal depends mostly on waste biorefineries. Conversion of biological waste streams into energy, chemicals, and materials helps them to create circular value chains from linear waste flows, as for example:

- Agricultural residues can be converted into bioethanol, bioplastics, and biofertilizers.
- Food waste can be digested anaerobically to generate biogas and nutrient-rich digestate.
- Sewage sludge can be valorized into biocrude oil and biosolids for soil amendment.

Furthermore, waste biorefineries promote nexus thinking, linking sectors such as waste management, energy, water, agriculture, and manufacturing. This interconnectedness creates opportunities for industrial symbiosis, wherein the waste or by-products of one industry serve as feedstock for another, fostering resource efficiency and economic resilience.

II. Bio-Refinery and Biomass Production

Bio-refining is one of the most vital and chief path to simplify the concepts and approaches of the circular bioeconomy that fix and grips the series between fresh and raw resources, mineral, water and carbon.

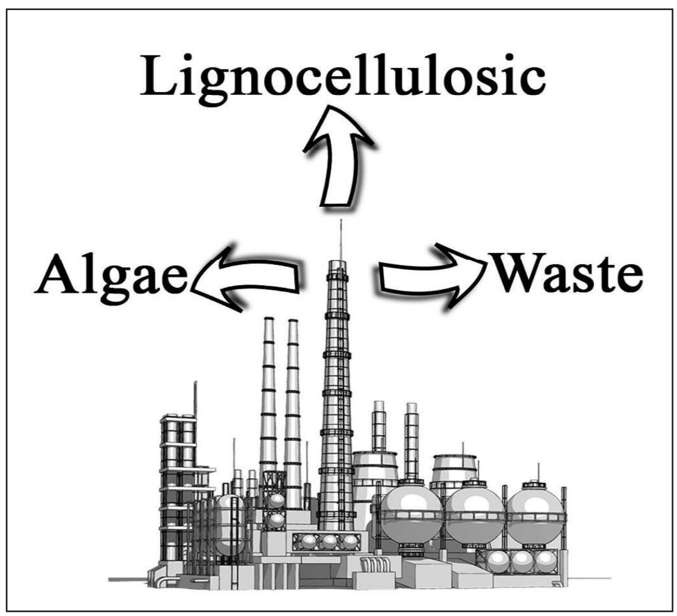

Fig. 2: Major Types of Biorefineries

The sustainable procedure that efficiently uses biomass grounded resources for the manufacturing of several commercialised goods and metabolites for example: lipids, carbohydrates, proteins, bioactive compounds, biochemicals and biomaterials [16-18] are known as a “biorefinery”. Because they offer a suitable and relevant waste management channel, biorefineries attract much more attention [19-21].

As demonstrated in Fig. 2, this idea developed and applied to process more biomass feedstocks including lignocelluloses, algae and several kinds of wastes.

III. Waste Biorefinery

Although the expanding population of the planet Earth is regarded as a main concern nowadays, we also have to take into account growing waste in the form of solid (unwanted material, used goods), liquids (unwanted liquids, cleaned liquids), and combination of both compounds, semi-solids and liquids. In order to manage, recycle, and reuse the trash produced by the population, several researchers in the relevant subject have examined several technologies of valorisation. Nowadays, several biorefineries are designed to transform this waste into a rich supply of renewable feedstock, therefore generating energy and value-added goods. It falls into food, biomass (agricultural), industrial and municipal garbage [22-25].

A. Food Waste

Main in the organic component of municipal solid waste, food waste belongs to the category of waste biorefinery [26]. Majorly generated food waste comes from food production and distribution; as the planet's population is rising, so is the food waste. The most evolved handling techniques for food waste disposal are composting, landfilling, and manufacturing of animal feed [27]. Apart from established environmental issues, these methods appear to be rather expensive and generate rather low value-added goods. Recent studies contend that food waste can be either fuel or nutritious source. Examples involving food waste valorising deal with compounds extraction utilising hydrolysis and the synthesis of bio-based chemicals [28]. Other biotechnologies using and producing bioenergy products from food waste are enzymatic and thermal conversion systems [29-31]. Still, there are few studies confirming the practicality of valorising techniques. Still need performance in marketability, profitability, and economies of scale [32].

B. Solid Waste

Solid wastes' detrimental effects on the environment and human health have long been a concern for the populace and the government, particularly in highly urbanised areas. In order to achieve the ultimate aim of a zero-waste economy, the circular economy model has also drastically altered the way trash is handled and treated, moving away from traditional disposal and recycling methods and towards highly usable utilisation methods [33]. The source, collecting method, and social surrounding activities of a given area have a significant impact on the composition of municipal solid trash [34]. Over the years, there has been a lot of interest in creating new policies to address the current problem of dynamically regenerating energy in different fields or separating these substances and converting them into beneficial environmental effects or possible economic revenue due to the presence of different substances in municipal solid waste watercourses. For example, the organic matter found in municipal solid trash has shown promise as a free energy source since it doesn't cost more compared to other biomass materials that need to be grown and harvested [35]. A technical conversion technique for producing heat, chemicals, and energy from municipal solid waste is incineration [36]. Additionally, studies have been conducted to try to efficiently measure and recover precious metals, particularly from electronic trash [37, 38]. Operative process design and integration to produce multiple bioproducts, including chemicals, metals, energy, and fertilizers, have been confirmed to exhibit viability in terms of techno-economic aspects, despite the fact that the effective retrieval of desired substances in municipal solid waste has been restricted due to their inherent impurities [39-41].

C. Biomass (Agricultural Waste)

Biorefineries have also been researched for manufacturing biochemicals and biofuels from agricultural wastes such bagasse, grapeseed, corn stover, olive mills, fruit and vegetable scraps and manure. The previous assessment found that these feedstocks are mostly used to make low-value compounds like energy and fertilizers [42, 43]. These materials economical advantages have just recently pushed research into using their extra biochemicals [44]. The majority of them are lignocellulosic biomass, so they can be rejuvenated into biocompounds and useful bioproducts. Thus, these materials have been pretreated, fractionated, and bioactive chemical isolated using lignocellulosic feedstock procedures. Solvent, ultrasonic, microwave, and supercritical fluid extraction technologies are used [45]. These methods are also being linked with profitable businesses like first-generation biofuel facilities to improve sustainability [46].

D. Industrial Waste

Byproducts and wastewaters from the last process increase with any main industrial product's demand, requiring treatment or recycling. Biodiesel factories produce glycerol with high impurities, which lowers its value [47]. Wastewater from metals and mining processes is also produced in large quantities [48]. Circular economy policies and incentives encourage several sectors to study or implement waste usage and treatment methods. Methods for efficiently and effectively recovering valuable pharmaceuticals from byproducts and wastewater are also of interest since they allow for further research [49]. Bioactive chemical extraction and biomaterials synthesis have been shown in numerous industrial wastes, including glycerol [50], beetroot pulp [51], and paper [52]. Industrial symbiosis, when one company uses its wastes as raw material for another, can reduce their dependence on natural resources [53]. Bioeconomy expertise has also enabled cogeneration, which would allow the private sector to diversify products, solve waste distribution, and improve product environmental performance. Although logistical and budgetary difficulties have always prevented their true deployment, technology advances to optimise systems and processes are expected to boost productivity [54].

IV. Green Products from the Waste Bio-Refineries

The several technologies have been established to minimize the waste problem resulting from factories, businesses, and other spheres of innovation. Using the several forms of garbage transformed into valuable products utilised in daily life and so minimising the negative impact on the environment, the waste biorefineries are playing a significant part in decreasing the difficulties into key. With rising waste generation value, Earth by 2057 reaches the 10 billion population and preserves the environmental value required to design new plans with consecutively capacity of technologies. For the conversion of biomass into bioenergy, waste biorefinery applies multiple techniques, however, different kinds of bio-based products are represented in Fig. 3.

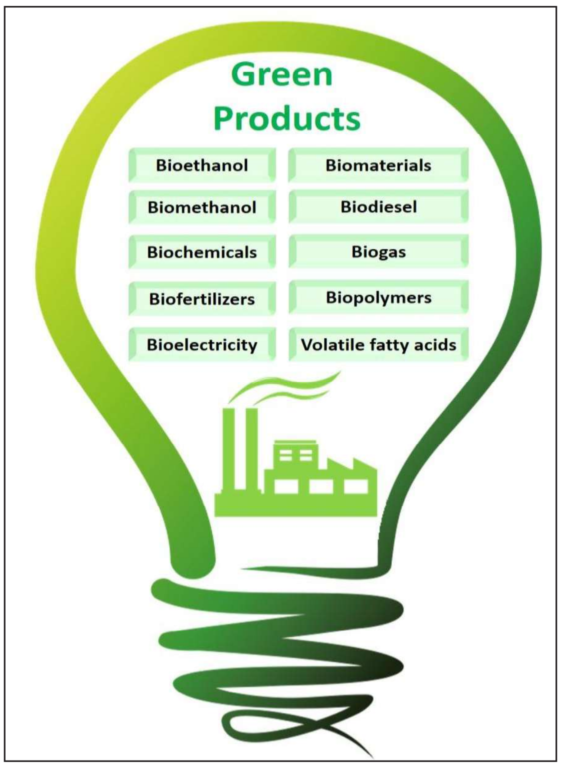

Fig. 3: Green Products from the Waste Biorefinery

A. Bioethanol

The worldwide ethanol production demand exceeded 100 billion litres in 2015 and is continuously increasing to satisfy the great demand. As such, it is imperative to replace generating ethanol from fossil fuels with renewable based resources. Currently, sugarcane and maize are utilised for the manufacturing of bioethanol; they are also consumed as food and animal feed for their survival; so, they create a challenge in the form of competition since they used for both food and fuel.

Bioethanol generated worldwide to meet society's demand is global. Every nation concentrates in order to meet demand for bioethanol [56]. With tremendous hurdles, the use of the waste generated during the synthesis of bioethanol form bagasse can be ecologically and economically appropriate. Currently, relatively low concentration liquid residuals of pentoses used by the micro-organism produce bioethanol [57, 58].

B. Biobutanol

Commonly employed as solvent in the chemical process, extractant, vitamin in the health sector, elutent, precursor for other useful compounds, butyl alcohol is also bio-butanol. On the other hand, mixed with petrol, it can be used as biofuel for transportation. Low vapour pressure, no sensitivity to water, low volatility, low toxicity level and minimal flammability define the features of biobutanol. Considered a drop-in-fuel, biobutanol is of especially interest since it may immediately replace petrol. Based on the substrate used, starch-rich crops including maize, wheat, rice, cassava, grasses, trees and energy crops and algae are assigned first, second, and third generation bio-butanol synthesis [59].

C. Biodiesel

A sustainable energy source made from renewable resources is biodiesel. Chemically, biodiesel is a blend of long-chain fatty acids and methyl esters. Traditionally, a range of feedstock, such as vegetable oils, leftover cooking oils, and animal fat, are used to make biodiesel. The biodiesel industry's ability to grow further is hampered by the scarcity of these feedstocks. Organic waste may be used as a feedstock by oleaginous yeasts and fungi, particularly moulds, to synthesise lipids. Oleaginous yeast has been cultivated using a range of low-cost carbon sources—such as molasses, flour extracts, grape must radish brine, hydrolyzates of agricultural residue, distillery wastewater, municipal wastewater [60], food and feed waste, cheese whey [61], food/municipal wastewater, etc. It has been observed that certain yeast strains, including Lipomyces sp., Rhodosporidium sp., and Rhodotorula sp., can collect intracellular lipids up to 70% of their biomass dry weight.

D. Bioelectricity

Microbial fuel cell (MFC) is a sustainable and futuristic technology that is capable of converting the chemical energy of waste directly to bio-electrical energy. The microorganisms in the anode function as biocatalyst, producing reducing equivalents (electrons and protons) that help in electrochemical oxidation of organic substrate. The presence of a terminal electron acceptor (TEA) in the cathode acts as an electron driving force, helping in transfer of electrons (e-) through the external circuit, where they can be harnessed for bioelectricity production, whereas the protons (H+) are delivered to the cathode via a membrane separating the anode and cathode [62].

E. Biogas

Biogas is produced from different methods and environments. Its composition includes several factors such as the nature of the substrate used to produce biogas, and the process design. Europe is producing in large number of Mtoe in comparison of other parts of the world as shown in Fig. 4. Crops include energy crops, crop residues and sequential crops. 1 Mtoe = 11.63 terawatt-hours (TWh) = 41.9 petajoules (PJ) [63].

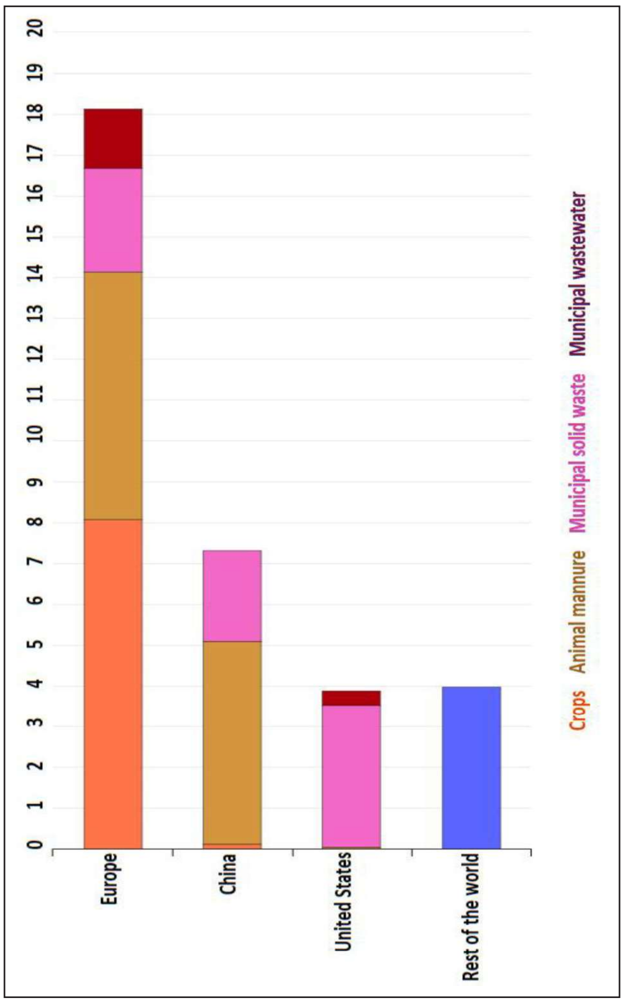

Fig. 4: Biogas Production in (Mtoe) by Region and Feedstock Type [63]

Anaerobic digestion, which is also called the biological conversion process, happens in a place without air. It has four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Several types of waste can be used as feedstock for anaerobic digestion, such as food waste, waste from farms and factories, city solid waste, wastewater, and crops. Methane and carbon dioxide are two of the main parts of biogas. Biogas is mostly made up of methane (CH_4), carbon dioxide (CO_2), nitrogen (N_2), water, and small amounts of hydrogen sulphide (H_2S).

F. Biohydrogen

Biohydrogen (H_2) is regarded as a sustainable renewable fuel, and its production from waste has garnered the attention of researchers worldwide. Biologically, H_2 can be generated through the integration of anaerobic fermentation, bio-photolysis, and photo-fermentation. The action of obligatory H_2 producing acetogenic bacteria involves the production of H_2. A diverse array of waste, including composite vegetable-based market waste, food waste, effluent, vegetable waste, and co-supplemented domestic sewage supplementation, was primarily employed to investigate biological H_2 production. Semi-pilot and pilot-scale studies have established the potential of food waste for H_2 production [64].

V. Future Perspective

The continuous discovery and development of novel processes and value-added products occurs while carrying different waste substrates and microorganisms. Along with the commercially successful green products that are currently available, there are other "rounds" of items that offer value that are just waiting to reach the same stage of development. Of course, metrics related to cost-effectiveness will play a role in this. The primary motivator for the ongoing discovery of new prospective goods, such as the biogas process, is a more accurate description of underdevelopment processes.

A. Technological Advancements and Integration

The evolution of waste biorefineries will be marked by the integration of advanced and hybrid technologies. Future biorefineries will increasingly combine thermochemical and biochemical processes to maximize resource recovery from complex and heterogeneous waste streams. For instance, integrating anaerobic digestion (AD) with hydrothermal liquefaction (HTL) or pyrolysis can enable the recovery of both energy and high-value chemicals from food waste and municipal solid waste (MSW). Moreover, emerging biotechnologies such as synthetic biology, metabolic engineering, and CRISPR-based genome editing are expected to enhance microbial pathways for efficient bioconversion of waste. The development of robust microbial consortia that can tolerate inhibitors and handle mixed feedstocks will be instrumental in improving process efficiency. Advanced reactor designs, including membrane bioreactors (MBRs) and continuous flow systems, will further contribute to scalability and process intensification.

B. High-Value Product Diversification

While biofuels remain a primary product of waste biorefineries, the future lies in product diversification. Emphasis is shifting toward producing high-value biochemicals, bioplastics, biosurfactants, nutraceuticals, and biopesticides, which offer higher economic returns and reduce reliance on fossil-derived chemicals. Platform chemicals such as lactic acid, succinic acid, 5-hydroxymethylfurfural (HMF), and levulinic acid will gain prominence due to their applicability in various industrial sectors. The integration of microalgal systems into biorefineries offers avenues for producing omega-3 fatty acids, pigments, and bioactive compounds, expanding the commercial scope of waste valorization. Moreover, the development of modular biorefineries tailored to specific end-products will support decentralized and localized production systems, enhancing community resilience and job creation.

C. Economic Viability and Business Models

To ensure long-term sustainability, future biorefineries must achieve economic competitiveness with conventional waste management and fossil-based systems. This will require optimization of capital and operational expenditures, development of circular and symbiotic business models, and exploration of novel revenue streams. The concept of industrial symbiosis, where waste from one process becomes the input for another, will be central to improving economic returns. Co-location of biorefineries with food processing units, breweries, or municipal waste facilities can reduce logistics costs and ensure consistent feedstock supply.

D. Environmental and Social Impacts

Beyond economics, waste biorefineries contribute significantly to environmental protection and social welfare. They reduce landfill dependency, lower greenhouse gas emissions, and recover nutrients, contributing to improved soil and water quality. As biorefineries evolve, life cycle assessment (LCA) and environmental impact assessments (EIA) will be essential tools to ensure that the benefits outweigh the costs. Socially, the development of biorefineries offers job creation, rural empowerment, and skill development. Future models must integrate community-based approaches, ensuring that local populations are actively involved and benefit from the value chains. Education and training programs focusing on green chemistry, biotechnology, and waste management will prepare a skilled workforce for the emerging bioeconomy.

E. Policy, Regulation, and Governance

Policy and regulatory frameworks will have a decisive impact on the trajectory of waste biorefineries. Governments must develop clear and harmonized policies that promote investment, innovation, and market access. These should include:

- Subsidies and tax incentives for green technologies,
- Feed-in tariffs and renewable energy credits for bioenergy,
- Mandates for biodegradable packaging and compostable materials, and
- Standards for waste segregation and quality control.

In the future, cross-border collaboration and international standards will become essential to address global waste management challenges. Integration of biorefineries into urban planning, smart cities, and climate mitigation strategies will enhance their visibility and uptake.

F. Research and Innovation Roadmap

Sustained research and innovation are vital for addressing the existing bottlenecks in waste biorefinery systems. Key areas of focus in the future include:

- Development of robust microbial strains with high substrate specificity,
- Low-energy and green separation techniques for product purification,
- Valorization of recalcitrant waste streams, including electronic and plastic waste,
- Use of nanotechnology in catalysis and biosensing,
- Development of bioinformatics tools for metabolic pathway optimization.

Global research collaborations and open-access data platforms will accelerate innovation by allowing knowledge-sharing and benchmarking across regions and industries.

VI. Conclusion

The extraction of fuel products derived from petroleum has resulted in a precarious scenario, which has necessitated the use of renewable energy sources that do not lead to any negative consequences. To a large extent, algae, plants, and animals are used in the production of biofuels. Plants are a source of starch, and both cellulosic and non-cellulosic macromolecules have been widely included into the production cycle of bioethanol and biobutanol. The creation of biogas and biodiesel requires the use of fats and oils derived from animals, plants, and algae as raw materials. The establishment of biorefineries and the subsequent development of their practical applications made a substantial contribution to the mechanism that facilitated the transfer of energy sectors from petrochemical to biochemical energy. Therefore, it is imperative that biorefineries that are efficient, highly productive, and have a feasible handling method be developed. This will ensure that no detrimental effects on our environment are spread, and it will also reduce the amount of climate conditions that are present. It is possible to achieve environmentally friendly processes and clean technologies through the utilisation of integrated biorefineries.

Acknowledgments

The author would like to thank Sharda University for the publication.

References

[1] https://www.worldometers.info/world-population/ Accessed: May 09, 2025.

[2] R. J. Patinvoh, O. A. Osadolor, K. Chandolias, I. S. Horváth, and M. J. Taherzadeh, *Bioresour. Technol.* vol. 224, p. 13, 2017.

[3] J. H. Clark, and F. Deswarte, *Introduction to Chemicals from Biomass*. John Wiley & Sons, 2015.

[4] S. Venkata Mohan, "Reorienting waste remediation towards harnessing bioenergy: A paradigm shift," *Ind. Wastewater Treat. Recycl. Reuse,* p. 235, 2014.

[5] https://www.macrotrends.net/countries/WLD/world/population-growth-rate/ Accessed: May 11, 2025.

[6] S. Satchatippavarn, E. Martinez-Hernandez, M. Y. L. P. Hang, M. Leach, and A. Yang, *Chem. Eng. Res. Des.,* vol. 107, p. 81, 2016.

[7] J. Sadhukhan, J. R. Lloyd, K. Scott, G. C. Premier, H. Y. Eileen, T. Curtis, and I. M. Head, *Renew. Sustain. Energy Rev.,* vol. 56, p. 116, 2016.

[8] United Nations Foundation, "5 Global issues to watch in 2020," 2020. Accessed: May 12, 2025. [Online]. Available: https://unfoundation.org/blog/post/5-global-issues-to-watch-in-2020/

[9] J. Enriquez, *Science*, vol. 281, p. 925, 1998.

[10] R. Birner, *Bioeconomy*. Springer, Cham, 2018, p. 17.

[11] C. Fund, B. El-Chichakli, C. Patermann, and P. Dieckhoff, *Bioeconomy Policy (Part II).* Synopsis of National Strategies around the World. 2015.

[12] J. Baruah, B. K. Nath, R. Sharma, S. Kumar, R. C. Deka, D. C. Baruah, and E. Kalita, *Front. Energy Res.,* vol. 6, p. 141, 2018.

[13] D. Carrez, M. Carus, M. Griffon, J. Jilkova, A. Juhász, L. Lange, and O. Consuelo Varela, "Expert group report - Review of the EU bioeconomy strategy and its action plan," 2017.

[14] M. Carus, and L. Dammer, *Ind. Biotechnol.,* vol. 14, p. 83, 2018.

[15] S. V. Mohan, G. N. Nikhil, P. Chiranjeevi, C. N. Reddy, M. V. Rohit, A. N. Kumar, and O. Sarkar, *Bioresour. Technol.*, vol. 215, p. 2, 2016.

[16] S. V. Mohan, J. A. Modestra, K. Amulya, S. K. Butti, and G. Velvizhi, *Trends Biotechnol.,* vol. 34, p. 506, 2016.

[17] S. Dahiya, A. N. Kumar, J. S. Sravan, S. Chatterjee, O. Sarkar, and S. V. Mohan, *Bioresour. Technol.,* vol. 248, p. 2, 2018.

[18] S. Mishra, M. Roy, and K. Mohanty, *Bioresour. Technol.,* vol. 292, p. 122008, 2019.

[19] https://task42.ieabioenergy.com/publications/global-biorefinery-status-report-2022. Accessed: May 15, 2025.

[20] I. A. Severo, S. F. Siqueira, M. C. Depra, M. M. Maroneze, L. Q. Zepka, and E. Jacob-Lopes, *Renew. Sustain. Energy Rev.*, vol. 112, p. 686, 2019.

[21] D. Hoornweg, P. Bhada-Tata, and C. Kennedy, *Nature*, vol. 502, p. 615, 2013.

[22] T. Bhaskar, A. Pandey, S. V. Mohan, D. J. Lee, S. K. Khanal (Eds.), *Waste Biorefinery: Potential and Perspectives.* Elsevier, 2018.

[23] A. S. Nizami, M. Rehan, M. Waqas, M. Naqvi, O. K. Ouda, K. Shahzad, and D. Pant, *Bioresour. Technol.,* vol. 241, p. 1101, 2017.

[24] G. Yadav, S. K. Dash, and R. Sen, *Sci. Total Environ.*, vol. 688, p. 129, 2019.

[25] P. R. Yaashikaa, P. S. Kumar, and S. Varjani, *Bioresour. Technol.,* vol. 343, p. 126126, 2022.

[26] E. M. Barampouti, S. Mai, D. Malamis, K. Moustakas, and M. Loizidou, *Renew. Sustain. Energy Rev.,* vol. 110, no. 298, 2019.

[27] G. Capson-Tojo, M. Rouez, M. Crest, J. P. Steyer, J. P. Delgenès, and R. Escudié, *Rev. Environ. Sci. Biotechnol.,* vol. 15, no. 3, p. 499, 2016.

[28] S. Y. Li, I. S. Ng, P. T. Chen, C. J. Chiang, and Y. P. Chao, *Biotechnol. Biofuels,* vol. 11, no. 1, p. 1, 2018.

[29] S. Banerjee, V. Ranganathan, A. Patti, and A. Arora, *Trends Food Sci. Technol.,* vol. 82, p. 60, 2018.

[30] E. Gnansounou, and A. Pandey, Book Chap., Elsevier, 2017.

[31] M. Giampietro, *Ecol. Econ.* vol. 162, p. 143, 2019.

[32] J. Cristóbal, C. Caldeira, S. Corrado, and S. Sala, *Bioresour. Technol*., vol. 259, p. 244, 2018.

[33] S. V. Mohan, S. K. Butti, K. Amulya, S. Dahiya, and J. A. Modestra, *Trends Biotechnol*., vol. 34, no. 11, p. 852, 2016.

[34] S. Maina, V. Kachrimanidou, and A. Koutinas, *Curr. Opin. Green Sustain. Chem.,* vol. 8, p. 18, 2017.

[35] G. Iaquaniello, G. Centi, A. Salladini, E. Palo, and S. Perathoner, *Chem. Eur. J.*, vol. 24, no. 46, p. 11831, 2018.

[36] E. Hytönen, and P. Stuart, *Comput. Aided Chem. Eng.,* vol. 29, p. 1376, 2011.

[37] L. S. Morf, R. Gloor, O. Haag, M. Haupt, S. Skutan, F. Di Lorenzo, and D. Böni, *Waste Manag.*, vol. 33, no. 3, p. 634, 2013.

[38] S. Rana, P. Mishra, Z. Ab Wahid, S. Thakur, D. Pant, and L. Singh, *J. Environ. Sci.,* vol. 89, p. 47, 2020.

[39] J. Sadhukhan, K. S. Ng, and E. Martinez-Hernandez, *Bioresour. Technol.*, vol. 215, p. 131, 2016.

[40] J. Sadhukhan, E. Martinez-Hernandez, R. J. Murphy, D. K. Ng, M. H. Hassim, K. S. Ng, and V. Andiappan, *Renew. Sustain. Energy Rev.,* vol. 81, p. 1966, 2018.

[41] M. Rakotovao, J. Gobert, and S. Dermine-Brullot, in *26th Eur. Biomass Conf. Exhib.,* 2018.

[42] M. K. Awasthi, S. Sarsaiya, S. Wainaina, K. Rajendran, S. Kumar, W. Quan, and M. J. Taherzadeh, *Renew. Sustain. Energy Rev.,* vol. 111, p. 115, 2019.

[43] F. Bosco, A. Casale, G. Gribaudo, C. Mollea, and G. Malucelli, *Ind. Crops Prod.,* vol. 108, p. 208, 2017.

[44] M. Lucarini, A. Durazzo, A. Romani, M. Campo, G. Lombardi-Boccia, and F. Cecchini, *Molecules,* vol. 23, no. 8, p. 1888, 2018.

[45] V. G. Zuin, and L. Z. Ramin, *Chem. Chem. Technol. Waste Valorization*, p. 229, 2018.

[46] J. A. Ferreira, P. Brancoli, S. Agnihotri, K. Bolton, and M. J. Taherzadeh, *Process Biochem.,* vol. 75, p. 173, 2018.

[47] P. Manara, and A. Zabaniotou, *Waste Biomass Valorization*, vol. 7, no. 1, p. 135, 2016.

[48] S. Maina, V. Kachrimanidou, and A. Koutinas, *Curr. Opin. Green Sustain. Chem.*, vol. 8, p. 18, 2017.

[49] T. Lotti, E. Carretti, D. Berti, M. R. Martina, C. Lubello, and F. Malpei, *J. Environ. Manag.* vol. 236, p. 649, 2019.

[50] S. C. D'Angelo, A. Dall'Ara, C. Mondelli, J. Perez-Ramirez, and S. Papadokonstantakis, *ACS Sustain. Chem. Eng.,* vol. 6, no. 12, p. 16563, 2018.

[51] M. Alexandri, R. Schneider, H. Papapostolou, D. Ladakis, A. Koutinas, and J. Venus, *ACS Sustain. Chem. Eng.,* vol. 7, no. 7, p. 6569, no. 2019.

[52] C. Adu, M. Jolly, and V. K. Thakur, *Curr. Opin. Green Sustain. Chem.*, vol. 13, p. 21, 2018.

[53] U. B. Strategy, "A sustainable bioeconomy for Europe: Strengthening the connection between economy, society and the environment," *Eur. Comm.,* 2018, Accessed: May 19, 2025. [Online]. Available: https://ec.europa.eu/research/bioeconomy/pdf/ec_bioeconomy_strategy_2018.pdf

[54] G. Kaur, K. Uisan, K. L. Ong, and C. S. K. Lin, *Curr. Opin. Green Sustain. Chem.,* vol. 9, p. 30, 2018.

[55] R. J. Wicker, G. Kumar, E. Khan, and A. Bhatnagar, *Chem. Eng. J.,* vol. 415, p. 128932, 2021.

[56] P. Kaparaju, M. Serrano, A. B. Thomsen, P. Kongjan, and I. Angelidaki, *Bioresour. Technol.*, vol. 100, p. 2562, 2009.

[57] R. R. Andrade, E. A. C. Rivera, D. I. P. Atala, F. Maugeri Filho, R. Maciel Filho, and A. C. Costa, *Bioethanol: Production, Benefits and Economics*. Nova Sci. Publ., New York, 2009, p. 75.

[58] D. Liu, D. Liu, R. J. Zeng, and I. Angelidaki, *Water Res.,* vol. 40, p. 2230, 2006.

[59] P. Sassner, C. G. Mårtensson, M. Galbe, G. Zacchi, *Bioresour. Technol.,* vol. 99, p. 137, 2008.

[60] M. Stoeberl, R. Werkmeister, M. Faulstich, and W. Russ, *Procedia Food Sci.* vol. 1, p. 1867, 2011.

[61] H. Huang, V. Singh, and N. Qureshi, *Biotechnol. Biofuels,* vol. 8, p. 1, 2015.

[62] R. M. Alvarez, B. Rodriguez, J. M. Romano, A. O. Diaz, E. Gomez, D. Miro, J. L. Garcia, *World J. Microbiol. Biotechnol.,* vol. 8, p. 214, 1992.

[63] https://www.iea.org/data-and-statistics/charts/biogas-production-by-region-and-by-feedstock-type-2018. Accessed: May 22, 2025.

[64] Z. Chi, Y. Zheng, A. Jiang, and S. Chen, *Appl. Biochem. Biotechnol.*, vol. 165, p. 442, 2011.