


Review

# Integration of Waste to Bioenergy Conversion Systems: A Critical Review

Richard Ochieng, Alemayehu Gebremedhin and Shiplu Sarker \* 

Department of Manufacturing and Civil Engineering, Faculty of Engineering, Norwegian University of Science and Technology, 2815 Gjøvik, Norway; richard.ochieng@ntnu.no (R.O.); alemayehu.gbremedhin@ntnu.no (A.G.)

\* Correspondence: shiplu.sarker@ntnu.no; Tel.: +47-91-271-077

**Abstract:** 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. To achieve optimal integration, the classification of biomass wastes to match the available bioprocesses is vital, as it minimizes unnecessary processes that may increase the production costs of the biorefinery. Based on biomass classification, this study discusses the suitability of the commonly used waste-to-energy conversion methods and the creation of integrated biorefineries. In this study, the integration of waste biorefineries is discussed through the integration of feedstocks, processes, platforms, and the symbiosis of wastes and byproducts. This review seeks to conceptualize a framework for identifying and integrating waste-to-energy technologies for the various sets of biomass wastes.



**Citation:** Ochieng, R.; Gebremedhin, A.; Sarker, S. Integration of Waste to Bioenergy Conversion Systems: A Critical Review. *Energies* **2022**, *15*, 2697. <https://doi.org/10.3390/en15072697>

Academic Editor: Dimitrios Sidiras

Received: 26 February 2022

Accepted: 2 April 2022

Published: 6 April 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

**Keywords:** lignocellulosic waste; organic waste; waste-to-energy; biorefinery integration; industrial symbiosis

## 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<sub>2</sub> 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 [4–6]. 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 [7–10]. 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, the authors 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 authors 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.

In this review, we discuss the integration of biorefineries focusing on the identification of the most suitable combination of conversion technologies for the selected set of biomass wastes. In a descriptive approach to biorefinery integration, biomass feedstocks, conversion processes, platforms, byproducts, products, and existing industrial infrastructures are considered as the integration variables. This study aims to demonstrate how biomass waste characteristics influence the integration of biomass conversion technologies in waste biorefineries. As a result, the critical review process is adopted to conceptualize information from multiple literature sources [17]. The study examines data collected from 123 documents, including books, reports, and articles from 2010 to the present. The literature review in this study is structured into four main sections. Section 2 classifies biomass waste as feedstock to waste biorefineries, and using the biowaste classification, Section 3 discusses the suitability of various waste-to-energy technologies, Section 4 describes waste biorefineries, and Section 5 discusses some of the key features that govern the creation of integrated biorefineries.

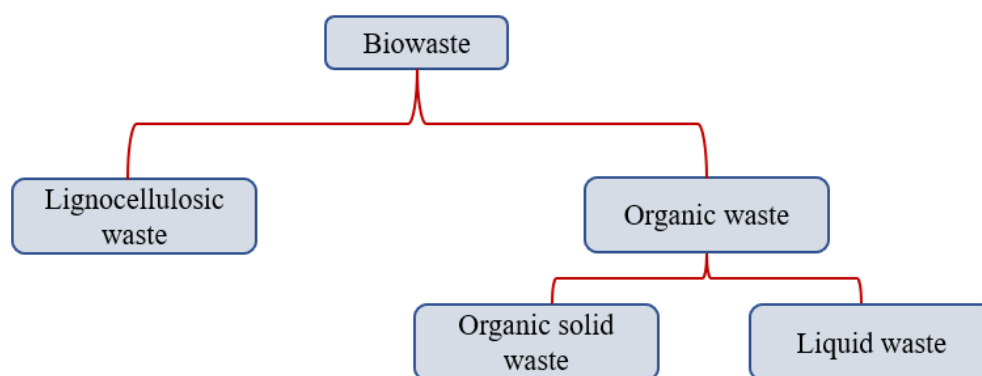
## 2. Biomass Waste

Biomass residues and waste originate from all levels of biomass production and processing including municipal waste, industrial waste, aquaculture, animal manures, agricultural and forestry, and others [8,18,19]. However, the technical classification of biogenic waste is rarely discussed in the literature, despite its importance in resolving the issues of biomass heterogeneity in waste biorefineries [18]. With the broad variation in the quality of biomass wastes, waste biorefineries tend to be more sophisticated than typical biorefineries [14]. As a result, understanding the qualities of biowaste is critical for selecting the most appropriate waste biorefinery technologies [20–22].

There have been numerous studies conducted to describe the relationship between biomass feedstock characteristics and conversion technologies. Melendez et al. [21] pro-

posed a classification system for biomass waste based on conversion process requirements. The authors classified biomass feedstock as sugar and starch, vegetable oils and animal fats, lignocellulosic and biodegradable waste. Although the authors discussed suitable conversion technologies, liquid biogenic waste was not included in the classification. The need for more ecologically friendly industries has motivated scientists to evaluate the potential of using wastewater as a feedstock for waste biorefineries [23]. Chen et al. [24] examined municipal solid and liquid waste as feedstocks, taking into consideration several conversion technological options to maximize energy and value recovery for biorefineries. Furthermore, numerous biorefining schemes have been proposed by Chen et al. [25] for producing chemicals, fertilizers, bioenergy and clean water from organic and liquid municipal wastes.

For bioenergy applications, biomass waste can be described as lignocellulosic or organic waste, depending on the level of moisture [26]. For example, lignocellulosic biomass waste such as agricultural and forest residues often have low moisture (often less than 60%), making it amenable for treatment using thermochemical procedures. Residues with a high moisture content, as well as wastewater, are examples of organic or fermentable biomass waste. The moisture content of this sort of waste is frequently high (often greater than 60%), making it appropriate for biochemical treatment. Livestock manure, the organic part of municipal waste, industrial waste, and wastewater are examples of such residues [26]. In this study, biogenic waste is defined as lignocellulosic, organic solid, and liquid waste, as shown in Figure 1.

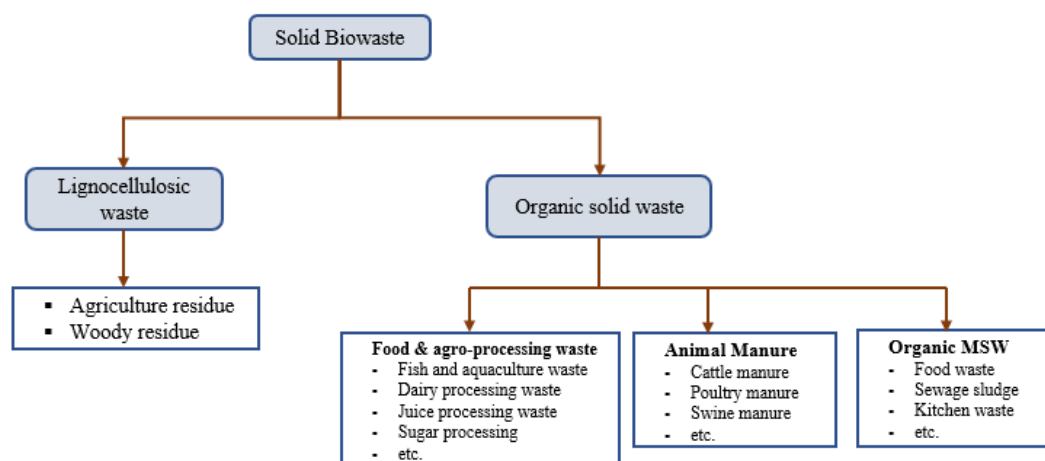


**Figure 1.** Classification of biomass waste.

### 2.1. Lignocellulosic Biomass Waste

All biomass residues formed from materials that primarily comprise of celluloses, hemicelluloses, and lignin are classified as lignocellulosic waste [27]. Examples of lignocellulosic wastes include forest residues, agricultural residues, wood residue, the lignocellulosic fraction of municipal solid waste, and others, as shown in Figure 2.

Lignocellulosic waste has high energy value, low moisture content, and rigid structures that necessitate harsh conversion conditions (i.e., high temperature) only available in thermochemical processes such as combustion, gasification, or pyrolysis [18,21,28]. Conversion of lignocellulosic waste through biochemical or biological processes will require pretreatment to enhance the reactivity and accessibility of carbohydrates before undergoing biological degradation [10,29]. The addition of energy-intensive pretreatment processes might result in additional processing expenses, which can impair the biorefinery's economic performance [21,30,31].



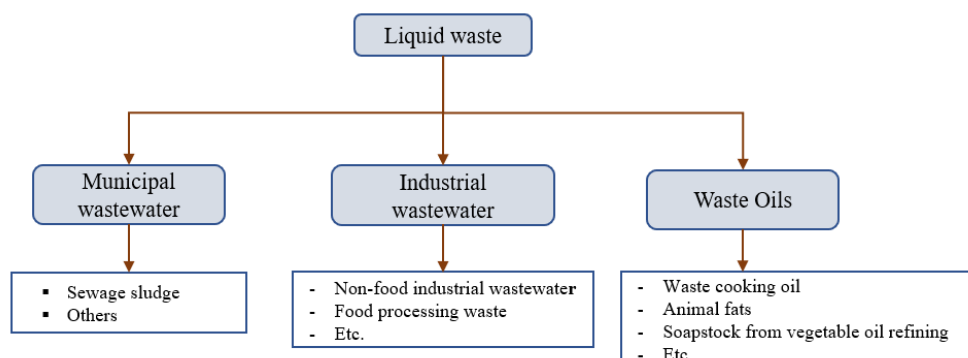
**Figure 2.** Classification of solid biomass waste.

### 2.2. Organic Solid Waste

The organic fraction of solid waste, on the other hand, is characterized as a solid waste that has a high moisture content and is easily biodegradable, such as municipal solid waste, livestock manure, sewage sludge, industrial waste, and food waste [21,32]. According to the Landfill Directive (1999/31/EC) [33], biodegradable waste is defined as “any waste that can undergo anaerobic or aerobic decomposition, such as food and green waste, and paper and paperboard”. Furthermore, the presence of high moisture and biodegradable carbon material in organic solid waste makes it appropriate to apply biological processes like anaerobic digestion and fermentation [6]. While thermochemical processes require biomass with low moisture, pretreatment methods such as drying can be used to reduce the moisture content to suitable levels [28]. Even though such a pathway is technically possible, the addition of a preprocessing step may increase the processing costs of the biorefinery [30,34]. As a result, identifying the most appropriate technology for transforming organic solid waste into energy is critical to the economics of the biorefinery.

### 2.3. Liquid Biomass Waste

As shown in Figure 3, liquid waste can be collected as municipal wastewater or industrial waste, primarily from food processing industries such as fish, vegetable oil refining, and dairy processing. The effluent obtained from industrial processing is also often obtained as a by-product of extracting solid organic matter solids from the industrial effluents [35]. The organic matter contained in wastewater can serve as a good source of bioenergy [25], freshwater [36], and organic fertilizer [37]. The treatment of liquid waste may include mechanical techniques for removing organic and inorganic suspended particulates, as well as biochemical conversion methods for degrading and removing soluble biodegradable organics [37].



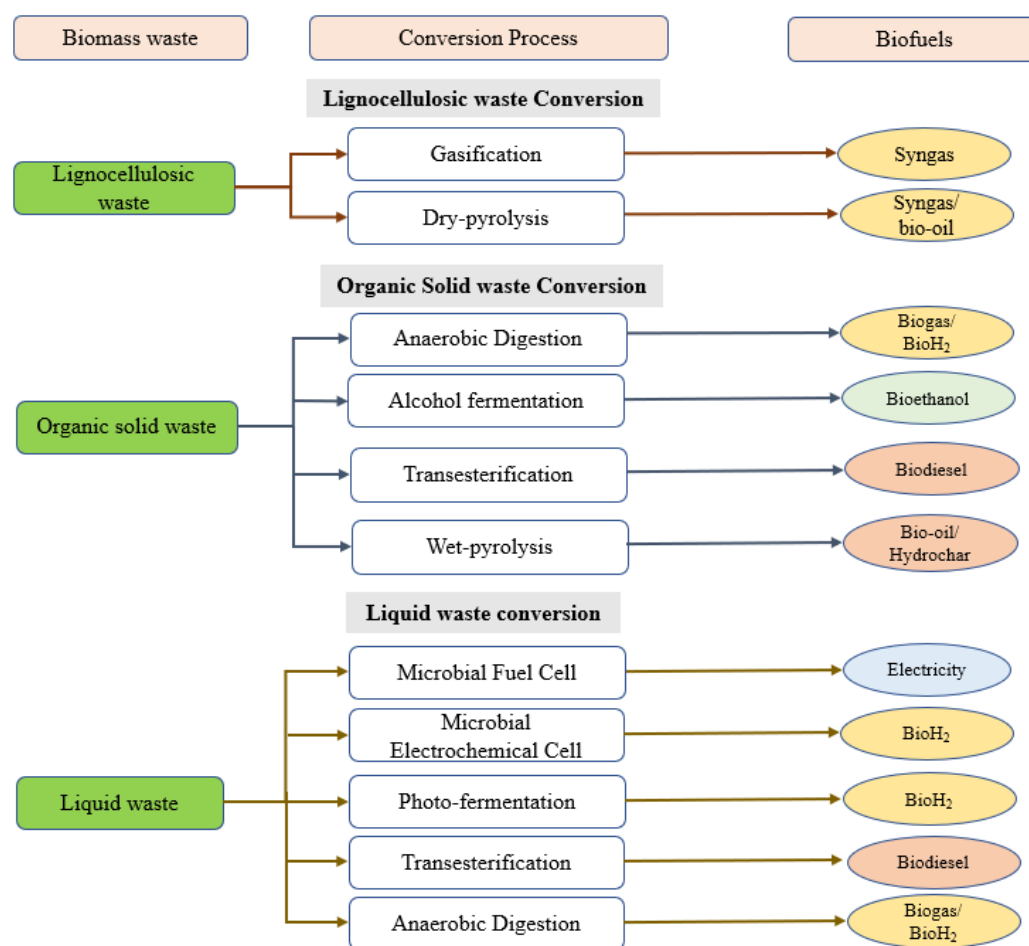
**Figure 3.** Classification of liquid biomass waste.

Other liquid wastes, such as used cooking oil, have been treated using chemical processes that transform the triglycerides (fats) in the oil into useful biodiesel [38]. With proper process conditions, transesterification of waste oils can produce high-quality biodiesel that can replace fossil diesel in engines, without any major modifications [39]. Feedstocks for biodiesel production may include waste cooking oils from homes and businesses, animal fats, and wastes or by-products from vegetable oil refining [40].

### 3. Waste to Energy Conversion Processes

#### 3.1. Thermochemical Methods

Besides combustion, the thermochemical conversion methods involve the treatment of biomass with pyrolysis to produce solid, liquid, or gaseous compounds that can then be upgraded into fuels, heat, or electricity (see Figure 4) [41]. Gasification and pyrolysis are the two most popular thermochemical conversion processes in modern biorefineries. These technologies have a short processing time and operate under harsh circumstances (high temperature and pressure), hence having the ability to handle biomass waste that is difficult to decompose through biochemical processes [6,28].



**Figure 4.** Conversion technologies for lignocellulosic, organic solid and liquid biomass waste.

Unlike biological methods, which rely solely on the biodegradable carbon content of biomass, thermochemical pathways make use of the entire biomass, thus minimizing the energy-intensive step of feedstock pretreatment [41]. Low energy recovery and emission of harmful compounds such as toxic gases and particles into the environment are some of the issues faced by the thermochemical conversion of solid waste to energy [42]. Although studies reveal waste incineration as the most cost-effective among the thermochemical

technologies, the high volume of particulate matter and greenhouse gases emitted by the technology makes it inappropriate for use in modern biorefineries [8,43].

On the other hand, hydrothermal carbonization (HTC), also known as wet pyrolysis, is an emerging type of pyrolysis technology that is thermochemical and is capable of handling biomass with a high moisture content [44]. While hydrothermal carbonization is capable to process wet biowaste, it is often used as a pretreatment method to produce hydrochar and liquid effluent which further processed to produce bioenergy [45,46]. Nonetheless, HTC technology is still in its infancy, and additional research is needed to better understand the impact of parameters on final product qualities and applications [44].

### 3.2. Biochemical Methods

#### 3.2.1. Solid Organic Waste Conversion

In contrast to thermochemical processes, biochemical or biological conversion techniques use enzymes to break down substrates, making them more suitable for biomass that is high in moisture and easily biodegradable [14,21]. Biochemical routes convert wet biomass waste into biofuels and other value-added products using aerobic and anaerobic microbes. Anaerobic digestion and fermentation are two of the most prevalent biochemical techniques for this type of biomass waste into biofuels (see Figure 4) [6].

Anaerobic digestion (AD) is a process that involves decomposing organic waste by the anaerobic microbes in the absence of oxygen to create biogas, biohydrogen, and digestate, which can be utilized as a biofertilizer in agricultural [6]. The enzymatic breakdown process consists of several phases (i.e., hydrolysis, acidogenesis, acetogenesis, and methanogenesis) that result in biogas which could be used for heating, transportation, and/or electricity production [47,48]. To increase the yield of biogas, accessibility of the substrate by microorganisms can be increased by adding a pretreatment step to the AD process [29,49]. Additionally, due to the sensitivity of AD process, optimization of design and operation parameters is critical for maximizing biogas yield and quality [50].

Fermentation is a biological process that aerobically breaks down compounds like glucose in biomass waste to produce primarily ethyl alcohol and carbon dioxide [21]. One of the oldest fermentation technologies is the synthesis of bioethanol from fermentable carbohydrates. Vegetable and fruit waste, corn stover, and sugarcane bagasse all contain considerable amounts of sugar, which can be utilized in the fermentation process to generate bioethanol [51]. The microorganisms used in ethanol fermentation break down the sugars available in organic waste into pyruvate molecules, which are subsequently converted to ethanol and carbon dioxide [52,53]. Organic wastes containing complex sugars such as cellulose and hemicellulose, on the other hand, are difficult for fermentation microbes to digest, necessitating a pretreatment phase (hydrolysis) to convert the polysaccharides into simple sugars prior to fermentation [6,51]. For example, Byadgi and Kalburgi [54] investigated the three-step fermentation of waste newspapers to produce bioethanol. According to the authors, lignin is removed from cellulosic material, and polysaccharides are hydrolyzed to simple sugars before commencement of the fermentation process. The procedure for producing ethanol from lignocellulosic biomass has been considered attractive, but its economic performance is not effective [55].

#### 3.2.2. Liquid Waste Conversion

In comparison to solid waste, the energy potential of liquid waste has been underutilized [56]. The wastewater contains a lot of organic substrates, which means there's a lot of room for bioenergy and other value-added goods [57,58]. Furthermore, producing biofuels and treating wastewater at the same time allows for financial savings while also making the biorefinery environmentally sustainable [57].

Advances in biological and electrochemical processes such as anaerobic digestion, microbial fuel cells (MFC), and microbial electrochemical cells (MEC) have prompted researchers to look into the possibility of recovering bioenergy from liquid waste. A summary

of some studies that demonstrate the production of bioenergy products from liquid biomass waste has been provided in Table 1.

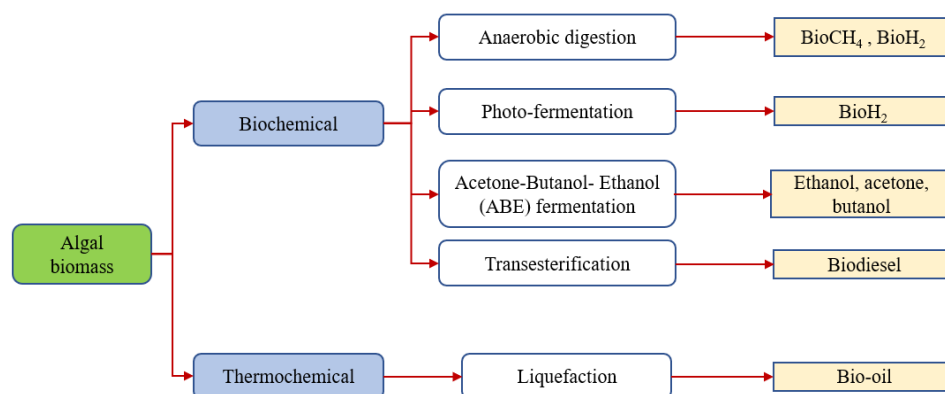
**Table 1.** Liquid biowaste to energy technologies, feedstock, and bioenergy products.

Technology	Liquid Waste	Bioenergy	Challenges	References
Conventional AD	Water ponds	Biogas	- Long retention time - Large treatment area	[59]
Upflow anaerobic sludge blanket, UASB	Industrial, municipal wastewaters	Biogas	- Forming and AD inhibitions at high organic loading rates (OLR).	[52,60,61]
Photobiological hydrogen production, Anaerobic Digestion	Agricultural, industrial, municipal wastewaters	Algal biomass, Hydrogen, methane	- Low biomass yield - Requires a large amount of wastewater supply - Technology not yet mature - high capital costs for photobioreactor systems - High variability in wastewater composition may introduce toxicity compounds to microorganisms (i.e., NH <sub>3</sub> , pH, heavy metals)	[62–64]
Microbial fuel cells (MFCs)	Agricultural, industrial, municipal wastewaters	Bioelectricity	- Technology not yet mature - Electricity produced is still very low for commercialization	[65,66]
Microbial Electrolysis Cells (MEC)	Agricultural, industrial, municipal wastewaters	Biohydrogen	- high capital costs - Technology not yet mature - High ohmic and concentration losses. - Lower volumes of H <sub>2</sub> production	[67–69]
Transesterification (Acid/Base/Enzyme catalyst)	Household and industrial cooking waste oils from vegetable oil, animal fats	Biodiesel	Chemical-catalyzed: - additional costs for product separation and catalyst recovery, - high energy demand - undesirable side reactions Enzyme catalyzed: - Enzymes sensitive to temperature and alcohol	[38,40]

- **Anaerobic Digestion:** Anaerobic digestion of wastewater entails the breakdown of organic matter in wastewater in the absence of oxygen, resulting in the production of biogas, carbon dioxide, and treated water as products [57]. Aside from the products, wastewater treatment using anaerobic digestion (AD) reduces pollutant levels, stabilizes sludge, and reduces sludge tonnage significantly with minimal energy input [49]. Traditional anaerobic digestion has long been used to breakdown organic compounds and pathogens in wastewater collected in ponds [59]. Because conventional AD methods necessitate a long retention period and large treatment areas, more advanced anaerobic reactors, such as the Upflow anaerobic sludge blanket reactor (UASB), with short contact time between bacteria and wastewater, have been developed [59,60]. Even though Upflow anaerobic sludge blanket (UASB) reactors have the potential to significantly increase biogas yield [61], the technology still requires further development to overcome foaming and other AD inhibitions, particularly at high organic loading rates (OLR) [52].
- **Bioelectrochemical systems (BECS):** Bioelectrochemical conversion has emerged as one of the most efficient ways to cleanse wastewater and produce bioenergy (bioelectricity and hydrogen) [70]. Microbial fuel cells (MFCs) and microbial electrochemical cells (MECs) are two types of bioelectrochemical cells in which one of the electrodes interacts with microorganisms (usually anode respiring bacteria, ARB) to transfer electrons

from the organic substrate to the electrode [71,72]. While MFCs require the presence of an oxidative agent (i.e., oxygen) to generate electricity, MECs require a modest amount of energy from an external source to fuel the redox reactions that produce hydrogen gas [68]. MFC's ability to generate energy from wastewater makes it more eco-friendly; however, the technology is still in its early stages, and the electricity generated is insufficient for large-scale application [65,66]. Studies show that MECs offer the substantial potential to improve the efficiency of liquid waste biorefineries; nevertheless, the process is economically unfavorable due to the high capital costs of technology adoption [69]. Furthermore, obstacles such as ohmic and concentration losses, saturation kinetics, and competing reactions like methanogenesis, which reduce the rate of hydrogen production, continue to stymie MEC technology's commercialization [67].

- *Microalgal Cultivation*: The process of algae cultivation requires carbon dioxide and light energy, organic and inorganic carbon, as well as inorganic nitrogen (N) and phosphorous (P), present in wastewater [73]. Because algae biomass is unicellular and buoyant, structurally complex substances such as lignin and hemicellulose are not required for growth [74]. For this reason, microalgae are most desirable biofuel source because the cell walls are not resistant to treatment conditions, necessitating just moderate pretreatments [75]. Microalgae contain valuable components like proteins, carbohydrates, and lipids that can be converted into biofuels such as alcohols, biogas, and biodiesel through a number of conversion routes [76], as shown in Figure 5.



**Figure 5.** Production of biofuels from microalgae.

As a result of the role microalgae play in capturing carbon dioxide from the atmosphere, development of microalgae biorefineries have also attracted increased attention from scientists. Studies show that microalgae cultivation can be integrated into biorefinery processes to capture flue gas and transform liquid by-products into biofuels. Details on some of these concepts are found in the studies by Bahr et al. [77], Ren et al. [78], and Chen et al. [79].

Despite advancements, large-scale biofuel generation from microalgae remains technically and economically unviable (see; [80]). Low biomass productivity and a lack of a substantial and consistent supply of wastewater are the two major obstacles to the technology's commercialization [64]. Furthermore, cost-analysis studies have found that photobioreactor systems are expensive, greatly increasing the investment cost [63].

- *Transesterification*: Transesterification is a crucial step in the conversion of waste oils into biodiesel, which has the potential to completely replace fossil fuel [39]. The production of low-cost biodiesel from waste oils such as household and industrial waste cooking oil, animal fats, and soapstock from vegetable oil refining has been suggested as a viable solution to the waste oil disposal problems [40].

To convert waste oils into biodiesel, transesterification uses chemicals (i.e., acid and base) or enzyme catalyzed processes [6]. Higher biodiesel yields are produced by chemical transesterification reactions catalyzed by acids, especially when the feedstock contains



more Free Fatty Acids (FFA). However, the reaction is slow and requires operations at high temperatures [38]. Additionally, both acid and base-catalyzed processes necessitate extra costs for product purification and catalyst recovery [38,40]. Enzyme-catalyzed reactions, as opposed to chemically catalyzed reactions, have several advantages, including reusability, low energy intensity, and environmental friendliness, as well as the elimination of a separation step. However, due to the presence of alcohols and high temperatures in the reactor, substantial problems such as enzyme deactivation may develop in enzyme-catalyzed processes [6].

#### 4. 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 [81], dairy waste [82], forest residue [83] 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 [14,32]. However, this paper considers organic waste to be comprised of biomass wastes with high moisture content and easily biodegradable, whereas lignocellulosic waste is defined as one with high cellulose, hemicellulose, and lignin content. In the following subsections, we discuss some examples of lignocellulosic and organic waste biorefineries.

##### 4.1. 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. [84] 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. [85], 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. [35] 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. [86] 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. [87], 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 [88].
- *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. [89] discussed the features of municipal solid waste biorefineries by considering conversion pathways for the lignocellulosic and organic waste fractions. The authors also examined the extent of research in the organic fraction of MSW when it comes to converting it into bioenergy via the biochemical conversion processes.

- *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 [56]. 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 [90]. According to Jung et al. [90], the co-production of biogas, bioethanol, and fertilizer presents a cost-effective way to maximize value from livestock manure. Liu et al. [91] 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).

#### 4.2. 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. [92] examined the use of dates and palm residues as feedstocks for waste biorefineries in the Middle East and North Africa (MENA). The authors 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. [93] 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. Finally, the study reveals that the transformation of agricultural residue can be improved through the use of integrated bioprocesses.
- *Forest residue biorefineries:* In order to assess the opportunities of forestry biorefineries, Stafford et al. [83] 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 authors 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. [94] reveals that introducing bioprocess integration results in more appealing carbon conversion yields in the forest waste biorefineries.

### 5. Integration of Biorefinery Systems

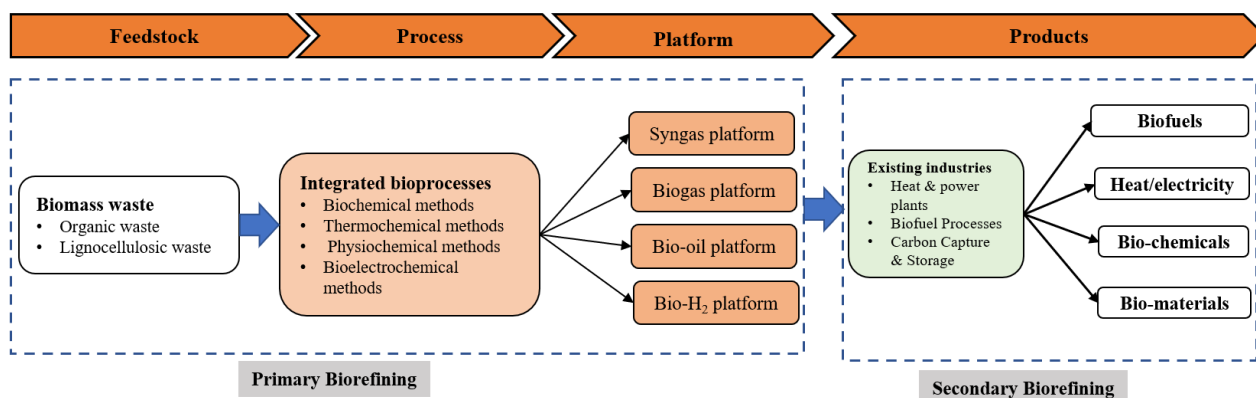
According to Takkellapati et al. [12], integrated biorefineries are designated as Phase III biorefineries, that generate a wide range of products from a multitude of feedstocks and conversion technologies. Meanwhile, the integration focuses on the maximization of the economic and environmental benefits 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. [95] 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. The study

shows that designing economically viable biorefinery systems necessitates tight component integration at all levels of the biorefinery value chain. According to the authors, feedstocks, conversion processes, platforms, and end products all play essential roles in integrating biorefinery systems.

As Total Chain Integration focuses on a holistic approach [13,96], 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. [97] 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, the authors identified several symbiotic material and energy recovery pathways that maximize waste usage between sugar, energy, and construction industries. According to Yazan et al. [98], 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 [99].

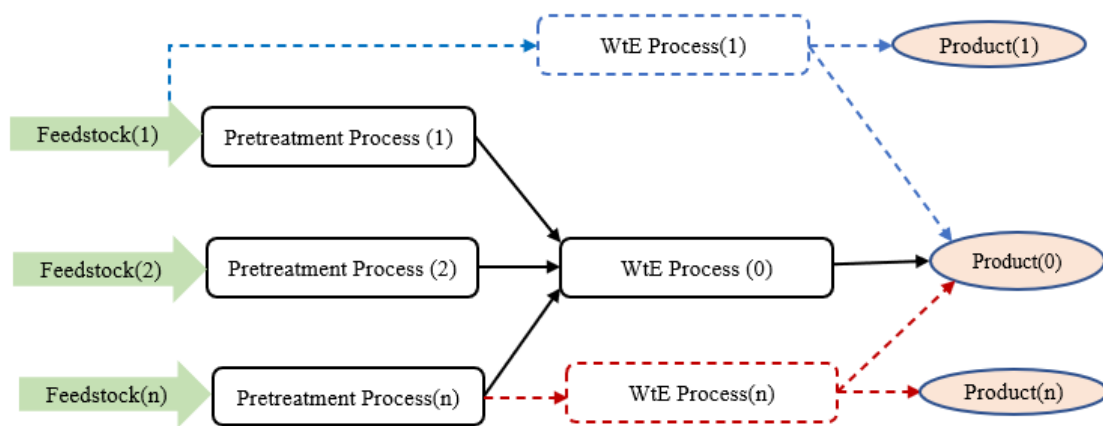
Although the benefits from the interdependencies between processes are well known, there is still a need to develop systematic methods in selecting and integrating conversion options that complement the available biomass feedstock, wastes, and byproducts [88]. Furthermore, as symbiosis characterizes the causality between subsystems, material and energy integration methods can be employed to optimize the subsystem integrations in the biorefinery [100]. 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 (Figure 6). 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.



**Figure 6.** Schematic representation of an integrated waste biorefinery.

### 5.1. 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 [29,101]. 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 as shown in Figure 7.

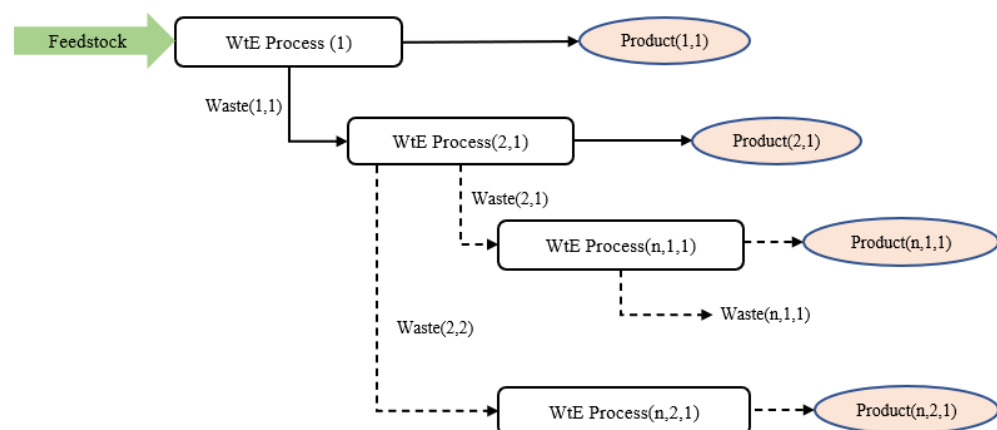


**Figure 7.** Illustration of the possible biorefinery integration by feedstocks.

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 [6,29]. 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.

### 5.2. Integration by Products, Byproducts, and Waste

The concepts of industrial symbiosis are used to integrate biorefineries by exchanging wastes, byproducts, and products [97]. 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 [102]. This concept can lead to increasingly complex biorefinery superstructures (see Figure 8) 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. From literature, some examples of integrated waste biorefinery concepts that highlight waste and by-product integration are summarized in Table 2.



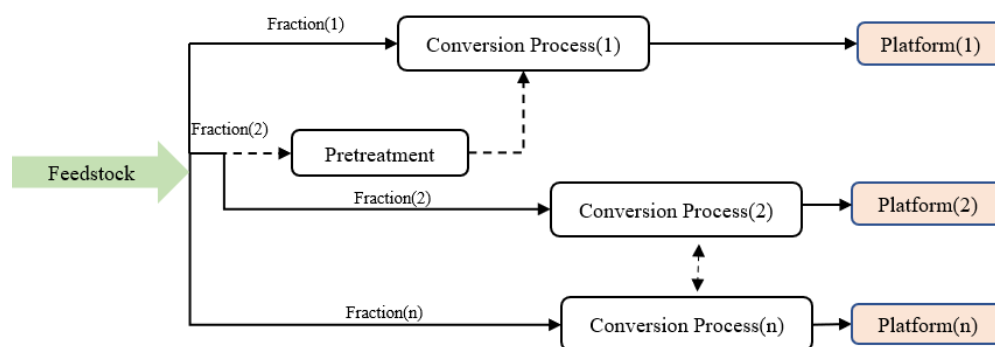
**Figure 8.** An illustration of biorefinery integration by waste, and/or byproducts.

**Table 2.** Examples for biorefinery integration based on the exchange of waste/by-product.

Primary Feedstock/Process	Primary Product	Secondary Feedstock/Process	Secondary Product	Reference
Yard waste/AD	Biogas 2930 Nm <sup>3</sup> d <sup>-1</sup>	AD residue & woody biomass/gasification	Syngas 17.17 Nm <sup>3</sup> h <sup>-1</sup> LHV: 5.17 MJ/Nm <sup>3</sup>	[103]
Mixed animal manure & agricultural residues/AD	Biogas	AD digestate/Pyrolysis	Bio-oil: 51 wt% Biochar: 34.0 wt% Syngas: 15.0 wt%	[104]
Grass & Chicken manure/AD	Biogas 237 mL (gVS) <sup>-1</sup>	AD digestate & woodchips/Gasification	Syngas 15.75 Nm <sup>3</sup> h <sup>-1</sup> LHV 8.1 MJ/kg	[105]
Mixed agricultural wastes (pig manure, cow manure, maize and triticale silages, and cereal bran)/AD	Biogas 9477 Nm <sup>3</sup> d <sup>-1</sup>	AD digestate/Gasification	Syngas 65.5 wt% LHV: 2.88 MJ/Nm <sup>3</sup>	[106]
Lignocellulosic waste & animal manure	Biogas 5150 Nm <sup>3</sup> d <sup>-1</sup> 61 % v/v	AD digestate/Pyrolysis	Bio-oil: 58.4 wt% Biochar: 32.0 wt% Syngas: 8.8 %wt, 15.7 MJ/Nm <sup>3</sup>	[107]
Wastewater/AD	Biohydrogen 1.16 mol H <sub>2</sub> (kgCOD) <sup>-1</sup>	AD effluent/MFC	Bioelectricity 176.35 J/kgCOD/m <sup>3</sup>	[108]
Lignocellulosic biomass wastes/AD Waste type 1: 18.68 MJ/kg (HHV) Waste type 2: 17.87 MJ/kg (HHV) Waste type 3: 21.55 MJ/kg (HHV)	Biogas 0.2 kJ/kgTS 0.2 kJ/kgTS 0.5 kJ/kgTS	AD digestate/Gasification	Syngas HHV: 2.5 MJ/Nm <sup>3</sup> HHV: 2.4 MJ/Nm <sup>3</sup> HHV: 2.6 MJ/Nm <sup>3</sup>	[109]
Animal manure/AD Feedstock: HHV 19.39 MJ/Kg 51.5 MWth	Biogas 49 % LHV (dry) 25 MWth	AD diges- tate/Gasification/Solid Oxide electrolysis cell	Synthetic Natural Gas 138% LHV (dry) 71.1 MWth	[110]

### 5.3. Integration by Platform

According to IEA Bioenergy Task 42 [111], platforms are intermediates that connect feedstocks and final products. However, as shown in Table 3, 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 [112–114]. 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 bio-products and better economics of the biorefinery [115]. 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, as illustrated in Figure 9. While the economic advantage of producing multiple platforms is obvious, the biorefinery complexity index (BCI) increases with the increasing number of platforms [112], as shown in Table 3.

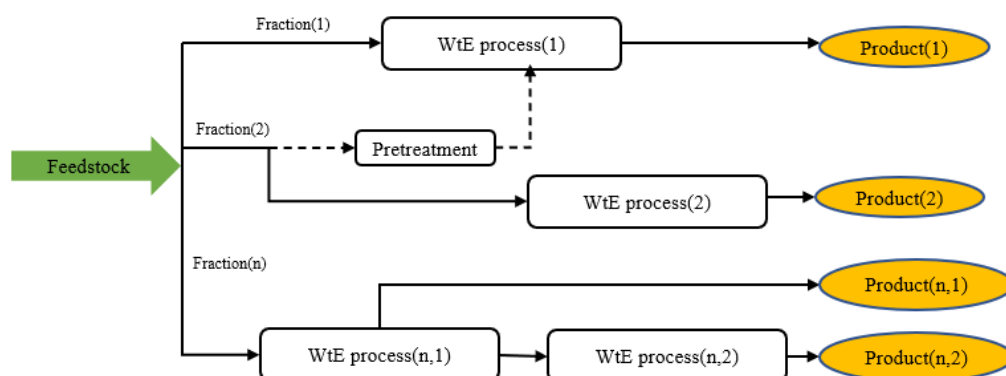
**Figure 9.** An illustration for biorefinery integration by platform.

**Table 3.** Examples of biorefinery integration to produce two or more platforms.

Feedstock	Platforms	Processes	Products	BCI	References
Woodchips	3-Platforms (C5 & C6 sugar, electricity and heat, lignin)	Pyrolysis, fermentation, combustion	Phenols, bioethanol, electricity, and heat	29	[112,114]
Algae	4-platform(biogas, biomethane, oil, electricity and heat)	Anaerobic Digestion, Combustion, Esterification	Fertilizer, biodiesel, fertilizer, omega 3, electricity and heat, glycerin	35	[114]
Straw	3-platform (pyrolysis oil, syngas, and electricity and heat)	Pyrolysis, gasification, combustion, methanol synthesis, FT-synthesis	Methanol, electricity and heat, biofuels	25	[114]
Wood chips	2-platform (syngas, electricity and heat)	Steam gasification, combustion, Fischer-Tropsch (FT) Synthesis	FT-diesel, FT-gasoline, wax, electricity and heat	16	[112]
Oil based residues	1-Platform(Bio-oil)	Esterification	Biodiesel, Bio-oil, glycerine and fertilizer	8	[113]

#### 5.4. Integration by Processes

The diversity of biomass waste has prompted researchers to investigate hybrid conversion systems that can process a variety of feedstocks [13,29]. 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 [21]. As a result, combining different bioprocesses enables for the processing of a diverse range of feedstocks and production of a diverse range of bioproducts, as shown in Figure 10.

**Figure 10.** An illustration for biorefinery integration by conversion process.

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 [116]. 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) in Figure 10 will need to be the same.

#### 5.5. Integration with Industrial Infrastructure

The integration of biorefineries with other downstream processes (see Figure 11) helps address the environmental and economic challenges originating the use of crude or raw biofuels as the source of bioenergy. Jungmeier and Buchsbaum [117] 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.

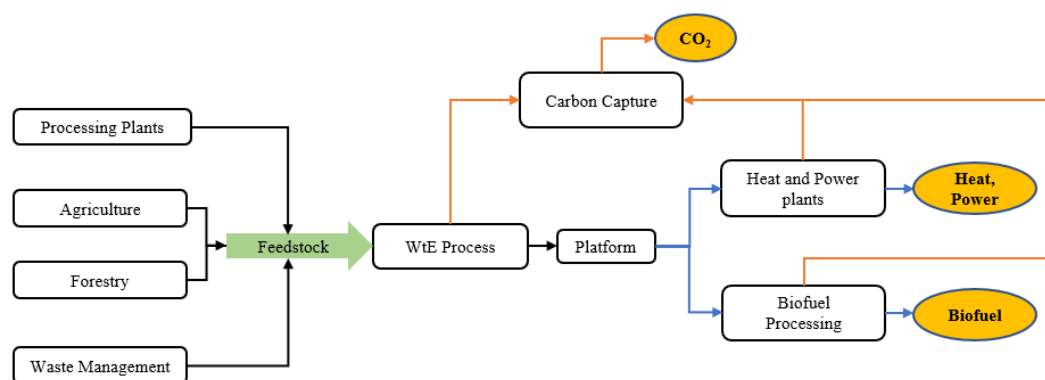


Figure 11. Biorefinery integration with downstream processes.

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. [118]. Hameed et al. [119] 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 [120]. According to the energy reports [121], combining biorefineries with carbon capture and storage presents an opportunity to generate bioenergy while creating a net carbon dioxide removal from the atmosphere. Table 4 summarizes a range of studies that demonstrate the integration of various biowaste conversion paths with other industrial infrastructures with CCS inclusive.

Table 4. Examples on the Integration of biorefineries with other industries.

Feedstock	Technology	Industry Infrastructure	Products	Reference
Forest biomass	Combustion	BECCS, Biomass-fired CHP plant	CCS: 0.9–1.84 tCO <sub>2</sub> /tdm* Heat: 10.18 GJ/tdm* Electricity: 6.48 GJ/tdm*	[122]
Wood	Gasification	Solid Oxide Fuel Cell-based CHP	Heat: Air 4877 MJ/tdm*, Steam: 967 MJ/tdm* Electricity: Air 2 GJ/tdm*, Steam: 4.5 GJ/tdm*	[118]
Eucalyptus biomass	Combustion	Biomass-fired CHP plant, CCS & algae growth and utilization.	CCS: 85.4 tCO <sub>2</sub> /d Heat: 419 GJ/d (internally consumed) Electricity: 177 GJ/d	[123]
Sewage water (40,000 m <sup>3</sup> /d 10 kgCOD/m <sup>3</sup> )	Anaerobic & Aerobic Digestion	Sewage water treatment, biogas-fired CHP plant & CCS	CCS: 0.6 kgCO <sub>2</sub> /KgCOD (removed) Electricity: 7.92 KWh/tonne (reusable water) Heat: Not reported	[124]
Miscanthus poplar, MSW, forest residue and crop residue	Combustion	Pulverized biomass-fired power plant with CCS (BE-CHP-CCS)	CCS: 90% CO <sub>2</sub> Capture rate Electricity: 1.58 MWh <sub>eq</sub> ./tCO <sub>2</sub> captured	[120]
	Combustion	Biomass -fueled CHP plant with CCS (BECCS)	CCS: 90% CO <sub>2</sub> Capture rate Electricity: 1.3 MWh <sub>eq</sub> ./tCO <sub>2</sub> captured	
	Gasification & Water-gas-shift technologies	Biomass-derived hydrogen production with CCS (BHCCS)	CCS: 90% CO <sub>2</sub> Capture rate Electricity: 0.7 MWh <sub>eq</sub> ./tCO <sub>2</sub> captured	

### 6. Future Integrated Waste Biorefineries

In contrast to conventional biorefineries, waste biorefineries play an important role in reducing land use impacts and environmental pollution originating from waste disposal. While waste biorefineries have been widely established as standalone technologies, integration enables more efficient material and energy utilization, thus enhancing their economic and environmental viability. As a result, the future concept of an energy-driven waste

biorefinery is one that integrates physical, thermal, chemical, and biological processes with other sectors to generate biofuels and other useful bio-based products while keeping emissions in sight. Furthermore, the development of integrated waste biorefineries minimizes the risks associated with the seasonal variations in feedstock availability. However, since biomass waste is diverse, characterization of the feedstock is essential in minimizing the number of conversion processes required to process the individual feedstocks.

According to studies, integration of waste biorefineries with existing low-carbon infrastructures like CHPs, waste management, and others enhance the quality of bioenergy, while the addition of Carbon Capture and Storage (CCS) will deliver carbon negative electricity and heat to support the decarbonization of the energy sector. Nevertheless, the development of integrated biorefineries is still at conceptual, pilot, or laboratory scale.

There is still a need for more research studies that target improvement in technology and optimization methods that address the challenges of feedstock diversity and increase process recoveries. As depicted in Figure 12, different types of feedstocks and applicable conversion processes lead to different biorefinery configurations, platforms, and products. However, provided the biorefinery's economics is not compromised, modifying feedstock quality for the desired conversion process can also be an option.

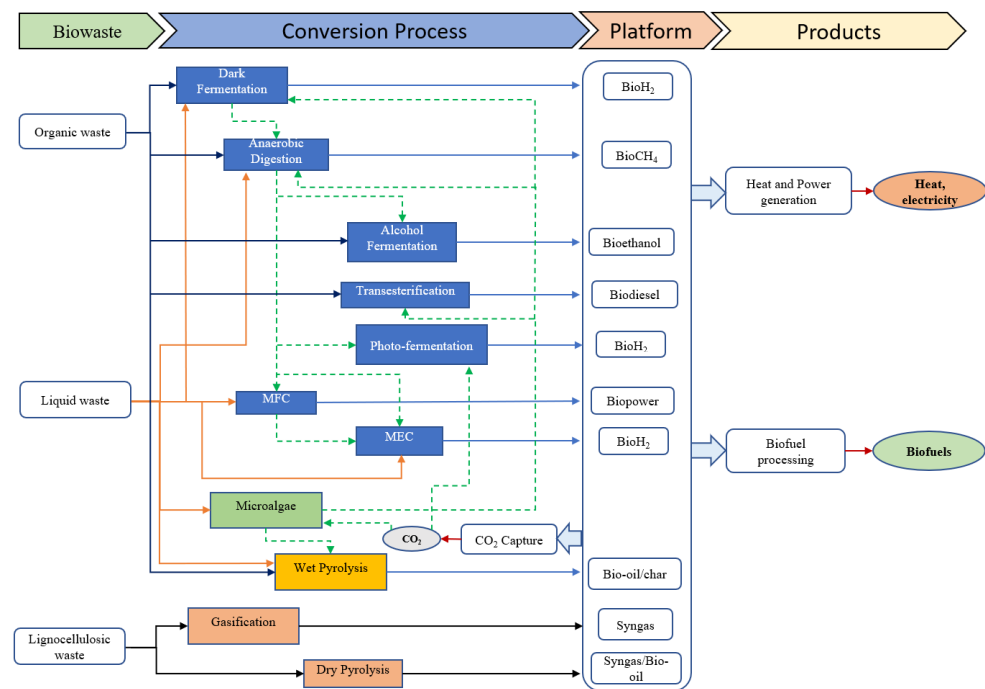


Figure 12. Pathways to bioenergy production through waste biorefineries.

## 7. Conclusions

Attributes of the biomass feedstock directly influence the selection of conversion pathways and bioenergy end-products, which in turn influence the synthesis of a waste biorefinery. As a result, most of the waste biorefineries are classified according to the type or source of feedstocks. Therefore, combining waste biorefineries to process multiple biomass wastes as feedstocks necessitates a technical and cost-effective aggregation of biomass waste to match with the existing technologies and desired products.

The moisture content of biomass waste is one of the most crucial aggregation components for waste conversion technologies. Feedstock for waste biorefineries towards energy application can be classified as lignocellulosic or organic waste based on moisture content. For example, lignocellulosic biomass waste has a low moisture content (usually below 60%) and a high lignocellulosic material content. Since lignocellulosic waste contains lignin, thermochemical processes such as gasification, pyrolysis, and incineration are favored for energy conversion. Other thermochemical processes, such as wet pyrolysis, have been



investigated to handle biomass waste with high moisture content, but the technology is still at inception stage. Organic waste has a high moisture content (usually above 60%), as well as easily biodegradable materials. The most common methods of converting organic waste into energy are biochemical methods such as anaerobic digestion and fermentation. The use of bioelectrochemical technologies such as microbial fuel cells and microbial electrochemical cells to handle organic waste have been proposed as a solution pathway to energy decarbonization. These techniques, however, are still in the laboratory stage, and additional work needs to be done to overcome the limitations of their application.

The development of integrated waste biorefineries focusing on integration by feedstocks, processes, waste, platforms, and end-products can be illustrated using organic and lignocellulosic waste classification. Furthermore, a need-centric strategy for feedstock to end-product can be implemented to synthesize an integrated waste biorefinery using a defined set of biochemical and thermochemical processes. This study is a first step toward creating a systematic framework for identifying and integrating waste-to-energy conversion processes based on the available set of biomass sources for waste biorefineries.

**Author Contributions:** R.O. prepared the original draft under the guidance of S.S. as the principal investigator on the project. In addition, S.S. validated the accuracy of the information on biomass conversion to energy systems, and A.G. reviewed the information on biorefinery integration with other energy sectors. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Norwegian University of Science and Technology, Project No. 81148046.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors acknowledge the financial support from the Department of Manufacturing and Civil Engineering, NTNU, Gjøvik.

**Conflicts of Interest:** The authors declare no conflict of interest.

## 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. [[CrossRef](#)]
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. [[CrossRef](#)]
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. [[CrossRef](#)]
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. [[CrossRef](#)]
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. [[CrossRef](#)]
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. [[CrossRef](#)]

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. [[CrossRef](#)]
13. Budzianowski, W.M.; Postawa, K. Total Chain Integration of sustainable biorefinery systems. *Appl. Energy* **2016**, *184*, 1432–1446. [[CrossRef](#)]
14. Alibardi, L.; Astrup, T.F.; Asunis, F.; Clarke, W.P.; De Gioannis, G.; Dessi, 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. [[CrossRef](#)]
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. [[CrossRef](#)]
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. [[CrossRef](#)]
17. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [[CrossRef](#)]
18. Fantini, M. Biomass Availability, Potential and Characteristics. In *Biorefineries: Targeting Energy, High Value Products and Waste Valorisation*; Rabaçal, M., Ferreira, A.F., Silva, C.A.M., Costa, M., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 21–54.
19. Badgujar, K.; Bhanage, B. Dedicated and Waste Feedstocks for Biorefinery: An Approach to Develop a Sustainable Society. In *Waste Biorefinery*; Bhaskar, T., Pandey, A., Mohan, S.V., Lee, D.-J., Khanal, S.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 3–38.
20. Brosowski, A.; Thrän, D.; Mantau, U.; Mahro, B.; Erdmann, G.; Adler, P.; Stinner, W.; Reinhold, G.; Hering, T.; Blanke, C. A review of biomass potential and current utilization—Status quo for 93 biogenic wastes and residues in Germany. *Biomass Bioenergy* **2016**, *95*, 257–272. [[CrossRef](#)]
21. 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.
22. Martínez-Hernández, E.; Sadhukhan, J. Process Design and Integration Philosophy for Competitive Waste Biorefineries: Example of Levulinic Acid Production From Representative Lignocellulosic Biomasses. In *Waste Biorefinery*; Bhaskar, T., Pandey, A., Mohan, S.V., Lee, D.-J., Khanal, S.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 695–725.
23. O’Callaghan, K. Technologies for the Utilisation of Biogenic Waste in the Bioeconomy. *Food Chem.* **2015**, *198*, 2–11. [[CrossRef](#)]
24. Chen, P.; Xie, Q.; Addy, M.; Zhou, W.; Liu, Y.; Wang, Y.; Cheng, Y.; Li, K.; Ruan, R. Utilization of municipal solid and liquid wastes for bioenergy and bioproducts production. *Bioresour. Technol.* **2016**, *215*, 163–172. [[CrossRef](#)]
25. Chen, P.; Anderson, E.; Addy, M.; Zhang, R.; Cheng, Y.; Peng, P.; Ma, Y.; Fan, L.; Zhang, Y.; Lu, Q.; et al. Breakthrough Technologies for the Biorefining of Organic Solid and Liquid Wastes. *Engineering* **2018**, *4*, 574–580. [[CrossRef](#)]
26. Ciria, P.; Barro, R. 3-Biomass resource assessment. In *Biomass Supply Chains for Bioenergy and Biorefining*; Holm-Nielsen, J.B., Ehimen, E.A., Eds.; Woodhead Publishing: Sawston, UK, 2016; pp. 53–83.
27. Monlau, F.; Barakat, A.; Trably, E.; Dumas, C.; Steyer, J.-P.; Carrère, H. Lignocellulosic Materials Into Biohydrogen and Biomethane: Impact of Structural Features and Pretreatment. *Crit. Rev. Environ. Sci. Technol.* **2013**, *43*, 260–322. [[CrossRef](#)]
28. Kirtania, K. Chapter 4—Thermochemical Conversion Processes for Waste Biorefinery. In *Waste Biorefinery*; Bhaskar, T., Pandey, A., Mohan, S.V., Lee, D.-J., Khanal, S.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 129–156.
29. Hashemi, B.; Sarker, S.; Lamb, J.J.; Lien, K.M. Yield improvements in anaerobic digestion of lignocellulosic feedstocks. *J. Clean. Prod.* **2021**, *288*, 125447. [[CrossRef](#)]
30. García, R.; Pizarro, C.; Lavín, A.; Bueno, J. Biomass sources for thermal conversion. Techno-economical overview. *Fuel* **2017**, *195*, 182–189. [[CrossRef](#)]
31. Sayara, T.; Sánchez, A. A Review on Anaerobic Digestion of Lignocellulosic Wastes: Pretreatments and Operational Conditions. *Appl. Sci.* **2019**, *9*, 4655. [[CrossRef](#)]
32. Coma, M.; Martínez-Hernández, 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. [[CrossRef](#)] [[PubMed](#)]
33. EU. Council Directive 75/442/EEC of 15 July 1975 on waste (OJ L 194 25.07.1975 p. 39). In *Documents in European Community Environmental Law*, 2nd ed.; Galizzi, P., Sands, P., Eds.; Cambridge University Press: Cambridge, UK, 2006; pp. 617–626.
34. Saravanan, A.; Hemavathy, R.V.; Sundararaman, T.R.; Jeevanantham, S.; Kumar, P.S.; Yaashikaa, P.R. Solid waste biorefineries. In *Refining Biomass Residues for Sustainable Energy and Bioproducts*; Kumar, R.P., Gnansounou, E., Raman, J.K., Baskar, G., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 3–17.
35. 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. [[CrossRef](#)] [[PubMed](#)]
36. Sánchez, A.S. Chapter Nine—Toward “Zero Liquid Discharge” industrial facilities: Reducing the impact on freshwater resources by reusing industrial and urban wastewaters. In *Concepts of Advanced Zero Waste Tools*; Hussain, C.M., Ed.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 215–246.
37. Sánchez, J.; Curt, M.D.; Robert, N.; Fernández, J. Biomass Resources. In *The Role of Bioenergy in the Bioeconomy*; Academic Press: Cambridge, MA, USA, 2019.

38. Mumtaz, M.W.; Adnan, A.; Mukhtar, H.; Rashid, U.; Danish, M. Biodiesel production through chemical and biochemical transesterification: Trends, technicalities, and future perspectives. In *Clean Energy for Sustainable Development: Resources, Technologies, Sustainability and Policy*; Carmen, L., Natalia, C., Lechon, Y., Eds.; Elsevier: Amsterdam, The Netherlands, 2017; pp. 465–485.
39. Uzun, B.B.; Kılıç, M.; Özbay, N.; Pütün, A.E.; Pütün, E. Biodiesel production from waste frying oils: Optimization of reaction parameters and determination of fuel properties. *Energy* **2012**, *44*, 347–351. [[CrossRef](#)]
40. Huynh, L.-H.; Kasim, N.S.; Ju, Y.-H. Chapter 16—Biodiesel Production from Waste Oils. In *Biofuels*; Pandey, A., Larroche, C., Ricke, S.C., Dussap, C.-G., Gnansounou, E., Eds.; Academic Press: Amsterdam, The Netherlands, 2011; pp. 375–396.
41. Bhaskar, T.; Pandey, A. Advances in Thermochemical Conversion of Biomass—Introduction. In *Recent Advances in Thermo-Chemical Conversion of Biomass*; Michael, S., Sukumaran, R.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2015; pp. 3–30.
42. Kumar, A.; Samadder, S.R. A review on technological options of waste to energy for effective management of municipal solid waste. *Waste Manag.* **2017**, *69*, 407–422. [[CrossRef](#)]
43. Ferreira, A.F. Biorefinery Concept. In *Biorefineries: Targeting Energy, High Value Products and Waste Valorisation*; Rabaçal, M., Ferreira, A.F., Silva, C.A.M., Costa, M., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 1–20.
44. Maniscalco, M.P.; Volpe, M.; Messineo, A. Hydrothermal carbonization as a valuable tool for energy and environmental applications: A review. *Energies* **2020**, *13*, 4098. [[CrossRef](#)]
45. Fitri Faradilla, R.H.; Lucia, L.; Hakovirta, M. Hydrothermal carbonization of soybean hulls for the generation of hydrochar: A promising valorization pathway for low value biomass. *Environ. Nanotechnol. Monit. Manag.* **2021**, *16*, 100571. [[CrossRef](#)]
46. Zhuang, X.; Liu, J.; Zhang, Q.; Wang, C.; Zhan, H.; Ma, L. A review on the utilization of industrial biowaste via hydrothermal carbonization. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111877. [[CrossRef](#)]
47. Kumar, S.; Ankaram, S. Waste-to-Energy Model/Tool Presentation. In *Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 239–258.
48. Ellacuriaga, M.; García-Cascallana, J.; Gómez, X. Biogas Production from Organic Wastes: Integrating Concepts of Circular Economy. *Fuels* **2021**, *2*, 144–167. [[CrossRef](#)]
49. Shrestha, B.; Hernandez, R.; Fortela, D.L.B.; Sharp, W.; Chistoserdov, A.; Gang, D.; Revellame, E.; Holmes, W.; Zappi, M.E. A Review of Pretreatment Methods to Enhance Solids Reduction during Anaerobic Digestion of Municipal Wastewater Sludges and the Resulting Digester Performance: Implications to Future Urban Biorefineries. *Appl. Sci.* **2020**, *10*, 9141. [[CrossRef](#)]
50. Sarker, S.; Lamb, J.J.; Hjelme, D.R.; Lien, K.M. A Review of the Role of Critical Parameters in the Design and Operation of Biogas Production Plants. *Appl. Sci.* **2019**, *9*, 1915. [[CrossRef](#)]
51. da Silva, A.S.A.; de Sá, L.R.V.; Aguiéiras, E.C.G.; de Souza, M.F.; Teixeira, R.S.S.; Cammarota, M.C.; Bon, E.P.S.; Freire, D.M.G.; Ferreira-Leitão, V.S. Productive Chain of Biofuels and Industrial Biocatalysis: Two Important Opportunities for Brazilian Sustainable Development. In *Biotechnology of Microbial Enzymes*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 545–581.
52. Sampaio, M.A.; Gonçalves, M.R.; Marques, I.P. Anaerobic digestion challenge of raw olive mill wastewater. *Bioresour. Technol.* **2011**, *102*, 10810–10818. [[CrossRef](#)] [[PubMed](#)]
53. Malakar, S.; Paul, S.K.; Pou, K.R.J. Biotechnological interventions in beverage production. In *Biotechnological Progress and Beverage Consumption*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 1–37.
54. Byadgi, S.A.; Kalburgi, P.B. Production of bioethanol from waste newspaper. *Procedia Environ. Sci.* **2016**, *35*, 555–562. [[CrossRef](#)]
55. Khandaker, M.M.; Qiamuddin, K.; Majrashi, A.; Dalorima, T. Bio-ethanol production from fruit and vegetable waste by using *saccharomyces cerevisiae*. In *Bioethanol Technologies*; Inambao, F., Ed.; Intechopen: London, UK, 2021.
56. 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. [[CrossRef](#)]
57. Venkata Mohan, S. Reorienting waste remediation towards harnessing bioenergy. In *Industrial Wastewater Treatment, Recycling and Reuse*; Ranade, V.V., Bhandari, V.M., Eds.; Butterworth-Heinemann: Oxford, UK, 2014; pp. 235–281.
58. Mehariya, S.; Goswami, R.K.; Verma, P.; Lavecchia, R.; Zuurro, A. Integrated approach for wastewater treatment and biofuel production in microalgae biorefineries. *Energies* **2021**, *14*, 2282. [[CrossRef](#)]
59. Poh, P.E.; Gouwanda, D.; Mohan, Y.; Gopalai, A.A.; Tan, H.M. Optimization of wastewater anaerobic digestion using mechanistic and meta-heuristic methods: Current limitations and future opportunities. *Water Conserv. Sci. Eng.* **2016**, *1*, 1–20. [[CrossRef](#)]
60. Rajakumar, R.; Meenambal, T.; Banu, J.R.; Yeom, I.T. Treatment of poultry slaughterhouse wastewater in upflow anaerobic filter under low upflow velocity. *Int. J. Environ. Sci. Technol.* **2011**, *8*, 149–158. [[CrossRef](#)]
61. Fito, J.; Tefera, N.; Van Hulle, S.W.H. Sugarcane biorefineries wastewater: Bioremediation technologies for environmental sustainability. *Chem. Biol. Technol. Agric.* **2019**, *6*, 1–13. [[CrossRef](#)]
62. Zhao, B.; Ma, J.; Zhao, Q.; Laurens, L.; Jarvis, E.; Chen, S.; Frear, C. Efficient anaerobic digestion of whole microalgae and lipid-extracted microalgae residues for methane energy production. *Bioresour. Technol.* **2014**, *161*, 423–430. [[CrossRef](#)]
63. Acién, F.G.; Molina, E.; Fernández-Sevilla, J.M.; Barbosa, M.; Gouveia, L.; Sepúlveda, C.; Bazaes, J.; Arbib, Z. Economics of microalgae production. In *Microalgae-Based Biofuels and Bioproducts*; Gonzalez-Fernandez, C., Muñoz, R., Eds.; Woodhead Publishing: Sawston, UK, 2017; pp. 485–503.
64. Moreno García, L.; Gariépy, Y.; Barnabé, S.; Raghavan, V. Biorefinery of microalgae biomass cultivated in wastewaters. In *Refining Biomass Residues for Sustainable Energy and Bioproducts: Technology, Advances, Life Cycle Assessment, and Economics*; Praveen Kumar, R., Jegannathan, K.R., Edgard, G., Baskar, G., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 149–180.

65. Escapa, A.; Mateos, R.; Martínez, E.J.; Blanes, J. Microbial electrolysis cells: An emerging technology for wastewater treatment and energy recovery. From laboratory to pilot plant and beyond. *Renew. Sustain. Energy Rev.* **2016**, *55*, 942–956. [CrossRef]
66. Senthilkumar, K.; Naveen Kumar, M. Generation of bioenergy from industrial waste using microbial fuel cell technology for the sustainable future. In *Refining Biomass Residues for Sustainable Energy and Bioproducts: Technology, Advances, Life Cycle Assessment, and Economics*; Praveen Kumar, R., Jegannathan, K.R., Edgard, G., Baskar, G., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 183–193.
67. Khan, M.Z.; Nizami, A.S.; Rehan, M.; Ouda, O.K.M.; Sultana, S.; Ismail, I.M.; Shahzad, K. Microbial electrolysis cells for hydrogen production and urban wastewater treatment: A case study of Saudi Arabia. *Appl. Energy* **2017**, *185*, 410–420. [CrossRef]
68. Kadier, A.; Jain, P.; Lai, B.; Kalil, M.S.; Kondaveeti, S.; Alabbosh, K.F.S.; Abu-Reesh, I.M.; Mohanakrishna, G. Biorefinery perspectives of microbial electrolysis cells (MECs) for hydrogen and valuable chemicals production through wastewater treatment. *Biofuel Res. J.* **2020**, *7*, 1128–1142. [CrossRef]
69. Fudge, T.; Bulmer, I.; Bowman, K.; Pathmakanthan, S.; Gambier, W.; Dehouche, Z.; Al-Salem, S.M.; Constantinou, A. Microbial Electrolysis Cells for Decentralised Wastewater Treatment: The Next Steps. *Water* **2021**, *13*, 445. [CrossRef]
70. Saravanan, A.; Karishma, S.; Kumar, P.S.; Yaashikaa, P.R.; Jeevanantham, S.; Gayathri, B. Microbial electrolysis cells and microbial fuel cells for biohydrogen production: Current advances and emerging challenges. *Biomass Convers. Biorefin.* **2020**. Available online: <https://link.springer.com/article/10.1007/s13399-020-00973-x> (accessed on 13 July 2021). [CrossRef]
71. Escapa, A.; San-Martín, M.I.; Morán, A. Potential use of microbial electrolysis cells in domestic wastewater treatment plants for energy recovery. *Front. Energy Res.* **2014**, *2*, 19. [CrossRef]
72. Seelam, J.S.; Maesara, S.A.; Mohanakrishna, G.; Patil, S.A.; ter Heijne, A.; Pant, D. Resource recovery from wastes and wastewaters using bioelectrochemical systems. In *Waste Biorefinery*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 535–570.
73. Mohsenpour, S.F.; Hennige, S.; Willoughby, N.; Adeloye, A.; Gutierrez, T. Integrating micro-algae into wastewater treatment: A review. *Sci. Total Environ.* **2021**, *752*, 142168. [CrossRef] [PubMed]
74. Khetkorn, W.; Rastogi, R.P.; Incharoensakdi, A.; Lindblad, P.; Madamwar, D.; Pandey, A.; Larroche, C. Microalgal hydrogen production—A review. *Bioresour. Technol.* **2017**, *243*, 1194–1206. [CrossRef] [PubMed]
75. Nagarajan, D.; Lee, D.-J.; Kondo, A.; Chang, J.-S. Recent insights into biohydrogen production by microalgae—From biophotolysis to dark fermentation. *Bioresour. Technol.* **2017**, *227*, 373–387. [CrossRef] [PubMed]
76. Dalena, F.; Senatore, A.; Tursi, A.; Basile, A. 17-Bioenergy production from second- and third-generation feedstocks. In *Bioenergy Systems for the Future*; Dalena, F., Basile, A., Rossi, C., Eds.; Woodhead Publishing: Sawston, UK, 2017; pp. 559–599.
77. Bahr, M.; Díaz, I.; Dominguez, A.; Gonzalez Sanchez, A.; Muñoz, R. Microalgal-biotechnology as a platform for an integral biogas upgrading and nutrient removal from anaerobic effluents. *Environ. Sci. Technol.* **2014**, *48*, 573–581. [CrossRef]
78. Ren, H.-Y.; Liu, B.-F.; Kong, F.; Zhao, L.; Ren, N.-Q. Sequential generation of hydrogen and lipids from starch by combination of dark fermentation and microalgal cultivation. *RSC Adv.* **2015**, *5*, 76779–76782. [CrossRef]
79. Chen, Y.D.; Ho, S.H.; Nagarajan, D.; Ren, N.Q.; Chang, J.S. Waste biorefineries-integrating anaerobic digestion and microalgae cultivation for bioenergy production. *Curr. Opin. Biotechnol.* **2018**, *50*, 101–110. [CrossRef]
80. Vermuë, M.H.; Eppink, M.H.M.; Wijffels, R.H.; Van Den Berg, C. Multi-product microalgae biorefineries: From concept towards reality. *Trends Biotechnol.* **2018**, *36*, 216–227.
81. Dahiya, S.; Kumar, A.N.; Shanthi Sraavan, J.; Chatterjee, S.; Sarkar, O.; Mohan, S.V. Food waste biorefinery: Sustainable strategy for circular bioeconomy. *Bioresour. Technol.* **2018**, *248*, 2–12. [CrossRef] [PubMed]
82. Chandra, R.; Castillo-Zacarias, 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. [CrossRef]
83. 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. [CrossRef]
84. 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. [CrossRef]
85. Mirabella, N.; Castellani, V.; Sala, S. Current options for the valorization of food manufacturing waste: A review. *J. Clean. Prod.* **2014**, *65*, 28–41. [CrossRef]
86. Tsegaye, B.; Jaiswal, S.; Jaiswal, A.K. Food Waste Biorefinery: Pathway towards Circular Bioeconomy. *Foods* **2021**, *10*, 1174. [CrossRef]
87. 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. [CrossRef]
88. 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.
89. 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.

90. 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. [[CrossRef](#)]
91. Liu, Z.; Liao, W.; Liu, Y. A sustainable biorefinery to convert agricultural residues into value-added chemicals. *Biotechnol. Biofuels* **2016**, *9*, 197. [[CrossRef](#)]
92. 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. [[CrossRef](#)] [[PubMed](#)]
93. 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.
94. 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. [[CrossRef](#)] [[PubMed](#)]
95. Stuart, P.R.; El-Halwagi, M.M. *Integrated Biorefineries: Design, Analysis, and Optimization*; CRC Press: Boca Raton, FL, USA, 2012; pp. 36–58.
96. 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. [[CrossRef](#)]
97. 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. [[CrossRef](#)]
98. Yazan, D.M.; Romano, V.A.; Albino, V. The design of industrial symbiosis: An input–output approach. *J. Clean. Prod.* **2016**, *129*, 537–547. [[CrossRef](#)]
99. 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.
100. 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. [[CrossRef](#)]
101. Katakai, 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.
102. 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.
103. Yao, Z.; Li, W.; Kan, X.; Dai, Y.; Tong, Y.W.; Wang, C.-H. Anaerobic digestion and gasification hybrid system for potential energy recovery from yard waste and woody biomass. *Energy* **2017**, *124*, 133–145. [[CrossRef](#)]
104. Monlau, F.; Francavilla, M.; Sambusiti, C.; Antoniou, N.; Solhy, A.; Libutti, A.; Zabaniotou, A.; Barakat, A.; Monteleone, M. Toward a functional integration of anaerobic digestion and pyrolysis for a sustainable resource management. Comparison between solid-digestate and its derived pyrochar as soil amendment. *Appl. Energy* **2016**, *169*, 652–662. [[CrossRef](#)]
105. Li, W.; Lu, C.; An, G.; Zhang, Y.; Tong, Y.W. Integration of high-solid digestion and gasification to dispose horticultural waste and chicken manure. *Chin. J. Chem. Eng.* **2018**, *26*, 1145–1151. [[CrossRef](#)]
106. Antoniou, N.; Monlau, F.; Sambusiti, C.; Ficara, E.; Barakat, A.; Zabaniotou, A. Contribution to Circular Economy options of mixed agricultural wastes management: Coupling anaerobic digestion with gasification for enhanced energy and material recovery. *J. Clean. Prod.* **2019**, *209*, 505–514. [[CrossRef](#)]
107. Monlau, F.; Sambusiti, C.; Antoniou, N.; Barakat, A.; Zabaniotou, A. A new concept for enhancing energy recovery from agricultural residues by coupling anaerobic digestion and pyrolysis process. *Appl. Energy* **2015**, *148*, 32–38. [[CrossRef](#)]
108. Mohanakrishna, G.; Mohan, S.V.; Sarma, P.N. Utilizing acid-rich effluents of fermentative hydrogen production process as substrate for harnessing bioelectricity: An integrative approach. *Int. J. Hydrogen Energy* **2010**, *35*, 3440–3449. [[CrossRef](#)]
109. Kan, X.; Yao, Z.; Zhang, J.; Tong, Y.W.; Yang, W.; Dai, Y.; Wang, C.-H. Energy performance of an integrated bio-and-thermal hybrid system for lignocellulosic biomass waste treatment. *Bioresour. Technol.* **2017**, *228*, 77–88. [[CrossRef](#)]
110. Clausen, L.R.; Butera, G.; Jensen, S.H. Integration of anaerobic digestion with thermal gasification and pressurized solid oxide electrolysis cells for high efficiency bio-SNG production. *Energy* **2019**, *188*, 116018. [[CrossRef](#)]
111. 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.
112. Jungmeier, G. *The Biorefinery Complexity Index*; Working Document—2014-07-09; IEA-Bioenergy Task 42 Biorefining: Wageningen, The Netherlands, 2014; p. 36.
113. 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.
114. 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.
115. 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.

116. 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. [[CrossRef](#)]
117. 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.
118. 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. [[CrossRef](#)]
119. 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. [[CrossRef](#)]
120. 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. [[CrossRef](#)]
121. Carbo, M. *Biomass-Based Industrial CO<sub>2</sub> Sources: Biofuels Production with CCS*; United Nations Industrial Development Organization: Vienna, Austria, 2011.
122. Kraxner, F.; Aoki, K.; Leduc, S.; Kindermann, G.; Fuss, S.; Yang, J.; Yamagata, Y.; Tak, K.-I.; Obersteiner, M. BECCS in South Korea—Analyzing the negative emissions potential of bioenergy as a mitigation tool. *Renew. Energy* **2014**, *61*, 102–108. [[CrossRef](#)]
123. Beal, C.M.; Archibald, I.; Huntley, M.E.; Greene, C.H.; Johnson, Z.I. Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) Increases Sustainability. *Earth's Future* **2018**, *6*, 524–542. [[CrossRef](#)]
124. Poblete, I.B.S.; Araújo, O.D.Q.F.; de Medeiros, J.L. Sewage-water treatment with bio-energy production and carbon capture and storage. *Chemosphere* **2022**, *286*, 131763. [[CrossRef](#)] [[PubMed](#)]