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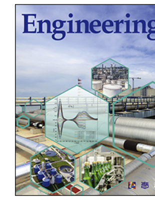

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Breakthrough Technologies for the Biorefining of Organic Solid and Liquid Wastes

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A B S T R A C T

Organic solid and liquid wastes contain large amounts of energy, nutrients, and water, and should not be perceived as merely waste. Recycling, composting, and combustion of non-recyclables have been practiced for decades to capture the energy and values from municipal solid wastes. Treatment and disposal have been the primary management strategy for wastewater. As new technologies are emerging, alternative options for the utilization of both solid wastes and wastewater have become available. Considering the complexity of the chemical, physical, and biological properties of these wastes, multiple technologies may be required to maximize the energy and value recovery from the wastes. For this purpose, biorefining tends to be an appropriate approach to completely utilize the energy and value available in wastes. Research has demonstrated that non-recyclable waste materials and bio-solids can be converted into usable heat, electricity, fuel, and chemicals through a variety of processes, and the liquid waste streams have the potential to support crop and algae growth and provide other energy recovery and food production options. In this paper, we propose new biorefining schemes aimed at organic solid and liquid wastes from municipal sources, food and biological processing plants, and animal production facilities. Four new breakthrough technologies—namely, vacuum-assisted thermophilic anaerobic digestion, extended aquaponics, oily wastes to biodiesel via glycerolysis, and microwave-assisted thermochemical conversion—can be incorporated into the biorefining schemes, thereby enabling the complete utilization of those wastes for the production of chemicals, fertilizer, energy (biogas, syngas, biodiesel, and bio-oil), foods, and feeds, and resulting in clean water and a significant reduction in pollutant emissions.

1. Introduction

The world generates tremendous amounts of solid and liquid wastes every year from sources that include domestic, commercial, industry, construction, and farming activities. Global municipal solid waste (MSW) annual generation exceeds 2×10^9 t. On a per capita basis, the developed countries produce at least five times more MSW than the developing countries. However, as the largest developing country, China alone generates more than 2×10^8 t MSW, accounting for more than 10% of the world's MSW. If not disposed of properly, MSW poses a serious threat to the environment. At present, composting, landfilling, and incineration are the main methods of non-recyclable MSW disposal. In China, non-recyclable MSW is primarily disposed of through landfill (65.5%) and incineration (32.5%) [1], both of which have the potential of causing unintended groundwater contamination [2] and air pollution [3].

China produced 6.85×10^{10} t municipal wastewater (MWW) in 2012 [4], while the United States produced around 4.46×10^{10} t in 2008 [5]. MWW treatment consumes 0.4% and 3%–4% of total electricity use in China [6] and the United States [7], respectively. Therefore, MWW is not only a large pollutant source but also a

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huge energy consumer and a source of significant energy-related emissions. In addition to MWW, there are many other sources of wastewater; in particular, agricultural activities generate millions of tons of concentrated wastewater. Greenhouse gases (GHGs) such as methane (CH_4) and carbon dioxide (CO_2) are emitted from these wastewaters due to natural biological processes. Some of the MWW sludge and animal wastewater is used to produce biogas through controlled anaerobic digestion (AD) [8]. However, the majority of the resources in the wastewaters remains uncaptured.

Proper management and, especially, utilization of solid and liquid wastes can have potential positive impacts on our environment, renewable energy and materials production, and economy. Solid and liquid wastes are composed of large amounts of organic materials and compounds that contain a great deal of recoverable energy. Table 1 lists the energy contents of major solid wastes. The world's MWW contains $30–60 \times 10^{15}$ $kJ \cdot a^{-1}$, given a chemical oxygen demand (COD) of 60–120 g per capita per day, an energy density of 17.6 $kJ \cdot g^{-1}$ for COD, and 7.8 billion people in the world [9]. This does not include the energy present in agricultural and industrial wastewaters. Therefore, there is a great potential to recover a tremendous amount of energy from solid and liquid wastes. Recent research has demonstrated that non-recyclable waste materials and bio-solids can be converted to usable heat, electricity, fuels, and chemicals through a variety of processes. Liquid waste streams can be sent through additional energy recovery options, with the potential to support agricultural crops and algae growth, and provide other usable byproducts.

The objectives of the present paper are: to describe biorefining schemes for the beneficial utilization of organic solid and wastewater wastes as a sustainable waste management strategy; to identify technological options; and to present some important technical breakthroughs being developed in the authors' laboratories.

2. Biorefining schemes

Considering the complexity of the chemical, physical, and biological properties of various solid and liquid wastes, multiple technologies may be required to maximize the energy and value recovery from the wastes. The physical and chemical states of a particular waste change during the management and utilization process. For example, solid sludge is produced during wastewater treatment, and the scum from an MWW treatment plant can be separated into three distinct streams—namely, oil, water, and dry solids. Additional processes need to be brought in to deal with the new states and streams. This leads to the concept of biorefining, which has been broadly discussed in the field of biomass energy production.

Many different biorefining schemes have been proposed [10,11]. In biorefining schemes, biomass is used in the place of fossil oil as a feedstock in conventional petrorefining, through which biomass is converted to different forms of energy, chemicals, and materials, which may be conventionally derived from fossil resources (Fig. 1) [12]. This scheme is mostly designed for plant-based biomass feedstocks, which contain high contents of lignocellulosics, sugars, or oil. Such feedstocks are not suitable for MSW, MWW, or agricultural and food-processing wastewater, which are generally relatively low in cellulosics, sugars, and oil (except oily scum), and high in moisture content. To tailor a biorefining scheme to these unique wastes, we propose a new systems approach illustrated in Fig. 2. This systems approach consists of processes that will enable the production of chemicals, fertilizer, energy (biogas, syngas, biodiesel, and bio-oil), foods, cleaner water, and a reduction in air pollution emissions. The core conversion technology blocks are the AD of wet solid and semi-solid wastes; aquaponics using wastewaters; an oily waste to biodiesel process; and the thermochemical conversion of organic solids. Some of these technologies have been used in commercial applications but have not been without issues and challenges. In the next section, we will discuss these core technology options and report on the latest progress from ongoing research and development in the authors' laboratories.

3. Technology options and new development

3.1. Conventional AD

For wet organic solids such as sludge and food wastes, and for high-strength wastewaters, AD is very effective in stabilizing these wastes and producing biogas as an energy source. Biogas, whose main component is methane, is used for electricity generation through combustion and for hydrogen production via catalytic reforming [13,14]. AD is quite robust to a different moisture-content range of feedstocks, and is therefore suitable for a wide range of solid and liquid wastes, as long as they contain a sufficient carbon source and nutrients. Several issues affect the effectiveness and efficiency of AD technology. First, the remaining liquid and solid residues after AD still contain a certain level of nutrients, making them unsuitable for direct discharge. However, after solid–liquid separation, it is possible to use the liquid to cultivate microalgae and hydroponic crops, while converting the solids to bio-oil, syngas, and biochar through thermochemical conversion. Second, the concentration of free ammonia and hydrogen sulfide is often so high during the AD process that it inhibits methane production [15–17]. Third, as a related issue, the high sulfur content in the biogas can cause problems for gas turbines, and can result in high sulfur emission into the air when the biogas is combusted. Finally, the liquid portion, if containing high-level ammonia, will not be suitable for hydroponic vegetable growth because of phytotoxicity. Ammonia is also toxic to fish in aquaculture [18].

Table 1
Energy contents of MSWs (10^6 Btu/t).

Biogenic	Energy	Non-biogenic	Energy
Leather	14.4	Polyethylene terephthalate (PET)	20.5
Textiles	13.8	High-density polyethylene (HDPE)	38.0
Wood	10.0	Polyvinyl chloride (PVC)	16.5
Food	5.2	Low-density polyethylene/linear low-density polyethylene (LDPE/LLDPE)	24.1
Yard trimmings	6.0	Polypropylene (PP)	38.0
Newspaper	16.0	Polystyrene (PS)	35.6
Corrugated cardboard	16.5	Other Plastics	20.5
Mixed paper	6.7	Rubber	26.9

1 Btu = 1.055 kJ.

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