Applied Energy 225 (2018) 1143–1157

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A comparative life cycle assessment on four waste-to-energy scenarios for food waste generated in eateries

Huanhuan Tong[a], Ye Shen[a,b], Jingxin Zhang[a], Chi-Hwa Wang[a,b], Tian Shu Ge[c], Yen Wah Tong[a,b,*]

[a] NUS Environmental Research Institute, National University of Singapore, 1 Create Way, Create Tower, #15-02, Singapore 138602, Singapore
[b] Department of Chemical and Biomolecular Engineering, National University of Singapore, 4 Engineering Drive 4, Singapore 117585, Singapore
[c] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Key Laboratory of Power Mechanical Engineering, 800 Dongchuan Road, Shanghai 200240, China

HIGHLIGHTS

- Table FW has more putrescible fraction and fewer impurities than kitchen FW.
- Three anaerobic digestion scenarios are compared with incineration practice.
- AD followed by composting digestate is best in most of the impact categories.
- AD followed by gasifying digestate outputs the largest electricity.
- Gas engine emission, and water consumption should be lowered.

ARTICLE INFO

Keywords:
Food waste
LCA
Incineration
AD
Gasification

ABSTRACT

A life cycle assessment (LCA) was conducted to determine the best solution for dealing with the food waste (FW) generated in Singapore eateries. Since the representativeness of the life cycle inventory (LCI) data determined the overall quality of the LCA, this study made a significant endeavor to capture the local specificities, such as waste composition, water supply and treatment plant operation. Characterization data showed that eatery FW from Singapore contained 16% non-biodegradable impurities (such as plastic and metal) and a higher methane generation potential was found in FW from the dining table than in FW from the kitchen. Based on the FW chemical element composition, mass balances were established for the four examined scenarios, including incineration (Inci), anaerobic digestion (AD) followed by composting (ADcom), AD followed by incineration (ADinci) and AD followed by gasification (ADgas). Because of the environmental benefits from compost production in addition to electricity generation, ADcom outperformed other scenarios in all impact categories except *Eutro* (eutrophication), *GW* (global warming) and *POC* (photochemical ozone creation). The best score of *GW* was observed in ADgas, mainly ascribed to the highest electricity output and the carbon sequestration of biochar. The disadvantages of the AD scenarios in *Eutro* and *POC* were associated with NOx and CO emissions from the biogas engine. Finally, the sensitivity analysis demonstrated that better environmental profiles could be achieved if improvements can be made by minimizing water usage, mitigating gas engine pollution, and diverting as much FW as possible from incineration plants to AD plants. However, based on the local context, source separation was not an urgent issue for improving the sustainability of eatery FW management.

1. Introduction

The shortage of fossil fuel and the growing concern of global warming have sparked a great development of renewable biofuel applications worldwide. The first-generation biofuels (biodiesel, bioethanol and biogas from food crops) have been criticized for their threat to biodiversity and competition with the food industry [1]. To overcome these disadvantages, the second-generation biofuels source the feedstock from cheap and abundant nonfood biomass, such as agricultural and forest residues, aquatic biomass and urban biowaste [2]. Among the plethora of urban biowaste (such as animal manure and horticulture waste), food waste (FW) is of paramount importance, because it is generated in significant quantities at the relatively stable rate year-round, thus making it a reliable renewable energy source.

* Corresponding author at: Department of Chemical and Biomolecular Engineering, National University of Singapore, 4 Engineering Drive 4, Singapore 117585, Singapore.
E-mail address: chetyw@nus.edu.sg (Y.W. Tong).

https://doi.org/10.1016/j.apenergy.2018.05.062
Received 16 January 2018; Received in revised form 9 May 2018; Accepted 15 May 2018
Available online 31 May 2018
0306-2619/

Nomenclature

Acronym	Definition of Acronym
Adep-E	abiotic depletion element
Adep-F	abiotic depletion fossil fuel
Acid	acidification
AD	anaerobic digestion
ADcom	anaerobic digestion followed by composting
ADcom-L	ADcom scenario in the literature
ADinci	anaerobic digestion followed by incineration
ADinci-L	ADinci scenario in the literature
ADgas	anaerobic digestion followed by gasification
ADsoil-L	AD followed by direct soil application of digestate in literature
ADOS	anaerobic digestion of organic slurry
APC	air pollution control
BMP	biological methane potential
CHP	combined heat & power
DCB	1,4-dichlorobenzene
Eutro	eutrophication
FAETox	freshwater aquatic ecotoxicity
FW	food waste
GHG	greenhouse gas
FU	functional unit
GW	global warming
HumTox	human toxicity
Inci	incineration
LCA	life cycle assessment
LCI	life cycle inventory
MariTox	marine aquatic ecotoxicity
MSW	municipal solid waste
NEA	national environmental agency
Odeplet	ozone layer depletion
POC	photochemical ozone creation
R11	trichloromonofluoromethane
TerrTox	terrestric ecotoxicity
TMTS	tuas marine transfer station
TS	totol solid
VFA	volatile fatty acid
VOCs	volatile organic compounds
VS	volatile solid
WTTP	wastewater treatment plant

In view of environmental and economic performances, anaerobic digestion (AD) is a more sustainable treatment method for FW, which is putrescible and high in water content. Previous studies have demonstrated that FW converted by AD outputs 1–2 times more electricity than incineration [3], occupies much less land space than landfilling [4], and significantly reduces acidification and eutrophication impacts compared to composting [5]. The produced biogas after cleaning can be used directly as gaseous fuel to produce heat and/or electricity [6,7], or be upgraded to biomethane for injection to the gas network serving as a transport fuel [8]. After digestion, there is still a considerable amount of organic matter left in the residue (digestate), which contains both undegraded and nondegradable organic compounds as well as nutrients. To further stabilize the residue and recover the nitrogen, phosphate and potassium (NPK) nutrients, one option is to separate the digestate into a liquid and a solid fraction, the latter being composted to obtain a stable and nuisance-free soil conditioner [9]. In addition to traditional thermal conversion by incineration, digestate gasification has been recently promoted as a promising biomass treatment technology [10,11]. On the one hand, gasification could harvest the remaining energy embedded in the carbonaceous digestate in the form of the combustible syngas that mainly consists of CO_2, H_2, CO, and CH_4 [7,12]. On the other hand, gasification reserves the nutrient content left in the digestate in its solid byproduct – biochar, which in agricultural application is proven to increase crop productivity by improving the soil quality [13,14]. Although successful operation has been reported for gasifying the digestate of the FW-AD system [10,15], there is only a limited side-by-side comparison between gasification and other digestate treatment options from the life cycle perspective.

The life cycle perspective seeks to extend the focus beyond the physical boundaries of a waste treatment facility and takes into account the upstream and downstream processes to avoid problem shifting from a waste area to other environmental aspects (such as air or water). The life cycle assessment (LCA) is widely accepted international tool to transpose life cycle perspective principles into a quantitative framework [16]. It seeks to quantify all relevant emissions, consumed/depleted resources, and the related environmental and health impacts associated with the full waste management cycle [17]. The LCA results complement techno-economic measurements and help decision makers determine which strategy to use to achieve a high level of sustainability and identify the weak points and main areas needing potential improvements [18,19]. The reliability of LCA depends on the robustness of the inventory data [20]. Instead of relying on generic or average secondary data, researchers make great efforts to collect and develop the location and process specific data [2,21]. For FW specific LCA, the basic step in data collection is to quantify the target waste stream and identify its intrinsic properties (such as heating value, element content and biogas generation potential), which have strong influences on determining the optimal strategy. Compared with household FW, eatery FW has a higher level of purity, which reduces the stress on pre-treatment and creates fewer challenges for the following treatment process [22]. Thus, higher priority should be given to eatery FW for diversion from incineration/landfills to an AD plant for better energy and resource production. Eatery FW could be classified into two types. One is table FW, referring to the food residue (organic fraction) left on the food plate and other food-related impurity fractions, such as disposable chopsticks, source dip dishes, tissues, wet wrappers, straws, glass bottles, and plastic bags. The other type is kitchen FW, representing food-related pre-consumer waste that inevitably occurs during the food preparation process, such as non-edible food portions (e.g., peels, roots of vegetables, chicken bones) and food-related impurities (e.g., wrapping paper, plastic, can, and carton). These two types of FW have different features, which may lead to different environmental impacts and benefits during treatment. However, to our knowledge, few studies have characterized the details of these two types of FW and investigated their influences on the choice of treatment technology.

Using Singapore context as an example, the current study conducted FW-specific LCA to determine the extent to which the proposed integration of AD and gasification is environmentally friendly and sustainable by comparing it with direct incineration and other AD strategies (AD followed by compost or incineration). First, the waste samples from two food courts were collected to capture the properties of table and kitchen FW. Then, a mass balance was established for each scenario. Substantial data were collected in this study to thoroughly model the complex treatment system and, at the same time, reflect the local specificities. The full dataset available in the 25-page Supplementary Materials provides not only a highly clear and reliable report of this LCA work but also a great reference for other similar LCA studies. The results were interpreted in a way to assist the local waste manager to identify ways of minimizing the adverse impacts and maximizing the sustainability of waste management. Thus, this work adds to and extends existing LCA practices in several ways: (1) quantifying the environmental profile of gasifying AD digestate and identifying the main environmental bottlenecks for large-scale application; (2) characterizing the compositional differences between kitchen FW and table FW