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Review

Anaerobic biorefinery: Current status, challenges, and opportunities

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HIGHLIGHTS

- Anaerobic biorefineries are a new approach for producing biobased products.
- Most organic substrates can be used as feedstocks for anaerobic biorefineries.
- Large-scale biorefineries have the potential to maximize economic benefit.
- Small-scale anaerobic biorefineries improves living quality in developing countries.

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ABSTRACT

Anaerobic digestion (AD) has been in use for many decades. To date, it has been primarily aimed at treating organic wastes, mainly manures and wastewater sludge, and industrial wastewaters. However, with the current advancements, a more open mind is required to look beyond these somewhat restricted original applications of AD. Biorefineries are such concepts, where multiple products including chemicals, fuels, polymers etc. are produced from organic feedstocks. The anaerobic biorefinery concept is now gaining increased attention, utilizing AD as the final disposal step. This review aims at evaluating the potential significance of anaerobic biorefineries, including types of feedstocks, uses for the produced energy, as well as sustainable applications of the generated residual digestate. A comprehensive analysis of various types of anaerobic biorefineries has been developed, including both large-scale and household level applications. Finally, future directives are highlighted showing how anaerobic biorefinery concept could impact the bioeconomy in the near future.

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1. Introduction

The global total primary energy consumption was reported around 524 Quadrillion Btu (QBtu) in 2010 (Energy Information Administration (EIA), 2013). The energy consumption is expected to increase by nearly 50% by 2050 due to growing demand from emerging nations such as India, China, and Brazil among others. Currently, fossil-based fuels supply over 85% of world energy demands. The excessive use of fossil fuels has also been linked to several environmental issues, especially greenhouse gas (GHG) emissions and local and regional air quality degradation. The CO_2 emissions from the combustion of fossil fuels alone contributes to more than 90% of energy-related GHG emissions (International Energy Agency (IEA), 2015). Moreover, energy security is also a major concern for countries that rely on imports of fossil energy resources. In the recent years, renewable energy technologies (e.g., wind, solar, hydro, and biomass) have been promoted to address environmental issues such as climate change and local air quality degradation, as well as energy insecurity. The renewable-based power generation in 2014 increased to 128 GW which is over 40% higher than renewable power generation in 2010 (IEA, 2015). Among the various renewable energy sources, biomass has so far been the largest single source currently being used, especially in developing countries where biomass (e.g., firewood, crop residues, and cattle dung) is used as a primary energy source for heating and cooking.

Anaerobic digestion (AD) is one of the most promising biotechnologies for converting diverse organic substrates, ranging from high solid feedstocks (i.e., animal manure, food wastes, municipal solid waste, and lignocellulosic biomass), as well as municipal and industrial wastewaters, to energy-rich biogas (Khanal, 2008). Although AD technology had primarily been developed and adopted for waste stabilization, in recent years, AD process has been widely adopted for bioenergy production. Over 14,000 commercial AD plants are already in operation in Europe, while Germany alone has more than 8000 plants (EBA, 2014). The produced biogas is used for combined heat and power (CHP) generation, and/or upgraded to biomethane to be used as transportation fuels, or injected into natural gas grid.

In developing nations, AD processes are becoming immensely popular for conversion of organic wastes (e.g., animal manures, food wastes, agri-residues, etc.) into biogas. The biogas serves as a clean energy for cooking and lighting in rural households. The residuals after digestion, commonly known as bioslurry, serve as an organic fertilizer for crop production and as a fish feed for aquaculture application (Surendra et al., 2014). There have been several successful examples of implementation of biodigester technologies in developing countries in Asia including Nepal, Vietnam, Bangladesh, Cambodia, and Laos among others. Using biogas for CHP generation or transportation fuels is a well-established process in developed countries. However, producing biogas alone might not be economically competitive, especially due to the volatility of market and price indexes of fossil fuels (Surendra et al., 2015). One approach to circumvent this problem is to identify and explore alternative products/chemicals apart from bioenergy production by adopting the biorefinery approach. The biorefinery concept is analogous to a traditional petrochemical refinery in which multiple products are produced from crude petroleum. According to the National Renewable Energy Laboratory (NREL), a biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass. Thus, such approach aims at maximizing the profit by producing low volume high-value products while meeting the energy needs by producing low-value high volume fuels. The anaerobic biorefinery is one of the biorefinery concepts, in which AD serves as a centerpiece to produce high-value, but low volume products (i.e., chemicals and drop-in biofuels to enhance economic viability of the system) and high-volume but low value products (i.e., heat, electricity, and conventional transportation biofuels) to achieve energy security. Recently many studies have discussed the biorefinery concept in general, but there exists only limited studies primarily focusing on the anaerobic biorefinery (Maclellan et al., 2013; Surendra et al., 2015). This review provides an overview of the anaerobic biorefinery concept and critically examines the recent advancements in anaerobic biorefineries. Moreover, this review also highlights the challenges and opportunities associated with both commercial and small-scale anaerobic biorefineries, and outlines directions for future research and development.

2. Potential feedstocks for an anaerobic biorefinery

2.1. Lignocellulosic biomass

Lignocellulosic biomass (e.g., agricultural and forest residues, energy crops, and paper wastes among others) is one of the most promising feedstocks for producing bioenergy (e.g., biomethane, biohydrogen, bioethanol, and biobutanol) and a plethora of

Table 1
The composition of selected lignocellulosic biomass.

Biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
Corn stover	39.7	29.9	8.9	Teater et al. (2011)
Wheat straw	37.9	21.8	22.1	Cui et al. (2011)
Switch grass	37.1	29.9	17.6	Teater et al. (2011)
Rice straw	35.0	26.7	13.3	Ye et al. (2013)
Napier grass	45.7	33.7	20.6	Reddy et al. (2012)
Barley straw	37.5	25.3	26.1	Monlau et al. (2012)
Miscanthus	38.0	18.5	20.9	Vasco-Correa et al. (2016)
Coffee pulp	35.0	46.3	18.8	Karthikeyan and Visvanathan (2012)
Paper waste	11.9	1.0	33.0	Elliston et al. (2013)

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