WALAILAK JOURNAL
http://wjst.wu.ac.th MiniReview

Comparison of Electricity Generation of Food Waste *via* Anaerobic Processes: A Mini-Review

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Received: 29 July 2016, Revised: 19 December 2016, Accepted: 30 January 2017

Abstract

Three biological methods, of anaerobic digestion (AD) (Method I), fermentation for bio-hydrogen (Method II), and fermentation for bio-hydrogen and bio-methane (Method III), were reviewed and evaluated for the capacity of bioenergy conversion from food waste (FW) at real scale based on some case studies. AD could give the highest energy benefits, and is the most suitable method for the commercialization of FW treatment, with 220 kWh/ton FW in comparison with the 12.5 and 51.3 kWh/ton FW of Method II and Method III, respectively. Furthermore, FW treatment-based AD has been proven to play a primary role in the electricity industry, with high potential and economic benefits. FW treatment *via* anaerobic processes for bioenergy usage is expected to be an ideal renewable energy in the future. The results reveal that China, India, and the United States could commercialize bioenergy use by converting the annual amount of FW *via* AD to produce 42,900 GWh/year, 15,830 GWh/year, and 13,387 GWh/year of electricity annually, respectively.

Keywords: Anaerobic digestion, Anaerobic process, Bioenergy, Fermentation, Food waste, Bio−H_2, Bio−CH_4

Nomenclature

AD is Anaerobic digestion,
COD is Chemical oxygen demand,
EU is European Union,
FW is Food waste,
GWh is Gigawatt-hour,
kWh is Kilowatt-hour,
RNG is Renewable natural gas

Introduction

In recent years, the escalating increase in energy consumption due to rapid industrial development has threatened the environmental balance. The generation of food waste (FW) also results in environmental pollution problems if not well managed. FW contains lots of biodegradable organic components and could be anaerobically digested to produce biogas as a green bioenergy [1]. Moreover, the approach of FW as a source of bioenergy feedstock is expected to solve these issues of waste treatment and green energy generation and also help to overcome the controversy on using crops for fuel/energy.

Treating FW *via* anaerobic processes could greatly maximize the efficiency of hydrogen and methane production for potential energy use [2]. This energy conversion might offer a stable electricity source for many countries. At present, anaerobic digestion (AD) is the most suitable biological method for FW treatment and biogas recovery (mostly bio-methane generation). Some previous studies demonstrated that FW could also be treated by a 2-stage process of dark- and photo-fermentation for bio-hydrogen production, or a 3-stage process of fermentation for bio-hydrogen and bio-methane production [3].

Treating FW to produce biogas and then to generate electricity demonstrates that FW is becoming a prospective electricity supplement source among various renewable energy suppliers. However, the competitiveness of this electricity with other main renewable energy sources of wind and solar has not been reported. Therefore, this review aims to obtain a prediction analysis of bioenergy from anaerobic processes in lab and full-scale plants; from this, the economic benefits and feasible technical applications of FW treatment *via* anaerobic processes are elucidated.

Potential of bioenergy from treating FW *via* anaerobic processes

The data of the FW generation of twenty countries were collected from published documents and tertiary sources, as shown in **Table 1**. The results of 3 anaerobic processes on FW were reviewed to evaluate their feasibility: Anaerobic digestion (AD, Method I), based on theoretical study [4] and feasible study [5]; fermentation for bio-hydrogen production (Method II) in lab-scale [6] and in pilot-scale [7]; and fermentation for bio-hydrogen and bio-methane production (Method III) in lab-scale [3] and in pilot-scale (real-scale plant) [8]. **Table 1** presents the potential generating electrical power from FW.

Table 1 Potential efficiency prediction of generating electrical power by treating food waste *via* 3 anaerobic processes in various countries.

Country	Food waste generation (tons/year)	Potential of bioenergy from FW						
		AD (GWh/year)		Dark fermentation for bio-H_2 (GWh/year)		Three-stage fermentation for bio-H_2 and bio-CH_4 (GWh/year)	Dark-fermentation for bio-H_2 coupled AD for bio-CH_4 (GWh/year)	Fermentation for bio-H_2 and bio-CH_4 (GWh/year)
		Theoretical	Practical	Lab scale	Pilot scale	Lab scale	Pilot scale	Full-scale plant
Australia	2,261,061[4]	1,915	497	3,898	28.35	720	913	116
Brazil	33,489,000[9]	28,357	7,368	57,741	419.89	10,661	13,530	1,719
Canada	27,000,000[10]	22,254	5,940	46,553	338.53	8,595	10,908	1,386
China	195,000,000[11]	165,119	42,900	336,214	2,444.92	62,075	78,780	10,008
Denmark	790,502[12,13]	669	174	1,363	9.91	252	319	41
Germany	12,257,998[12,13]	10,380	2,697	21,135	153.69	3,902	4,952	629
India	71,952,838[14,15]	29,868	15,830	124,059	902.15	22,905	29,069	3,693
Ireland	1,000,000[16]	847	220	1,724	12.54	318	404	51
Japan	32,000,000[17]	27,096	7,040	55,174	401.22	10,187	12,928	1,642
The Netherlands	8,841,307[12,13]	7,486	1,945	15,244	110.85	2,814	3,572	454
New Zealand	258,886[18]	219	57	446	3.25	82	105	13
Singapore	796,000[19]	674	175	1,372	9.98	253	322	41
South Africa	9,040,000[19,20]	7,655	1,989	15,587	113.34	2,878	3,652	464
South Korea	6,241,500[21]	5,285	1,373	10,761	78.26	1,987	2,522	320
Sweden	1,915,460[12,13]	1,622	421	3,303	24.02	610	774	98
Taiwan	2,318,169[22]	1,963	510	3,997	29.07	738	937	119
Thailand	9,312,788[23]	7,886	2,049	16,057	116.76	2,965	3,762	478
The United Kingdom	15,000,000[24,25]	12,701	3,300	25,863	188.07	4,775	6,060	770
The United States	60,849,145[26]	51,525	13,387	104,914	762.93	19,370	24,583	3,123
Vietnam	5,743,056[27]	4,863	1,263	9,902	72.01	1,828	2,320	295

Anaerobic digestion (Method I)

AD is a well-known method for treating bio-wastes or organic wastes. This is a process of breaking down biodegradable wastes in the absence of oxygen to produce biogas, which is used to generate electricity and heat. This method is widely applied as an efficient FW treatment [4]. AD has been widely applied for FW treatment in North America and European countries. This method provides more beneficial end-products and easy operation.

Theoretically, one ton of FW could potentially produce 247 m^3 methane and generate approximately 89.78 GJ of heat or 847 kWh electricity [4]. In a real scale application, a case study in the United Kingdom, AD was commercialized to generate energy and digestate [28]. The total methane yield of each ton of wet FW feedstock was 98 m^3, composing 62 % of total biogas generation. The electricity generation of the plant was 405 kWh/ton FW [28]. Consequently, the electricity potential from the FW plants equaled half of the theoretical bioenergy of the FW. For larger scales, such as commercial FW treatment facilities in Canada and the United States, energy output of FW treatment-based AD technology was found to be as high as 220 kWh/ton FW [29].

In commercial applications, AD for FW treatment has been widely adopted throughout the world. There are thousands of large-scale FW treatment plants in France, Italy, Germany, Denmark, the United Kingdom, Sweden, the United States, Canada, and Southeast Asian countries [30,31]. For power generation purposes, many organic waste-AD plants are connected to the current grid for nationwide energy supplies in Germany, Switzerland, Netherlands, the United Kingdom, and Sweden [30,31]. To date, German FW treatment-based AD has reached 2 million ton of FW disposal per year, which composes 16.3 % of their annual FW generation. The Netherlands have disposed of their FW by about 0.8 million tons/year, with the average capacity per AD facility being 54,000 tons/year [30,31]. The United Kingdom has reached 500,000 tons of FW treatment by AD (3 % of total FW) for an average capital of 35,000 tons FW/year per plant.

China has the highest population, and also contributes the highest amount of FW, in the world. It is estimated that China, with 195 million tons of FW generation annually, could produce approximately 42,900 GWh/year of electricity *via* the AD process, and contribute to 0.87 % of their electricity generation. It is estimated that the FW of the United States, Canada, and Brazil could produce 13,387 GWh/year (sharing 0.31 % total electricity generation), 5,940 GWh/year (sharing 0.97 % total electricity generation) and 7,368 GWh/year (sharing 1.33 % total electricity generation), respectively.

Among the listed European countries in **Table 1**, Germany, the Netherlands, and the United Kingdom have the highest chances of expanding AD technology to treat FW, since they could convert 2,697 GWh/year (sharing 0.44 % of total national electricity generation), 1,945 GWh/year (sharing 1.92 % of total national electricity generation), and 3,300 GWh/year (sharing 0.91 % of total national electricity generation), respectively. In addition, it could highlight the steadily increasing role in biological treatment for FW in Europe, whereas Germany targets using Renewable Natural Gas (RNG), which has been set to reach 6 % of total gas consumption by 2020, and 10 % by 2030 [32]. The Netherlands' government set a strategy for using bio-methane FIT (Feed-in Tariff) of 2,300 GWh/year by 2015 and 6.8 GWh/year by 2020 [32]. The United Kingdom government has also targeted using bio-methane generation, with an expected injection to the whole RNG for up to 7,000 GWh/year by 2015 [32].

In South Korea, where a law forbidding direct landfilling was promulgated in 2005, AD is widely used in treating Korean FW [33]. The South Korean government set their approach in AD to obtain 161 GWh/year of biogas for non-landfill gas by 2030, and 1,340 GWh/year of biogas from landfill gas by 2030 [34]. Another Asian country, Thailand, has also targeted increasing AD technology from FW treatment to achieve a capacity of 600 MW per year by 2021 [35]. Therefore, Thailand is facing an opportunity to convert their 9.3 million tons FW to 2,049 GWh/year by AD application.

Dark fermentation for bio-hydrogen (Method II)

In practical applications, a pilot-scale plant with an H_2-producing anaerobic sequencing batch reactor (ASBR) could only achieve a maximum electricity yield of 12.54 kWh/ton FW [7]. The inhibition of hydrogen production might be due to increasing concentrations of lactate, propionate, and valerate through the whole process. The key point for enhancing hydrogen fermentation of FW was also shown in a technical communication study [7], which demonstrated that the C/N ratio needs to be maintained at a ratio lower than 20. Additionally, good management of the main environmental factors is necessary for successful bio-hydrogen production. These important parameters include pH, temperature, seed culture, and hydrogen partial pressure [36]. Some other parameters, such as microorganism stability, undesirable acid inhibition, and metal ion effect, need to be further studied, in order to fully understand the overall production of hydrogen [37-39].

Table 1 shows the potential electricity generation of fermentation for annual bio-hydrogen production by treating FW *via* technology of batch scale (a lab-scale reactor) and commercial application (a pilot-scale reactor) with the following results: Australia, 3,898 kWh and 28.35 kWh; Germany, 21,135 kWh and 153.69 kWh; Japan, 55,174 kWh and 401.22 kWh; the United States, 104,914 kWh and 762.93 kWh.

Among the 3 methods discussed, the 2-step process of hydrogen fermentation at a lab-scale (a batch reactor) offers the best electricity production potential results. However, transferring a successful result from lab-scale to practical application might lose some efficiency, due to the discordance of real conditions [40,41]. In general, the potential efficiency of generating electrical power from FW *via* Method II has few economic benefits and, therefore, it is difficult to compare it with Methods I and II in terms of technical investment. However, bio-hydrogen revolution brings considerable environmental benefits, due to zero carbon emissions, which has been highlighted in the literatures [42-44]. Therefore, in the future, Method II needs to be implemented at an industrial scale, in order to make hydrogen production from FW more commercial and more cost effective.

Fermentation for bio-hydrogen and bio-methane production (Method III)

Although hydrogen carries high energy content and is clean, it cannot be utilized as a method of complete disposal of FW because of the technical issues associated with low conversion or COD removal efficiency (mainly by products, such as volatile fatty acids formation) and of feedstock storage problems. Hydrogen fermentation usually needs to be combined with another ancillary process, such as photo-hydrogen fermentation or AD, to completely maximize hydrogen generation [8]. Furthermore, the combination of bio-hydrogen and bio-methane fermentation could enhance benefits in electricity production. A system of dark-fermentation for bio-hydrogen coupled with AD for bio-methane (CSTR-continuously stirred tank reactors with working volumes of 0.2 m^3 and 0.76 m^3 for each phase) has been reported to recover energy at 404 kWh/ton FW [45]. This energy recovery is higher than those of the 2-stage process (325 kWh/ton FW) [46] and the 3-stage process (318 kWh/ton FW) for hydrogen and methane production [3].

Moreover, efficiency comparisons of lab-scale and pilot-scale results have also been conducted in order to estimate the changes between different operation conditions. **Table 1** shows the potential electricity generation of bio-hydrogen and bio-methane fermentation based on some lab-scale and pilot-scale reactor studies. Treating each ton of FW to produce bio-hydrogen and bio-methane in a full-scale plant (200 tons FW treatment per day) could generate 51.33 kWh electricity [8]. Comparing the energy yields of a lab-scale research and a full-scale plant, it is shown that the total electricity generation of a real practical plant reduced energy recovery by 6.2 times (in comparison with a 3-stage fermentation for hydrogen and methane), 6.3 times (in comparison with a 2-stage fermentation for hydrogen and methane) and 7.9 times (in comparison with a 2-phase process of dark-fermentation coupled with AD), respectively.

Meanwhile, in a comparison between 3 real-scale systems in practical applications of FW treatment, the potential electricity of a bio-hydrogen and bio-methane fermentation system could have been expected to be 4 times greater than that of bio-hydrogen fermentation system, but 2.3 times lower than that of an AD system. For further applications, fermentation for bio-hydrogen and bio-methane should be commercialized through more investment.

Ultimately, in a comparison between these 3 methods, dark fermentation for bio-hydrogen (Method II) has low efficiency in commercial applications due to its low energy generation achievement from FW. The potential bioenergy values of Methods I, II, and III, documented from real-scale plants, were 220, 12.54, and 51.33 kWh/ton FW, respectively. In investment comparisons, treating one ton of FW by Method I (AD) takes an average investment of installation costs of US \$309 - 500/ton FW, and operation and maintenance costs of about US \$23 to \$48/ton FW, respectively [29]. Capital and operation costs of a plant (200 tons FW/day) by Method III had been evaluated by Lee and Chung (2010) as US \$1,256,987 and \$417,686, respectively [8]. AD is the most feasible and bio-natural technology. AD has also especially been researched as the primary technical solution for FW management [47,48].

Based on the above analyses, it is strongly identified that AD technology is the most economical method for FW treatment. However, due to the promising results of energy production from the pilot-scale plant *via* the 2-phase anaerobic digestion process for hydrogen and methane production [45], further research for commercialized applications of Method III is necessary for developing real-scale or practical plants for FW treatment. In addition, its long-term working system also needs to be carried out, without any inoculum treatment or pH control [45], which promises to bring economical consideration by reducing operation costs.

Conventional food waste treatments

The "zero waste" policies in some countries, such as EU-15, Australia, New Zealand, and the United States, motivate FW management in developed countries with forward sustainable development. The European Commission set up strategies for FW management early, in the EU Waste Framework Directive 2008/98/EC and the Landfill Directive 1999/31/EC, which obligated the treating of FW by landfilling across Europe, and aimed to reduce FW generation by 30 % by 2025 [49].

Figure 1 presents the different trends of FW treatment between developed and developing countries. In France, the FW recycling target was specifically pinpointed to achieve a recycling rate of 35 % by 2010 [50], and slice FW 50 % by 2025 [51]. The French parliament has banned FW in supermarkets from 2015. The government demands supermarkets donate any unsold but still edible food goods to charity, or for feeding animals or farming compost. In developed countries, the conventional treatments are composting and anaerobic digestion, used at rates of 15 - 34 % and 5 %, respectively [52,53]. In developing countries, landfills are the most common method to dispose of FW (rate use 90 %), which is proven to be the worst option, since this contributes to high greenhouse gas emissions and causes environmental pollution. The second most common method is composting (with a rate ranging from 1 % to 6 %), and then anaerobic digestion (0.6 %) [1].

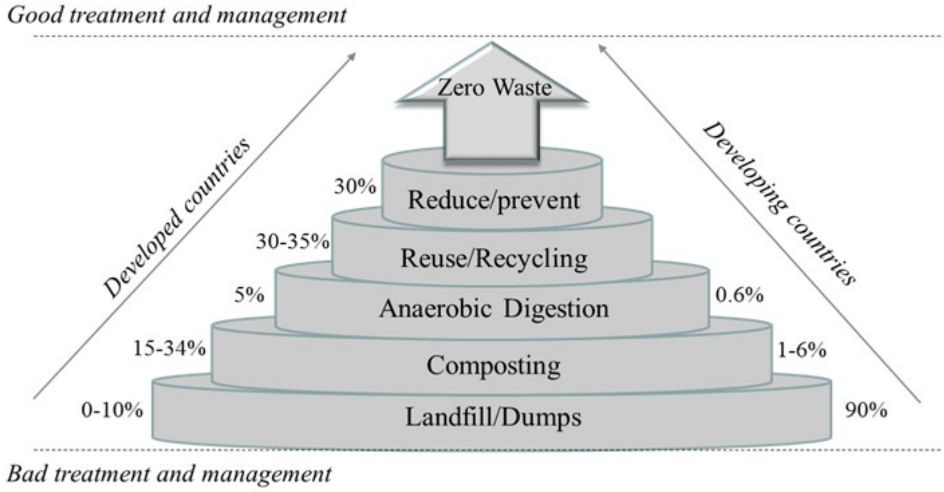

Figure 1 Trend of FW treatment between developed and developing countries.

Perspective of utilizing food waste as bioenergy resource

Figure 2 suggests 2 hierarchies for FW management for developing countries and developed countries. The order of recommended options is conceived with the condition of current treatment and the further perspective of FW management for both country groups. In developing countries, where the economy mostly focuses on agriculture and animal husbandry, the FW treatment should use FW to produce composting or feedstock for animal feeding. On the other hand, developed countries currently have strong economies and industrial development; hence, they have a high demand for energy for industrial use, and also have developed statements on renewable energy utilization. At the bottom of both hierarchies, using incineration and landfill to disposal of FW are the least desirable options due to these treatments causing many pollutants in general environment.

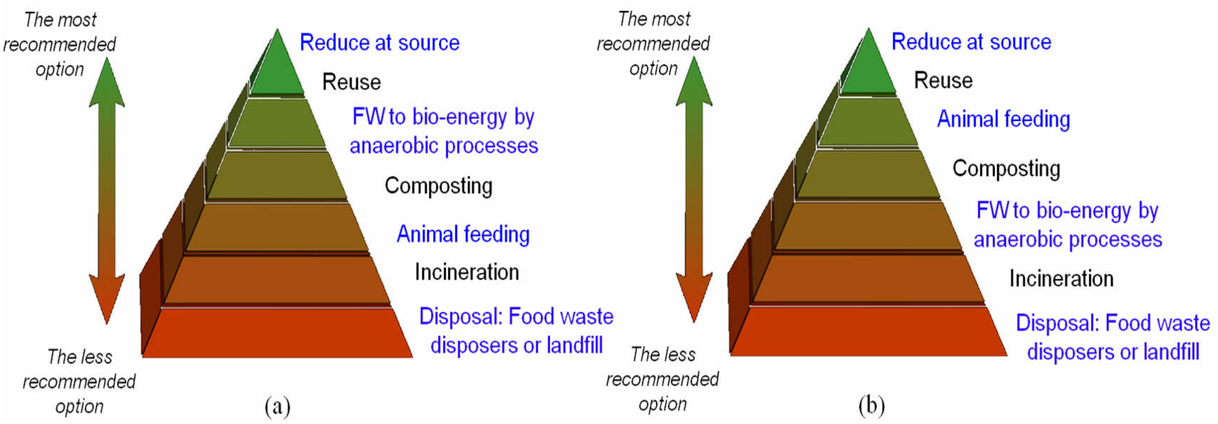

Figure 2 Suggested hierarchies for food waste management *via* approaching bioenergy production: (a) for developed countries, (b) for developing and underdeveloped countries.

Conclusions

This paper has elucidated that, among various anaerobic processes, anaerobic digestion is the most economical and mature method for FW treatment for bioenergy production. In practical application of energy production, anaerobic digestion for methane provides the highest values of 405 kWh/ton FW (small scale plant of FW treatment, working capacity thousand tons FW per year) and 220 kWh/ton FW (large scale plant of FW treatment, working capacity hundred thousand tons FW per year), with the next two being fermentation for bio-hydrogen and bio-methane at 51.33 kWh/ton FW (Method III), and fermentation for bio-hydrogen at 12.536 kWh/ton FW (Method II). By commercializing anaerobic processes for FW treatment, it is expected that countries could not only reduce their electricity production costs, but also tackle FW management.

Acknowledgement

The author gratefully acknowledges the financial support provided by Ton Duc Thang University which supported this study.

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