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Contractor's Report

Integration of Rotary Drum Reactor and Anaerobic Digestion Technologies for Treatment of Municipal Solid Waste

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Executive Summary

Each year, more than 250 million tons of municipal solid waste is generated in the U.S. Despite very successful recycling campaigns throughout the country, two-thirds of the municipal solid waste is still going into landfills. According to CalRecycle, biomass (i.e., paper, food waste, and yard waste) makes up about 50 percent of the waste going to landfills in California. Although in many communities, green waste (e.g., yard trimmings) and paper are separately collected and treated or recycled, food waste is largely going to landfills. Nationwide, according to data from the US Environmental Protection Agency, more than 40 million tons of food scraps are produced each year, which represents 25 percent of the food prepared. Such highly degradable materials contribute greatly to the gaseous emissions from landfills. It will be beneficial to recover the food scraps and other organic residuals from the municipal solid wastes and convert them into energy and other valuable products.

Source separation and collection are good options but wet and easily degradable materials, such as food scraps, putrefy quickly, making their collection and storage very challenging for households and businesses. Even the so-called "source separated" waste streams contain many contaminants that need to be removed if the organics will be composted or anaerobically digested. Alternatively, the organic materials can be separated from the mixed municipal solid waste after collection and transport to a central location where advanced treatment and separation technologies are employed. One practical way to separate biodegradable organic materials from the municipal solid waste is to break the organic factions into smaller particles and then screen them out. Organic materials break down naturally due to biological activity, and when combined with mechanical agitation this breakdown can be forced to occur rapidly. One of the most widely used mechanical-biological treatment technologies is the rotary drum reactor. This report is focused on the evaluation of the organic materials derived from the rotary drum reactor-treated municipal solid waste for anaerobic digestion with an aim to integrate the rotary drum reactor with the anaerobic digestion and compost processes to achieve energy and compost recovery and waste reduction.

Rotary Drum Reactors as a Pretreatment Technology for Municipal Solid Waste

Rotary drum reactors have been used since early 1970s by the waste composting industry for pretreating and separating the organic fractions from the municipal solid waste prior to composting process. Bedminster, Biomixer and Dano are among the trade names used by the waste industry for the processes. Different designs and operational conditions have been developed over the years for the rotary drum reactor processes employed in the U.S., Canada, Australia, Japan, and several European countries. About a dozen municipal solid waste composting plants in North America currently use the rotary drums in their facilities as a pretreatment process for the production of compost from solid wastes, such as the organic fractions of municipal solid waste, biosolids, paper, or animal manure. The facilities in the U.S. that use rotary drums span the climate range from Arizona to Florida to Alaska, and they treat from 3 to 300 tons of waste per day.

The rotary drum process consists of a long, inclined rotating vessel, followed by screens for separating the organic fraction. In some systems, the end of the drum is lined with an inner drum perforated with 2.54 to 7.62 cm (1 to 3 in) holes for solids separation. Other systems employ a trommel screen after the drum. The drum design depends on the desired retention time, the amount of waste treated, and the drum's slope and rotational speed, but typical drums used in the U.S. range from 30.5 -61 m (100-200 ft) long and 3.1- 4.6 m (10-15 ft) in diameter. They rotate at 1-5 rpm and most include forced air blowers, although a few do not.

Rotary drum systems are not only used to separate organic materials from municipal solid waste, but they also increase the rate of biodegradation in composting. The gasses and odors emitted from the rotary drum reactors are usually collected and treated with biofilters. In most systems, waste materials remain in the drum for two to three days, and biological degradation begins almost immediately after the waste enters the drum. Due to natural biological activities, the temperatures inside the drums could rise to 55-68 °C (135-155°F). In cold climates, the drums are normally insulated to maintain the temperature. At a South Dakota facility that uses retention time of six hours, the internal temperature still rises to 20°C (70°F) in the winter. The capital and operating cost of rotary drum systems can be quite high, especially considering the energy required to operate them. The drums in the U.S. require 100-400 hp per drum, depending on the drum size and rotational speed. This translates to 80-110 kWh per ton of waste treated. The economics of the rotary drum system could be improved by recovering the energy from the waste using anaerobic digestion or other technologies.

At least two waste treatment facilities in France and Belgium use rotary drums as a pretreatment for anaerobic digestion and then compost the residual solids from the digesters. At the SIVOM composting facility in Varennes-Jarcy in France, 80 tons per day of source-separated and 190 tons per day of mixed municipal solid waste pass through two rotary drums before going to a Valorga-brand anaerobic digester. In three days, the drums recover 80 percent and 50 percent of the mass of the source-separated and mixed waste, respectively, as feedstock for the anaerobic digester. In Brecht, Belgium, 200 tons of source-separated vegetable, kitchen, and garden wastes per day pass through two rotary drums in series. The drums are used primarily to break open bags and bottles, as the total residence time is only six hours. The recovered waste then goes to a Dranco-brand anaerobic digester. The residual solids after the digestion is separated from the digestate and conveyed to an enclosed aeration bed for composting treatment.

UC Davis Research on the Rotary Drum Reactor and Anaerobic Digestion

Considering the increasing interests in energy recovery from organic residuals, researchers at the University of California, Davis partnered recently with Norcal Waste Systems, Inc. to evaluate the organic materials coming out of rotary drums at six municipal waste treatment plants in the U.S. for anaerobic digestibility and biogas production potential with an aim to integrate the rotary drums with anaerobic digestion and composting processes. The six plants were located in Pinetop-Lakeside, Ariz.; Nantucket, Mass.; Delaware County, N.Y.; Rapid City, S.D.; Sevierville, Tenn., and Cobb County, Ga. Five of the six plants primarily treated the municipal solid waste, using the biosolids to balance the moisture content at 50-55 percent. However, the plant in Pinetop-Lakeside, Ariz. had the primary purpose of treating biosolids, while using the municipal solid waste (mainly paper and cardboard) for moisture content control. All six plants accepted municipal solid waste with marginal or no source separation. Three plants pre-sorted the waste at the recovery facilities to remove aluminum, ferrous materials, and plastics for recycling. They also manually removed materials that could potentially create problems in the rotary drums, such as cables, wires, ropes, hoses, and cloth. The retention time of waste in the drums varied from 2 to 5 days, with the exception of the plant in Rapid City, S.D., where the retention time was approximately six hours and the solid waste was loaded daily in single batches.

To determine the characteristics of the organic materials derived from the rotary drum reactors, three random samples were taken at least one week apart from each of the six plants surveyed. The samples were analyzed for chemical compositions, anaerobic digestibility, and biogas and methane yields. The total solids (TS) contents of the samples were determined to be from 35-55 percent (wet base). The volatile solids (VS) contents were 71-81 percent of TS, indicating the high organic content of the materials. The carbon-to-nitrogen ratio (C/N) ranged from 25-43. The biogas yields after 13 days of batch anaerobic digestion at a thermophilic temperature (50°C or 122 °F) were determined to be from 0.483 to 0.611 L/gVS. The biogas yields after 20 days of batch digestion ranged from 0.533 to 0.676 L/gVS. Methane content of biogas ranged from 58-60 percent. As a comparison, a food waste sample from a UC Davis cafeteria was tested along with the RDR samples. A biogas yield of 0.609 L/gVS with a methane content of 58 percent could be determined for food waste after 20 days of digestion. Based on the laboratory testing results, it was concluded that the organic materials derived from the rotary drum-treated municipal solid waste were highly digestible, in terms of C/N ratio, for anaerobic digestion. The samples from different plants showed similar biogas yields despite the widely varying treatment conditions in the drums. Most notably, the samples from the plant in Rapid City, S.D., had the highest biogas yield, which might be attributed to the short retention time in the rotary drum and hence less time for the readily degradable organics to decompose during the process. If the biogas were converted to electricity at 30 percent efficiency, assuming the higher heating value for methane, the Rapid City plant could recover about 360 kWh of electricity per ton of waste treated (almost three times as much as is consumed by the drums). About 545 kg (1200 lb) residual solids per ton of waste treated would be recovered from the digesters. An estimated one to three weeks of additional composting (e.g., aerated windrows) would be required to obtain stable compost.

Operating the drums with a reduced retention time can potentially have both positive and negative effects. The organic fraction separated from the municipal solid waste may be lower due to insufficient time for the larger organic materials to break down enough to fit through the screen pores after the rotary drum treatment. On the other hand, smaller drums would be required, which means less capital expenditure and energy input. This trade-off suggests that the drum could be sized to optimize the energy balance if the biogas yield were determined as a function of the retention time. Based on this principle, the effect of retention time in the drum on biogas production potential of the organic materials derived was investigated at the plant in Pinetop-Lakeside, Ariz. The drum had a length of 38.1 m (125 ft) and a diameter of 3.1 m (10 ft) and was normally used to treat 20-30 tons per day of municipal solid waste, cardboard and paper waste, and biosolids with an average retention time of three days. Air was blown into the foam-insulated drum to maintain marginally aerobic microbial activity and keep the temperature at 46-68 °C (115 – 155°F). The material discharged from the rotary drum passed over a trommel screen with openings of 3.17 cm (1.25 in). The fine fraction contained mainly biodegradable organic matter and was further processed in aerated piles to produce compost. The coarse fraction was sent to a landfill. The fines accounted for 50-55 percent of the original weight of the wastes treated and had a moisture content of 55-60 percent and the TS content of 40-45 percent. The VS was 70-80 percent of the TS. For this study, the rotary drum was operated for a week from Feb. 26, 2007, to March 4, 2007, with four different waste types: municipal solid waste; a mixture of municipal solid waste, cardboard and paper waste; a mixture of municipal solid waste and biosolids; and a mixture of cardboard, paper waste and biosolids. Each type of waste was sampled after one, two, and three days in the reactor by accessing sampling ports at different points along the length of the drum. The samples were analyzed for chemical composition and later digested at thermophilic conditions (50°C or 122°F) in batch anaerobic digesters for 20 days. In general, the biogas yields of the samples were similar for all treatment conditions. However, they tended to be slightly higher when the retention time in the rotary drum was longer but only if the waste stream did not contain large amounts of paper. When paper was present in the original waste treated, the feedstock with retention time of two days in the rotary drum yielded the most biogas. This may indicate that the aerobic treatment process may increase the bioavailability of the cellulose in the paper. The methane content of biogas was about 60 percent for all of the samples tested.

The waste samples from the Pinetop-Lakeside facility was further tested in a continuous two-stage Anaerobic Phased Solids Digester in the UC Davis laboratory. The digesters were operated at 12-day solid retention time, thermophilic temperature (50°C or 122°F), and organic loading rate from 1.0 to 9.2 kg VS m^{-3} d^{-1}. At the loading rate of 9.2 kg VS m^{-3} d^{-1}, the biogas production rate was determined to be 3.5 m^3 (biogas) m^{-3} (reactor volume) d^{-1} and the biogas and methane yields were 0.38 and 0.19 m^3 kg^{-1} VS, respectively. Anaerobic digestion resulted in 38 percent TS reduction and 53 percent VS reduction in the organic solids. The residual solids recovered from the digesters had a high heating value of about 14.7 MJ kg^{-1} TS. In comparison, the original samples had a high heating value of 15.4 MJ kg^{-1}TS.

The results of the UC Davis study suggest that existing municipal waste composting plants that utilize rotary drum treatment processing could install anaerobic digesters and recover the energy from the waste without significantly affecting the compost output. Furthermore, the elevated temperatures achieved in the rotary drum reactors reduce the energy input to the digester and increase the energy output. Conversion of easily biodegradable organics into biogas in the anaerobic digesters and capturing the biogas for energy production will decrease the emissions of greenhouse gases during the composting process. However, a full financial analysis should be conducted to determine whether anaerobic digestion is a feasible option for both existing and new waste treatment plants. Composting facilities that plan to install these systems may wish to consider a smaller rotary drum in conjunction with an anaerobic digester as an alternative to the larger rotary drum required for aerobic composting alone.

Further research should be pursued to test and demonstrate an integrated system at pilot and commercial scales to determine the equipment requirement and process control and operational specifications. The integrated system could include rotary drum reactors, anaerobic digestion, composting, and other processes for achieving the purposes of energy recovery, compost production, and waste reduction. For such an integrated system, energy and mass balance calculations are needed to determine the separation, conversion and transformation efficiencies for individual components present in the municipal solid waste and an economic analysis will be useful for assessing the costs and benefits of applying such an integrated system to the municipal solid waste treatment.

Abbreviations and Acronyms

AB 939	California State Assembly Bill 939
AD	anaerobic digestion/digester
ADC	alternative daily cover
BOD	biochemical oxygen demand
BOD-5	5-day biochemical oxygen demand
BTU	British thermal unit (a standard unit measure of energy)
C&D	construction and demolition waste
C/N	carbon to nitrogen ratio
CH_4	methane
CO_2	carbon dioxide
COD	chemical oxygen demand
CSTR	continuously stirred tank reactor
d	day
EC	European Community
EPR	extended producer responsibility
g	gram
GDP	gross domestic product
GHG	greenhouse gas
GWh	gigawatt hours (1 million megawatt hours)
H_2S	hydrogen sulfide
hr	hour
HRT	hydraulic retention time
ISO	international standards organization
kg	kilogram
kW	kilowatt
kWe	kilowatts of electricity
kWh	kilowatt hour
L	liter
lbs	pounds
LCA	life cycle assessment

m	meter
m^3	cubic meter (gas volumes assume 0°C and 1.101 bar)
mmBTU	million BTU
MBT	mechanical-biological treatment
MC	moisture content
MRF	material recovery facility
MS-OFMSW	mechanically sorted organic fraction of municipal solid waste
MSW	municipal solid waste
MT	metric ton
MW	megawatt
MWe	megawatts of electricity
MWh	megawatt hour
N:P:K	nitrogen to phosphorus to potassium ratio
NREL	National Renewable Energy Laboratory
OFMSW	organic fraction of municipal solid waste
OLR	organic loading rate
PIA	Prison Industry Authority
ppm	parts per million
PPP	purchasing power parity
rpm	revolutions per minute
scf	standard cubic feet (for gas volumes assume -32°F and 15.97 psi)
SMUD	Sacramento Municipal Utility District
SRT	solids retention time
SS-OFMSW	source separated municipal solid waste
tons	short ton
tpy	ton per year
TS	total solids
UMP	ultimate methane potential
VS	volatile solids
WAS	waste activated sludge
y	year

Glossary of Terms

Alternative Daily Cover	Material other than soil used to cover the surface of active landfills at the end of each day to control diseases, fires, odors, etc.
Anaerobic digester	A dedicated unit process for controlling the anaerobic decomposition of organic material. Typically consists of one or more enclosed, temperature controlled tanks with material handling equipment designed to prevent the introduction of oxygen from the atmosphere.
Biomixer	A rotating drum often with a trommel screen used for size reduction and pretreatment of the organic fraction in mixed MSW for sorting. Can be aerated to encourage biological breakdown. Can be operated at retention times from several hours to several days.
Bioreactor-landfill	A landfill operated as a bioreactor using leachate recycling (or other management schemes) to increase the rate of organic decomposition and biogas production. Not to be confused with anaerobic digester.
Biochemical oxygen demand	Biochemical oxygen demand is the amount of oxygen required for complete (aerobic) biological decomposition of a material. The standard laboratory method (BOD_5) tests the amount of dissolved oxygen consumed in a closed aqueous system over a five-day period. It is a fairly direct but time-consuming measure of biodegradability of liquid streams.
Compost	Compost here refers to stabilized and screened organic material ready for horticultural or agricultural use. If anaerobically digested material is used as compost, it must be biologically stabilized, typically through aeration and maturation.
Continuously stirred tank reactor	A digester configuration in which the entire digester contents are mixed to create a homogeneous slurry.
Gray waste	The material left over after separation of recyclables and putrescible material from the mixed waste stream. Composed mostly of inorganic material, gray waste usually contains a significant amount of organic material. Depending on its composition, gray waste and can be treated biologically or burned prior to final disposal.
Hydraulic retention time	The average length of time liquids and soluble compounds remain in a reactor. Increasing the HRT allows more contact time between substrate and bacteria but requires slower feeding and/or larger reactor volume.
Mechanical-biological treatment	A waste processing system that combines a sorting facility for materials recovery (the mechanical portion) with biological treatment, either aerobic or anaerobic, for stabilizing the organic fraction before landfilling.
Materials recovery facility	A facility where mixed MSW is sorted in order to recover material for reuse or recycling. In California, the “post MRF fraction” is

	typically landfilled.
Mechanically separated OFMSW	Organic material separated from the mixed waste stream by mechanical means (i.e., trommels, screens, shredders, magnets, density dependent mechanisms). Isolating the OFMSW from mixed waste is less effective using mechanical separation as compared with source separation.
Municipal solid waste	MSW includes all of the solid wastes that are generated from residential (homes and apartments) sources, commercial and business establishments, institutional facilities, construction and demolition activities, municipal services, and treatment plant sites. Hazardous wastes are generally not considered MSW. Some regions or countries consider only residential solid waste as MSW
Organic fraction of municipal solid waste	The biogenic fraction of MSW. OFMSW can be removed from the waste stream at the source (source-separation), or downstream by mechanical separation, picking lines a combination of the two. The wood and paper fraction is more recalcitrant to biological degradation and is therefore not desired for biochemical conversion feedstocks
Plug flow digester	A digester in which materials enter at one end and push older materials toward the opposite end. Plug flow digesters do not usually have internal mixers, and the breakdown of organic matter naturally segregates itself along the length of the digester.
Pretreatment	In reference to municipal solid waste, pretreatment can refer to any process used to treat the raw MSW stream before disposal. This includes separation, drying, comminuting, hydrolysis, biological treatment, heating, pyrolysis, and others.
Solids retention time	The average length of time solid material remains in a reactor. SRT and HRT are equal for complete mix and plug flow reactors. Some two-stage reactor concepts and UASB reactors decouple HRT from the SRT allowing the solids to have longer contact time with microbes while maintaining smaller reactor volume and higher throughput.
Source-separated OFMSW	Organic solid waste separated at the source (i.e., not mixed in with the other solid wastes). Often comes from municipal curbside recycling programs in which yard waste and sometimes kitchen scraps are collected separately from the rest of the MSW stream. The precise composition of SS-OFMSW can change significantly depending on the collection scheme used.
Total solids	The amount of solid material (or dry matter) remaining after removing moisture from a sample. Usually expressed as a percentage of the as-received or wet weight. Moisture content plus TS (both expressed as percentage of wet weight) equals 100 percent.
Ultimate methane potential	This is a standard laboratory technique used to measure the anaerobic biodegradability and associated methane yield from a

	given substrate. The test is run until no further gas production is detected and can last up to 100 days. The results can be influenced by the substrate concentration and particle size, the inoculum source, the food to microorganism ratio, and the presence or build-up of inhibitory compounds among others. (Also known as ultimate biomethane potential, BMP, and B_o.)
Volatile solids	The amount of combustible material in a sample (the remainder is ash). The value is usually reported as a percentage of the TS, but may occasionally be given as a fraction of the wet weight. VS is used as an indicator or proxy for the biodegradability of a material, though recalcitrant biomass (i.e., lignin) which is part of the VS is less digestible. Because of the simplicity of the measurement procedure, it is commonly reported in the AD literature.

Introduction

Papers, food scraps, and yard waste make up about 50 percent of the municipal solid waste going to landfills. Although in many communities, green waste (e.g., yard trimmings) and paper are separately collected and treated or recycled, very little food waste is separated. Nationwide, according to data from the U.S. Environmental Protection Agency, more than 40 million tons of food scraps are produced each year, which represents 25 percent of the food prepared. Only about 3 percent of the food waste is sent to composting facilities, with the rest going to landfills. Such highly degradable materials contribute greatly to the gas emissions from landfills. It will be beneficial to recover the food scraps and other biodegradable organic wastes from the municipal solid waste and convert them into energy and other valuable products.

Source separation and collection of wastes are good options but wet and easily degradable materials, such as food scraps, putrefy quickly, making their collection and storage very challenging for households and businesses. Even the so-called "source-separated" waste streams contain many contaminants that need to be removed if the organics will be composted or anaerobically digested. Alternatively, the organic materials can be separated from the mixed municipal solid waste after collection and transport to a central location where advanced treatment and separation technologies are employed.

Common approaches for separating biodegradable organic materials include screening and a combination of size reduction and screening. For source-separated wastes such as food and green wastes, direct screening may work well for removing large contaminants (e.g., plastics, metals). However, for the wastes that contain papers, cardboard and woody residues (e.g., tree trimmings), size reduction is often necessary in order to have them to pass the screens of 1-2 inch openings which are normally used to separate the food waste from the mixed municipal solid waste. Grinding followed by wet pulping/separation, steam autoclave and rotating drum reactor are three major processes used by the waste processing industry. The organic materials produced from grinding and wet pulping/separation typically have high moisture content of more than 90 percent, while the organic materials produced from autoclave steam treatment and rotary drum processes have lower moisture content of 50-70 percent.

This report provides an overview of rotary drum reactor and anaerobic digestion technologies available for treatment of municipal solid waste. It also presents the results of a recent research project conducted at UC Davis for evaluating the rotary drum reactor as a pretreatment technology for separating and treating the organic fractions of municipal solid waste for use as anaerobic digester feedstock. Moreover, this report presents the research results that show the feasibility of integration of the rotary drum system with the anaerobic digestion (Figure 1) to achieve energy and compost recovery and waste reduction. Some of the results presented in this report have been published in the articles of Zhang et al. (2009), Zhu et al. (2009) and Zhu et al. (2010). The projects were in collaboration with companies involved in the municipal solid waste collection and processing.

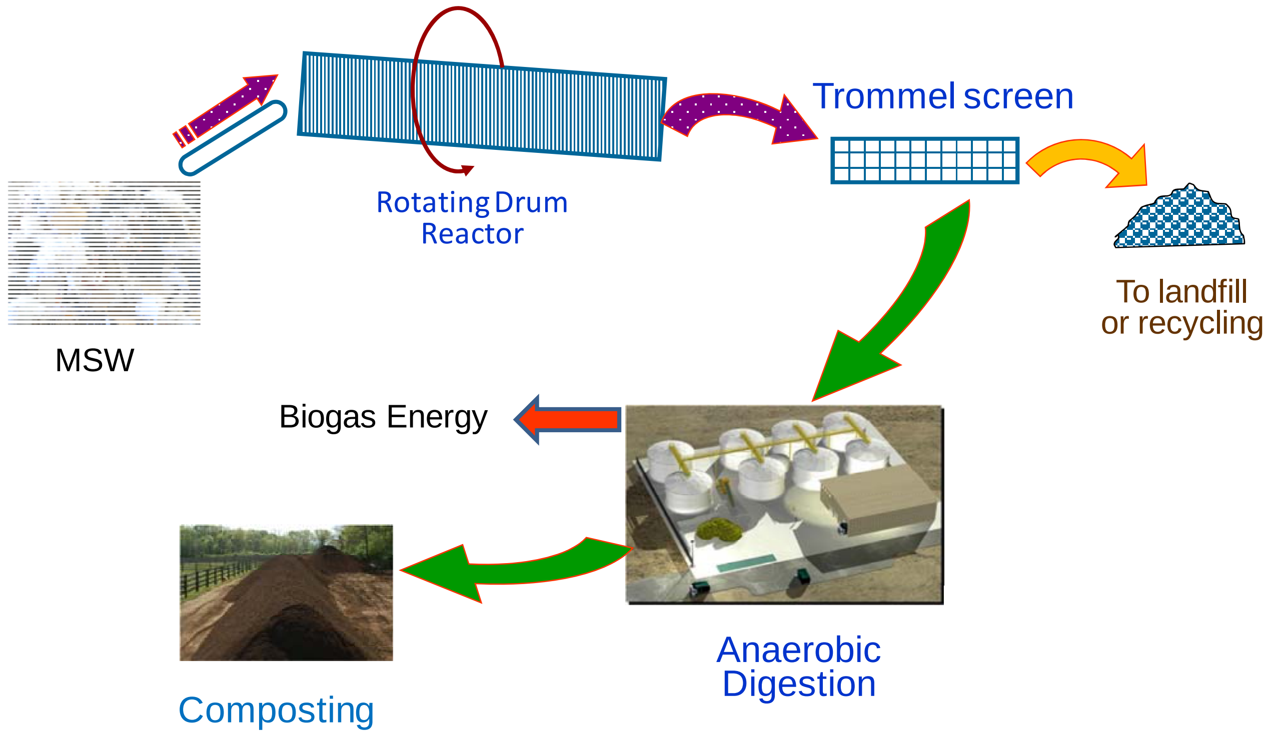

Figure 1. Integrated Rotary Drum Reactor-Anaerobic Digester-Composting System for treatment of municipal solid waste.

Background on Rotary Drum Reactor and Anaerobic Digestion Technologies

Description of the Rotary Drum Reactor Process

The rotary drum reactor is an in-vessel aerobic treatment process, which has been used as a pretreatment process for the production of compost from solid wastes, such as municipal solid waste, biosolids, or animal manure. The initial rotary drum process was patented during the 1980s by Dr. Eric Eweson (Eweson, 1991). It comprises a specially designed rotary drum, followed by solid-solid separation using trommel screens. The rotary drum is used to break down the biodegradable materials in the municipal solid waste through a combination of aerobic biological reactions and mechanical forces, thus making them easily separable, via screening, from the bulky materials, such as plastics metals and glasses. The separated biodegradable material is often further processed for compost production.

A typical rotary drum system is schematically illustrated in Figure 2. The solid wastes (typically a mixture of MSW and biosolids) is initially placed onto a tipping floor, where bulky materials, usually recyclables (such as plastics, metals, etc), are removed by hand or using automated screening processes. The waste is then fed into a large rotary drum resembling a cement kiln. Loading in the rotary drum is usually assisted by a hydraulic ram. The waste is retained inside the drum for six hours to three or more days, moving slowly from one end (entrance) to the other end (exit) of the drum. The drum has headspace between 20-30 percent and usually operates as a continuous plug-flow reactor though it has also been used as a batch reactor. The movement of the materials through the drum is controlled by the loading rate of the fresh materials, which pushes the older materials in the drum towards the exit. A slight drum declination towards the exit also assists in material movement inside the drum. In some cases the movement of the materials can be controlled by the drum rotation speed, if multiple speed rotation mechanism is available. Some drums are compartmentalized by the use of specially designed baffles. The material is discharged from the exit of the drum through hydraulically or pneumatically controlled gates. The drum normally rotates at a constant speed, 1 to 5 rpm, depending on the design characteristics of the plant. Some drums are equipped with multiple speed gearboxes, employing higher rotation speeds during the loading or unloading stages. The drums in the plants studied in this research had lengths of 9.1 to 73.1 m and the diameters of 3.0 to 4.9 m.

In most rotary drum facilities, air is blown into the drums from the unloading side to ensure aerobic conditions during processing. The optimum moisture content inside the drum is reported to be around 55 percent. Because municipal solid waste in North America and Europe typically contains 35-40 percent moisture, water or other wet materials, such as biosolids of 75-95 percent moisture content, are added into the drum together with the municipal solid waste. The heat produced from the microbial degradation of municipal solid waste inside the drum allows the temperature to rise and be maintained at a relatively high level (50- 69 °C). Selected rotary drum reactors used in the U.S. waste composting plants are shown in Figure 3.

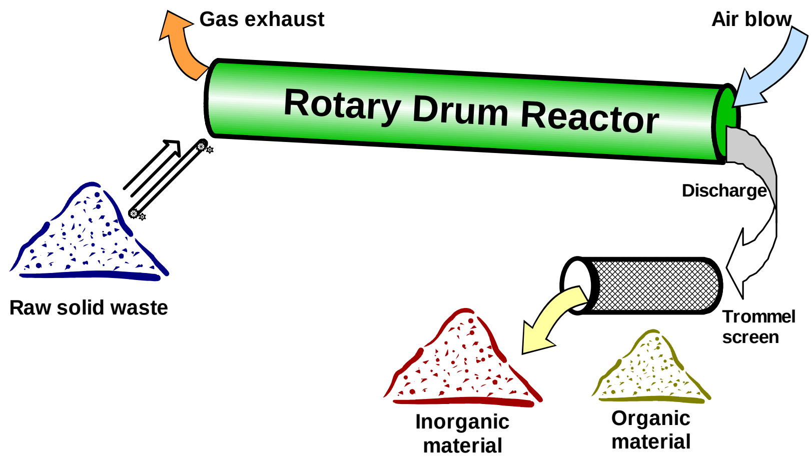

Figure 2. The Rotary Drum Reactor (RDR) process (A) for treatment of MSW

Figure 3. Rotary Drum Reactors used in the U.S. waste composting plants.

After leaving the rotary drum, the treated waste is screened (primary screening) through a trommel screen with openings of 2.5 to 4.5 cm. The materials retained over the screen (mainly plastics, synthetic fabrics, glass and metals) are collected for recycling or for disposal in a landfill. The materials that pass through the screens are mainly biodegradable materials; they are collected and sent to the composting operation. In most composting plants, the organics are composted in piles over aerated floors for four to six weeks before they are sieved through another trommel screen (secondary screening) of about 0.6 cm openings. The materials passing the fine screen are the compost product while the materials retained on the screen are disposed in a landfill, or they may be used as an inert material for road construction.

Some previous studies have reported that the pretreatment methods could be effective to increase the digestibility of the organic solids and increase the efficiencies of anaerobic digesters (Bernal et al., 1992). In the study reported by Capela et al. (1999), a pre-composting stage was used for the pulp mill sludge to obtain a slight degradation of organics to prevent fast acidification during anaerobic digestion. After a 49-day experiment, the pretreated sludge had higher VS reduction (50 percent) than the untreated sludge (34 percent). Previous studies have also shown that a rotary drum reactor process provided an effective means for separating the organics from municipal solid waste using a combination of mechanical forces and biological reactions (Hayes, 2004; Spencer, 2006).

Anaerobic Digestion Process Description

Anaerobic digestion is a biotechnology that can be used to convert various biodegradable organic materials into methane-rich biogas fuel. The anaerobic digestion of organic material is accomplished by a consortium of microorganisms working synergistically. Digestion occurs in a four-step process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Figure 4):

1. Large protein macromolecules, fats and carbohydrate polymers (such as cellulose and starch) are broken down through hydrolysis to amino acids, long-chain fatty acids, and sugars.
2. These products are then fermented during acidogenesis to form three, four, and five-carbon volatile fatty acids, such as lactic, butyric, propionic, and valeric acid.
3. In acetogenesis, bacteria consume these fermentation products and generate acetic acid, carbon dioxide, and hydrogen.
4. Finally, methanogenic organisms consume the acetate, hydrogen, and some of the carbon dioxide to produce methane. Three biochemical pathways are used by methanogens to produce methane gas. The pathways along with the stoichiometries of the overall chemical reactions are:
    a. Acetotrophic methanogenesis: $4\ CH_3COOH \rightarrow 4\ CO_2 + 4\ CH_4$
    b. Hydrogenotrophic methanogenesis: $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$
    c. Methylotrophic methanogenesis: $4\ CH_3OH + 6\ H_2 \rightarrow 3\ CH_4 + 2\ H_2O$

Methanol is shown as the substrate for the methylotrophic pathway, although other methylated substrates can be converted. Sugars and sugar-containing polymers such as starch and cellulose yield one mole of acetate per mole of sugar degraded. Since acetotrophic methanogenesis is the primary pathway used, theoretical yield calculations are often made using this pathway alone.

From the stoichiometry above, it can be seen that the biogas produced would theoretically contain 50 percent methane and 50 percent carbon dioxide. However, acetogenesis typically produces some hydrogen, and for every four moles of hydrogen consumed by hydrogenotrophic methanogens a mole of carbon dioxide is converted to methane. Substrates other than sugar, such as fats and proteins, can yield larger amounts of hydrogen leading to higher typical methane content for these substrates. Therefore, the overall biogas yield and methane content will vary for different substrates, biological consortia and digester conditions. Typically, in a healthy methane digester the methane content of biogas ranges from 50-70 percent (by volume).

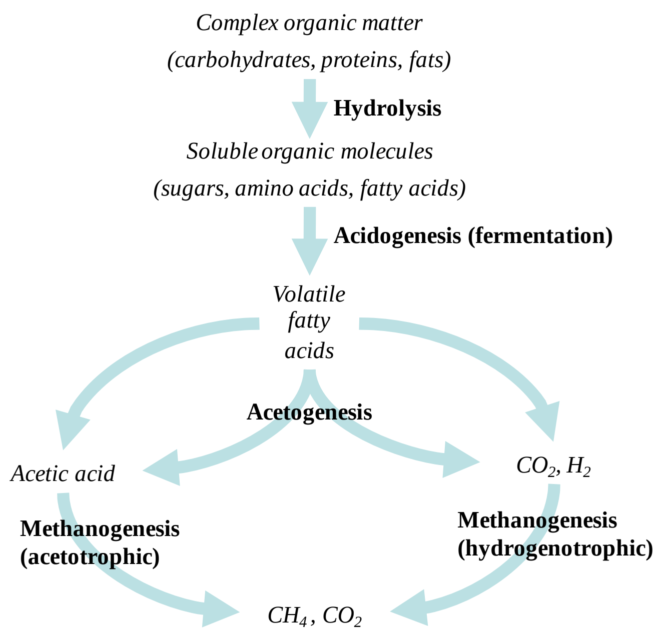

Figure 4. Anaerobic digestion biochemical conversion pathways

Anaerobic conditions are required for healthy methanogenesis to occur. This means that the reactors used must be well-sealed which allows the biogas to be collected for energy conversion and eliminates methane emissions during the anaerobic digestion process. In addition to methane and carbon dioxide, semi-harmful contaminants such as hydrogen sulfide and ammonia are produced, albeit in much smaller amounts (<1 percent by volume). The production of these trace gases in the biogas depends on the sulfur and nitrogen contents of the feedstock. However, these elements are also nutrients required by the bacteria.

In fact, anaerobic digestion requires attention to the nutritional needs of the bacteria degrading the waste substrates. The most important nutrients for bacteria are carbon and nitrogen, but these two elements must be provided in the proper ratio; otherwise, ammonia can build up to levels that can inhibit the microorganisms. The appropriate carbon/nitrogen (C/N) ratio depends on the digestibility of the carbon and nitrogen sources; therefore, the appropriate C/N ratio for organic MSW may be different from that for other feedstocks such as manure or wastewater sludge.

In general, the optimal conditions for anaerobic digestion of organic matter are near-neutral pH, constant temperature, and a relatively consistent feeding rate. Higher temperatures result in faster reaction kinetics which, in practice, translates to smaller reactors needed to process a given waste stream. However, the micro-organisms themselves are adapted to relatively narrow temperature ranges. Mesophilic and thermophilic microbes are adapted to roughly 30-40 °C (86-104 °F) and 50-60 °C (122-140 °F) respectively.

Imbalances among the different microorganisms can develop if conditions are not maintained near optimum. The most common result of imbalance is the buildup of organic acids which suppresses the methanogenic organisms adding to even more buildup of acidity. Acid buildup is usually controlled naturally by inherent chemical buffers and by the methanogens themselves as they consume acids to produce methane. These natural controls can break down if too much feed is added and organic acids are produced faster than they are consumed, if inhibitory compounds accumulate, or if the feed stream lacks natural pH buffers such as carbonate and ammonium.

Solid concentrations higher than about 40 percent TS can also result in process inhibition, likely due to the presence of high concentrations of the inhibitory compounds. The TS content of the organic fraction of municipal solid waste typically ranges from 30-60 percent, thus some water may be added before loading digester. Recycling the process water can be used, but this may also result in the buildup of inhibitory compounds. Thus, low-solids digesters require the addition of fresh water.

Biogas energy produced from anaerobic digestion systems is one of the leading renewable energy sources and provides an environmental solution for waste treatment and management:

- Biogas produced from microbial digestion of organic waste will provide hydrogen and methane gas as a biofuel helping to displace some reliance on petroleum.
- The amount of biogas energy produced from one ton of food waste was estimated to be enough to power 10 American homes for one day.
- Biogas technologies will reduce the greenhouse gas emissions from landfill and other waste storages as well as agricultural operations.
- Biogas technologies will provide many public benefits, including renewable energy production, environmental protection, and public health improvement.

Anaerobic Digestion Technologies for Solid Waste Treatment

The development of anaerobic digester technologies for treating solid waste is more recent and less mature, as compared to the technologies for wastewater treatment. Applying a traditional wastewater-treatment technology to high-solids biomass, such as straw, grasses, food waste, and dry manure, requires extensive material pre-processing (such as particle size reduction, water addition and mixing) and tends to be energy intensive. Several digester designs have been developed to handle high solids feedstock and are called “high-solids” or “dry” digesters. High-solids digesters treat waste streams with 20-40 percent total solids. These systems may retain some process water or add some fresh water depending on the moisture content of feedstock. Heavy duty pumps, conveyors, and augers are commonly used for handling the low-moisture feedstock. The digesters can be designed to treat waste in one, two, or more stages. Single-stage digesters are simpler to design, build, and operate and are generally less expensive than multiple-stage digesters. However, single-stage digesters are normally operated at lower organic loading rates, which mean larger digesters, and are less tolerable to variability in loading rate and feedstock composition than multi-stage digesters. Table 1 lists the anaerobic digestion technologies that have been used for high solids feedstocks. These technologies have mainly been applied for digestion of municipal organic solid wastes, such as food waste and grass clippings. A review of the working principles and performance of digesters treating municipal organic solid waste are included in a recent report by Rapport et al. (2008).

Table 1. Examples of anaerobic digester technologies for solid waste treatment

Process Name	No. of Stages		Operating Temperature	
	1	2	35°C	55°C
Biocel	x		x	
Biopercolat		x	x	
DRANCO	x			x
Kompogas	x			x
Linde-KCA/BRV	x	x	x	x
Valorga	x		x	x
SEBAC		x	x	X
APS-Digester		x	x	x

The APS-Digester is one of several anaerobic digestion technologies commercially available for treating organic solid materials. It was recently developed at the University of California, Davis (UC Davis) (Zhang and Zhang, 1999; Zhang, 2002; Hartman, 2004; Zhang et al., 2006) and has been successfully scaled up for commercial applications after it was first proven in the laboratory and then demonstrated at a pilot scale on the UC Davis campus (Zhang et al., 2005; Konwinski et al., 2008;). The APS-Digester technology was featured at the California State Fair in 2008 and was celebrated as one of 100 ways that UC Davis transformed the world in its 100 years of history (http://centennial.ucdavis.edu/). The APS-Digester combines favorable features of both batch and continuous biological processes in a single system and makes it possible to achieve efficient and stable production of both hydrogen and methane gases from a variety of organic solid and liquid wastes, including grass clippings, food scraps, food processing byproducts, crop residues, and animal wastes. Its innovative engineering design and process control features include biological phase separation, solid-liquid phase separation, interphacial liquid recirculation, thermophilic temperature, and a combination of attached and suspended growth bioreactors. Specific environmental and process conditions are created and controlled in the APS-Digester to achieve optimum microbial growth and fast conversion of the organic wastes.

Overview of Rotary Drum Reactor Applications at U.S. Municipal Solid Waste Treatment Facilities

A number of rotary drum reactor facilities are currently under operation worldwide, with about 20 in North America, some of which are summarized in Table 2 that shows plant capacity, number of drums, and commencing year of operation. Six municipal solid waste treatment plants located in the U.S. were surveyed in this project. The name, location, ownership, management, and type and daily load of waste are shown in Table 4. The aim of operation in all but one (Pinetop-Lakeside) facilities is the treatment of municipal solid waste, with biosolids used for adjustments of moisture and carbon to nitrogen ratio (C/N). The Pinetop-Lakeside facility is owned by a Sanitary District, thus its primary aim is the conversion of biosolids to compost, while the solid wastes including municipal solid waste and paper and cardboard is used for the moisture content reduction. All six treatment plants utilize municipal solid waste with marginal or no source separation. Three plants practices waste sorting to recover recyclable materials (primarily aluminum, ferrous materials, and plastics) and reduce the volume of the materials loaded in the drum. Materials which are likely to create problems during the rotating process, such as cables, wires, ropes, and hoses, are manually removed in all the facilities prior to loading. The retention time in the drum varies between 2-5 days, with the exemption of the Rapid City facility where the retention time is approximately six hours and the operation mode resembles more batch than continuous. The operational parameters of the six plants are summarized in Table 4.

The capital cost for installing a rotary drum system can be estimated after the specification of the installation characteristics. The quality of materials, the degree of automation, the use of auxiliary facilities, and the possible payment of royalty fees strongly affect the total cost. On the other hand, cost may be indirectly estimated from the construction cost of existing facilities. However, as the existing rotary drum facilities have been constructed at different time periods, have different capacities, and often have utilized different technologies, only an approximate cost can be calculated. The single more expensive component of a rotary drum reactor facility is the drum itself. A rotary drum with municipal solid waste processing capacity of about 100 ton/day costs between \$3 million and \$5 million. The cost can be significantly reduced, if a second-hand drum is available. For example, old cement kilns are ideal to be converted into rotary drums for municipal solid waste processing. Based on the cost of the rotary drum facilities used, the cost for a complete plant (excluding compost maturing site and auxiliary processes) with capacity 100,000 tons of municipal solid waste per day (waste retention time between 2 to 3 days) is between \$10 million and \$14 million, but higher costs have also been reported. Obviously, the waste retention time inside the rotary drum will affect the size of the plant and thus the cost. If the municipal solid waste loading rate is affected by seasonal phenomena (e.g.: in tourist areas), then the use of two drums, instead of a single one, may prove beneficial, as this will provide operational flexibility and will consume reduced energy during the low season. The installation of two drums, each with half the capacity of a single drum, is estimated to add about 20 percent to the capital cost of the facility.

The major operational costs comprise energy consumption, labor and maintenance. It is logical to assume that a relatively small rotary drum facility will require at least five personnel (including management). More people will be needed if extended municipal solid waste shorting is practiced. The facilities that have been visited for this project are employing between 5 and 22 people. Electrical energy is the major operational cost. Between 50 to 70 percent of the total energy used in a rotary drum facility is consumed for drum rotation and material screening; the rest is for maintaining negative pressure in the enclosed areas (and thus avoiding the escape of odors), municipal solid waste shorting and conveyance, biofilter operation, etc. An average rotary drum facility is estimated to consume between 70-110 kWh per ton of municipal solid waste. If high rotation speed is used (as is the practice in the Dano process), the energy consumption can be up to 150 kWh/ton of waste. Lower retention time will result to lower energy requirements per ton of waste. The major maintenance work consists of gearing system lubrication (which should be continuous during operation), and on repairs in the inner part of the drum. The latter consists of repairs to the gear because of abrasion. To minimize abrasion caused by the hard materials present in municipal solid waste, steel rails are welded on the internal surface of the drum, along its length. The rails have a height of about a 50 mm, and are welded at distances between 100 to 150 mm, so that the gap between the rails is filled with soft materials from the municipal solid waste, which acts as a protective cushion for the drum. Baffled drums also require intense maintenance, as the internal gates are often damaged because of collision with heavy and bulky materials in the waste.

Table 2. Rotary drum reactor (RDR) facilities in North America

Location	Opened	Number of drums	Plant capacity ton/d
Big Sandy, TX	1971	1	30
Pinetop-Lakeside, AZ	1991	1	75
Sevierville, TN	1992	5	350
Sorrel-Tracy, QC	1992	1	100
Cobb Country, GA	1996	5	350
Rapid City, SD	1996	2	220
Sumter County, FL	1997	1	75
Marlborough, MA	1999	2	150
Nantucket, MA	1999	1	100
Edmonton, AL	2000	5	750
Hines, AK	2002	1	3
Delaware County, NY	2005	1	100

Table 3. Brief description of the six rotary drum reactor (RDR) facilities studied by the UC Davis study.

PLANT	DESCRIPTION
Pinetop-Lakeside, AZ	The RDR facility is owned and operated by the Pinetop-Lakeside Sanitary District and is part of the district wastewater treatment plant. The primary purpose of using the RDR process is to convert the dewatered biosolids, which are produced by the wastewater treatment plant, into compost. Calculated amounts of solid wastes (MSW, paper or cardboard) are mixed with the biosolids to reduce the moisture content inside the drum to the desired level. Plant management is currently considering replacement of MSW with paper and cardboard, to reduce the amount of glasses and reduce the quantity of waste that has to be processed because paper and cardboard contain less moisture compared with MSW. The RDR facility started operation in 1991; however, the rotary drum reactor was replaced in 2003. The facility is processing approximately 10 tons of dewatered biosolids (wet basis) per day, along with either 20 tons of MSW or 10 tons of paper and cardboard waste. The facility has a staff of five, including management.
Nantucket, MA	Waste Options Nantucket LLC owns and operates the solid waste management plant on Nantucket Island, and consequently the RDR facility. The RDR has operated since 1999 and uses one rotary drum reactor. It currently processes all the MSW generated on Nantucket, after source separation for recyclables, and all the biosolids generated in the wastewater treatment plant of the island. Some yard waste is also co-processed in order to enhance the biological activity during the composting process. Because Nantucket is a popular summer resort, the population of the island changes by a factor of five between the low and high season, thus the daily loading in the biomixer (and respectively the retention time) varies with the season from 20 to 100 tons MSW per day. Eight people are working at the RDR facility, including management. The drum used in this plant is unique in that there is no air injection in the drum. However, aerobic conditions still prevail, as the temperature in the drum is 52-58 °C.
Delaware County, NY	This facility is owned and operated by the County of Delaware. It has one RDR, which has operated since 2005. The facility aims to reduce the disposal of biodegradable organics in the local landfill. It processes approximately 100 tons MSW per day (primarily source-separated household wastes, and some industrial wastes) along with approximately 30 tons of dewatered biosolids (wet basis). It employs 12 people (including management), and it is highly automated.
Rapid City, SD	The plant is owned and operated by the municipality of Rapid City. The plant started to operate in 1996 and has two parallel rotary drums. It processes approximately 200 tons of MSW and nine tons of biosolids (wet basis) per day. Biosolids are supplied in liquid phase (8 percent solids) Source separation is not practiced in Rapid City, however, recyclable materials are removed prior to the RDR process. The facility employs 18 people, including management. The main difference among the six plants is the this RDR operates in batch mode, with six hour retention time, and with rotation speed up to five times higher than the others (*Dano* process). Size separation takes place right after unloading, utilizing a trommel screen which is permanently mounted on the rotary drum.
Sevierville, TN	The Sevierville facility has served the municipalities of Gatlinburg, Sevierville, Pigeon Forge, and Pittman Center since 1992. It is owned and operated by the "Sevier Solid Waste Inc." The daily loading is affected by its location, next to the popular tourist destination of the Smoky Mountains. Thus during the summer it rises to up to 225 tons MSW per day, while during the off season it falls to less than half of the above. Daily, 55 tons of dewatered biosolids (wet basis) are co-processed with the MSW. Only limited source-separation is practiced in the towns that served by this RDR plant. The plant initially had three parallel rotary drums, one of which is currently out of operation, while three new drums have been added. Thus, the plant now has two original drums plus three new ones. The plant employs 15 people, including management.
Cobb County,	This plant was built in 1996, and has five rotary drums. The drums initially were compartmentalized, however, the baffles have been recently removed due to their requirements for

GA	frequent maintenance. No change in the product characteristics was observed after the removal of the baffles. However, the loading rate was slightly reduced, as due to the relatively high slope of the drums, the MSW tends to move towards the exit of the drum. The plant processes approximately 200 tons of MSW plus 60 tons of biosolids (wet weight). Water is added occasionally for moisture content correction. The facility is owned and operated by Cobb County.

Table 4. Operational characteristics of six RDR facilities surveyed by the UC Davis study.

Parameter	Pinetop-Lakeside, AZ	Nantucket, MA	Delaware County, NY	Rapid City, SD	Sevierville, TN	Cobb County, GA
Operation started	1991	1999	2005	1995	1992	1996
Type of waste	Biosolids (BS) MSW Paper & cardboard (P&C)	MSW Biosolids (BS) Yard waste	MSW Biosolids (BS)	MSW Biosolids (BS)	MSW Biosolids (BS)	MSW Biosolids (BS)
Population served	High season: 12,000 Low season: 5,000	High season: 60,000 Low season: 10,000	48,000	60,000	High season: 180,000 Low season: 80,000	300,000
Capacity (ton/d)	20MSW+10 BS or 10 P&C +10 BS	20-100 MSW plus 2000 tonBS/y	100 MSW plus 30 BS (16% TS)	220 MSW plus 9 BS (8% TS)	225 MSW plus 55 BS (18% TS)	200 MSW 60 BS (20% TS)
Employee Number	5	8	12	18	15	22
Tipping fee (2007) (US$/ton)	MSW: No fee Biosolids: No fee	106 MSW: 106 Yearly fee for BS	MSW: free Biosolids: free	47 MSW: 47 Biosolids: No fee	MSW: 40 Biosolids: 23.5	MSW: 32 Biosolids: 32
Compost sale (2007) (US$/$m^3$)	4.6	15.4	7.7	free	free	7.7
Biodegradable fraction recovered (% of MSW)	55	80	55-60	52	60	65
Moisture content in drum (%)	55-60	55	50-55	55	55	55
Maximum temperature in drum (ºC)	44	52-58	35	13-20	46-52	45-50
Retention in drum (d)	3	3	3-5	¼	3	2
Number of drums	1	1	1	2	5	5
Drum length (m)	38.1	56.4	47.9	24.4	56.4	48.8
Drum diameter (m)	3.1	3.8	4.6	4.3	2 × 3.6 m 3 × 4.3 m	4.0
Rotation speed (rpm)	1	1	1	5	0.83	1
Compartments in drum	No	Yes	Yes	No	Yes	No
Aeration in drum	Yes	No	Yes	Yes	Yes	Yes
Openings, primary screening (mm)	31.8	25.4	31.8	44.5	38.1	31.8
Drum horse power (per drum)	75	200		120 × 4	125 (Ø 3.6 m) 300 (Ø 4.3 m)	450

Characterization of Organic Waste Derived from Rotary Drum Reactors

Sampling and Characterization of Organic Waste Derived from RDR-Treated MSW at Six Plants

Six MSW treatment plants including Pinetop-Lakeside, AZ; Nantucket, MA; Delaware County, NY; Rapid City, SD; Sevierville, TN and Cobb County, GA were visited and samples were collected from the materials that had passed through the primary trommel screen located right after the unloading gate of the rotary drum. The plant information and RDR operational conditions are shown in Table 4. Three random samples, with at least one week apart between the two samples, were collected from each plant. Most of the samples were collected on Thursdays or Fridays, to ensure that the retention time of the collected material was not affected by the weekend period during which most of the plants were out of work. The samples were kept on ice and shipped overnight to the Bioenvironmental Engineering Research Laboratory (BERL) in the Department of Biological and Agricultural Engineering, University of California, Davis. The samples were stored in -20 ºC until analysis. Examples samples collected from each RDR facility are shown in Figure 5

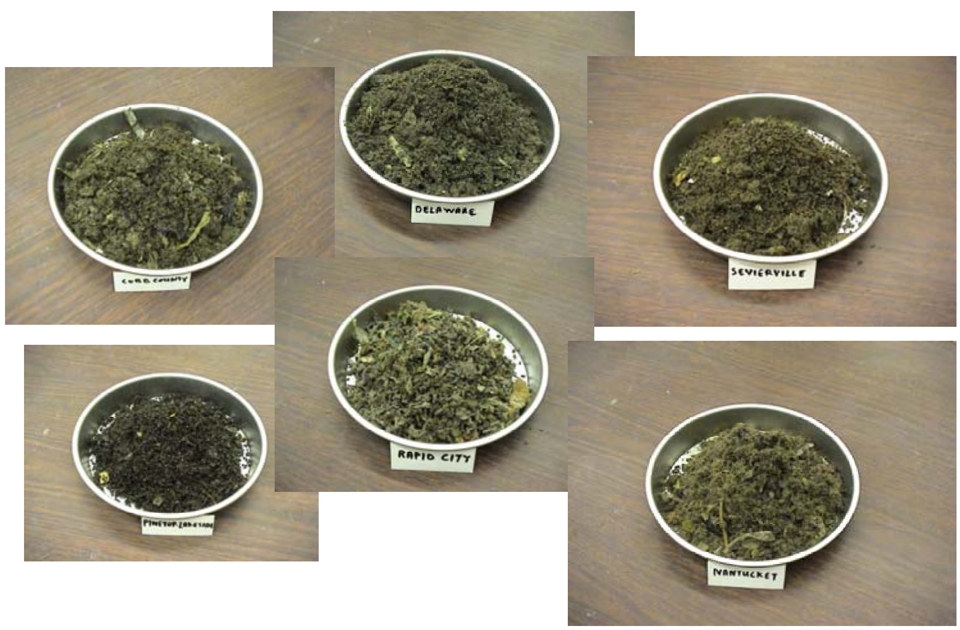

Figure 5. Samples collected from the rotary drum reactors in six U.S. waste composting plants.

Chemical and physicochemical characteristics

The carbon and nitrogen contents of the samples were measured by the ANR laboratory at UC Davis based on the standard operation procedures (http://groups.ucanr.org/danranlab/Methods_of_Analyses545). The moisture content, total solids (TS) and volatile solids (VS) were measured by the laboratory according to the standard methods (APHA, 1998). The biogas and methane production potential were also measured as described below.

Anaerobic digestibility and biogas production potential

Batch anaerobic digestion tests of the collected samples were performed using the method described by Zhang et al. (2006). Thermophilic (50±1 ºC) anaerobic digestion was carried out in 1.0 L glass bottles (KIMAX® No.14397, USA). Digestion tests were performed in duplicate on all the samples (18 samples).

Anaerobic sludge, collected from the thermophilic anaerobic digesters of the wastewater treatment plant in Oakland, CA, was used as inoculum for all batch reactors. The TS, VS, VS to TS ratio (VS/TS) and pH of the anaerobic sludge (inoculum) were measured to be 2.47 percent, 1.48 percent, 0.60 and 6.74, respectively. Each batch reactor had 0.5 L working volume. A portion of material containing 2.65 g VS, inoculum corresponding to 2.2 g VS, and 340 ml distilled water, were added at the beginning of batch digestion tests, in each reactor. The initial sample loading was 5.3 gVS/L with a food to microorganism ratio (F/M) of 1.2. The F/M ratios were calculated based on the VS of waste sample and inoculum. Each reactor was sealed with a rubber septa and screw cap, purged with nitrogen to remove oxygen and placed in a temperature-controlled room for incubation. The amount of biogas produced by the inoculum was estimated by the use of two blank rectors, which contained the same amount of inoculum and water as the testing reactors. All the reactors were manually shaken once a day when the biogas production was measured.

Biogas production was calculated using the principle of the ideal gas law, by measuring the pressure difference in the headspace of the reactors between the two measurements. The pressure was measured using an electronic pressure gauge (Model 3150, WAL Mess-und Regelsysteme GmbH, Germany). After each pressure measurement, the biogas in the head space was released under water to prevent gas exchange between the head space and the ambient air. Then the pressure in the head space was measured again as an initial condition for the next measurement. The volume of the biogas produced between two pressure measurements is calculated using the following equation (ideal gas law):

$$V_{biogas} = \frac{(P_2 - P_1) \cdot T_a}{P_a \cdot T_r} \cdot V_r$$

where:

V_{biogas} = volume of daily biogas production (ml);

P_1 = after-released headspace pressure of the previous day (kPa);

P_2 = headspace pressure before biogas release (kPa);

P_a = ambient pressure (kPa);

T_a = ambient temperature (K);

T_r = temperature of the reactor (K);

V_r = headspace volume (ml).

Biogas production rate was determined by dividing the volume of daily produced biogas by the initial VS loading of the sample. At the end of the experiment, cumulative biogas yield (mlg^{-1} VS) was calculated for each testing reactor at ambient pressure and temperature (1 atm, 20 ºC).

Biogas samples were taken from the testing reactors every day. hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2) contents were measured using a gas chromatograph (GC) (Agilent® GC6890N, USA) equipped with thermal conductivity detector (TCD) as described by Zhang et al. (2007).The average methane content (WA) over the digestion period was calculated as follows:

$$\mathrm{WA} = \frac{\sum_{i=1}^{n} DBP_i \times MP_i}{\sum_{i=1}^{n} DBP_i}$$

Where:

WA = average methane content (%);

DBP_i = biogas production rate of the i day (ml/gVS·day);

MP_i = daily methane content of the *i* day (%).

Characteristics of the Samples Collected from Different Rotary Drum Reactors

Table 5 presents the average values of the chemical and physicochemical characteristics of all the samples (6×3=18 samples) collected from the six rotary drum facilities, plus those of the food waste. For comparison purposes a sample of food waste was also digested. Two measurements for each parameter were performed per sample, thus each value in Table 5 represents the average of six measurements (except for the food waste). The average moisture contents (MC) of the samples were found to vary between 44.4 percent (Nantucket) and 64.7 percent (Cobb County) As stated earlier, the moisture content inside the drum was adjusted in most plants by the addition of biosolids. At the Cobb County facility water was also added, hence probably resulting in the relatively high moisture content value. In the Rapid City facility, biosolids were supplied in slurry form of approximately 8 percent total solid using a piping installation. The average moisture content in Rapid City facility was measured to be over 52.2 percent. It is worth noting that in those two plants (Cobb County and Rapid City), the moisture contents had higher standard deviations (5.36 percent and 7.59 percent, respectively) than the other four plants, which may be attributed to the difficulty in controlling accurately the moisture content by the use of biosolids or water. The availability of biosolids was relatively limited in Nantucket due to the small size of the wastewater treatment plant, thus the Nantucket facility used relatively little biosolids, which probably is one of the main reasons for the relatively low moisture content in the Nantucket drum. The moisture content of the food waste (74.4 percent) was significantly higher than those of the samples.

The average VS content of the samples varied between 27.0 percent (Cobb County) to 41.3 percent (Nantucket). As a general note, the higher the moisture content, the lower the VS value. Additionally, it is worth mentioning that air was not injected inside the rotary drum at the Nantucket facility, which probably resulted in relatively lower carbon consumption, thus keeping the VS value relatively high. The material from Sevierville plant had relatively higher VS/TS (average 81.1 percent), which may be attributed to the fact that the Sevierville facility served a region of high tourism with many hotels and restaurants. This probably resulted in higher content of biodegradable materials such as food waste in municipal solid waste. The lower VS/TS value was observed for the samples collected from the Pinetop-Lakeside facility (average 70.6 percent). The Sevierville samples with the higher VS/TS appeared to also have the higher carbon content (average 39.5 percent), while the Pinetop-Lakeside samples has lower carbon content (average 35.3 percent). From the sample analysis it is obvious that there exists a positive correlation between the VS/TS and the carbon content of the samples. The samples from the Pinetop-Lakeside contained the higher nitrogen content (average 1.44 percent), with the samples collected from the Rapid City facility having the lower nitrogen content (average 0.88 percent). The relatively high nitrogen content of the Pinetop-Lakeside samples may be due to the use of relatively high amount of biosolids, which were richer in nitrogen, compared to municipal solid waste. The relatively high nitrogen and low carbon contents of the Pinetop-Lakeside samples have as a result the calculation of relatively small C/N (w/w) ratios (average 24.5). The highest C/N values were measured for the Rapid City facility (average 42.7).

Obviously, the TS content of the food waste was smaller of all the samples (due to high moisture content), however, it was almost exclusively composed of VS (96.4 percent). Additionally, food waste had significantly lower C/N ratio (7.2), as a result of the high proteinic content of food waste.

Table 5. Chemical and physical characteristics of the samples collected from the six rotary drum reactor (RDR) facilities.

RDR facility		TS (%)	MC (%)	VS (%)	VS/TS	C (%)	N (%)	C:N
Pinetop-Lakeside, AZ	Average	49.38	50.62	34.79	0.706	35.33	1.44	24.51
	St. dev.	3.82	3.82	2.30	0.041	3.01	0.08	2.24
Nantucket, MA	Average	55.61	44.39	41.28	0.743	37.57	0.92	40.87
	St. dev.	2.38	2.38	2.40	0.025	3.20	0.08	2.18
Delaware County, NY	Average	43.85	56.14	32.67	0.745	37.30	1.03	36.46
	St. dev.	3.93	3.93	3.15	0.021	1.97	0.11	2.03
Rapid City, SD	Average	47.75	52.25	34.79	0.735	37.07	0.88	42.74
	St. dev.	7.59	7.59	2.87	0.058	0.60	0.13	7.72
Sevierville, TN	Average	47.67	52.33	38.59	0.811	39.53	1.08	36.88
	St. dev.	4.52	4.52	3.32	0.026	2.18	0.12	2.34
Cobb County, GA	Average	35.24	64.76	26.97	0.766	38.47	1.09	35.37
	St. dev.	5.36	5.36	4.22	0.033	1.62	0.07	2.58
Food waste		25.6	74.4	24.68	0.964	50.0	6.9	7.2

Biogas production and yield

Figure 6 shows the average daily biogas production (mL g^{-1}VS day^{-1}), and average cumulative biogas yield (mL g^{-1}VS) for the samples collected from the six plants. The maximum daily biogas production, for all samples, was measured on the fourth day of digestion, with the exception of the Pinetop-Lakeside samples, which was measured on the fifth day. The maximum average daily biogas productions are shown in Table 6. The samples from the Cobb County facility had the highest daily biogas production (116 mL g^{-1}VS day^{-1}), while the samples from the Pinetop-Lakeside facility had the lowest values (81 mL g^{-1}VS day^{-1}).

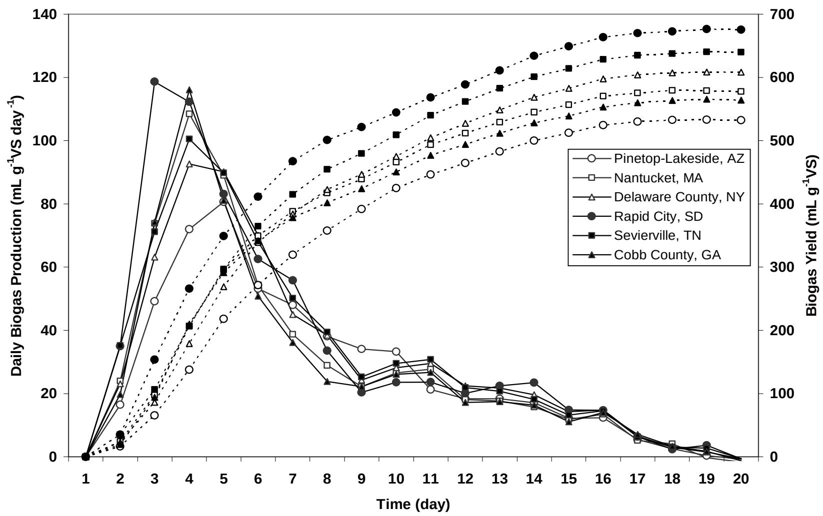

Figure 6. Average daily biogas production and average cumulative biogas yield of anaerobically digested samples collected from the six plants.

Table 6. Biogas production yield and methane content

RDR facility		13-day Yield (mL g^{-1} VS)	20-day Yield (mL g^{-1} VS)	Avg CH_4 (%)
Pinetop-Lakeside, AZ	Average	483	533	59.1
	St. dev.	39.0	37	
Nantucket, MA	Average	529	579	58.1
	St. dev.	13	16	
Delaware County, NY	Average	549	609	58.2
	St. dev.	30	26	
Rapid City, SD	Average	611	676	60.0
	St. dev.	37	35	
Sevierville, TN	Average	583	641	58.7
	St. dev.	36	44	
Cobb County, GA	Average	512	565	58.0
	St. dev.	9	12	
Food waste		564	598	68.2

The average cumulative biogas yield after 20 days of digestion lies between 533 (Pinetop-Lakeside) and 676 mL g^{-1}VS (Rapid City). It is worth mentioning that 90 percent of the biogas production occurred at the 13^{th} day of digestion for all the samples. The average cumulative biogas yield and the relative standard deviations for 13 and 20 days of digestion are shown in Table 6. The highest cumulative biogas yield was seen for the samples collected from Rapid City facility. The main differences of this facility from others are (1) the significantly small retention time inside the rotary drum (six hours, compared with 3-5 days of the other plants), (2) the high rotation speed (5 rpm compared to 1-2 rpm), (3) the differences in the internal geometry of the drum, and (4) the fact that the rotary drum reactor process was effectively operated in batch mode.

The above results might indicate that sufficient separation of the biodegradable materials from municipal solid waste can be achieved even at relatively low retention times. Obviously, at retention times as short as six hours, not much biological oxidation takes place inside the rotary drum, thus mechanical treatment is the main force for the fractionation of the organic materials. The relatively high rotation speed also assists in this direction. It is worth pointing out that the biogas yield in this study was calculated based on unit mass of VS in the samples analyzed. Thus the higher biogas yield reported in this paper may not translate into the higher biogas production for the raw municipal solid waste. The biodegradable material recovery efficiencies also need to be considered when the total biogas production potential is calculated for the municipal solid waste. Based on draft calculations by the operators of the six rotary drum plants, the Rapid City facility had the relatively lower recovery efficiency (Table 4).

The biogas yields measured in this study are close to the biogas yields reported in the literature. Zhang et al. (2007) reported biogas yield of 435 mL g^{-1}VS for food waste mechanically separated from restaurant wastes. Commercial plants utilizing the "Valorga®" process for the anaerobic digestion of pre-processed municipal solid waste have achieved biogas yields between 470 to 530 mL g^{-1}VS (ValorgaInternational, 2005). Similarly, anaerobic digestion of pre-processed municipal solid waste by the "Dranco®" process has been calculated to yield 468 mL g^{-1}VS (De Baere, 2000) , while the biogas yield of 622 mL g^{-1}VS for the anaerobic digestion of kitchen and yard waste mixture has been reported (De Baere, 2000).

It would have been interesting to compare the biogas production between raw and rotary drum-treated municipal solid waste. However, this was not feasible, due to the heterogenic nature of the waste, which does not allow the collection of relatively homogeneous and representative samples. Besides, the rotary drum process is primarily employed in the present study as a means to "extract" the digestible material from municipal solid waste, which then can be used as a feed stock (free of bulky and inert materials) for biogas production.

The methane content of the biogas produced from the rotary drum-treated waste was similar to the values reported in the literature for municipal solid waste-derived organics. Zhu et al. (2009) reported average 59 percent methane content of the biogas produced from the samples taken from the biodegradable materials separated from several types of municipal solid waste, paper and biosolids, processed by a rotary drum. The methane content of biogas produced from anaerobic digestion of pre-processed municipal solid waste in a commercial plant of "Valorga®" process was measured as 56 percent (Valorga International 2005). Zhang et al. (2007) reported methane content of 73 percent in the biogas produced from food wastes.

Characterization of the Organic Waste from Different Sources, Treated in RDR with Different Retention Times

Retention time of the waste in the drum is one of the critical parameters for the design and operation of rotary drum reactors. Operating the reactors with a shorter retention time can potentially have both positive and negative effects as compared with a longer retention time. Shorter retention time translates to smaller drums and reduced capital expenditure and energy input. They may also result in more highly degradable feedstocks for anaerobic digestion. On the one hand, fewer organics may be recovered due to insufficient time for the larger organic materials to break down enough to fit through the screen openings. In order to investigate the effects of drum retention time on the characteristics and biogas production potential of the organics derived from different types of municipal solid waste, experimental trials were conducted at the Pinetop-Lakeside plant, AZ. The specific objectives of this study were to characterize the organic materials separated from different types of solid waste available in municipalities by a rotary drum process operated at different retention times, to determine their anaerobic digestibility and biogas production potential, and to assess their suitability for use as feedstock for anaerobic digestion systems.

Studying the effect of retention time and waste types on biogas yield

Figures 7 and 8 show the operations of the rotary drum reactor at the Pinetop-Lakeside plant. The process is comprised of a rotary drum reactor of 3 m diameter and 38 m length followed by a trommel screen with 31.8 mm openings. It was normally used to process 20 - 30 t d^{-1} of municipal solid waste, cardboard and paper waste, and biosolids with an average retention time of three days. Air was blown into the drum to enhance the aerobic microbial activities. The drum was foam-insulated to keep the temperature at 45 – 68 ^{o}C. The material discharged from the rotary drum was passed through the trommel screen with the finer size fraction being collected through the screen and the coarser size fraction being collected on the screen. The finer fraction contains mainly biodegradable organic materials and was sent to windrow composting and the coarse fraction contains mainly non-biodegradable organic (e.g., plastics) and inorganic (e.g., metals, glass) materials and was sent to a landfill. The fines account for 50-55 percent of the original weight of material and have a moisture content of 55-60 percent.

Figure 7. RDR in the Pinetop-Lakeside plant

Figure 8. Feeding the RDR in the Pinetop-Lakeside plant

The experiments for this study were designed to examine the characteristics of the organic materials (fines) produced by the rotary drum reactor, as affected by different types of waste and retention times. To accomplish this, the reactor was operated for a week from Feb. 26-March 4, 2007, with four different waste types: municipal solid waste, mixture of municipal solid waste and cardboard and paper waste, mixture of municipal solid waste and biosolids, and mixture of cardboard and paper waste and biosolids. Cardboard and paper waste was referred to as simply paper. For each type of waste, three retention times (1, 2 and 3 days) were evaluated. The weight and composition of the four waste types tested are shown in Table 7.

Table 7. Quantities of wastes and water used in conducting RDR tests for organic material recovery

Waste Type	Amount			
	MSW (kg)	Paper (kg)	Biosolids (kg)	Water (kg)
MSW	9400	-	-	3600
MSW and Paper	6800	450	-	3200
MSW and Biosolids	1500 0	-	10500	-
Paper and Biosolids	-	6500	7800	-

According to the regular rotary drum operational protocols, the desired moisture content of the material entering the drum should be about 55 percent, wet basis. Therefore, water was added to municipal solid waste and to the mixture of municipal solid waste and paper to bring the moisture content to this value. No water was needed for the mixtures containing biosolids because the moisture content of biosolids was already high (*ca* 82 percent). The average speed by which the waste traveled inside the drum was controlled by the loading and unloading rates. This speed was kept constant at approximately 1/3 of the drum length each day, or 0.53 m h^{-1}. One waste type was introduced into the drum each day, with the simultaneous unloading of pretreated material from the exit of the drum. Thus, one-third of the drum was occupied by fresh waste every day and there was no back-mixing observed before wastes were discharged from the other end of the drum. Samples were collected every day from the drum exit and two sampling ports located at one-third and two-thirds drum length from the entrance. A total of 12 samples were collected from the drum, corresponding to the above mentioned four different waste types with three retention times in the drum for each waste type. All the samples collected from the rotary drum were screened on-site using a trommel screen of 31.8 mm openings to remove the large size fraction (mainly nonbiodegradable materials). The recovery of organic materials (fines) from 3-d rotary drum-treated solid wastes was calculated (Table 4). The screened samples were packed on ice and shipped overnight to the Bioenvironmental Engineering Research Laboratory at UC Davis. The samples were then put into a freezer for storage at -20 °C until analyses. Prior to the anaerobic digestion tests, samples were manually screened using a stainless steel screen with 6.4 mm openings to remove the large glass and metal particles. Two sets of analyses were performed on the collected samples. The samples collected from three-day retention time trials were analyzed in greater detail than the samples collected with one-day and two-day retention time trials because the three-day retention time is the current standard for the rotary drum plant used for this study.

Physical and chemical characteristics of the organic waste samples

The analyses performed for different samples are shown in Tables 8-10. The moisture content, VS/TS, TC and TN, C/N and pH of all the samples analyzed are shown in Table 8. The moisture content of the samples varied from 49.8 percent to 59.6 percent. Generally, longer retention time in the drum resulted in lower moisture content in the organic material, most likely due to the moisture loss under the forced aeration. In comparison, the food waste had a moisture content of 74.4±1.8 percent.

The VS/TS of all the rotary drum pretreated waste samples were in the range of 69.2 – 80.0 percent. Theoretically, longer retention time in the drum could result in lower VS/TS because of the removal of biodegradable organics from the waste due to the biological oxidation inside the rotary drum. However, measurements did not support this prediction. For each type of waste, VS/TS changed less than 5 percent with extension in retention time, indicating that the loss of volatile matter during pretreatment was small. Organic materials separated from the mixture of paper and biosolids resulted in the highest VS/TS, which may be attributed to the fact that biosolids and paper waste contained more volatile matter compared to municipal solid waste. Regarding all the rotary drum-treated wastes, the VS/TS values were lower than that of food waste (96.4 percent), as expected. Similar to the VS/TS, the TC values of the samples were fairly consistent (40.3 percent to 43.4 percent). The TC of food waste was approximately 20 percent higher than that of the rotary drum waste samples.

For a particular waste type pretreated in the rotary drum for different retention times, the TN contents of the recovered organics were similar. The organic material produced from the wastes containing biosolids had slightly higher TN (1.5 percent to 1.9 percent) and lower C/N (21.1 to 26.7) than the organic material from the wastes containing no biosolids (1.1 percent to 1.6 percent TN and 26.2 to 36.6 C/N). The C/N values of all the organic materials recovered were considered to be appropriate for anaerobic digestion, as they were in the optimum range of 20 - 30 reported by McCarty (1964). In comparison, the food waste had TN of 6.9 percent and C/N of 7.2. The pH of the organic materials recovered from one-day retention time in RDR was 6.0 - 7.5, with an average of 7.1. The pH of the materials recovered from three-day retention time in RDR was 5.4 – 6.2, with an average of 5.9. As a general observation from Table 8, the pH decreased in most cases along with the retention time in the rotary drum. In comparison, the pH of the food waste was 4.2.

Compositions and elemental analyses of the organic materials recovered from four different waste types with three-day retention time in rotary drum reactors are shown in Tables 8-10. The compositions and elements of the four different wastes were also similar except that the wastes containing biosolids showed higher total Kjeldahl nitrogen (TKN) and ammonia-nitrogen (NH^+_4-N).

Table 8. Characteristics of organic materials recovered from municipal solid wastes using the RDR process with different retention times (characteristics of food waste are included for comparison)

Waste Type	Retention Time in RDR (d)	Organic recovery after RDR and trommel screen* (% wet weight)	Characteristics of the organics recovered from RDR process					
			Moisture Content (%)	VS/TS (%)	Total C (% dry weight)	Total N (% dry weight)	C/N	pH
MSW	1	-	59.6	75.7	41.5	1.3	30.8	6.0
	2	-	50.7	73.9	42.1	1.6	27.0	7.5
	3	37	49.8	71.9	41.2	1.6	26.2	5.4
MSW and Paper	1	-	57.5	72.4	41.2	1.2	33.8	7.3
	2	-	50.9	69.2	38.8	1.1	36.6	7.1
	3	41	51.6	75.3	40.3	1.3	30.0	6.1
MSW and Biosolids	1	-	57.2	70.8	38.2	1.8	21.8	7.5
	2	-	56.6	73.1	43.4	1.9	22.5	7.3
	3	57	54.0	76.0	41.4	1.5	26.7	6.2
Paper and Biosolids	1	-	52.5	75.0	38.9	1.8	21.1	7.5
	2	-	56.0	76.9	40.7	1.7	24.6	6.2
	3	68	57.4	80.0	43.2	1.8	23.8	5.9
Food Waste	-	-	74.4	96.4	50.0	6.9	7.2	4.2

* Organic recovery for 1 and 2 d retention time in the RDR were not determined. Organic recovery was calculated as (amount of wet organics collected after the trommel screen divided by the total amount of waste entering the RDR process)

Table 9. Compositions of organic materials recovered from different types of municipal solid wastes via RDR process at 3-d retention time

Parameters	Unit	MSW	MSW and Paper	MSW and Biosolids	Paper and Biosolids
Cellulose	%	37.4	37.8	37.2	38.5
Hemi-cellulose	%	9.1	9.05	9.4	8.5
Lignin	%	10.5	10.25	9.2	9.7
Starch	%	0.70	0.50	0.60	<0.5
Glucose-Total	%	0.80	0.55	0.70	<0.5
Fructose	%	<0.2	<0.2	<0.2	<0.2
Sucrose	%	<0.2	<0.2	<0.2	<0.2
Total Nonstructural Carbohydrates (TNC)	%	0.80	0.60	0.70	<0.5
Total Kjeldahl Nitrogen (TKN)	%	1.35	1.12	1.35	1.63
Ammonia Nitrogen (NH^{+}_{4}-N)	ppm	240	165	305	410
Nitrate Nitrogen (NO_3-N)	ppm	<10	10	15	10

Table 10. Element concentrations in organic materials recovered from different types of municipal solid wastes via RDR process at 3-d retention time

Parameters	Unit	MSW	MSW and Paper	MSW and Biosolids	Paper and Biosolids
Phosphorus (P)	%	0.33	0.31	0.35	0.40
Potassium (K)	%	0.30	0.34	0.47	0.41
Calcium (Ca)	%	2.04	2.33	2.85	2.41
Magnesium (Mg)	%	0.17	0.16	0.20	0.18
Chloride (Cl)	%	0.34	0.38	0.47	0.40
Sodium (Na)	%	0.38	0.42	0.51	0.45
Sulfur (S)	%	0.35	0.38	0.55	0.43
Iron (Fe)	%	0.83	0.87	0.95	0.91
Aluminum (Al)	%	1.16	1.26	1.28	1.15
Silicon (Si)	%	4.00	4.12	2.77	2.14
Zink (Zn)	ppm	444	524	478	410
Manganese (Mn)	ppm	213	256	243	214
Copper (Cu)	ppm	152	201	164	124
Cadmium (Cd)	ppm	0.8	1.1	1.3	1.1
Chromium (Cr)	ppm	13.7	15.7	15.8	14.1
Cobalt (Co)	ppm	2.1	2.1	2.2	2.0
Lead (Pb)	ppm	68.2	98.5	98.1	61.0
Molybdenum (Mo)	ppm	3.0	3.2	3.1	2.8
Nickel (Ni)	ppm	25	28	29	27
Selenium (Se)	ppm	0.8	0.6	0.8	1.0
Arsenic (As)	ppm	1.8	2.0	1.7	1.9

Biogas production potential of the organic waste samples

The biogas production potential of different samples is presented in terms of biogas yield, methane content and methane yield. The results of daily and cumulative biogas yield are shown in Figures 9-13. Biogas production after the 15th day of digestion was negligible, and most of the biogas was produced during the first 10 days of digestion. Regarding all the rotary drum-treated wastes, the peak value of daily biogas yield usually occurred on the fourth day of digestion. For the municipal solid waste samples with different retention times in the rotary drum, the daily and cumulative biogas yields are presented in Figure 9. The daily biogas yields appeared to decrease slightly with the increase of retention time in the drum, probably due to the aerobic degradation of organics occurring in the drum. The peak values were calculated to be 131, 121 and 97 mL gVS^{-1} d^{-1}, for 1, 2 and 3 day retention times in the rotary drum, respectively. The cumulative biogas yields were calculated to be 521, 502 and 466 mL gVS^{-1}, respectively.

Similar trends were found for the biogas yields of rotary drum-treated municipal solid waste and paper mixtures (Figure 10). The peak values of daily biogas yield were 124, 116 and 100 mL gVS^{-1} day^{-1}, for 1, 2 and 3 day retention times. The cumulative biogas yields did not vary significantly (α=0.05) with the retention time in the rotary drum reactor, as they were determined to be 485, 526 and 516 mL gVS^{-1}, respectively.

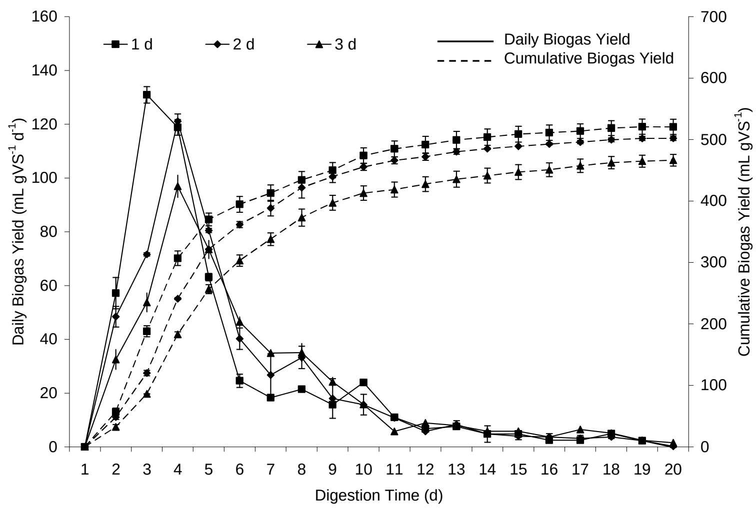

Figure 9. Daily and cumulative biogas yields of RDR pretreated MSW

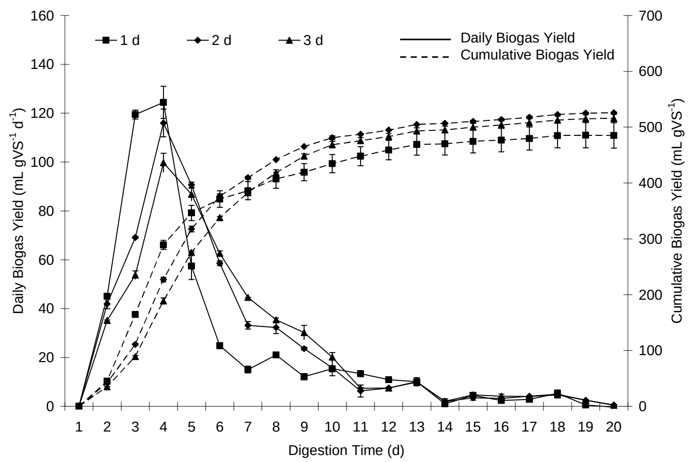

Figure 10. Daily and cumulative biogas yields of RDR pretreated mixture of MSW and paper

As shown in Figure 11, the daily biogas yields of the waste samples produced from mixtures of municipal solid waste and biosolids showed minor differences. The peak values for 1, 2 and 3 day retention times in the drum were 119, 126 and 110 mL gVS^{-1} d^{-1}, respectively, on the fourth day of digestion. The cumulative biogas yields were 557, 534 and 492 mL gVS^{-1}, respectively. Compared with the other three types of rotary drum-treated wastes, the cumulative biogas yields for the municipal solid waste and biosolids mixtures were clearly higher. This combination appears to be more favorable for biogas production compared to the other combinations, possibly because of comparatively higher nitrogen content.

The samples produced from the mixture of paper and biosolids had the lowest biogas yields (Figure 12) among all the samples evaluated. The peak values of daily biogas yield were 98, 125 and 111 mL gVS^{-1} d^{-1}, respectively, while the cumulative biogas yields were 457, 507 and 504 mL gVS^{-1}, respectively. This may be attributed to the fact that cellulose contained in paper is more difficult to digest than other organics contained in municipal solid waste (Müller et al, 2004).

As a comparison, the daily and cumulative biogas yields of the food waste are shown in Figure 13. The main difference between food waste and rotary drum-treated solid wastes lay in the daily biogas yield and the duration of the anaerobic digestion process. The biogas production duration of food waste was prolonged, with lower daily biogas yields (peak value: 90 mL gVS^{-1} d^{-1}) compared to the four rotary drum-treated wastes. However, the cumulative biogas yield of the food waste (609 mL gVS^{-1}) was significantly (α=0.05) higher than the cumulative biogas yields obtained from the rotary drum-treated wastes. Higher cumulative biogas yield with lower daily biogas yield was expected for food waste, as food waste contained more protein compared to the organic materials in municipal solid waste and paper. According to Bushwell's formula (Symons and Bushwell, 1933), proteins have higher biogas production potential but lower degradation rates compared to carbohydrates.

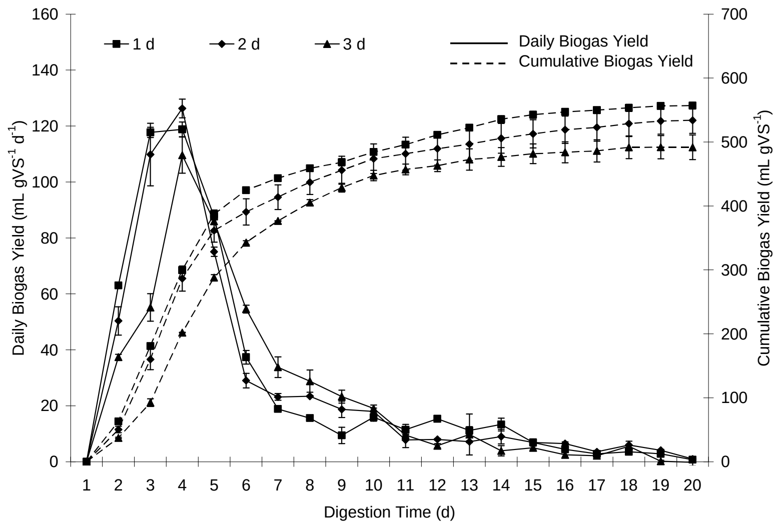

Figure 11. Daily and cumulative biogas yields of RDR pretreated mixture of MSW and biosolids

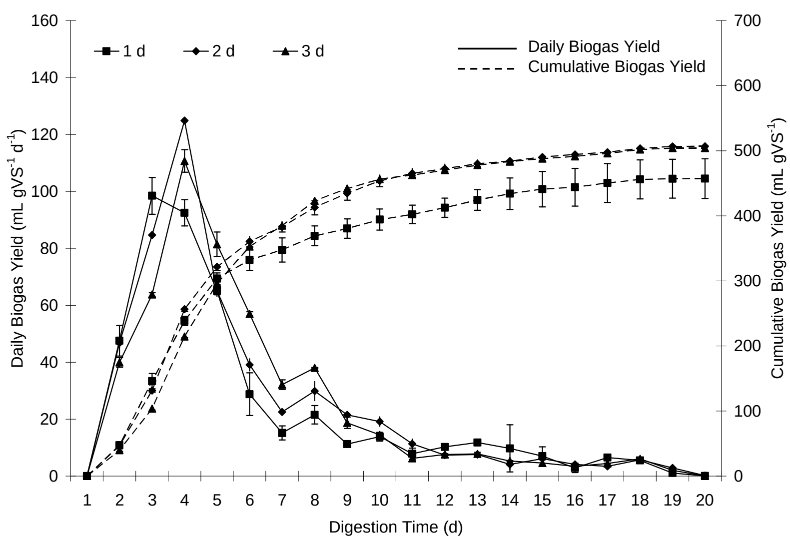

Figure 12. Daily and cumulative biogas yields of RDR pretreated mixture of paper and biosolids

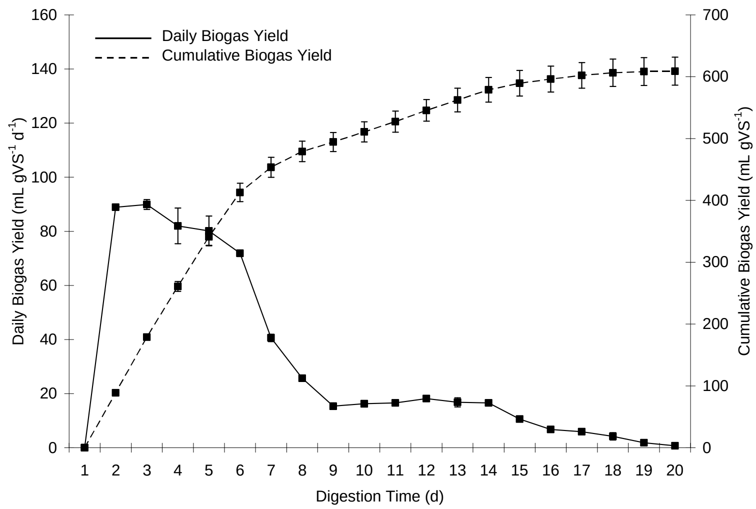

Figure 13. Daily and cumulative biogas yields of food waste

For the rotary drum-treated wastes, biogas methane concentrations showed similar trends for different retention times in the drum. Therefore the average methane content of these treated wastes is shown in Figure 14 together with other digested wastes. On the first day of digestion, the methane contents were around 52 percent, with trace amounts of hydrogen. After the second day, the methane contents stabilized at about 61 percent, while headspace hydrogen concentration was negligible. It must be noted that the experimental conditions for this study were designed for complete biomass degradation. Bio-hydrogen production could be distinct if higher initial loading rate had been selected. The methane content of biogas produced by food waste continued increasing from 37 percent to 68 percent until the 11th day of digestion.

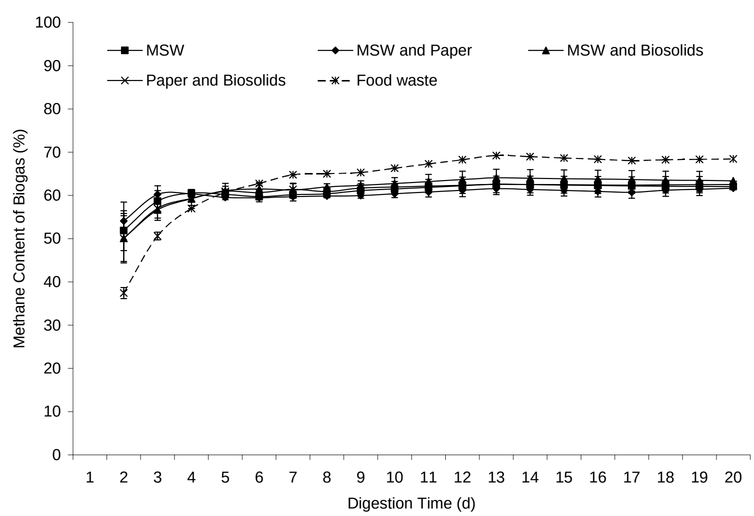

Figure 14. Methane concentrations of the biogas produced from RDR treated solid wastes and from food waste

TS and VS reduction and biogas and methane yields of organic materials recovered from different types of municipal solid wastes via the rotary drum process are shown in Table 11. Based on the results of Tukey's significance test, for each type of rotary drum-treated waste, no significant difference ($P<0.05$) was found among the experimental biogas yields for the samples collected under different rotary drum reactor retention times (1, 2 and 3 days). Since a shorter retention time in the rotary drum system translates to a smaller size of rotary drum and better economics, one-day retention time in the rotary drum is recommended for providing the pretreatment of municipal solid waste prior to anaerobic digestion. Further research needs to be carried out in order to determine if the retention time in the drum could be further reduced (i.e., whether simple separation might be equally beneficial). This study did not quantify the separation or recovery efficiencies of organic materials separated from the wastes which were treated by rotary drum reactors with different retention times. The effect of the rotary drum retention time on organic recovery needs to be investigated in the future research. A final recommendation for the retention time in rotary drums for a specific type of waste should be based on combined considerations of both the organic recovery through rotary drum process and biogas yield of the organic material recovered from wastes.

Table 11. TS and VS reduction and biogas and methane yields of organic materials recovered from different types of municipal solid wastes via RDR process.

Waste Type	Retention time in RDR (d)	Feedstock TS Reduction (%)	Feedstock VS Reduction (%)	Biogas Yield * (mL gVS^{-1})	Methane Yield (mL gVS^{-1})	Methane Content of Biogas (%)
MSW	1	52.3	59.0	520[a *]	298	57.3
	2	60.1	63.9	502[a,b]	300	59.9
	3	65.0	66.8	466[b]	282	60.6
MSW and Paper	1	48.4	53.8	485[c]	282	58.2
	2	56.5	57.2	526[c]	313	59.8
	3	58.8	62.6	516[c]	308	59.9
MSW and Biosolids	1	60.0	64.2	557[d]	320	57.3
	2	54.5	57.0	534[d]	319	59.7
	3	61.9	69.3	492[d]	296	60.2
Paper and Biosolids	1	55.3	57.5	457[e]	261	57.2
	2	50.2	51.8	507[e]	300	59.4
	3	52.2	58.8	504[e]	304	60.3
Food Waste	-	86.0	88.1	609	350	57.5

* Values within the same type of waste followed by different letters are significantly different at $P<0.05$.

The methane yields of rotary drum-treated wastes and food waste were calculated from daily biogas yield and methane content of biogas. The methane yields of the treated wastes were in the range of 261 - 320 mL gVS^{-1}, while food waste presented higher methane yield of 350 mL gVS^{-1}. Among the four types of solid wastes evaluated in this study, the organic material recovered from rotary drum-treated mixtures of municipal solid waste and biosolids showed the highest methane production potential of 320 mL gVS^{-1}.

As shown in Table 11, the organic materials separated from municipal solid waste presented the highest TS and VS reduction which were in the range of 52.3 - 65.0 percent and 59.0 - 66.8 percent, respectively. The mixture of paper and biosolids showed the lowest TS and VS reductions of 50.2 - 55.3 percent and 51.8 - 58.8 percent between the rotary drum-treated wastes and food wastes. The wastes containing biosolids showed comparatively higher TS and VS reduction than the wastes containing paper. The above results suggest that municipal solid waste consists of more easily biodegradable materials than biosolids and paper. Food waste presented higher TS and VS reduction (86.0 percent and 88.1 percent, respectively) than all the rotary drum-treated wastes.

Conclusions and Recommendation for Future Research

The results of this study showed that the rotary drum reactor process could be used as an effective technology for separation and pretreatment of the organic materials in municipal solid waste prior to anaerobic digestion. The existing municipal waste composting plants that utilize rotary drum treatment processing could install anaerobic digesters and recover the energy they consume without significantly affecting the compost output. Furthermore, the elevated temperatures achieved in the rotary drum reduce the energy input to the digester and increase the energy output. However, a full financial analysis should be conducted to determine whether anaerobic digestion is a feasible option for both existing and new waste treatment plants. Composting facilities that plan to install rotary drum systems may wish to consider a smaller rotary drum in conjunction with an anaerobic digester as an alternative to the larger system required for aerobic composting alone.

The results from the organic waste samples collected from the six rotary drum plants showed that the organic materials derived from the rotary drum-treated municipal solid waste are highly digestible and will be good feedstock for anaerobic digesters. The biogas yields of all the collected samples, after 20 days of thermophilic anaerobic digestion, varied between 533 to 676 mL g^{-1}VS, while 90 percent of biogas production was achieved after 13 days of anaerobic digestion. The final methane content of the samples varied between 58.0 to 59.9 percent. The results also indicated that rotary drum facilities with significant variation in the retention time (from six hours to five days) yielded similar quantities of biogas. However, the plant with the shorter retention time (six hours) showed the relatively higher biogas production potential. This observation is significant if the method is to further be exploited for commercialization, as reduction in retention time results to a smaller plant. The biogas yields of the organic waste samples were comparable to the biogas yield of food waste.

For the four types of waste materials studied at the Pinetop-Lakeside plant in AZ, the organic fractions recovered from the rotary drum process showed similar characteristics with regard to the anaerobic digestion, in terms of biogas and methane yields, which ranged 457 - 557 mL gVS^{-1} and 261 - 320 mL gVS^{-1}, respectively, after 20 day of thermophilic digestion. Methane content of biogas ranged from 57-61 percent. The organic material recovered from the mixture of municipal solid waste and biosolids with 1-d retention time in the rotary drum showed the highest biogas yield (557 mL gVS^{-1}), while the organic material recovered from paper and biosolids mixture with one-day retention time in the rotary drum showed the lowest biogas yield (457 mL gVS^{-1}). About 90 percent of the total biogas yield was achieved in the first 10 days of digestion for most of the samples. The TS and VS reductions in the various RDR treated wastes after 20 d anaerobic digestion were 48.4 - 65.0 percent and 51.8 - 69.3 percent, respectively. One-day retention time is preferable among the three retention times tested based on the test results of organic fractions as shorter retention time translates to either smaller drums or fewer drums and better economics. However, further studies are recommended to determine the minimum retention time requirements in the drum for different types of wastes, and to assess the separation efficiencies of the organic fraction under different retention times.

Anaerobic Digestion of Organic Wastes Derived from Rotary Drum Reactors Using Anaerobic Phase Solids Digester System

Description of the APS-Digester System used to study continuous RDR waste digestion

The APS-Digester used in this experiment (Figure 15 and Figure 16) consisted of four 1.4 L hydrolysis reactors (HRs) and one 2.0 L biogasification reactor (BR) with liquid recirculation between the HRs and BR. Each HR was operated as a batch reactor with 12-day solids digestion time (SRT), while the BR was operated as a continuous anaerobic mixed biofilm reactor, fed with the liquid transferred from the HRs (Figure 15). Polyethylene Raschig-ring pellets (10 × 10 mm, 0.95 kg L-1 density) were suspended in 0.6 L of the BR to provide an extended surface area for microorganism attachment. The BR was mixed intermittently by a gas recirculation system and 3 d HRT. The reactor mixing and liquid recirculation were controlled by a time controller (Model XL, Chrontrol, San Diego, CA). The whole system was operated continuously by recharging one of the four HRs every three days. The temperature of all the reactors was maintained at 55±1 °C in a temperature-controlled environmental chamber.

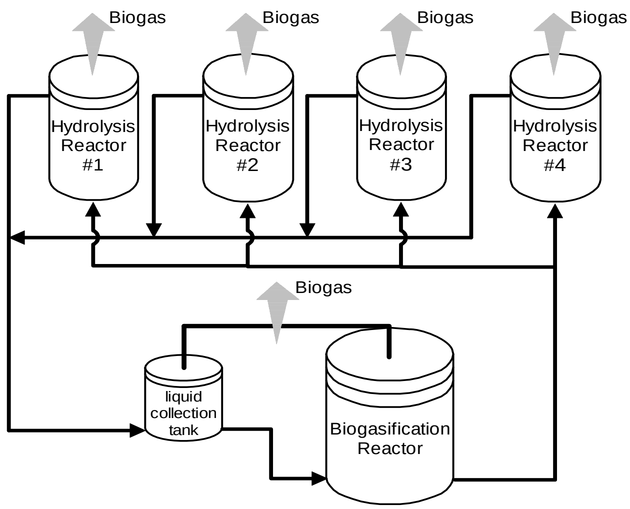

Figure 15. Schematic of the APS-Digester used in the laboratory experiments**.**

Figure 16. Photo of the APS-Digester used in the laboratory experiments.

At the start-up, the APS-Digester was seeded with the anaerobic sludge collected from a thermophilic anaerobic digester at a wastewater treatment plant in Oakland, CA. The TS and VS of the seed sludge were determined to be 14,000 and 9,000 mg L^{-1}, respectively. Tables 12 and 13 show the configuration and operational parameters of APS-Digester, respectively. The ratio between the BR volume and total HR volume (BR/HR) (sum of four HR reactors) was selected according to the results of previous studies that used the APS-Digester to digest food and green wastes (Zhang and Zhang, 2002). The anaerobic digestion experiment was conducted in three parts. The first part was for start-up and stabilization of the APS-Digester. The second part was for determining the maximum stable organic loading rate (OLRmax). The third part was for evaluating the performance of the APS-Digester operated at OLRmax. The whole experiment lasted for 105 days, which included 24 days for digester start-up, 48 days for increasing the OLR, and 33 days for digester performance evaluation at the OLRmax.

Table 12. Configurations of the APS-Digester for digestion of RDR pretreated MSW

Operational parameters	Hydrolysis reactor (HR)	Biogasification reactor (BR)
Number of reactors	4	1
Total volume in each reactor (L)	1.5	4
Working volume in each reactor (L)	1.4	2
Hydraulic retention time (d)	8.4	3

Table 13. Operational parameters of the APS-Digester for digestion of RDR pretreated MSW

Operational parameters	
Solid retention time (d)	12
Temperature (^{o}C)	55±1
Total working volume (L)	8
BR/HR	0.36
Experiment duration (d)	105

At the start-up, all the reactors in the APS-Digester system were inoculated with thermophilic seed sludge. The system was operated for five days to test for leaks and allow the microbes to acclimate to the reactor environment. Afterwards, the first hydrolysis reactor (HR1) was loaded with the organic waste containing 72 gVS. As the waste was digested, the volume in HR1 decreased. Tap water was added to restore the digester's working volume. The other three hydrolysis reactors (HR2, HR3 and HR4) were fed similarly on day 3, 6, and 9 after HR1 was loaded. The solids retention time in each HR was 12 days. At the end of each batch digestion in a HR, the reactor was disconnected with the system and the digestate was emptied out and manually squeezed through a stainless steel screen (with 1-mm openings) to separate the solids from the liquid. The liquid was put back into the reactor with new feedstock while solids were analyzed for the TS and VS. Water was added to bring the liquid level in the HR to a designed level. The start-up of the APS-Digester was deemed successful when the following conditions were met: the biogas production rate and biogas composition were similar among all four HRs; the biogas production rate and biogas composition of the BR reached a relatively constant value and the pH in the BR was stabilized above 7.

After the APS-Digester had been successfully started at the initial OLR of 3.1 gVS L^{-1} d^{-1}, three higher OLRs (4.6, 7.7 and 9.2 gVS L^{-1} d^{-1}) were tested. The OLR of 9.2 gVS L^{-1} $d^{-1}$was considered to be the maximum OLR (OLRmax) because the HR reached the maximum waste loading capacity. At each OLR, the digester system was operated for at least 12 days to allow all the four HRs to receive the new loading. The OLR was only increased to the next level when the biogas production rate and biogas composition from all the reactors were relatively stable The APS-Digester was operated at the 9.2 gVS L^{-1} d^{-1} (OLRmax) for 24 days to ensure the system stability.

APS-Digester measurement and data analysis

Throughout the experiment, the biogas production from each reactor was measured on daily basis using a wet-tip gas meter (Rebel Point Wet Tip Gas Meter Company, Nashville, TN). The values reported for the biogas volumes in this paper were adjusted to 20°C temperature and 1 atm pressure. The contents of H_2, CH_4 and CO_2 in the biogas was determined using a gas chromatograph (GC) (Agilent® GC6890N) equipped with a thermal conductivity detector (TCD) and a 3.05 m long packed column (Alltech® C-9000). The packed column had 3.18 mm outer diameter and 2.16 mm inner diameter and was packed with 80/100 mesh carbosphere. The carrier gas was Argon at a flow rate of 30.8 mL min^{-1}. The injector, oven and detector temperatures were 120, 100 and 120 °C, respectively.

After 12 days digestion, the undigested residue in each HR was recovered using the following procedure. A HR was first disconnected with the system and its contents were emptied out over a screen with 1 mm openings to separate solids from liquid. The solids on the screen were then pressed through a screw extruder to remove more liquid. All the liquid was collected and fed back into the HR for next batch feedstock loading. The solids were analyzed for pH, wet weight, TS and VS. The TS and VS reductions in the waste were calculated based on the mass balances of TS and VS before and after digestion. Effluent pH of the biogasification reactor was also measured on daily basis. In order to determine the energy conversion efficiency, the high heating values of feedstock and digested solids were also measured using a calorimeter (IKA-WERKE C5000). The feedstock and digested solid samples from four consecutive batches of loading and unloading of the HRs were analyzed when the digester system was operated at OLRmax. Before measurement, the samples were air dried and compressed to small pellets. The pellets were dried in an oven at 105°C to measure the moisture content and combusted in the calorimeter under ASTM D5865-01 standard test method for gross calorific value of coal and coke (ASTM, 2001). The condensed water in the calorimeter was collected and titrated with 3.76 g L^{-1} Na_2CO_3 standard solution to correct acid deviation.

After the APS-Digester had been steadily operated at OLRmax for 36 days, liquid samples were collected daily from HR1, HR3 and BR over 18 days (e.g., HR1 was sampled from day 84 to day 96, HR3 was sampled from day 90 to day 102) to determine the changes in pH and VFA concentrations in the HRs over the 12-day digestion cycle. The VFA concentration was measured with a GC (Agilent® GC6890N) equipped with a hydrogen flame ionization detector (FID) and a 30 m (0.53 mm ID, 1 µm film) capillary column (J&W DB-Wax), using helium as carrier gas at a flow rate of 12.5 mL min^{-1} . The injector and detector temperatures were 150 and 275°C, respectively. The oven temperature was programmed as such: 35°C for 1 min, increase to

45°C at 2°C min^{-1}, 45°C for 0.5 min, increase to 65°C at 5°C min^{-1}, 65°C for 0.5 min, increase to 160 °C at 25 °C min-1 and 160°C for 7 min.

APS-Digester system start-up

During the start-up period, biogas production rate from all the reactors and pH in the biogasification reactor was used as indicators for evaluating the system stability. The TS and VS reduction of the feedstock were measured to ensure sufficient degradation. After 15 days, the pH in the BR was maintained at 7.97 ± 0.03. Minor biogas production was observed from the BR (Figure 17). The cumulative biogas production and feedstock VS reduction of each HR after each 12-day cycle were in the range of 19.0 ± 1.6 L L^{-1} and 56.2 percent ± 3.6 percent, respectively (Table). The system biogas yield was calculated as 0.42 L gVS^{-1}, using the data collected during the periods of 16-24 days. The methane content of the biogas from the HRs was found to vary with the digestion time from 30 percent shortly after loading to 65 percent towards the end of each 12-day digestion cycle. In contrast, the methane content of the biogas produced from the BR was consistently higher at around 70 percent. This indicated that hydrolysis/acidification and methanogenesis were separated to some extent into their respective reactors. However, the increasing of the methane content in the biogas produced in the HRs indicated that a methanogenesis culture had been established in the HRs over the 12-day digestion period.

Biogas production and solid reduction in the APS-Digester

Following the start-up of the APS-Digester, three OLRs, 4.6, 7.7 and 9.2 gVS L^{-1} d^{-1} were subsequently tested. The system performed stably at each OLR including the highest OLR of 9.2 gVS L^{-1} d^{-1}, at which point the HR had reached the maximum loading capacity without compacting the feedstock . This organic loading rate was considered to be the OLRmax.

The APS-Digester performed stably at the OLRmax during the rest of the experiment. The significance test showed that the VS and TS reductions and biogas and methane yields were statistically the same with the same parameters at the initial 3.1 gVS L^{-1} d^{-1} OLR (Table 14). For each HR, most of the digestion was completed within 10 days. The biogas production rate of each HR reached a peak of 11.5 L L^{-1} d^{-1} on day five. For the whole APS-digester system, the average biogas production rate was fairly constant at an average of 3.5 L L^{-1} d^{-1}. The VS and TS reduction at OLRmax were 53.2 percent and 37.5 percent on average, respectively. The majority of the biogas was produced from the HRs (Figure 18). The reason may be that the most of the digestible compounds released from the feedstock had already been digested in the HRs prior to being transferred to the BR. This indicates that there is a potential for reducing the volume of BR and increasing the frequency of liquid recirculation in future studies.

For each OLR tested after start-up, the cumulative biogas production increased almost linearly over time (Figure 18). For the OLR of 4.6, 7.7 and 9.2 gVS L^{-1} d^{-1}, the biogas production rate and biogas yield were calculated using the data collected over the period of 24-36, 36-48 and 81–93 days, respectively. For the two intermediate OLR (4.6 and 7.7 gVS L^{-1} d^{-1}), the system was not given enough time to mature and stabilize, therefore the biogas yield was lower at 0.33 L gVS^{-1} (Table 14). When the loading rate was held constant for longer than 12 days at OLRmax, the biogas yield increased from 0.33 to 0.38 L gVS^{-1} and remained relatively constant from day 80 to the end of the experiment.

The composition of biogas produced from HRs and BR at 9.2 gVS L^{-1} d^{-1} was analyzed and the average results of four HRs are shown in Figure 19. The biogas compositions of different HRs were close to each other throughout the 12-day digestion cycle (the standard deviations ranged from 0.1 - 4 percent). On the first day of digestion, the biogas from the HRs contained 10 percent H_2, 20 percent CH_4 and 70 percent CO_2, indicating active hydrolysis/acidogenesis fermentation in the HRs. After four days, the H_2 concentration decreased to zero. In the same period, the CH_4 concentration increased to 55 percent and eventually reached 60 percent. The change of biogas composition indicated that the primary fermentation step switched from hydrolysis/acidogenesis to methanogenesis. The biogas produced in the BR had a relatively steady CH_4 content of 68 - 72 percent with no H_2 detected, indicating that the methanogenesis was well maintained in the BR. The overall methane content of the biogas produced from the APS-Digester was around 50 percent.

The high heating values of feedstock and residue were determined to be 15.4±0.7 kJ gTS^{-1} and 14.7±1.4 kJ gTS^{-1}, respectively. Based on energy contents of the biogas produced and heating values of the feedstock and residue, it was estimated that about 37 percent energy in the feedstock was converted into biogas energy through anaerobic digestion.

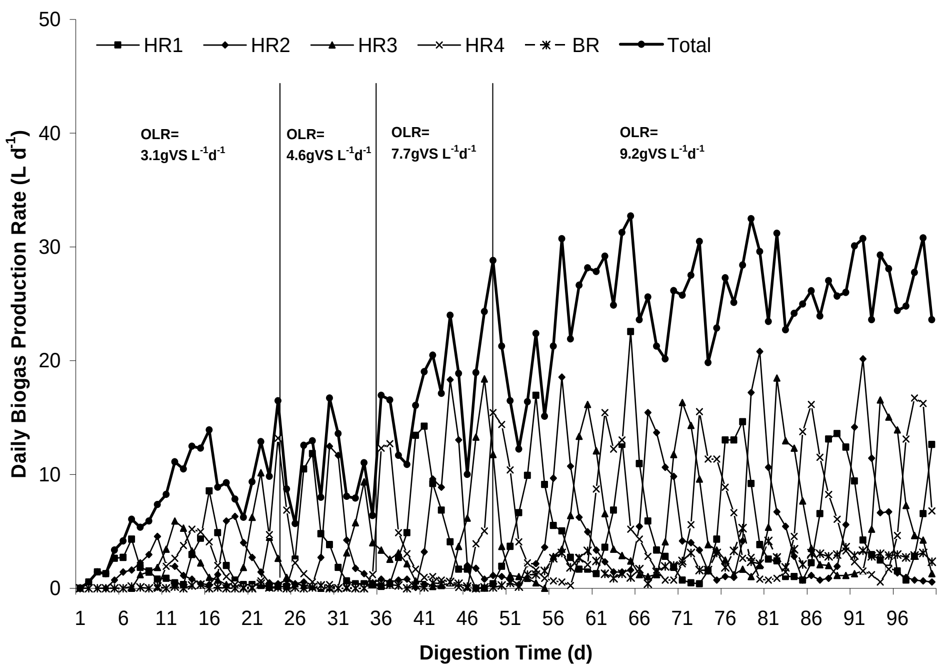

Figure 17. Biogas production rate of the APS reactors

(HR: hydrolysis reactor, BR: biogasification reactor)

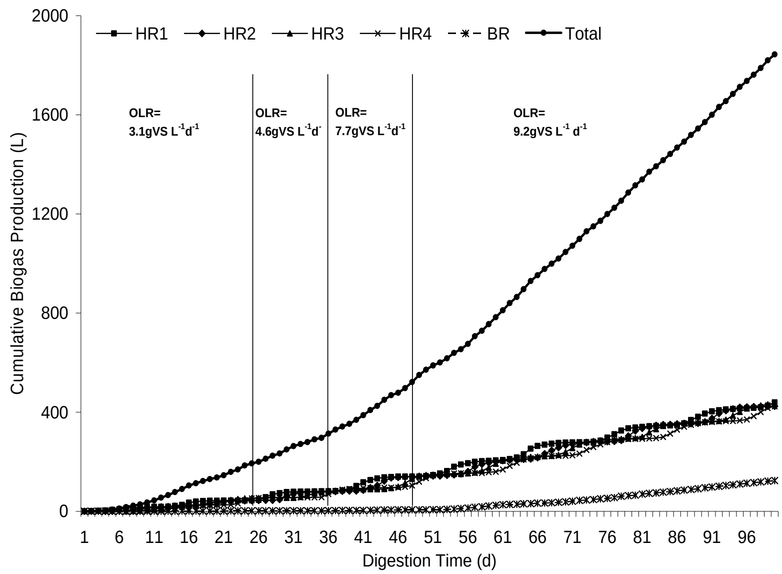

Figure 18. Cumulative biogas production of APS reactors
(HR: hydrolysis reactor, BR: biogasification reactor)

Table 14. Performance of the APS-Digester under different organic loading rates (OLRs)

OLR ($gVS\ L^{-1}\ d^{-1}$)	VS reduction (%)	TS reduction (%)	Biogas production rate ($L\ L^{-1}\ d^{-1}$)	Biogas yield ($ml\ gVS^{-1}$)	Methane yield ($ml\ gVS^{-1}$)
3.1	56.2 ± 3.6	44.4 ± 3.4	1.3	420	170
4.6	52.4 ± 5.9	36.8 ± 4.5	1.5	330	130
7.7	51.5 ± 2.3	36.0 ± 4.7	2.5	330	140
9.2	53.2 ± 2.7	37.5 ± 2.1	3.5	380	190

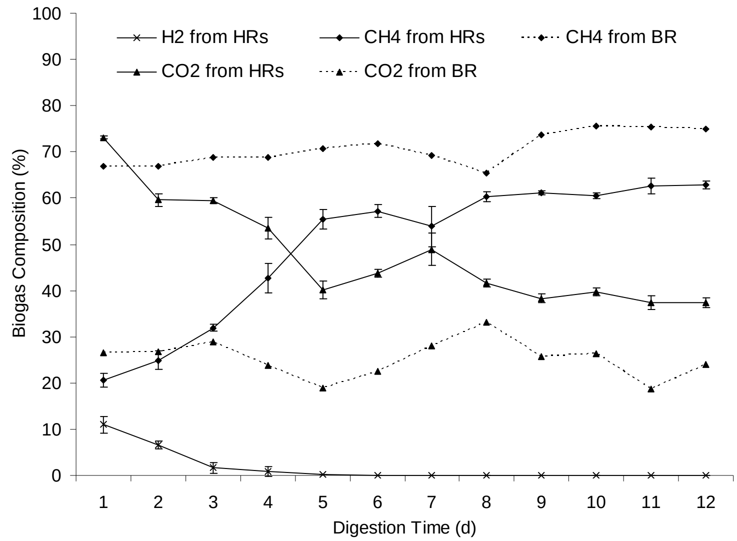

Figure 19. Methane and hydrogen contents of the biogas produced by the reactors in the APS-Digester system (HR: hydrolysis reactor, BR: biogasification reactor)

The pH in the HRs and the BR remained stable during this period at 7.3 - 7.8 and 7.9 - 8.1, respectively. In a previous study of the APS-Digester using food waste as feedstock (Withrow, 2005), the pH of the HRs decreased to 6 after loading. These facts indicate that the hydrolysis of RDR pretreated MSW provided more pH buffer than food waste. The pH of the BR remained steady at about 8.

The concentration of VFs in the hydrolysis reactor is shown in Figure 20. Acetic acid and butyric acid were the predominant VFAs in the HRs. In this study, their concentration accounted for more than 75 percent of the total VFA. On the second day after loading the hydrolysis reactor, the concentrations of acetic acid and butyric acid in the HRs reached peak values of 7,300 and 4,200 mg L^{-1}, respectively, and the total VFA concentration was 15,000 mg L^{-1} as acetic acid. At the same time, the pH in the HR decreased to 7.1. After the third day, the VFA concentrations started to decrease and reached 550 mg L^{-1} as acetic acid by day 7, and the pH was back to 8. These results indicated that the hydrolysis rate was faster than the methanogenesis rate within the first two days after loading. It appeared that the liquid recirculation between the HRs and BR prevented the microbial inhibition by the VFAs in the hydrolysis reactors, resulting in a good biogas production rate in those reactors.

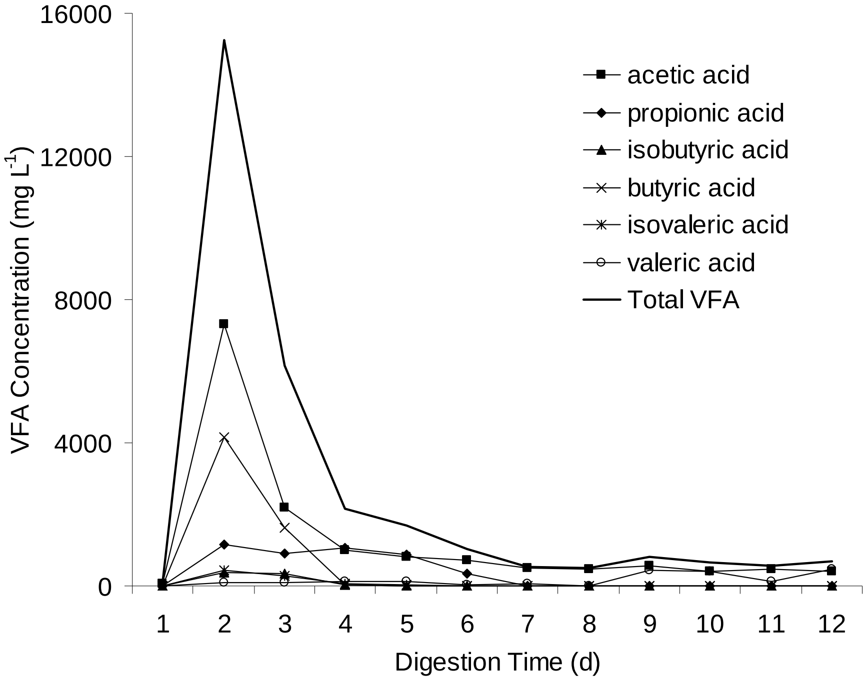

Figure 20. The VFA concentrations in a hydrolysis reactor over a 12-day digestion cycle

The results of this study have shown that an integrated RDR and APS-Digester system will be desirable for effective treatment of the organic fractions of municipal solid waste. The APS-Digester performed well for treating the rotary drum reactor-pretreated organic waste at OLR of 9.2 gVS L^{-1} d^{-1} with an average biogas and methane yields of 0.38 and 0.19 L gVS^{-1} and the average biogas production rate of 3.5 L $L^{-1}d^{-1}$.

Conclusions and Recommendations for Future Research

The organics generated from the rotary drum reactor contained 50 percent total solids (TS) and 36 percent volatile solids (VS) on wet basis and were used as feedstock for a continuous APS-Digester system. The results showed that the APS-Digester operated well at an organic solids loading rates (OLRs) from 3.1 to 9.2 gVS L^{-1} d^{-1}. At the OLR of 9.2 gVS L^{-1} d^{-1} the system biogas production rate was 3.5 L L^{-1} d^{-1} and the biogas and methane yields were 0.38 and 0.19 L gVS^{-1}, respectively. Anaerobic digestion resulted in 38 percent TS reduction and 53 percent VS reduction in the organic solids. The changes of pH and volatile fatty acids (VFA) in all the reactors were measured. It was found that the total VFA concentration reached a peak value of 15,000 mg L^{-1} as acetic acid in the first three days of batch digestion and later decreased to about 500 mg L^{-1}. The APS-Digester system remained stable at each OLRs for over 100 days with the pH in the hydrolysis reactors in the range of 7.3 - 7.8 and the pH in the biogasification reactor in 7.9 - 8.1. The residual solids after the digestion had a high heating value of 14.7 kJ gTS^{-1}. Further research is needed to test and demonstrate an integrated rotary drum reactor-APS Digester system at pilot and commercial scales to determine the equipment requirement and process control and operational specifications.

Overall Conclusions and Recommendations

Characterization of Organic Waste Derived from Rotary Drum Reactors

The results of this study show that the biodegradable materials separated from municipal solid waste via a rotary drum reactor process are excellent feedstock for anaerobic digesters. The biogas yield of the organic waste samples measured after 20 days of batch anaerobic digestion under thermophilic conditions were found to vary between 533.0 to 675.6 mL g^{-1}VS. The 90 percent of the biogas yield was achieved after 13 days of anaerobic digestion for all the samples tested. The average methane content of the biogas varied between 58.0 to 59.9 percent. As a comparison, a food waste sample was also tested and showed a biogas yield of 598.4 mL g^{-1}VS and 68.1 percent methane content in the biogas.

Although the six rotary drum facilities evaluated had significant variation in the retention time (from 6 h to 5 days), the biogas yields of their biodegradable organic waste samples were similar. The organic waste samples from the plant with the shorter retention time (six hours) showed a relatively higher biogas yield. This result is significant if a rotary drum plant is to be designed for preparing the municipal solid waste as feedstock for anaerobic digesters as a shorter retention time corresponds to a smaller rotary drum facility and less capital investment. The residuals after the anaerobic digestion could be further processed for compost production or use as feedstock for thermal conversion systems, such as combustion and gasification, for further energy recovery.

Effect of retention time in the RDR and waste types on the characteristics of organic waste recovered for anaerobic digestion

The results of this study showed that the rotary drum process could be used as an effective technology for separation and pretreatment of the organic materials in municipal solid waste prior to anaerobic digestion. For the four types of waste materials studied, the organic fractions recovered from the rotary drum process showed similar characteristics with regard to the anaerobic digestion, in terms of biogas and methane yields which ranged 457 - 557 mL gVS^{-1} and 261 - 320 mL gVS^{-1}, respectively, after 20 d digestion at 50$\pm$1°C. Methane content of biogas ranged from 57.3-60.6 percent. The organic material recovered from the mixture of municipal solid waste and biosolids with one-day retention time in the rotary drum showed the highest biogas yield (557 mL gVS^{-1}), while the organic material recovered from paper and biosolids mixture with one-day retention time in the rotary drum showed the lowest biogas yield (457 mL gVS^{-1}). About 90 percent of the total biogas yield was achieved in the first 10 days of digestion for most of the samples. The TS and VS reductions in the various rotary drum-treated wastes after 20 days of anaerobic digestion were 48.4 - 65.0 percent and 51.8 - 69.3 percent, respectively. One-day retention time is preferable among the three retention times (1, 2, and 3 days) tested based on the test results of organic fractions as shorter retention time translates to either smaller drums or fewer drums and better economics. However, further studies are recommended to determine the minimum retention time requirements in the drum for different types of wastes, and to assess the separation efficiencies of the organic fraction under different retention times.

Continuous anaerobic digestion of RDR treated waste using APS-Digester

The results of this study showed that the organic waste derived from rotary drum reactors could be well digested in a continuous anaerobic digester system. The APS-Digester showed very good performance at organic loading rates (OLRs) from 3.1 to 9.2 gVS L^{-1} d^{-1}. At the OLR of 9.2 gVS L^{-1} d^{-1} the system biogas production rate was 3.5 L L^{-1} d^{-1} and the biogas and methane yields were 0.38 and 0.19 L gVS^{-1}, respectively, using the organic waste with 50 percent TS and 36 percent VS. Anaerobic digestion resulted in 38 percent TS reduction and 53 percent VS reduction in the organic solids. The changes of pH and volatile fatty acids (VFA) in all the reactors were measured. It was found that the total VFA concentration reached a peak value of 15,000 mg L^{-1} as acetic acid in the first three days after the waste was loaded into a hydrolysis reactor and later decreased to about 500 mg L^{-1}. The APS-Digester system remained stable at each OLRs for over 100 days with the pH in the hydrolysis reactors in the range of 7.3 - 7.8 and the pH in the biogasification reactor in 7.9 - 8.1. The residual solids after the digestion had a high heating value of 14.7 kJ gTS^{-1}. Further research should be pursued to test and demonstrate an integrated system at pilot and commercial scales to determine the equipment requirement and process control and operational specifications. The integrated system could include rotary drum reactors, anaerobic digestion, composting, and other processes for achieving the purposes of energy recovery, compost production, and waste reduction. For such an integrated system, energy and mass balance calculations are needed to determine the separation, conversion, and transformation efficiencies for individual components present in the municipal solid waste and an economic analysis will be useful for assessing the costs and benefits of applying such an integrated system to the municipal solid waste treatment.

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