Waste to Energy Conversion Processes

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Sustainable biofuel production is the most effective way to mitigate greenhouse gas emissions associated with fossil fuels while preserving food security and land use. 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.

Keywords: Biorefineries ; Waste ; Thermochemical

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, the 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. 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 [17]. 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][18].

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 [17]. 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 [19]. 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][20].

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 [21]. 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 [22][23]. 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 [21].

3. Biochemical Methods

3.1. 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][24]. 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 [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 [25][26]. To increase the yield of biogas, accessibility of the substrate by microorganisms can be increased by adding a pretreatment step to the AD process [27][28]. Additionally, due to the sensitivity of AD process, optimization of design and operation parameters is critical for maximizing biogas yield and quality [29].

Fermentation is a biological process that aerobically breaks down compounds like glucose in biomass waste to produce primarily ethyl alcohol and carbon dioxide [24]. 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 [30]. 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 [31][32]. 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][30]. For example, Byadgi and Kalburgi [33] investigated the three-step fermentation of waste newspapers to produce bioethanol. According to the researchers, 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 it’s economic performance is not effective [34].

3.2. Liquid Waste Conversion

In comparison to solid waste, the energy potential of liquid waste has been underutilized [35]. The wastewater contains a lot of organic substrates, which means there’s a lot of room for bioenergy and other value-added goods [36][37]. Furthermore, producing biofuels and treating wastewater at the same time allows for financial savings while also making the biorefinery environmentally sustainable [36].

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.

- *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 [36]. Aside from the products, wastewater treatment using anaerobic digestion (AD) reduces pollutant levels, stabilizes sludge, and reduces sludge tonnage significantly with minimal energy input [28]. Traditional anaerobic digestion has long been used to breakdown organic compounds and pathogens in wastewater collected in ponds [38]. 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 [38][39]. Even though Upflow anaerobic sludge blanket (UASB) reactors have the potential to significantly increase biogas yield [40], the technology still requires further development to overcome foaming and other AD inhibitions, particularly at high organic loading rates (OLR) [31].

- *Bioelectrochemical systems (BECS)*: Bioelectrochemical conversion has emerged as one of the most efficient ways to cleanse wastewater and produce bioenergy (bioelectricity and hydrogen) [41]. 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 [42][43]. 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 [44]. 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 [45][46]. 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 [47]. 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 [48].

- *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 [49]. Because algae biomass is unicellular and buoyant, structurally complex substances such as lignin and hemicellulose are not required for growth [50]. For this reason, microalgae are most desirable biofuel source because the cell walls are not resistant to treatment conditions, necessitating just moderate pretreatments [51]. 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 [52].

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. [53], Ren et al. [54], and Chen et al. [55].

Despite advancements, large-scale biofuel generation from microalgae remains technically and economically unviable (see; [56]). Low biomass productivity and a lack of a substantial and consistent supply of wastewater are the two major obstacles to the technology's commercialization [57]. Furthermore, cost-analysis studies have found that photobioreactor systems are expensive, greatly increasing the investment cost [58].

- *Transesterification*: Transesterification is a crucial step in the conversion of waste oils into biodiesel, which has the potential to completely replace fossil fuel [59]. 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 [60].

To convert waste oils into biodiesel, transesterication 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 [61]. Additionally, both acid and base-catalyzed processes necessitate extra costs for product purification and catalyst recovery [60][61]. 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].

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