Waste Biorefineries

Subjects: Energy & Fuels
Contributor: Richard Ochieng , , Alemayehu Gebremedhin , Shiplu Sarker

Sustainable biofuel production is the most effective way to mitigate greenhouse gas emissions associated with fossil fuels while preserving food security and land use. In addition to producing bioenergy, waste biorefineries can be incorporated into the waste management system to solve the future challenges of waste disposal. Biomass waste, on the other hand, is regarded as a low-quality biorefinery feedstock with a wide range of compositions and seasonal variability. In light of these factors, biomass waste presents limitations on the conversion technologies available for value addition, and therefore more research is needed to enhance the profitability of waste biorefineries. Perhaps, to keep waste biorefineries economically and environmentally sustainable, bioprocesses need to be integrated to process a wide range of biomass resources and yield a diverse range of bioenergy products.

waste-to-energy | biorefinery integration | industrial symbiosis | waste biorefinieries

1. Introduction

The IEA (International Energy Agency) predicts that the global energy demand will be approximately 8% smaller than today in 2050, with 90% of the energy generation emanating from renewable energy sources such as hydropower, biomass, wind, tide, solar, and geothermal [1]. However, to achieve this target, the substitution of all fossil fuels with low-carbon renewable energy such as bioenergy before 2050 is crucial [2]. Biorefineries as alternatives to petroleum refineries have become increasingly important because of their ability to produce biofuels with a net-zero balance towards CO_2 emission and properties similar to fossil fuels [3]. Recently, second-generation biorefineries that use biomass residues and municipal waste have gained increasing attention from researchers in academia and industry due to their role in adding value to waste material and mitigating the risks associated with using virgin biomass [4][5][6]. According to the literature, the conversion of numerous types of biomass wastes into biofuels is widely studied [6]. However, due to the diverse range of biowastes, most research studies have described waste biorefineries based on the type of feedstock processed; for example, agriculture waste, municipal solid waste, and organic waste biorefineries [7][8][9][10]. Furthermore, studies reveal that biorefineries using single feedstock and conversion technology encounter challenges such as limited feedstock supply and heterogeneity, both of which have an impact on the biorefinery's economic recovery [11].

In recent years, several researchers have called for the adoption of integrated biorefinery concepts that integrate multiple conversion processes to improve efficiency and cost-effectiveness while adding value to multiple feedstocks [11][12]. However, despite the technological and economic advantages, integrated biorefineries are not being developed in a systematic manner due to the broad range of biomass sources, conversion processes, platforms, and products involved. As a result, each integrated biorefinery concept tends to have a unique output efficiency and process arrangement. In order to standardize the creation of integrated biorefineries, the relationship between the diverse properties of biomass waste and the various conversion technologies needs to be well-understood. Budzianowski [13] discussed the integration approaches suitable for integrating biorefinery systems in the total chain by investigating the increase of facility capacity through combining multiple platforms, exchanging wastes and products with other industries, applying more efficient biomass conversion processes, providing ecosystem, and optimizing the biomass supply chain on a broader scale. In an effort to systematize the knowledge in the literature, researchers characterize system boundaries, principles, and integration approaches in total chain integration. According to Alibardi et al. [14], the full-scale implementation of organic waste biorefineries requires a careful understanding of waste characteristics, markets for biorefinery products, and means to integrate processes with other industrial processes. Furthermore, Bisnella et al. [15] performed sensitivity analyses to show how waste characteristics affect the recovery and environmental performance of waste biorefineries. The researchers carefully quantify the results of life cycle analyses based on waste characteristics. Lodato et al. [16] have published a process-oriented modeling framework for environmental evaluation that parametrizes the physiochemical correlations between biomass feedstock material, conversion processes, and end products. The framework allows for more flexible modeling and selection of conversion technologies for life cycle assessments. Even though the impact of waste characteristics on individual conversion technologies has been extensively studied, no review on the combination of various technologies has been published.

2. Waste Biorefineries

Due to the ecological and economic burden of waste treatment, waste biorefineries provide a good alternative use of waste. The characteristics of feedstock used in waste biorefineries play a significant role in the selection of conversion technologies and end products [8]. As a result, most studies categorize waste biorefineries based on the sources of biomass waste. Biorefineries from food waste [17], dairy waste [18], forest residue [19] are some of the examples. Additionally, the term “organic waste” is often used to refer to all wastes and residues from biomass by some researchers [14][20].

2.1. Organic Waste Biorefineries

In organic waste biorefineries, biomass residues with high organic content such as food waste, food processing waste, organic fraction of municipal solid waste, animal manure, and industrial organic wastes are used.

- *Food waste biorefineries*: Sridhar et al. [21] reviewed the advantages and drawbacks of several thermochemical and biochemical processes utilized in food waste conversion. A comparison of numerous technologies shows that anaerobic digestion (AD) is the most promising technology for food waste valorization. AD requires less space, energy, and has the potential to produce renewable energy products, which are important in reducing greenhouse gas emissions. A study by Mirabella et al. [22], discussed the importance of waste characterization and technological maturity of conversion processes in adopting industrial symbiosis in the food industry. According to the findings, waste characterization is required for determining the type and quantity of waste, as well as identifying possible technologies and types of bioproducts to produce. Furthermore, a review by Zhang et al. [23] discusses the advantages of assessing the characteristics of cassava waste in the production of biofuels and biochemicals. Using the input-output-suitable technology strategy, Tsegaye et al. [24] emphasize the importance of aligning the composition of food waste to the desired final products as the first steps in choosing a more effective biorefinery conversion pathway. According to Caldeira et al. [25], some efforts are still needed to improve the efficiency of food waste biorefineries via technology integration. Moreover, the lack of willingness for food industries to share data on the nature of components in the food waste industries hinders the development of new food waste valorization routes [26].

- *Municipal waste biorefineries*: Nizami et al. [4] assessed the value of generating bioenergy from MSW during Muslim pilgrimage in Makkah. According to the study, the large fraction of organic content in MSW—particularly food waste—offers considerable economic and environmental benefits for developing a waste biorefinery in Makkah. In addition, Saini et al. [27] discussed the features of municipal solid waste biorefineries by considering conversion pathways for the lignocellulosic and organic waste fractions.

- *Animal waste biorefineries*: For a long time, the valorization of animal manure has been primarily centered on the solid fraction conversion for biogas production; however, new research reveals that interest in using the liquid fraction for bioenergy production is increasing [28]. Moreover, due to the availability of numerous chemical constituents in animal manure, researchers have recently focused on examining the possibilities of producing other products such as bioethanol and biodiesel from the substrate [29]. According to Jung et al. [29], the co-production of biogas, bioethanol, and fertilizer presents a cost-effective way to maximize value from livestock manure. Liu et al. [30] investigated an animal waste biorefinery that combines an AD, liquid digestate electrocoagulation (EC), and solid fiber fungal conversion into methane and fine biochemicals. In their approach, animal manure was first processed by an AD to produce methane gas, which is used to power the biorefinery. EC processed the resultant liquid digestate to recover water. The cellulose-rich solid digestate was then treated with enzyme hydrolysis and fungal fermentation to produce chitin (a polysaccharide containing nitrogen).

2.2. Lignocellulosic Waste Biorefineries

Agricultural residues, woody waste, and forest residues and by-products are the most prevalent feedstocks for lignocellulosic waste biorefineries.

- *Agricultural waste biorefineries*: Batidas-Oyanedel et al. [31] examined the use of dates and palm residues as feedstocks for waste biorefineries in the Middle East and North Africa (MENA). Researchers propose biorefining as a way to add value to date palm residue instead of burning it or using it to build conventional homes. Ginni et al. [32] presented a comprehensive review of the numerous biorefinery routes for the valorization of agricultural residues through the separation and conversion of cellulose, hemicellulose, and lignin fractions into biofuels and other useful products.

- *Forest residue biorefineries*: In order to assess the opportunities of forestry biorefineries, Stafford et al. [19] identified a total of 129 chemical, thermochemical, biological, and mechanical processing pathways that can lead to the production of 78 distinct bioproducts. The study also includes an assessment of the technology readiness and market potential of biorefinery products. Finally, the researchers suggest that bioproduct feasibility assessments need to consider environmental and social sustainability in addition to economics. Additionally, through an example of the pulp and paper industry, a study by Gottumukkala et al. [33] reveals that introducing bioprocess integration results in more appealing carbon conversion yields in the forest waste biorefineries.

3. Integration of Biorefinery Systems

According to Takkellapati et.al. [12], integrated biorefineries are designated as Phase III biorefineries, that generate a wide range of products from a multitude of feedstocks and conversion technologies. Meanwhile, the integration focuses on the maximization of the economic and environmental benefits of the biorefinery systems, it also plays a crucial role in overcoming the limitations associated with the wide variation in the physicochemical properties of biowaste [8]. The integration of bioprocesses provides biorefineries with the chance to upgrade multiple biomass waste streams, while maximizing resource efficiency.

In order to design a sustainable biorefinery, understanding the interactions between subsystems is essential for achieving economic, environmental, and social benefits. Stuart et al. [34] described the importance of process, infrastructure, feedstock and product integration, supply chain integration, and environmental integration in the development of integrated biorefineries. Feedstock and product integration takes advantage of the multifunctional qualities of biomass feedstocks and products, process integration concentrates on material and energy, and infrastructure integration connects processes to other sectors. Budzianowski et al. [13] studied the total chain integration of sustainable biorefineries by defining system limits, concepts, and integration approaches.

As Total Chain Integration focuses on a holistic approach [13][35], it is essential to understand the way biorefineries integrate at the process level in order to eliminate redundant processing steps and maximize resource efficiency. For example, Gopinath et.al. [36] studied the symbiotic framework in the sugar industry using primary and secondary by-products as source materials for energy production. Through the analysis of waste utilization options, researchers identified several symbiotic material and energy recovery pathways that maximize waste usage between sugar, energy, and construction industries. According to Yazan et al. [37], the volume of by-products and wastes is directly dependent on the efficiency of the primary processes and the quantity of the final product produced. As a result, the symbiosis between the primary and secondary processes is crucial to maximizing the overall economic benefits of the biorefinery [38].

Although the benefits from the interdependencies between processes are well known, there is still a need to develop systematic methods in selecting and integrating conversion options that complement the available biomass feedstock, wastes, and byproducts [26]. Furthermore, as symbiosis characterizes the causality between subsystems, material and energy integration methods can be employed to optimize the subsystem integrations in the biorefinery [39]. In order to conceptualize the process, a detailed understanding of how biomass and intermediate product characteristics influence the integration of bioprocesses is required to conceive the feedstock-product pathways. The following sections discuss how the integration of biorefinery systems can be attained based on the feedstock properties, Waste to Energy (WtE) conversion processes, multiple platforms, and products, as well as its integration with other industrial sectors.

3.1. Integration by Feedstock

Due to the heterogeneity of waste biomass, pretreatment is required to improve the quality and yield of the WtE conversion processes. To improve the moisture content, particle size, and cellulose-hemicellulose-lignin concentration, among other characteristics, preprocessing steps involving mechanical, chemical, biological, or thermal techniques can be applied [40][41]. Furthermore, diverse biomass feedstocks necessitate different preprocessing procedures in order to achieve the necessary biomass grade. As a result, biorefineries processing different feedstocks will require a combination of several pretreatment and conversion processes, increasing the biorefinery's complexity.

A biorefinery can eliminate the need for biomass pretreatment by selecting an alternative process that does not require or requires limited pretreatment to create a similar product. For example; to avoid the extra costs of pretreatment, gasification can be used instead of anaerobic digestion to produce hydrogen from lignocellulosic waste [6][40]. During integration, the economics of adding a biomass pretreatment step needs to be evaluated and compared with other WtE technologies. Alternatives to consider are integration of conversion processes, i.e., each type of feedstock is processed separately for a similar or distinct product; and integration of pretreatment steps: a single WtE process with several pretreatment processes.

3.2. Integration by Products, Byproducts, and Waste

The concepts of industrial symbiosis are used to integrate biorefineries by exchanging wastes, byproducts, and products [36]. The synergy between cascading processes maximizes the use of biomass resources while reducing waste output in biorefineries [13]. Furthermore, the growing notion of zero-waste biorefineries emphasizes value creation from all biorefinery waste streams [42]. This concept can lead to increasingly complex biorefinery superstructures which necessitate sophisticated process integration methods and tools. To illustrate the sequencing of WtE processes in the integrated system, classifications; process (i), sub-process (i,j), and sub-sub-process (i,j,k) are adopted to describe the primary, secondary and tertiary utilization of wastes or byproducts respectively.

3.3. Integration by Platform

According to IEA Bioenergy Task 42 [43], platforms are intermediates that connect feedstocks and final products. However, various researchers may as well interchangeably use the terms "platform" and "product". The integration of thermochemical and biochemical platforms allows for more effective use of biomass resources as well as greater flexibility in producing the required energy products [44][45][46]. The inherent variability of biomass necessitates the integration of many conversion processes to transform a diverse set of feedstocks that result in multiple platforms for distinct bioproducts and better economics of the biorefinery [47]. Nevertheless, the need to produce a single platform can also lead to the integration of multiple pretreatment methods to upgrade multiple feedstocks for the desired conversion process.

3.4. Integration by Processes

The diversity of biomass waste has prompted researchers to investigate hybrid conversion systems that can process a variety of feedstocks [13][40]. The use of integrated bioprocesses is essential for overcoming the shortcomings and inefficiencies of individual conversion processes that are only suitable for specific types of biomasses [48]. As a result, combining different bioprocesses enables for the processing of a diverse range of feedstocks and production of a diverse range of bioproducts.

In contrast to the parallel arrangement of conversion processes, other researchers have studied the sequential combination of bioprocesses to improve biomass conversion efficiency. For example, the sequential configuration of a microbial electrolysis cell (MEC) and an AD reactor has been found to increase biomethane yield in food waste biorefineries [49]. When products from the successive conversion processes are different, the integration can also be described as one that exchanges wastes or byproducts. For the integration to be under the sequential category, product (n,1) and product (n,2).

3.5. Integration with Industrial Infrastructure

The integration of biorefineries with other downstream processes helps address the environmental and economic challenges originating the use of crude or raw biofuels as the source of bioenergy. Jungmeier and Buchsbaum [50] studied how biorefineries could be integrated with a range of industrial infrastructures, including power and CHP plants, biofuel facilities, oil refineries, pulp and paper plants, the wood industry, and waste treatment facilities, among others. Furthermore, among the four elements of integration (feedstock, platforms, products, and processes), the study showed that feedstock and products offer better integration prospects than platforms and processes.

In addition, the performance of an integrated solid oxide fuel cell (SOFC) and biomass gasification system employing various gasification agents was investigated by Coplan et al. [51]. Hameed et al. [52] presented a review of the technical and economic benefits and challenges of combining energy recovery technologies like anaerobic digestion, fuel cells, nuclear, and solar with a gasification process that uses a mix of municipal solid waste and biomass as feedstocks. Nevertheless, the ability to generate carbon-negative bioenergy using bioenergy with carbon capture and storage (BECCS) has recently attracted the attention of researchers [53]. According to the energy reports [54], combining biorefineries with carbon capture and storage presents an opportunity to generate bioenergy while creating a net carbon dioxide removal from the atmosphere.

References

1. IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector; International Energy Agency: Paris, France, 2021; pp. 18–19.
2. IPCC. 2018: Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty; Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., Eds.; IPCC: Geneva, Switzerland, 2019.
3. Perea-Moreno, M.-A.; Samerón-Manzano, E.; Perea-Moreno, A.-J. Biomass as Renewable Energy: Worldwide Research Trends. Sustainability 2019, 11, 863.
4. Nizami, A.S.; Shahzad, K.; Rehan, M.; Ouda, O.K.M.; Khan, M.Z.; Ismail, I.M.I.; Almeelbi, T.; Basahi, J.M.; Demirbas, A. Developing waste biorefinery in Makkah: A way forward to convert urban waste into renewable energy. Appl. Energy 2017, 186, 189–196.
5. Lago, C.; Herrera, I.; Caldés, N.; Lechon, Y. Nexus Bioenergy–Bioeconomy. In The Role of Bioenergy in the Bioeconomy; Lago, C., Caldés, N., Lechón, Y., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 3–24.
6. Lee, S.Y.; Sankaran, R.; Chew, K.W.; Tan, C.H.; Krishnamoorthy, R.; Chu, D.-T.; Show, P.-L. Waste to bioenergy: A review on the recent conversion technologies. BMC Energy 2019, 1, 1–22.
7. Forster-Carneiro, T.; Berni, M.D.; Dorileo, I.L.; Rostagno, M.A. Biorefinery study of availability of agriculture residues and wastes for integrated biorefineries in Brazil. Resour. Conserv. Recycl. 2013, 77, 78–88.
8. Nizami, A.S.; Rehan, M.; Waqas, M.; Naqvi, M.; Ouda, O.K.M.; Shahzad, K.; Miandad, R.; Khan, M.Z.; Syamsiro, M.; Ismail, I.M.I.; et al. Waste biorefineries: Enabling circular economies in developing countries. Bioresour. Technol. 2017, 241, 1101–1117.
9. Ankush, Y.; Khushboo, Y.; Dubey, K.K. Food industry waste biorefineries: Future energy, valuable recovery, and waste treatment. In Refining Biomass Residues for Sustainable Energy and Bioproducts; Academic Press: Cambridge, MA, USA, 2020; pp. 391–406.
10. Clauser, N.M.; González, G.; Mendieta, C.M.; Kruyeniski, J.; Area, M.C.; Vallejos, M.E. Biomass Waste as Sustainable Raw Material for Energy and Fuels. Sustainability 2021, 13, 794.
11. Ng, D.K.S.; Ng, K.S.; Ng, R.T.L. Integrated Biorefineries. In Encyclopedia of Sustainable Technologies; Elsevier: Amsterdam, The Netherlands, 2017.
12. Takkellapati, S.; Li, T.; Gonzalez, M.A. An Overview of Biorefinery Derived Platform Chemicals from a Cellulose and Hemicellulose Biorefinery. Clean Technol. Environ. Policy 2018, 20, 1615–

1630.

13. Budzianowski, W.M.; Postawa, K. Total Chain Integration of sustainable biorefinery systems. Appl. Energy 2016, 184, 1432–1446.
14. Alibardi, L.; Astrup, T.F.; Asunis, F.; Clarke, W.P.; De Gioannis, G.; Dessì, P.; Lens, P.N.L.; Lavagnolo, M.C.; Lombardi, L.; Muntoni, A.; et al. Organic waste biorefineries: Looking towards implementation. Waste Manag. 2020, 114, 274–286.
15. Bisinella, V.; Götze, R.; Conradsen, K.; Damgaard, A.; Christensen, T.H.; Astrup, T.F. Importance of waste composition for Life Cycle Assessment of waste management solutions. J. Clean. Prod. 2017, 164, 1180–1191.
16. Lodato, C.; Tonini, D.; Damgaard, A.; Fruergaard Astrup, T. A process-oriented life-cycle assessment (LCA) model for environmental and resource-related technologies (EASETECH). Int. J. Life Cycle Assess. 2020, 25, 73–88.
17. Dahiya, S.; Kumar, A.N.; Shanthi Sravan, J.; Chatterjee, S.; Sarkar, O.; Mohan, S.V. Food waste biorefinery: Sustainable strategy for circular bioeconomy. Bioresour. Technol. 2018, 248, 2–12.
18. Chandra, R.; Castillo-Zacarías, C.; Delgado, P.A.V.; Parra-Saldívar, R. A biorefinery approach for dairy wastewater treatment and product recovery towards establishing a biorefinery complexity index. J. Clean. Prod. 2018, 183, 1184–1196.
19. Stafford, W.; De Lange, W.; Nahman, A.; Chunilall, V.; Lekha, P.; Andrew, J.; Johakimu, J.; Sithole, B.; Trotter, D. Forestry biorefineries. Renew. Energy 2020, 154, 461–475.
20. Coma, M.; Martinez-Hernandez, E.; Abeln, F.; Raikova, S.; Donnelly, J.; Arnot, T.C.; Allen, M.J.; Hong, D.D.; Chuck, C.J. Organic waste as a sustainable feedstock for platform chemicals. Faraday Discuss. 2017, 202, 175–195.
21. Sridhar, A.; Kapoor, A.; Kumar, P.S.; Ponnuchamy, M.; Balasubramanian, S.; Prabhakar, S. Conversion of food waste to energy: A focus on sustainability and life cycle assessment. Fuel 2021, 302, 121069.
22. Mirabella, N.; Castellani, V.; Sala, S. Current options for the valorization of food manufacturing waste: A review. J. Clean. Prod. 2014, 65, 28–41.
23. Zhang, M.; Xie, L.; Yin, Z.; Khanal, S.K.; Zhou, Q. Biorefinery approach for cassava-based industrial wastes: Current status and opportunities. Bioresour. Technol. 2016, 215, 50–62.
24. Tsegaye, B.; Jaiswal, S.; Jaiswal, A.K. Food Waste Biorefinery: Pathway towards Circular Bioeconomy. Foods 2021, 10, 1174.
25. Caldeira, C.; Vlysidis, A.; Fiore, G.; De Laurentiis, V.; Vignali, G.; Sala, S. Sustainability of food waste biorefinery: A review on valorisation pathways, techno-economic constraints, and environmental assessment. Bioresour. Technol. 2020, 312, 123575.

26. Kokossis, A.C.; Koutinas, A.A. Food waste as a renewable raw material for the development of integrated biorefineries: Current status and future potential. In Integrated Biorefineries: Design, Analysis, and Optimization, 1st ed.; Paul, R., Stuart, M.M.E.-H., Eds.; CRC Press: Boca Raton, FL, USA, 2013; pp. 469–491.

27. Saini, J.K.; Kumar, G.; Singh, S.; Hemansi; Kuhad, R.C. Chapter 8—Municipal solid waste biorefinery for sustainable production of bioenergy. In Waste Biorefinery; Bhaskar, T., Varjani, S., Pandey, A., Rene, E.R., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 207–233.

28. Khoshnevisan, B.; Duan, N.; Tsapekos, P.; Awasthi, M.K.; Liu, Z.; Mohammadi, A.; Angelidaki, I.; Tsang, D.C.W.; Zhang, Z.; Pan, J. A critical review on livestock manure biorefinery technologies: Sustainability, challenges, and future perspectives. Renew. Sustain. Energy Rev. 2021, 135, 110033.

29. Jung, S.; Shetti, N.P.; Reddy, K.R.; Nadagouda, M.N.; Park, Y.-K.; Aminabhavi, T.M.; Kwon, E.E. Synthesis of different biofuels from livestock waste materials and their potential as sustainable feedstocks—A review. Energy Convers. Manag. 2021, 236, 114038.

30. Liu, Z.; Liao, W.; Liu, Y. A sustainable biorefinery to convert agricultural residues into value-added chemicals. Biotechnol. Biofuels 2016, 9, 197.

31. Bastidas-Oyanedel, J.R.; Fang, C.; Almardeai, S.; Javid, U.; Yousuf, A.; Schmidt, J.E. Waste biorefinery in arid/semi-arid regions. Bioresour. Technol. 2016, 215, 21–28.

32. Ginni, G.; Kavitha, S.; Kannah, Y.; Bhatia, S.K.; Kumar, A.; Rajkumar, M.; Kumar, G.; Pugazhendhi, A.; Chi, N.T.L. Valorization of agricultural residues: Different biorefinery routes. J. Environ. Chem. Eng. 2021, 9, 105435.

33. Gottumukkala, L.D.; Haigh, K.; Collard, F.-X.; Van Rensburg, E.; Görgens, J. Opportunities and prospects of biorefinery-based valorisation of pulp and paper sludge. Bioresour. Technol. 2016, 215, 37–49.

34. Stuart, P.R.; El-Halwagi, M.M. Integrated Biorefineries: Design, Analysis, and Optimization; CRC Press: Boca Raton, FL, USA, 2012; pp. 36–58.

35. Özdenkçi, K.; De Blasio, C.; Muddassar, H.R.; Melin, K.; Oinas, P.; Koskinen, J.; Sarwar, G.; Järvinen, M. A novel biorefinery integration concept for lignocellulosic biomass. Energy Convers. Manag. 2017, 149, 974–987.

36. Gopinath, A.; Bahurudeen, A.; Appari, S.; Nanthagopalan, P. A circular framework for the valorisation of sugar industry wastes: Review on the industrial symbiosis between sugar, construction and energy industries. J. Clean. Prod. 2018, 203, 89–108.

37. Yazan, D.M.; Romano, V.A.; Albino, V. The design of industrial symbiosis: An input–output approach. J. Clean. Prod. 2016, 129, 537–547.

38. Li, X. Industrial Ecology and Industrial Symbiosis-Definitions and Development Histories. In Industrial Ecology and Industry Symbiosis for Environmental Sustainability: Definitions, Frameworks and Applications; Li, X., Ed.; Springer International Publishing: Cham, Switzerland, 2018; pp. 9–38.
39. Walmsley, T.G.; Ong, B.H.Y.; Klemeš, J.J.; Tan, R.R.; Varbanov, P.S. Circular Integration of processes, industries, and economies. Renew. Sustain. Energy Rev. 2019, 107, 507–515.
40. Hashemi, B.; Sarker, S.; Lamb, J.J.; Lien, K.M. Yield improvements in anaerobic digestion of lignocellulosic feedstocks. J. Clean. Prod. 2021, 288, 125447.
41. Kataki, R.; Chutia, R.S.; Mishra, M.; Bordoloi, N.; Saikia, R.; Bhaskar, T. Feedstock suitability for thermochemical processes. In Recent Advances in Thermo-Chemical Conversion of Biomass; Elsevier: Amsterdam, The Netherlands, 2015; pp. 31–74.
42. Mathew, A.K.; Abraham, A.; Mallapureddy, K.K.; Sukumaran, R.K. Chapter 9—Lignocellulosic Biorefinery Wastes, or Resources in; Bhaskar, T., Pandey, A., Mohan, S.V., Lee, D.-J., Khanal, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 267–297.
43. Bell, G.; Schuck, S.; Jungmeier, G.; Wellisch, M.; Felby, C.; Jorgensen, H.; Stichnothe, H.; Clancy, M.; De Bari, I.; Kimura, S. EA Bioenergy Task 42 Biorefining: Sustainable and Synergetic Processing of Biomass into Marketable Food & Feed Ingredients, Chemicals, mateRials and Energy (Fuels, Power, Heat); van Ree, R., van Zeeland, A.N.T., Eds.; IEA Bioenergy Task 42: Wageningen, The Netherlands, 2014.
44. Jungmeier, G. The Biorefinery Complexity Index; Working Document—2014-07-09; IEA-Bioenergy Task 42 Biorefining: Wageningen, The Netherlands, 2014; p. 36.
45. Gnansounou, E.; Pandey, A. Classification of Biorefineries Taking into Account Sustainability Potentials and Flexibility. In Life-Cycle Assessment of Biorefineries; Kostas, M., Ed.; Elsevier: Amsterdam, The Netherlands, 2017; pp. 1–39.
46. Hingsamer, M.; Jungmeier, G. Biorefineries. In The Role of Bioenergy in the Bioeconomy: Resources, Technologies, Sustainability and Policy; Carmen, L., Natalia, C., Lechon, Y., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 179–222.
47. Stephen, R.; Hughes; William, R.; Gibbons, B.R.M.; Rich, J.O. Sustainable Multipurpose Biorefineries for Third-Generation Biofuels and Value-Added Co-Products. In Biofuels-Economy, Environment and Sustainability; Fang, Z., Ed.; InTechOpen: London, UK, 2013.
48. Meléndez, J.; Lebel, L.; Stuart, P. A Literature Review of Biomass Feedstocks for a Biorefinery. In Integrated Biorefineries: Design, Analysis, and Optimization, 1st ed.; Paul, R., Stuart, M.M.E.-H., Eds.; CRC Press: Boca Raton, FL, USA, 2013; pp. 432–460.
49. Park, J.; Lee, B.; Tian, D.; Jun, H. Bioelectrochemical enhancement of methane production from highly concentrated food waste in a combined anaerobic digester and microbial electrolysis cell.

Bioresour. Technol. 2018, 247, 226–233.

50. Jungmeier, G.; Buchsbaum, M.; Van Ree, R.; De Jong, E.; Stichnothe, H.; De Bari, I. Upgrading strategies for industrial infrastructures–integration of biorefineries in existing industrial infrastructure. IEABioenergy 2014, 16, 2014.
51. Colpan, C.O.; Hamdullahpur, F.; Dincer, I.; Yoo, Y. Effect of gasification agent on the performance of solid oxide fuel cell and biomass gasification systems. Int. J. Hydrogen Energy 2010, 35, 5001–5009.
52. Hameed, Z.; Aslam, M.; Khan, Z.; Maqsood, K.; Atabani, A.E.; Ghauri, M.; Khurram, M.S.; Rehan, M.; Nizami, A.-S. Gasification of municipal solid waste blends with biomass for energy production and resources recovery: Current status, hybrid technologies and innovative prospects. Renew. Sustain. Energy Rev. 2021, 136, 110375.
53. Bui, M.; Zhang, D.; Fajardy, M.; Mac Dowell, N. Delivering carbon negative electricity, heat and hydrogen with BECCS–Comparing the options. Int. J. Hydrogen Energy 2021, 46, 15298–15321.
54. Carbo, M. Biomass-Based Industrial CO2 Sources: Biofuels Production with CCS; United Nations Industrial Development Organization: Vienna, Austria, 2011.