Utilization of municipal solid and liquid wastes for bioenergy and bioproducts
production

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Abstract

Municipal wastes, be it solid or liquid, are rising due to the global population growth and rapid urbanization and industrialization. Conventional management practice involving recycling, combustion, and treatment/disposal is deemed unsustainable. Solutions must be sought to not only increase the capacity but also improve the sustainability of waste management. Research has demonstrated that the non-recyclable waste materials and bio-solids can be converted into useable heat, electricity, or fuel and chemical through a variety of processes, including gasification,

pyrolysis, anaerobic digestion, and landfill gas in addition to combustion, and wastewater streams have the potential to support algae growth and provide other energy recovery options. The present review is intended to assess and analyze the current state of knowledge in the municipal solid wastes and wastewater treatment and utilization technologies and recommend practical solution options and future research and development needs.

Keywords: municipal solid waste, municipal wastewater, combustion, incineration, pyrolysis, gasification, anaerobic digestion, microalgae, landfill, scum, biodiesel, biorefining

1. Introduction

The world generates estimated 1.7 – 1.9 billion metric tons of municipal solid wastes (MSW) each year. In US alone, about 254 million tons of municipal solid wastes (MSW) were generated in 2013, among which about 34 percent was recycled according to US EPA (EPA, 2015). Organic materials such as paper and paperboard, yard trimmings, food waste, plastics, wood, rubber, etc. are the largest component of MSW and contain large amounts of energy (Table 1) that can be recovered. In 2013, 134.3 million tons of MSW went to landfills and 32.7 million tons were combusted for energy recovery. Improper management of these MSWs can cause large scale contamination of soil, water and air, is a significant contributor to greenhouse gas emissions and allow huge potential economic values uncaptured.

In 2008, the US EPA estimated 238.2 million people (74% of US population) served by about 14,748 centralized municipal wastewater (MWW) treatment facilities or Publicly Owned Treatment Works (POTWs) (EPA, 2016). Assuming 300 liter/cap/day, the annual volume of US municipal wastewater is more than 24 trillion liters. A 2013 report by Electric Power Research Institute, Inc. (EPRI) estimated that 2% of total U.S. electricity use went towards moving and treating water and wastewater (Electric Power Research Institute, 2013). Furthermore, treatment of this water in POTWs also generates over 8 million tons (dry weight) of sludge or biosolids, which requires about one third of total electricity use by a wastewater treatment system. Approximately 55% of the total biosolids are applied to agricultural land, with the remainder either incinerated/processed for energy recovery, composted or landfilled. In 2000, energy-related emissions from POTW operations resulted in total emissions of 15.5 million tons CO₂ -equivalents, an acidification potential of 145,000 tons SO₂ -equivalents, and eutrophication potential of 4,000 tons PO₄³⁻ -equivalents (Electric Power Research Institute, 2013). The degradation of bio-solids also emits large amounts of CH₄ and N₂O (EPA, 2014). Along with negative social and economic impacts, wastewater treatment is facing significant challenges.

The global population growth, urbanization, and rapid industrialization trend can only worsen the situations by putting increasing pressure on our existing MSW and POTW systems. Solutions must be developed to not only increase the capacity but also

improve the sustainability of MSW treatment and POTW operations. Research has demonstrated that the non-recyclable waste materials and bio-solids can be converted into useable heat, electricity, or fuel and chemical through a variety of processes, including gasification, pyrolysis, anaerobic digestion, and landfill gas (LFG) in addition to combustion, and wastewater streams have the potential to support algae growth and provide other energy recovery options. However, MSWs are highly heterogenous and their generations can be highly distributed in small municipalities. It is important to examine how individual technologies or combination of technology can be best used to convert specific wastes to a range of products (biorefining) and whether it is more sustainable to process wastes locally (distributed conversion) than centrally. The objective of the present review is to assess and analyze the current state of knowledge in the MSW and MWW treatment and utilization technologies and recommend practical solution options and future research and development needs.

2. Disposal and utilization of MSWs

2.1. Landfilling

Landfilling is the most common MSW disposal practice in the world (Gerçel, 2011) likely because it is most economical and does not required skilled operators. As a result, it is particularly suited for developing countries where low capital and maintenance cost depression or closed mining sites are commonly used for landfills (Daskalopoulos et al., 1998). In the US, modern landfills are well-engineered facilities that are designed, operated, and monitored in compliance with federal regulations.

Some new landfills collect potentially harmful landfill gas (LFG) and convert the gas into energy.

Although landfilling is of low cost, it poses serious threats to the environment.

Landfilling is a process in which MSWs is transferred from one place to another, rather than be used as a resource. The biodegradable fraction of MSW is slowly biodegraded in the landfills, resulting in liquid leachate and landfill gas. Liquid leachate will cause severe contamination of groundwater, while landfill gasses composed largely of methane and carbon dioxide, if not captured, will aggravate greenhouse effect and bring stench to surrounding environment. The number of U.S. landfills has steadily declined, which may be attributed in part to the stringent EPA regulations regarding MSW landfills. In some countries or cities whose land resources are restrained, landfilling is gradually replaced by other approaches.

In the US, governments at all levels are encouraged to decrease the generation and increase recycling of MSWs. Regulations are enforced to ensure safe disposal and require operators to provide final cover and post-closure care of landfill facilities.

Some landfill facilities collect the biogas (mainly methane) generated from the landfill wastes to generate electricity or heat. The estimated biogas generated globally is 57 million tons but only 10 or less is collected and used in 2000 (Themelis & Ulloa, 2007). Attempt to use microbial fuel cells to generate electricity from landfill leachate has also been reported (Damiano et al., 2014).

2.2. Thermal treatment/combustion/incineration

Burning of non-recyclable MSWs and bio-solids generates heat, CO₂, water, and ash.

Commercial incinerators are usually operated at 850°C in the presence of air to oxidize the feedstock. The heat generated is used to convert water to steam which is used for district heating or sent to a turbine generator to produce electricity. The ash produced (about 15-25 percent by weight of the MSW) is sent to landfills.

Incineration reduces the volume of incoming MSWs by 90% and the weight by 70%.

Incineration causes less pollution to the groundwater or the air than landfills.

Incineration is suitable for high calorific value waste; it can be located within city limits, reducing transportation costs, and operated as continuous process (Jha et al., 2011). However, it has several drawbacks. First, incineration of hazardous MSWs may produce many kinds of particulates and harmful gasses, among which dioxin is the most poisonous gaseous product. Secondly, the cost of incineration is generally higher than other treatment processes, especially in the areas where the heat value of waste is relatively low and oil or coal powder must be added in as additive for co-combustion. Thirdly, MSW combustion with energy recovery may be a viable option only for populations of 100,000 or more because a high minimum level of feed rate is required for an economically viable operation (Daskalopoulos et al., 1997).

2.3. Thermochemical processes

2.3.1. Pyrolysis

Pyrolysis is the conversion of biomass to bio-oil, biochar, and pyrolytic gas at

elevated temperatures (300–700 °C) in the absence of oxygen. The yield and properties of each fraction vary with feedstock composition, i.e., carbohydrates (cellulose, hemicellulose, lignin, and starch), protein, lipids, and ash contents and processing conditions. Pyrolysis is a plausible option to liquefy solid biomass and produce bio-oil that can be refined to heating oil and transportation fuels. It is superior to incineration in terms of pollutant control. However, its energy efficiency may suffer for high moisture content feedstock, and the fuel properties and stability of the bio-oil may be problematic for transportation, storage, combustion, or downstream processing.

Depending on the variables including temperature, heating rate, and residence time of vapors in the reactor, the pyrolysis process can be generally classified into three subclasses, i.e., slow, fast and flash pyrolysis, as shown in Table 2. Conventional slow pyrolysis has been practiced for thousands of years and has been mainly used for the production of charcoal. In slow pyrolysis, vapors do not escape as rapidly as they do in fast pyrolysis. Thus, components in the vapor phase continue to react with each other, which favors water vapor and CO₂ production in the volatile stream, and much of solid remain in the formation of solid char. Gerçel (Gerçel, 2011) conducted slow pyrolysis with the low heating rate of about 7 °C/min and obtained up to 24–43% of bio-oil. However, most studies on slow pyrolysis reported high production of char at the expense of bio-oil (Karaosmanoğlu et al., 1999). Karaosmanoglu et al. (Karaosmanoğlu et al., 1999) investigated slow pyrolysis of the straw and stalk of the

rapeseed plant in a tubular reactor at the temperature range of 350–650 °C. The maximum bio-oil yield was only about 17% while the maximum char yield reached up to 47% at the heating rate of 10 °C/min.

If the target product is liquid with low water content, a high heating rate, a moderately high temperature, and a short residence time should be used while an elevated temperature favors gas production. The most commonly used reactors for fast pyrolysis include fixed bed and fluidized bed. Ateş et al. (Ateş et al., 2004) studied fast pyrolysis of sesame stalk in a fixed-bed reactor and obtained the maximum bio-oil yield of 37.2 wt% at the temperature of 550°C and a heating rate of 500 °C/min. Lee et al. (Lee et al., 2005) investigated the production of bio-oil from rice straw by fast pyrolysis using a fluidized bed reactor. It was found that the optimum reaction temperature range for bio-oil production was 410–510°C, at which the bio-oil yield was about 50 wt%. In summary, fast pyrolysis technology is a more promising alternative approach than slow pyrolysis to convert a wide range of waste feedstocks for bio-oil production.

A new pyrolysis using microwave heating, dubbed “microwave assisted pyrolysis” (MAP), was developed (Du et al., 2011). Microwave heating has many advantages over conventional conduction heating. One of the key features of microwave heating is internal heating as illustrated in Figure 2. In conventional heating, heat is transferred from the surface to the center of the material through conduction driven by

temperature gradients. Mass flow, which is always outward, is the movement of gaseous compounds generated by thermochemical reactions. Thus, heat flow and mass flow are countercurrent for conventional heating. In microwave heating, microwaves induce heat at the molecular level by direct conversion of the electromagnetic energy into heat. Therefore, microwave irradiation can provide uniform internal heating for material particles, making the heat flow and mass flow concurrent. In addition, the surrounding of the biomass particle in conventional heating is very hot while that in microwave heating is relatively cool. A concern with earlier microwave heating based MAP was the slow heating rate. Recently, significant progress has been made in improving the heating rate and temperature by incorporating microwave absorbent in the process (Borges et al., 2014). This new heating mechanism makes fast microwave assisted pyrolysis (fMAP) and fast microwave assisted gasification (fMAG) feasible (Chen et al., 2015; Xie et al., 2014a), which can help overcome many of the disadvantages associated with fluidized bed processes, achieve higher yield and better product quality at the same time, and further enhance all the unique characteristics and quality of the MAP technology including feedstock diversity, simple and low capital cost, no carrying gas involved, ease of process control, etc.

Pyrolysis has been tested on various MSW feedstocks (Nurul Islam et al., 2005; Sørum et al., 2001). Life cycle assessment (LCA) study suggested that pyrolysis is an environment-friendly way to utilize the MSW (Wang et al., 2015). MSWs tend to

vary greatly with sites and seasons, which gives rise to the variations in product yields and quality (Sørum et al., 2001). There has been tremendous interests in pyrolysis of sewage sludge. Studies show that pyrolysis of sewage sludge reduced 50% waste volume (Inguanzo et al., 2002) while stabilizing organic matter, producing bio-fuels, concentrating minerals in the bio-char, which can then be used as the soil amendment or be upgraded to an adsorbent. The gas and oil produced can be either directly burned as a fuel to provide heat and electricity, or further converted to other chemicals through subsequent processes. In order to improve the yield and quality of the bio-oil, many researchers used different catalysts in the pyrolysis of sewage sludge. Kim and Parker (Kim & Parker, 2008) reported that use of zeolite as catalyst did not improve the oil and char yields due to the increased conversion of volatile matter to gas. However, Park et al. (Park et al., 2010) found that metal oxide catalysts (CaO and La₂O₃) contributed to a slight decrease in bio-oil yield but were significantly effective in the removal of chlorine from the bio-oil. Xie et al. (Xie et al., 2014b) conducted fMAP of sewage sludge in the presence of catalysts for bio-oil production. The optimal temperature and catalyst to feed ratio for bio-oil production were found to be 550°C and 2:1, respectively.

2.3.2. Gasification

Gasification involves partial combustion or oxidation of biomass to produce syngas and ash at high temperatures (> 800 °C) in partial air or with injected steam as the gasification agent to generate a mixture of CO, H₂, CO₂, CH₄, and some light

hydrocarbons. The syngas, after cleaning up, can be used in many ways, including heat and gas providing, electricity generation and chemical synthesis. Syngas may contain contaminants such as H_2S , HCl , tar, and solid particles. Among all the contaminants, tar is the most common and troublesome compound and has been extensively discussed in previous studies (Anis & Zainal, 2011). Tar is a complex mixture of organic chemicals largely composed of aromatic hydrocarbons and can cause serious problems including fouling of engines and deactivation of catalysts, due to its condensation and polymerization (Devi et al., 2003). Therefore, some techniques such as catalytic gasification and post-gasification cleaning have been considered to reduce tar and remove other contaminants in syngas.

The types of gasifiers include mainly fixed bed and fluidized bed systems. Dong et al. (Dong et al., 2010) studied gasification of coffee grounds using a two-stage dual fluidized bed gasifier (DFBG), obtaining syngas with H_2 and CO contents of 31.23% and 29.20%, respectively. The tar content was reduced from about 40 g/m^3 to 10 g/m^3 raw gas with Ca impregnation onto fuel. Xie et al (Xie et al., 2012) investigated two-stage catalytic pyrolysis and gasification of pine sawdust in a fixed bed reactor and observed a maximum syngas yield of $3.29 \text{ m}^3/\text{kg}$ feedstock.

Based on the tar removal technologies used, the gasification process can be broadly divided into two approaches: primary methods and secondary methods (Devi et al., 2003). In primary methods, gasification process and tar elimination are carried out

simultaneously in a gasifier; while in secondary methods, gas cleanup is conducted in a separate reformer in the downstream of a gasifier. The primary methods have gained much attention recently (Karmakar & Datta, 2011). Although the primary methods eliminate the need for downstream cleanup, they cannot effectively serve the purpose of tar reduction without affecting the useful gas composition and heating value (Devi et al., 2003). As a result, the syngas yields of primary methods will be relatively low compared with secondary methods. By steam gasification of pine sawdust using an updraft gasifier combined with a porous ceramic reformer, Gao et al. (Gao et al., 2009) obtained syngas with a maximum yield of $1.72 \text{ m}^3/\text{kg}$ feedstock and lower heating value (LHV) of $11.73 \text{ MJ}/\text{m}^3$ at 950°C . Xiao et al. (Xiao et al., 2011) utilized primary fluidized bed and secondary reforming fixed bed to investigate steam gasification of wastes with Ni/BCC as a catalyst and obtained syngas with a yield of $2 \text{ m}^3/\text{kg}$ feedstock and LHV of $14 \text{ MJ}/\text{m}^3$ around 600°C . Secondary methods are effective in reducing tar content and improving syngas yield, but additional equipment will increase the investment.

In general, MSW gasification systems have the characteristics of large scale, high automatic degree, and complicated technique. The gasification efficiency of these systems is up to 60%–80% and the heating value of the produced combustion gas is $17\text{--}25 \text{ MJ}/\text{m}^3$ (Ganesh & Banerjee, 2001), which is mainly used for electricity generation and heat supply. Some representative gasification projects include the down-draft gasification furnace by Imbert Energietechnik GMBH in German, the

fluidized bed by Omnifuel Gasification System Limited and the fixed bed by Moore Canada Ltd in Canada. Recently, an integrated gasification system combined with internal combustion set has been developed, promoting gasification for syngas generation in large-scale. To satisfy the energy needs in developing countries, some small-scale gasification equipment have been investigated. The gasifier designed by Thomas Reed and Ron Larson can be used in domestic cook using small blocks as raw material. The furnace designed by UTin Win can dispose rice husk as well as household garbage such as potato peel, tea, and other vegetables. The applications of MSW gasification technology mainly lie in electricity generation and chemical synthesis.

Syngas is not an ideal form of product for application, storage and transport. Attempts to use syngas as intermediate resource for production of hydrogen, ammonia, methanol, chemicals, liquid fuels or lubricant via chemical (syngas catalytic reforming) and biological processes (syngas fermentation) have been reported. A number of pathways for syngas reforming have been proposed and studied (Figure) (Spath & Dayton, 2003). Hydrogen and methane production remains the best options for syngas reforming. Since syngas production accounts for more than 50% of the product cost, it is important to produce inexpensive syngas, especially considering the low price of natural gas in current market. More study is needed to investigate the economic and environmental benefits of converting MSWs to syngas.

Syngas fermentation is an emerging area of research interest (Devarapalli & Atiyeh,

2015). Several companies are eyeing commercialization of their respective technologies (Daniell et al., 2012). In syngas fermentation, microorganisms (bacteria and archaea), both aerobic and anaerobic, are used as biocatalysts for the conversion of C1 and H2 fractions of syngas to a diversity of chemicals of high economic value. Compared with chemical catalysis, syngas fermentation can be operated at lower temperature and pressure, does not suffer from catalyst poisoning, and produces greater variety of products. Another significant advantage is that syngas fermentation is less susceptible to ratio of CO to H2 and trace amounts of contaminants in the syngas, requiring much less syngas cleaning. However, there are still many challenges before the technologies can be commercialized. For example, syngas suffers from low bacterial growth rate and the process is largely limited by CO and H2 diffusion from the gas phase to the liquid phase. Significant efforts should continue towards making the process cost-effective and reliable for large-scale implementations.

3. Utilization of municipal wastewater (MWW)

With the huge amount of wastewater generation rate in the US, the total estimated energy in wastewater is about 4.4×10^{11} MJ/year. Wastewater, rather than being perceived as a waste, has come to be viewed as a valuable resource for water, energy, and plant nutrients (Asano et al., 2007). Successfully capturing the energy in these wastewaters can reduce 54 billion gallon of gasoline use per year in the

transportation sector. It accounts for 40% of gasoline consumption in the U.S., and avoid 2.1×10^6 ton CO₂ equivalent (eq.) of nonrenewable greenhouse gas (GHG) emissions (Yang et al., 2012). In addition to the direct chemical energy, the beneficial use of nutrients, nitrogen (N) and phosphorus (P) of wastewater could save resources and energy to produce fertilizers, which could account as an additional energy potential of wastewaters. Furthermore, for every 100,000 million gallons of wastewater treated, 1,000 tons of scum, 85 million kg of dry sludge, and 500 million gallons of centrate (from sludge dewatering) are generated. All these waste streams contain energy and/or nutrients that can be utilized separately through different technology pathways.

3.1. Conventional treatment technologies

Various conventional treatment technologies are used in wastewater treatment. There are three main systems widely used in different countries: activated sludge reactors, stabilization ponds, and upflow anaerobic sludge blanket (UASB) reactors.

Stabilization ponds or lagoons used man-made basins consisting of an anaerobic treatment pond and a facultative treatment pond. It is more common in developing countries particularly in the tropical and subtropical regions where land is readily available and of low cost, and heat is ample in favor of high reaction rates. Due to the high land requirement, these pond systems are rarely used near urban areas. Activated

sludge is the most common technology adopted in urban areas especially in the developed countries. The activated sludge process can be mainly divided into five types: pre-treatment, primary treatment, secondary treatment, tertiary treatment and water reclamation (Council, 2012; Wichelns et al., 2015). The pre-treatment uses screening to remove grit, grease and gross solids to satisfy the requirements of subsequent treatment processes. Then those settleable matter and scum as part of the suspended solids are eliminated in the primary treatment. After that, secondary treatment is deployed to remove total suspended solids, dissolved organic matter and part of the nutrients in wastewater. The addition of tertiary treatment focusing on the removal of nitrogenous and phosphoric substances, poisonous compounds, suspended matter remained, or microbes before the discharge or reclamation of wastewater.

UASB is an emerging technology which has seen significant increase in use especially in Latin America and India (Chernicharo et al., 2015). UASB is essentially an anaerobic treatment, in which wastewater is introduced in the bottom of the reactor and flows upward through a sludge blanket, a thick layer of granules composed of microorganisms attached to each other or to small particles suspended in the reactor.

Wastewater is treated as it comes in contact with the granules. Because of the anaerobic conditions in the blanket, methane is produced and can be captured for heat and electricity generation, and therefore energy recovery is enabled. UASB reactors can be easily constructed without the need for high technology and the process can tolerate high organic loading (Lim & Kim, 2014). USAB systems are compact and can be operated in small scale, and therefore, suitable for urban as well as

decentralized applications. The costs of UASB process is much lower than the activated sludge process (Chernicharo, 2006), which is believed to be responsible for the significant expansion of wastewater treatment coverage in Latin America (Chernicharo et al., 2015). However, its nutrient removal rate remains relatively low compared with activated sludge method; odors and greenhouse gas emission is a concern; and its applications at moderate to low temperature are less practiced and known.

Many wastewater treatment plants are facing new challenges because of emerging contaminants such as pharmaceuticals, personal-care products, hormones, illicit drugs, flame retardants and perfluorinated compounds, which may be the target of near future regulations (Prieto-Rodríguez et al., 2013). Presence of antibiotics and associated resistant bacteria (Gao et al., 2012b) is also a significant concern. To achieve the goal of water reclamation, some engineered biological, chemical, and physical processes to mitigate these micro-pollutants have been reported (Council, 2012; Dolar et al., 2012; Gao et al., 2012a; Prieto-Rodríguez et al., 2013). Those biological systems are identified as multi-objective treatment processes which hold advantages in removal of micro-pollutants, such as bacteria and viruses, suspended particulate matter, dissolved organic matter, trace chemical substances and nutrient salts before the reuse of wastewater.

3.2. Algae based treatment and utilization technology

It is well known that wastewaters are good resources containing sufficient amounts of organic or inorganic carbon, ammonium or nitrate nitrogen, and phosphorus and other trace elements needed for algae growth (Zhou et al., 2014). The algae based treatment has showed great potential on cost saving and lower technology requirements as well as nutrients recovery without generating additional sludge by-products. Considering the specific characteristics of chemical composition and physical properties, many researchers have made efforts to cultivate algae using different types of wastewater to tap the great potential in mass production of algal biomass for biofuel or other applications (Zhou et al., 2014). The availability of nutrients in wastewaters influence the total biomass production of algae, and therefore it is crucial to select a wastewater with balanced nutrient composition. Among all types of wastewaters, municipal wastewater and agricultural wastewater were considered to be the most suitable sources which have been expansively studied focusing on the removal of nutrients and metals from wastewater (Zhou et al., 2014). It was recognized that algae cultivation using wastewater appears to be of huge economic benefits which could provide strong driving force for the commercial applications of algae in both wastewater treatment and biofuel production. Meanwhile, there are also some challenges and difficulties deserve further investigation, such as wastewater characteristics, C/N and N/P ratios, colored substances and suspended and dissolved solids affecting turbidity, toxic or noxious substances and competing microbes (Zhou et al., 2014).

3.2.1. Algae growth on MWW

The conventional municipal wastewater treatment processes consist of a primary treatment phase, a secondary treatment phase, a tertiary treatment phase and sludge treatment process (Pittman et al., 2011) as mentioned in 3.1, which generate four types of wastewater streams namely wastewater before primary settling, wastewater after primary settling, wastewater after activated sludge tank, and centrate generated in sludge dewatering. Almost all types of municipal wastewater are rich in nutrient salts including N, P and other necessary trace elements beneficial for the growth of algae. The centrate from sludge dewatering was found to be able to enhance the growth of algae significantly in comparison with the other three wastewaters because of the higher nutrients concentration (Arita et al., 2015; Wang et al., 2010). Esther Posadas et al. (Posadas et al., 2013) compared the carbon and nutrient removal of algal-bacterial and bacterial biofilm bioreactors treating centrates and domestic wastewater which confirmed the assumption that the addition of algal to bacterial biofilm bioreactors could significantly enhance the performance on the removal of organic matters and nutrients including N and P.

3.2.2. Key factors related to the applications of algae in wastewater treatment

Light intensity

Light intensity is considered to be a dominant limitation influencing the performance of algae. Only a small part of the energy from solar is converted into algal biomass which is influenced by the specific operational conditions. Usually the biomass

productivity would be enhanced with the increase of light intensity as proved in literatures (Min et al., 2012). Min Min et al. (Min et al., 2012) found light has a positive influence on the biomass accumulation through the two-stage algae cultivation period using concentrated wastewater from sludge dewatering. Yecong Li et al. (Li et al., 2011) concluded that the combination of higher light intensity and exogenous CO₂ could promote the biomass production as well as the removal of COD and nitrogen when using algae for municipal wastewater treatment, and the responses due to light intensity varied with the strains of algae. Furthermore, the light intensity and photoperiod could cause variations of lipid composition in harvested algae. High light intensity stimulates the synthesis of saturated and mono-unsaturated fatty acids, however, it could also cause photoinhibition which lead to a decrease of biomass productivity and nutrient removal efficiency (Mehrabadi et al., 2015).

CO₂ availability

The addition of exogenous CO₂ could enhanced the accumulation of algal biomass in the autotrophic growth stage of cultivation using wastewater, however, this effect might be negligible when there are adequate organic carbon sources (Min et al., 2011). The removal rate of nutrients including COD, ammonia and total nitrogen were similar with or without CO₂ addition while that of PO₄-P was affected significantly because of the acidification caused by CO₂. Moreover, CO₂ addition could contribute to the increase of C/N ratio which would be beneficial for the accumulation of energy content and the biomass productivity of algae.

Algae-bacteria interactions

Due to the nature of wastewater, there are concerns about the impact of bacteria on algae growth in wastewater. A mutual effect was found between algae and bacteria in a co-existing system (Ma et al., 2014). Bacteria could degrade those refractory organic substances into something more preferable for algae, while algae could promote the growth of bacteria by offering beneficial nutrients generated during the growth of algae or the decomposition of algal cells in return (Unnithan et al., 2014). Furthermore, algae can also play the role as a refuge protecting bacteria from extreme environmental conditions (Unnithan et al., 2014). Wenguang Zhou et al. (Zhou et al., 2012) developed a novel fungi-algae pellets that enhanced algae harvesting efficiency through bioflocculation, and this technology could significantly improve the technique economic viability of algae cultivation for commercialization. Similarly, Yanyan Su et al. (Su et al., 2011) discovered a settleable algal-bacterial culture using municipal wastewater that most suspended solid could settle down within 20 min, which indicated that the coexistence of algae and bacteria could be a enrichment strategy for algae harvesting. The enhancement of bioflocculation through the combination of bacteria or fungi with microalgae in wastewater treatment could save energy for harvesting and improve economic availability (Shen, 2014). However, some researchers may hold different opinions. Sunja Cho et al. (Cho et al., 2011) found that the removal of microbes with symbiotic and competitive relationships to

algae such as bacteria and fungi by an appropriate pre-treatment method could maximize the biomass productivity. Moreover, it was found that a two-stage cultivation mode (hetero-photoautotrophic algal growth model) for wastewater treatment could achieve not only high biomass concentration and lipid content but also high nutrient removal efficiencies for COD, ammonia, total nitrogen and total phosphorus.

3.2.3. Algae as valuable products

Yields of algal biomass from 2.8 to 34.6 g/m²/day from algae cultivation on municipal wastewater have been reported (Min et al., 2011; Woertz et al., 2009). With the huge amounts of wastewater generated every day, significant quantities of algal biomass can be generated and converted to a wide range of usable products including biodiesel, bio-ethanol, and non-fuel applications such as chemicals, fertilizer, biopolymers, bioplastics, paints, dyes, colorants, lubricants, pharmaceuticals, nutritious food and animal feed, etc. (Zhou et al., 2014). However, the potential of these products is limited by the cost of algal biomass. Compared with fresh water based algae production, the wastewater-grown microalgae are considered competitive feedstock for low-cost biodiesel production. Furthermore, alternative downstream processes such as thermo-chemical liquefaction may provide a pathway for converting low oil content algae to high energy density transportation fuels (Du et al., 2011).

3.3. Anaerobic digestion of sewage sludge

Anaerobic digestion (AD) of sewage sludge is a traditional and relatively matured technology for solids stabilization and energy recovery. Mesophilic AD with an operation temperature of 30°-38° C is a well-understood technology and has been practiced worldwide for decades. The advantages of using AD to treat organic waste are obvious. Different from combustion process in which feedstocks must be dry to be incinerated, AD has much less restriction on the moisture content of the feedstock, and therefore, many food processing waste and animal waste are ideal for AD process. Benefited from the biological reaction, a large amount of organic load is converted to burnable biogas with relative good conversion efficiency (60-80%). The slurry produced is a nutrient-rich byproduct and can be converted to fertilizer and soil amendment for land application.

However, according to the report of Willis et al. (Willis et al., 2012), many barriers still exist for AD biogas to be used for renewable energy, among which the economic barriers including inadequate payback and lack of available capital, are the main issues. In addition, the low prices of U.S., fossil fuel and electricity and lack of government policy further hindered the willingness of use AD process. In order to solve this problem, one feasible approach is to introduce high strength waste stream to increase biogas yield.

Carbohydrates, proteins, and lipids are the three major components in feedstocks that generate methane. The theoretical methane yields of each substrate are governed by the following equation (Boyle, 1976):

By calculation, the theoretical methane yields for carbohydrates, proteins, and lipids are 0.30, 0.25 and 0.74 g CH₄ per g substrate, respectively. Lipids are the most productive feedstock for methane gas.

Sludge's composition is complex and its nutrients are often confined in solids.

Numerous methods have been attempted to increase the availability of the nutrients for microorganisms (Tyagi & Lo, 2011). An interesting pretreatments method involving microwave irradiation was found to increase methane yields, which was attributed to improved solubilization of sludge to release nutrients (Koch et al., 2015).

Microwave treatment also reduced *Salmonella* spp., *E. coli*, and *C. perfringens*, resulting in certain degree of sanitation (Kuglarz et al., 2013). However, energy consumption is a major concern in implementation of this process, especially with sludge having high moisture content (Tang et al., 2010).

Research has been conducted to study the anaerobic co-digestion of sludge with food wastes and oily waste over the last few years. Iacovidou et al. (Iacovidou et al., 2012) summarized benefit and constraints of the co-digestion sewage sludge with food waste. By adding external food waste, many co-digestion systems experienced methane production increases due to increased carbon-to-nitrogen ratio. In addition to its higher methane potential, food wastes also contributed higher reaction rate (Koch

et al., 2015). Furthermore, there are lots of micronutrients contained in the food waste which can support microbial growth during the digestion process.

Many waste treatment facilities also encourage food wastes and other high strength wastes to be discharged directly to the facilities. For example, the City of Sheboygan, Wisconsin receives cheese whey processing waste and thin stillage from ethanol manufacture to increased biogas production. A waste treatment facility in Massachusetts (5-mgd) uses co-digestion of brewery, beverage, food, and dairy waste to increase biogas production (Willis et al., 2012).

Another widely studied co-digestion stream is grease trap waste that is a complex aqueous mixture of oil, solid and water. It belongs to the category of fats, oils, grease (FOG) and has high oil content with chemical oxygen demand (COD) of 138-375 g COD/L (Zhu et al., 2011). Greasy wastes are usually from restaurant grease, grease trap, or scum waste at wastewater treatment facilities. It was reported that co-digestion of FOG with municipal sludge can increase methane production by 30-80% (Long et al., 2012). However, inhibition of acetoclastic and methanogenic bacteria was often reported during the anaerobic digestion of high lipid wastes. In addition, because it is lighter than sludge, oil can gel up when the temperature is low. It also has the problem of sludge flotation and substrate transport limitation. The digester is also easy to get foamed up, blocking the pipes and pumps and also

clogging gas collection and handling systems. As a result, many of the greasy wastes are still separated and sent to landfill.

Recently, glycerol generated as a byproduct of biodiesel production process was discussed as a co-digestion material with sludge. It was reported that with 1-3% v/v glycerol addition, the methane production could be doubled from 1.1 L/day to 2.3 L/day (Fountoulakis et al., 2010).

3.4. Converting wastewater scum to biodiesel

Scum is an oily material floating on the surface of primary and secondary settling tank and collected by a horizontal moving skimmer board in POTWs. Scum, being in the category of fat, oil and grease (FOG), is made up of grease and entrained solids that are suspended in a wastewater matrix that is notoriously difficult to treat.

Technologies to treat the scum include co-digestion with sludge to produce methane, combustion for heat and electricity generation, landfill, and transesterification for biodiesel production. Currently, the most widely used method for scum treatment is co-digest scum with sludge that the biogas can be produced to generate electricity and heat for plant use. However the greasy material has a high content of long-chain fatty acids that are known to inhibit anaerobic digestion, at the same time, issues of foaming and blockage of the pipes and pumps, many POTWs also separated the scum

and sent it to landfill. For example, the current practice of the scum of WWTP at Saint Paul Minnesota is to landfill, and the related cost is about \$200,000.

Recently, researchers at the University of Minnesota (U of M) developed a novel process that converts fatty acid, lipid, and soap in scum directly to ASTM-grade biodiesel (Anderson et al., 2016; Bi et al., 2015). The researchers found that by utilizing scum derived biodiesel the wastewater treatment plant can not only reduce the cost of scum disposal to landfills, diesel fuel use but also reduce GHG emissions and generate additional revenue. Therefore, the new process and related benefits are likely to improve the economic and environmental sustainability of POTWs.

Differ from other biodiesel feedstocks, scum by far has the poorest oil quality. Due to high soap and FFA content, many scum impurities and moisture have been emulsified with the main oil complex and make it very difficult to separate. Acid wash combined with solvent extraction were needed to remove soap and fine solids particles and ease the downstream process. The key point in most the biodiesel process is how to reduce FFA content in the raw feedstock. Most traditional methods applied in the industry is to use acid esterification process that methanol react with FFA to produce methyl-ester-fatty-acid (FAME) at about 60-70°C with sulfuric acid as catalyst. The benefit of this method is the reaction temperature is low, and the process is not sensitive to moisture. However, FFA and methanol react and produce water; the disadvantage is that recycle the wet methanol can be an energy-intensive process

because the methanol and water have a very close boiling point.

The alternative process is glycerolysis that glycerol reacts with FFA and produce glycerides and water. Since the reaction happens at 238°C, any water produced through glycerolysis will be evaporated and driven off by nitrogen purge. Therefore, oil will be dry for following transesterification process. Although the reaction temperature is high, the overall reaction energy is low, with a high efficient heat exchanger, the heat can be recycled to preheat the incoming flow. Glycerolysis has many benefits over acid-esterification especially for high FFA feedstock that glycerolysis not only has less energy cost but also less material cost since glycerol produced after transesterification can be reused at the glycerolysis process.

4. Biorefining approach

As discussed above, a number of technologies have been investigated to convert MSWs and MWW to energy in the form of heat, electricity, gaseous and liquid biofuel, bio-products, and clean water. The choice of technology would depend on the composition and physical, chemical and biological properties of the wastes.

Thermochemical conversion processes are most suitable for low moisture content MSWs such as dry municipal solid waste and lignocellulosic biomass. These processes include direct combustion, gasification, and pyrolysis. Food wastes and other high moisture content MSWs are usually processed biologically. They may be anaerobically digested for biogas or fermented to product ethanol fuels and carbon

dioxide. It is also possible to process food wastes to animal and fish feed. Oily fraction from the wastes may be extracted for oil which is converted to biodiesel through different processes. Fertilizers and soil amendment agent may be produced as byproducts of several conversion processes. Microalgae technology is best suited for treatment and utilization of liquid wastes.

It is difficult to find a single universal process to utilize the complex nature of municipal wastes. Therefore a biorefining approach (Fig. 3) which uses different processes to convert various wastes to multiple products would be more appropriate. Further examination on this approach, including the technical feasibility study and improvement, life cycle assessment, and techno-economic analysis, is necessary.

5. Conclusions

Municipal solid and liquid wastes should not be perceived as merely wastes. As new technologies are emerging, alternative options for utilization of municipal wastes have become available. Considering the complexity of municipal wastes, multiple technologies may be required to maximize the energy and value recovery. A biorefining scheme tends to be an appropriate approach. We recommend that,

- 1) Research be conducted to investigate biorefining and utilization of municipal wastes;
- 2) Collaboration between municipality and research institutes be established to conduct demonstration projects;

- 3) Life cycle assessment and techno-economic analysis be conducted to examine the sustainability of technologies to be implemented.

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Figure captions

Fig. 1. Syngas conversion pathways.

Fig. 2. Schematic illustration of temperature gradient and heat and mass flows in cross-section of a wood cylinder subjected to conventional and microwave heating.

Fig. 3. Biorefining approach to converting municipal solid and liquid wastes to value-added products.

Fig. 1.

Fig. 2.

Fig. 3

Table 1. Energy content of municipal solid wastes (Million Btu Per Ton)

Biogenic		Non-biogenic	
Leather	14.4	Polyethylene terephthalate (PET)	20.5
Textiles	13.8	High density polyethylene (HDPE)	38
Wood	10	Polyvinyl chloride (PVC)	16.5
Food	5.2	Low density polyethylene/ Linear low density polyethylene (LDPE/LLDPE)	24.1
Yard trimmings	6	Polypropylene (PP)	38
Newspaper	16	Polystyrene (PS)	35.6
Corrugated Cardboard	16.5	Other	20.5
Mixed paper	6.7	Rubber	26.9

Table 2. Range of the main operating parameters for pyrolysis processes.

Pyrolysis process	Heating rate (°C s⁻¹)	Temperature (°C)	Residence time (s)
Slow	<1	300–700	>450
Fast	10–300	550–1000	0.5–10
Flash	>1000	800–1100	<0.5