New Approaches for Solid Waste Management to Maximize Organic Waste Reutilization

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1 Introduction

The world population is estimated to reach to 9.7 B by 2050 [1] and this growth in population will bring increased demand for energy, water, and food resources. The demand for food, in particular, is expected to increase on average by 70% by 2050 [2]. Increased population will also dramatically increase waste generation and the systems needed to manage it .

1.1 Food/Organic Waste Generation

In the US, about 40% of food produced goes unused [3]. As a result, the equivalent of $165 B in food costs are wasted each year, as well as 25% of all freshwater and a proportional amount of chemicals, energy, and land that is used in the food production process [3, 4]. The majority of waste food ends up in landfills where organic matter accounts for 16% of US methane emissions [3, 4]. In addition, getting food to the table consumes 10% of our energy and 80% of the freshwater in the US [5, 6]. Making current organic waste disposal practices cleaner and more efficient can

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reduce not only carbon emissions, but also help displace water intense fossil-based energy generation.

1.2 State of Landfills

Waste tonnages disposed in landfills have declined in recent years, first due to the downturn in the economy between 2009 and 2013, and later with the demand for further reductions in waste directed to landfills. Changes in economic and social norms favor more holistic approaches to current solid waste management practices, particularly in regards to organic wastes that have perceived value for reuse as compost/soil amendment materials. Despite concentrated efforts to manage waste by reusing, reducing, and recycling, landfilling remains the most predominant (and cost-effective) solid waste management method in the US. Although the number of landfills declined from 2500 to 1900 between 1995 and 2012, [7, 8] total landfill capacities are much larger to take advantage of economies of scale. Landfills currently accept mixed waste, which includes waste paper, food waste, manure, yard trimmings, wood, textiles, plastic, metals, glass, rubber, and leather. Approximately, 30% of landfilled waste is considered organic waste. Organic waste discarded into landfills decomposes at various rates with the more putrescible organic materials, like food waste, producing landfill gas (LFG) very quickly. Landfill gas that is collected is either flared or utilized for clean energy production, including; electricity, heat, and transportation fuel. Currently, there are 503 landfills nationwide that are utilizing LFG for energy production. An additional estimate of 545 landfills could incorporate energy production, but this has yet to be implemented [9]. Landfills are estimated to be the third largest source of anthropogenic methane emissions in the US, because of fugitive emissions and other emissions generated prior to cell closure and gas collection system installation [10, 11]. Current landfill designs and operational practices are generally not capable of collecting the majority of LFG that is quickly generated from these highly putrescible wastes. Hence, there is a growing interest in diverting organics, particularly highly putrescible food wastes, out of landfills to utilize them more efficiently for clean energy production and for compost. Currently, 23 states either ban certain organics, including leaves and grass clippings, or specifically enforce food waste disposal bans at landfills [7, 12]. In addition, large cities such as San Francisco, Seattle, Austin, and Portland have banned food waste disposal at landfills. These bans are expected to become more widespread nationally which raises an important question to be addressed: Is direct landfilling a relevant solution for future management of organic wastes? If not, how can waste management practices be optimized?

The use of waste for energy and nutrient recovery can result in both avoided emissions and increased revenue [13]. If both recoveries are performed together, the environmental and economic benefits can increase [13, 14]. In landfills, organic material residuals/nutrient is not recovered for beneficial reuse primarily due to the cost and difficulty of separating impurities from mixed MSW prior to disposal. Industrial-scale composting of organic waste does not deliver efficient solutions either, since the aerobic decomposition of the organic waste is not suitable for gas recovery. In addition, the composting process often creates significant odor problems resulting in complaints from the surrounding communities. Sending food waste to animal feeding and large-scale industrial composting applications has also been proven to be inefficient approaches.

1.3 Transitioning Traditional Linear Waste Disposal into "Closed-Loop Resource Recovery"

Neither landfilling nor industrial composting provide optimal reutilization of organic waste, and neither can achieve both energy and nutrient recovery in one process from organic waste. Therefore, there needs to be a transition from the current "Traditional Linear Waste Disposal" approach (Fig. 1) to a "Closed-Loop Resource Recovery" approach (Fig. 2) to achieve sustainability and resiliency. An alternative to direct landfilling and/or composting of organic waste is anaerobic digestion (AD) of the biodegradable organic fraction of MSW. AD is an excellent example of the closed-loop process and is considered to be a better solution for converting organic waste into clean energy. It also produces compost-based byproducts, thus extracting the maximum benefits from organic wastes [15, 16]. Closed-loop reutilization approaches can position organic waste as a valuable resource for energy generation, nutrient recovery, and reduced water consumption. In addition, anaerobic digestion will reduce GHG emissions. This is a very important feature of the AD process since research shows that landfills emit 16% of US methane emissions and manure management is responsible for about 10% of US methane emissions [17].

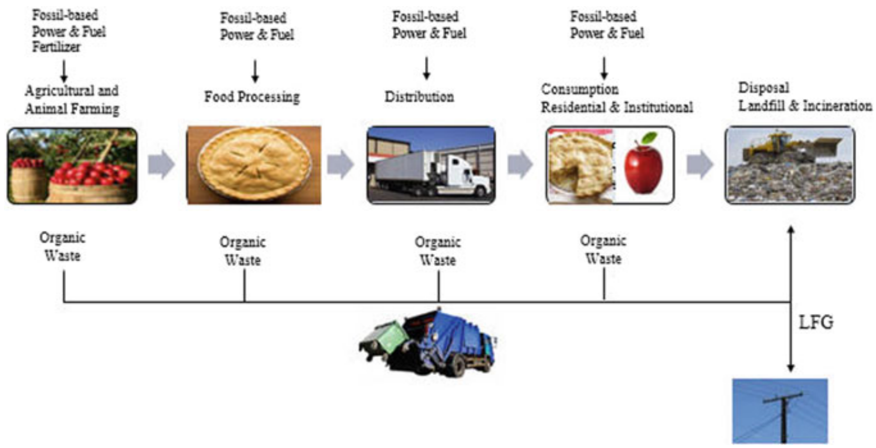

Fig. 1 Linear waste disposal and utilization

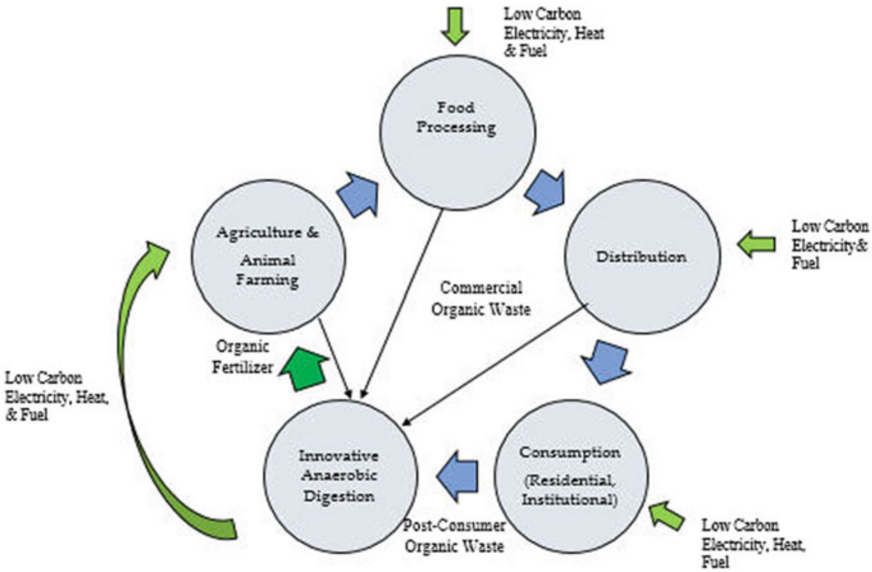

Fig. 2 Closed-loop resource recovery

1.4 *Overview of Anaerobic Digestion Systems*

Organic waste AD is an existing, well-known, and long practiced waste management and clean energy production technology in Europe, and has received increased attention in the United States. AD technology is an efficient, controlled, and totally enclosed system that breaks down the organic feedstock in the absence of oxygen. AD technology serves as one of the best pathways for treating organic materials because it results in better resource utilization than landfilling or aerobic composting [15]. These waste materials include food waste, yard waste, farm waste (agricultural waste, dairy poultry, and equine manure), biomass treatment byproducts, fats, and oils and wastewater. Biogas, produced from the AD process, can be utilized as a renewable energy source to generate electricity or heat alone or in a combined heat and power form (CHP). Biogas can also be processed into compressed natural gas (CNG) or liquefied natural gas (LNG) for transportation applications to displace fossil fuels after being pre-treated (Fig. 3). In addition, the biosolids and liquid digestate, which are byproducts of AD, can be utilized as fertilizers and soil amendments, thereby displacing fossil-based fertilizers and improving soil quality [16].

The conversion of organic waste to biogas is accomplished through four stages of biochemical reactions, which are known as hydrolysis, acidogenesis, acetagenesis, and methanogenesis [15, 17].

(1) Hydrolysis: The first stage of AD breaks down the organic waste feedstock into its components. In this stage, the following conversion reactions occur:

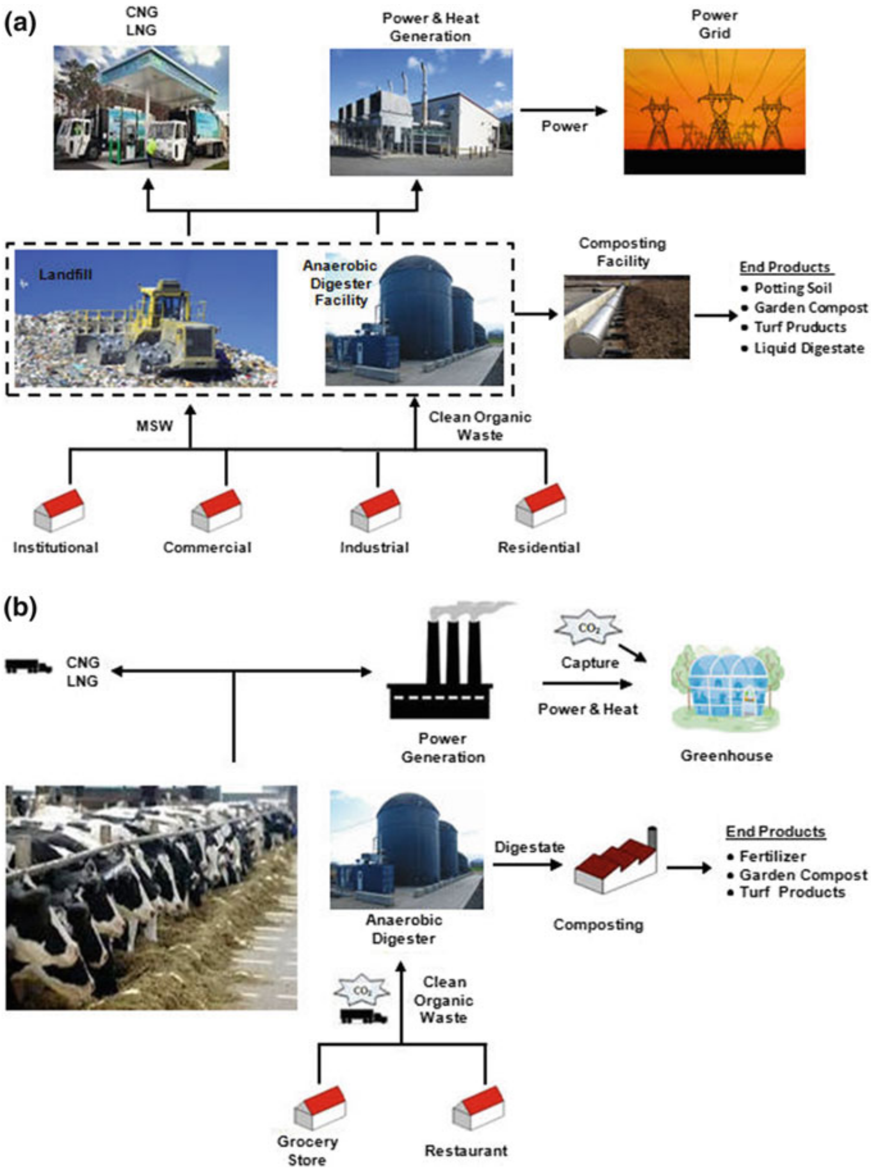

Fig. 3 **a** Co-locating digesters at landfills. **b** Co-locating digesters at dairy farms

1. Lipids → Fatty Acids
2. Polysaccharides → Monosaccharides
3. Protein → Amino Acids.

These reactions are catalyzed by enzymes excreted by bacteria such as cellulase, protease, and lipase [18]. If the biomass polymer is complex, the hydrolysis phase occurs slowly. Therefore, high lignin-containing biomass such as woody waste, is not a feasible feedstock for AD conversion. Carbohydrates, however, can be converted easily to simple sugars [15]. The chemical formula of an organic waste mixture can be presented as $C_6H_{10}O_4$ and the hydrolysis stage can convert the mixed organic waste into simple sugars [18].

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2$$

(2) Acidogenesis: During this stage, acid-forming reactions occur and products of hydrolysis are converted into primarily short chain acids such as lactic, formic, propionic, butyric, or succinic acids. In addition, ketones and alcohols are formed.
(3) Acetagenesis: This stage converts long fatty acids formed from the hydrolysis of lipids to acetate through carbohydrate fermentation. CO_2 and H_2 are also produced at this stage. The role of hydrogen as an intermediary is of critical importance to AD reactions in this stage.
(4) Methanogenesis: During this stage, methane is produced. This reaction is very sensitive to pH changes. Optimum pH levels are neutral to slightly alkaline and if the pH level becomes too acidic, essential microorganisms cannot survive and carry out the desired reactions [18, 19].

Currently, researchers are debating whether fermentation of carbohydrates to methane leads the loss of 1/3 of carbon as CO_2 [20].

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$
$$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2$$

Emerging research is considering the production of organic acids that are reduced electrochemically [20]. These chemicals can serve as intermediaries for the chemical industry to produce specialty chemicals and fuels to displace fossil-based counterparts. When the alternative three-stage AD approach is fully proven and demonstrated, having organic waste AD infrastructure in place will help to accelerate utilization of this new innovation.

$$C_6H_{12}O_6 \rightarrow 3C_2H_4O_2$$
$$C_2H_4O_2 + 2e^- + H^+ \rightarrow C_2H_5OH + H_2O$$

1.5 Choosing Locations for Anaerobic Digesters

AD facilities are currently being planned throughout the US to divert organic waste from landfills and to produce biogas and compost-based materials as stand-alone facilities. However, identifying a location that is logistically and technically suitable is difficult due to the high costs for infrastructure development; issues with securing clean organic waste; power generation system installation difficulties; and location-based permitting constraints. Stand-alone digesters have additional constraints since in-vessel AD, systems can only accept clean and preprocessed waste and the remaining digestate requires an aerobic composting step, adding to the equipment requirements and operational costs. As an alternative to developing stand-alone AD facilities, locating AD facilities at existing landfills should be considered as a sustainable option. Landfills are an important component of solid waste management systems and can serve as excellent locations to host AD facilities, since they have existing waste delivery and management infrastructure and permits. In addition, landfills that have an installed biogas-to-energy system can easily convert AD generated biogas utilizing the existing infrastructure without the need to install additional power generation capabilities, as would be the case with stand-alone AD systems (Fig. 3a, b). In addition, dairy farms and wastewater treatment facilities are good alternative sites for co-locating AD digesters.

Solid waste management systems (SWMSs) must proactively adapt to changing social norms, policy requirements, waste composition, and evolving energy systems to sustainably manage solid waste in the future [21]. If organic waste treatment options for food and other organic waste to energy applications are demonstrated and assessed systematically with FEW impacts in mind, along with social and economic cost–benefit analyses, then comprehensive data can be provided to landfill, county, municipal, and state decision makers. Overall, SWMS managers would understand the importance, benefits, and risks of available options leading to more informed and sound decision-making. The proposed approach, which includes a detailed implementation plan, can help inform near-term decision-making for sustainable closed-loop resource recovery and economic development. In addition, having a working AD infrastructure in place, demonstrating the value of organic waste for clean energy and bio-based fertilizer generation while reducing GHG emissions, will provide a very clear and easily understood educational opportunity for researchers and decision makers at the local, regional, and national levels.

2 Conclusions

There is an emerging need to find new approaches for solid waste management to maximize organic waste reutilization with the increased population and increased demand for food. In order to achieve energy and nutrient recovery at the same time to form organic waste, landfills can transform their operations for tomorrow's greener, cleaner, and more profitable operations. By hosting anaerobic digesters, landfills can increase their profitability, reduce carbon footprint, and avoid emerging trends of diverting organic wastes from landfills. Landfills can be part of this new approach and support creation of new innovative business plans and can play an essential role in policy-making.

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