THESIS

IMPLICATIONS OF SOLID AND LIQUID WASTE CO-DISPOSAL ON BIODEGRADATION AND BIOCHEMICAL COMPATIBILITY

Submitted by

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ABSTRACT

IMPLICATIONS OF SOLID AND LIQUID WASTE CO-DISPOSAL ON BIODEGRADATION AND BIOCHEMICAL COMPATIBILITY

Co-disposal of solid and liquid waste in municipal solid waste (MSW) landfills can benefit landfill operations via enhancing waste moisture content and accelerating in situ waste biodegradation. However, implications of co-disposal on organic waste biodegradation are currently unknown and co-disposal in full-scale landfills is ad hoc. The objective of this study was to evaluate waste biodegradation and biochemical compatibility for different co-disposed solid and liquid wastes in MSW. To meet this objective, laboratory-scale reactors were operated to evaluate the potential impacts of co-disposal and ultimately to provide guidance for full-scale MSW landfill operations. Waste collected for this project was identified as MSW, special solid waste (SW), liquid waste (LW), and sludge waste (Sludge), such that reactor experiments were conducted with representative co-disposal combinations of MSW-SW, MSW-LW, and MSW-Sludge. The MSW-SW and MSW-Sludge reactors included landfill leachate as a liquid source to generate effluent; MSW-LW reactors were operated with unique liquid wastes.

The MSW-LW reactors remained in the acid formation phase of biodegradation for the duration of the experiment. The liquid waste addition in the MSW-LW reactors was not an effective means to initiate biodegradation and is not recommended as an additive to fresh MSW without an inoculum that contains methanogenic microorganisms. All MSW-Sludge waste reactors and all but one set of the MSW-SW reactors reached methanogenesis. The solid and sludge wastes did not exhibit signs of biochemical incompatibility. The use of biochemical methane potential (BMP) assays as a selection tool for waste co-disposal was also evaluated. The BMP assays did not show good agreement with data from reactors that generated methane; therefore, use of BMP assays alone as a selection tool is not recommended.

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

There is considerable interest in solid waste management to develop operational strategies that accelerate waste decomposition, enhance methane (CH_4) production, and provide in-situ leachate treatment in municipal solid waste (MSW) landfills. The most common strategy is to operate a landfill as a bioreactor, which is typically achieved through leachate recirculation and addition of supplemental liquids to increase the in-situ moisture content and stimulate microbial-induced biodegradation (e.g., Bareither et al. 2010; Barlaz et al. 2010; Townsend et al. 2015). The specific strategy of interest for this study was the co-disposal of supplemental liquid waste with solid waste.

Co-disposal of solid and liquid waste is a practical waste management approach for landfills operating with a U.S. EPA Subtitle D Research, Development, and Demonstration permit (RD&D – 40CFR 285.4). An RD&D permit provides landfill owners operational and technological flexibility to enhance waste moisture content as long as there are no detrimental impacts on human health and the environment. The U.S. EPA initiated the RD&D rule in 2004 to promote innovative landfill technologies, which include bulk liquid waste addition. Individual states must apply to adapt the RD&D rule and receive formal approval from the U.S. EPA prior to issuing permits to landfills. A ten-year review of the rule revealed that 16 states had adopted the rule and that 30 landfills had active RD&D permits (USEPA 2014b).

Although the U.S. EPA RD&D review indicated relatively low participation nationally, landfills located in states where regulations require a reduction in degradable organic material prior to landfill closure have successfully implemented the RD&D rule. Of the active RD&D projects, nearly half (13 of 30) are located in the state of Wisconsin (USEPA 2014b). The Wisconsin Department of Natural Resources initiated an Organic Stability Rule (OSR) (Section NR 514.07(9), Wis. Adm. Code) in 2007 that requires landfills to reduce the amount of biodegradable organic material remaining after closure to reduce the time required to achieve organic stability and for post-closure care. Landfill operators in the state of Wisconsin have elected to participate in the RD&D program and use liquid waste addition to promote organic stability (Bareither et al. 2017).

A state-of-practice (SOP) review on organic waste stabilization in MSW landfills in Wisconsin indicated that in-situ anaerobic treatment via liquid waste addition and leachate recirculation was the predominant strategy to enhance waste stabilization (Bareither et al. 2017). Typical supplemental liquids added to MSW landfills included storm water, groundwater, on-site rinse water, gas condensate, commercial and residential liquid wastes, and solidified liquid wastes (e.g., sludge) (Bareither et al. 2017; Nwaokorie 2017). At all landfills practicing liquid waste addition, owners noted that co-disposal of solid and liquid waste was economically and environmentally attractive due to revenue from waste tipping fees and promotion of organic waste decomposition. Additionally, at sites where leachate treatment costs were high and liquid waste disposal was a revenue source, operators sought out high moisture retaining wastes such as foundry waste and automobile shredder residue to co-dispose with the liquid waste. However, compatibility testing to evaluate unintended consequences that may arise from co-disposal of a wide variety of waste types was not implemented at any of the landfills. Thus, one of the limitations identified during the OSR review of Wisconsin landfills operating with RD&D permits was a lack of understanding of the effects of co-disposing diverse solid and liquid wastes on biochemical compatibility and organic waste decomposition (Bareither et al. 2017).

1.2 Research Objectives and Tasks

Currently, there is no guidance on assessing biochemical compatibility of solid and liquid wastes co-disposed in MSW landfills, and there are no requirements to assess compatibility prior to co-disposal to ensure that the environmental benefits attributed to enhanced waste decomposition are realized. Additionally, increasing contributions of special solid wastes in MSW landfills may introduce unknown biochemical compatibility issues that hinder organic waste decomposition. Thus, there is a need to evaluate the effects of solid and liquid waste co-disposal on CH_4 generation and leachate quality (i.e., monitoring parameters of organic waste decomposition) with a future goal of developing decision tools to guide landfill-based solid waste management. There is also a need to establish indicator parameters based on waste composition that can be used to identify potentially compatible and incompatible solid and liquid wastes.

The objective of this project was to evaluate co-disposal of solid and liquid waste in laboratory-scale MSW reactors to develop guidance on biochemical compatibility issues and develop guidance for co-disposal operations. The following research tasks were conducted to complete this study:

I. Procured and characterized representative non-hazardous solid, sludge, and liquid wastes;
II. Conducted biochemical methane potential assays to characterize the anaerobic degradability and CH_4 yield of each waste type for use as an indicator parameter in selection of compatible wastes for co-disposal;
III. Designed, constructed, and operated laboratory-scale reactors that facilitated gas collection and leachate recirculation to study the co-disposal of different combinations of solid-solid, solid-liquid, and solid-sludge wastes;
IV. Quantified and characterized leachate and gas generated in each reactor throughout operation; and
V. Developed guidance for landfill operators for the co-disposal of non-hazardous solid, liquid, and sludge waste streams in MSW landfills.

CHAPTER 2: BACKGROUND

2.1 Bioreactor Landfills

A landfill is an engineered solid waste disposal facility that is designed and operated in a manner to protect human health and the environment. Conventional operation of landfills limits the ingress of moisture into the waste mass to minimize leachate generation. Waste containment barrier systems (i.e., liners and covers) are used to isolate the waste mass and prevent environmental contamination. With this conventional or “dry-tomb” approach, waste can remain undegraded for long periods of time, possibly in excess of the design life of the barrier system, which extends the time required for post-closure monitoring and maintenance of a landfill (Reinhart et al. 2002).

Biodegradation of the organic fraction of solid waste can be accelerated through operation of a landfill as a bioreactor. An anaerobic bioreactor landfill is an MSW landfill operated with the intended goal of enhanced anaerobic biodegradation of the organic fraction of the solid waste (Bareither et al. 2010). A schematic of a bioreactor landfill is included in Fig. 1 (Waste Management 2004). The benefits realized from operating a landfill as a bioreactor include increased potential for waste-to-energy conversion, storage and on-site treatment of leachate, airspace recovery from more rapid settlement, and reduced time required for long-term monitoring and maintenance of the landfill after closure (Reinhart et al. 2002; Barlaz et al. 2010). To stimulate the rate of biodegradation, favorable environmental conditions including pH, temperature, moisture content, waste particle size, oxidation-reduction potential, nutrient availability, and the absence of toxins can be modified. The most critical control parameter to enhance biodegradation has been found to be the waste moisture content (Reinhart and Al-Yousfi 1996; Reinhart et al. 2002).

The most common strategy to enhance waste moisture content in landfills is leachate recirculation and supplemental liquid addition (Bareither et al. 2010). Leachate recirculation has been found to be the most practical approach for moisture enhancement, such that most bioreactor strategies incorporate this technique (Reinhart et al. 2002). Leachate recirculation is also a proven method for in-situ leachate treatment. Studies have shown that leachate recirculation reduces waste stabilization time, improves final leachate quality, and enhances biogas generation (Reinhart and Al-Yousfi 1996; Sponza and Agdag 2004; Barlaz et al. 2010).

Landfill gas (LFG) is the major end product of biological decomposition in a landfill (Barlaz et al. 2009). The primary components of LFG are 50-60% CH_4 and 40-50% carbon dioxide (CO_2) during active anaerobic biodegradation (Amini et al. 2012). Methane is an important greenhouse gas and landfills are estimated to be the second largest source of anthropogenic CH_4 emissions in the U.S. (Barlaz et al. 2009). Therefore, LFG management is an important environmental consideration, especially in bioreactor landfills where gas production is accelerated.

Early and aggressive gas management strategies need to be initiated at bioreactor landfills operating to enhance waste degradation. The shortened lag-time between waste placement and gas generation combined with the enhanced rate of biogas generation from a bioreactor are advantageous from a gas collection and energy generation perspective. However, a more rapid onset and enhanced rate of biogas generation can increase fugitive emissions and odors, which are regulatory and operational concerns (Bareither et al. 2017).

2.1.1 Waste Stabilization

The goal of moisture addition in landfills is to achieve stabilization of the organic waste fraction in a shorter duration than a conventional landfill to reduce the post closure care period. Organic stability is viewed as a state of near complete decomposition of organic waste constituents such that human health, environmental, and financial risks associated with undecomposed waste are reduced (Bareither et al. 2017). Waste stabilization in landfills occurs in five phases: (i) initial adjustment phase, (ii) transition phase, (iii) acid formation phase, (iv) methanogenesis, and (v) maturation phase (Pohland and Gould 1986; Reinhart and Al-Yousfi

1996; Dhesi 2003). Temporal trends of gas generation, gas composition, and leachate chemistry during the five phases of waste stabilization are shown in Fig. 2 (Pohland and Gould 1986).

I. Initial adjustment: This phase is associated with initial solid waste placement and continues until sufficient moisture accumulates to support microbial activity.

II. Transition: The transformation from an aerobic to anaerobic environment occurs in this phase. Reducing conditions are established, oxygen (O_2) is displaced by CO_2, and increasing concentrations of total volatile acids (TVA) and chemical oxygen demand (COD) are observed in the leachate.

III. Acid Formation: In the acid phase, hydrolysis of solids followed by microbial conversion of organic compounds to intermediate organic acids occurs. The high acid concentrations result in a pH decrease in the leachate.

IV. Methanogenesis: In this phase, intermediate organic acids are consumed by methanogenic bacteria and mineralized to CH_4 and CO_2. Additionally, sulfates are reduced to sulfides, nitrates are reduced to ammonia, pH increases, and leachate strength decreases (e.g., reduction in COD).

V. Maturation: In the final phase of waste stabilization, nutrients and degradable substrate becomes limiting. As a result, biological activity and gas production dramatically decrease, and leachate quality remains constant at low concentrations.

2.1.2 Anaerobic Digestion Inhibition

Certain operational practices can be inhibitory to anaerobic digestion. Stable anaerobic digestion processes require an established microbial community to completely degrade organic substrate into CH_4, CO_2, and water (Griffin et al 1998). Failure to maintain balance between acid forming and CH_4 forming microorganisms was identified as a primary cause of reactor instability (Griffin et al. 1998; Chen et al. 2008). In a biosolids co-disposal experiment, an aggressive anaerobic digester start-up with high initial substrate loading resulted in organic acid accumulation, which lead to suboptimal digester performance. A more gradual reactor start-up strategy was recommended for anaerobic digesters to maintain sufficient methanogens in the system (Griffin et al. 1998). In general, leachate recirculation is an effective method for waste decomposition if managed properly; however, large recirculation volumes can generate high organic acid concentrations and yield low pH that can be inhibitory to methanogenesis (Sponza and Agdag 2004).

In addition to organic acid accumulation, common inhibitors to anaerobic digestion, including ammonia, sulfide, sodium, and heavy metals, were found to cause reactor upset when accumulation of these compounds occurred. Methanogens are the least tolerant of the anaerobic microorganisms and most likely to cease growth due to ammonia inhibition. Ammonia has been found to be inhibitory to anaerobic digestion at concentrations as low as 1,700 mg NH_3-N/L. Sulfate reduction to sulfide can suppress CH_4 production through competition for substrates. High sodium concentrations exceeding 3,500 mg/L can affect metabolic activity of methanogens. Heavy metal accumulation can disrupt enzyme function and can also be a major cause of digester instability. Co-digestion with other wastes can improve anaerobic treatment and counteract inhibition via buffering and dilution of inhibitory compounds (Chen et al. 2008).

2.1.3 Performance Evaluation of Bioreactor Landfills

A review of bioreactor landfill performance in the U.S. was conducted by Bareither et al. (2010) and Barlaz et al. (2010). Five full-scale landfills that recirculated leachate, and in some cases disposed supplemental liquids, were included in their study. Rationale for bioreactor operation at these sites included on-site leachate treatment, airspace recovery, enhanced gas generation, and maximization of waste decomposition to reduce long-term risks and costs of landfill operation. Contaminated runoff and leachate were the primary liquids recirculated in the landfills evaluated. In one landfill, pretreated industrial wastewater and septage from an on-site wastewater treatment plant were recirculated. Liquid dosing via horizontal trenches ranged from

30 to 419 L/Mg of waste, on average. Overall, only landfills with aggressive recirculation achieved moisture contents approaching field capacity, and supplemental liquid addition was identified as a potential option to further increase the moisture content and achieve field capacity (Bareither et al. 2010).

In addition to the physical aspects of bioreactor landfills, the study in Bareither et al. (2010) and Barlaz et al. (2010) also addressed biological and chemical aspects. Data from the landfills support accelerated CH_4 generation and increased gas collection. Trends in leachate chemistry were consistent with bioreactor behavior. The pH recovered to a value above neutral, consistent with conversion of organic acids to CH_4, the ratio of biological oxygen demand to chemical oxygen demand (BOD:COD) showed a decreasing trend consistent with degradation of organics, and ammonia concentrations increased, but not to inhibitory levels. Heavy metals and organic chemicals were not significantly different from leachate generated in conventional landfills (Barlaz et al. 2010).

Additional performance reviews were conducted on bioreactor landfills practicing moisture enhancement under the OSR in the state of Wisconsin (Bareither et al. 2017; Nwaokorie 2017). Wisconsin regulations now require that within 40 years of closure, new landfills are to have a monthly average gas production rate of ≤ 5% of the peak value and a cumulative gas yield of ≥ 75% of the projected total production (Bareither et al. 2017). This review included 10 landfills and found that leachate recirculation and liquid waste addition were the predominant operational strategies implemented. Eight of the ten landfills were practicing liquid addition under an RD&D permit. Common liquid waste sources included manufacturing cleaning water, automobile wash water, and industrial sludge. Liquids were added in volumes ranging from 0 to nearly 12,000 m^3/yr. Incompatibility during solid-liquid co-disposal was not observed, but the potential for biochemical incompatibility exists as more liquid wastes are disposed. Implementation of the OSR resulted in accelerated decomposition with no apparent negative environmental impacts, and all 10 landfills were on track to achieve the OSR requirements (Bareither et al. 2017).

Nwaokorie (2017) conducted a site-specific study to determine first-order decay rates for a bioreactor landfill with different moisture enhancement strategies that included leachate recirculation and liquid addition. Liquid waste was added during different phases of the landfill, with cumulative application rates ranging from 0 to 76 L/Mg of waste. Increased gas generation in all phases of the landfill demonstrated that the implemented moisture enhancement strategies promoted waste degradation. The greatest CH_4 flow rates per MSW mass and the largest cumulative CH_4 generation per MSW mass were measured in the operational phase that implemented early and aggressive recirculation as well as continuous liquid waste addition (Nwaokorie 2017).

2.2 Co-Disposal in Landfills

Co-disposal in landfills has been described as the disposal of industrial wastewaters and sludges in landfills containing domestic and other non-industrial wastes (Watson-Craik and Sinclair 1995). Properly managed co-disposal of compatible solid and liquid waste streams in landfills can be an effective method to manage multiple waste streams in one process through concurrent wastewater treatment and accelerated solid waste stabilization. The benefits of co-disposing wastes with complementary characteristics include dilution of potentially inhibitory compounds, improved availability of essential nutrients, synergistic effect of microorganisms, increased biodegradable organic loading, enhanced CH_4 yield, and increased anaerobic digestion rates (Agdag and Sponza 2005; Agdag and Sponza 2007; Sosnowski et al. 2003).

To achieve safe and effective co-disposal of liquid waste in landfills with no reduction in leachate quality, a thorough understanding of biochemical removal mechanisms of each waste and the effect on microbial communities is required (Watson-Craik and Senior 1989). The pH of the liquid waste is a major factor to consider before disposing liquid in a landfill, and the impact on microbial communities or the need to buffer should be assessed. Elevated concentrations of inhibitory compounds such as salts and heavy metals should also be evaluated. Municipal solid waste has some capacity to attenuate toxins and buffer against extreme pH values, but chemical composition of a liquid waste should be carefully evaluated prior to disposal (Townsend et al. 2015)

Biochemical methane potential assays are a convenient method to assess substrate degradation and ultimate CH_4 yield and can also serve as an indicator parameter for initial waste selection or screening for co-disposal applications (Townsend et al. 2015). Several different waste streams that represent a range of potential solid, liquid, or sludge wastes for co-disposal can be analyzed using a BMP assay. Wastes that show high methane potential indicate that co-disposal could enhance the degradation and methane yield relative to degradation of MSW alone. However, BMP assays create optimal conditions for anaerobic degradation and methane production, often masking toxicity issues. Therefore, BMP results and their use as a selection tool for co-disposal applications should be validated with lab-scale experiments (Moody et al. 2011).

2.2.1 Co-Disposal of MSW with Liquid Waste

Liquid waste co-disposal in landfills is advantageous as this practice generates revenue for landfills, relieves industrial wastewater loading at wastewater treatment plants, provides a disposal alternative to industrial liquid generators, and can aid in in-situ waste degradation (Bareither et al, 2017). Additionally, percolation through the waste body can provide treatment to the liquid waste due to the ability of the waste mass to serve as an anaerobic biofilter for the degradation of industrial wastewaters (Rahim and Watson-Craik 1997; Diamantis et al. 2013). The disposal of commercial liquid wastes can be a more sustainable practice to achieve enhanced degradation compared to supplementing recirculation with groundwater or freshwater sources (Dhesi 2003).

In addition to bioreactor projects that have used liquid waste co-disposal in the U.S. (Bareither et al. 2010; Barlaz et al. 2010; USEPA 2014b; Bareither et al. 2017; Nwaokorie 2017), industrial liquid waste co-disposal with MSW has been documented in landfills in the United

Kingdom (Knox 1983), Kuwait (Al Yaqout 2003), and Korea (Behera et al. 2011). Knox reported no adverse impacts on leachate quality from the disposal of liquid wastes directly into landfills over a 20-yr period. However, Al Yaqout (2003) reported that liquid and sludge waste comprised approximately 37% of the total waste disposed by mass, and these large unregulated quantities disposed in unlined landfills posed a major risk to the surrounding environment. Behera et al. (2011) demonstrated that food waste leachate injection directly into landfills can be a sustainable waste management solution that provides treatment to the leachate and enhances CH_4 production.

Limited laboratory-scale research has been conducted on the co-disposal of liquid wastes with MSW. Laboratory studies using lysimeters, refuse columns, and biochemical methane potential (BMP) assays have evaluated the impacts of olive vegetation wastewater (Cossu et al. 1993), phenolic wastewater (Watson-Craik and Senior 1989; Percival and Senior 1998), supplemental water for leachate recirculation (Sanphoti et al. 2006), food waste leachate (Lee et al. 2009), livestock wastewater (Zhang et al. 2012), dairy wastewater (Ko et al. 2012), brewery wastewater (Rahim and Watson-Craik 1997; Ko et al. 2012), and fishery wastewater (Ko et al. 2012). General trends and recommendations reported by these studies are summarized below.

- Co-disposal of liquid waste did not reduce leachate quality, but in fact, improved leachate quality with recirculation of the dissolved organic matter (Cossu et al. 1993, Rahim and Watson-Craik 1997). This is consistent with the common finding that leachate recirculation is more beneficial for waste decomposition than single elution experiments, because degradable substrates are reapplied to the waste containing microbial communities rather than flushed out with the leachate (Watson-Craik and Senior 1989; Percival and Senior 1998; Sponza and Agdag 2004; Sanphoti et al. 2006).
- Methane generation was enhanced by co-disposal with liquid waste (Watson-Craik and Senior 1989; Rahim and Watson-Craik 1997; Sanphoti et al. 2006).

- Wastewater loading and strength should be controlled, as high-strength wastewaters can adversely affect CH_4 production (Rahim and Watson-Craik 1997) or cause MSW to release rather than attenuate contaminants (Percival and Senior 1998).
- Fresh waste, compared to aged methanogenically active waste, requires buffering against acidic conditions (Watson-Craik and Senior 1989; Cossu et al. 1993; Percival and Senior 1998) and buffering was found to accelerate MSW stabilization (Sanphoti et al. 2006). Several studies recommended that wastewater should be applied during methanogenesis, rather than the acid formation phase, to achieve greater CH_4 generation and improved leachate quality. Wastewater application during the acid formation phase could inhibit or delay methanogenesis (Cossu et al. 1993; Percival and Senior 1998; Ko et al. 2012). However, other studies demonstrated contradictory results (Sanphoti et al. 2006; Nwaokorie 2017). Reactor experiments conducted by Sanphoti et al. (2006) suggested that supplemental water addition in the early acid formation phase accelerated CH_4 production and resulted in higher CH_4 generation, indicating early addition of water to the waste can be an effective strategy for the acceleration of the CH_4 generation phase. Nwaokorie (2017) also reported early and aggressive liquid addition was beneficial to waste decomposition in a field-scale landfill practicing liquid addition.
- Ko et al. (2012) identified that the phase when CH_4 generation begins to accelerate is the most environmentally sensitive period for methanogenesis and that liquid addition could have either a positive or negative effect depending on the liquid chemistry. However, the largest demand for moisture in a bioreactor is also when CH_4 generation begins to accelerate, therefore evaluation of moisture addition during this phase should be further evaluated.

Co-disposal can be an effective means for both wastewater treatment and solid waste stabilization if operational parameters are carefully researched and controlled (Rahim and Watson-Craik 1997; Percival and Senior 1998). However, basic information regarding liquid waste disposal in landfills is not currently available and the research available may have limited relevance due to varying environmental factors and diverse waste types (Sanphoti et al. 2006).

In addition to laboratory- and field-scale research on liquid addition in landfills, comprehensive literature and data reviews were conducted to better understand the impacts of liquid waste co-disposal. Dhesi (2003) evaluated potential industrial wastewaters for co-disposal and conducted feasibility studies as well as economic, hydraulic, and gas modeling. Several wastewater types were considered potential co-disposal sources, and four wastewater types were evaluated (municipal, food processing, brewery, and bakery). Dhesi (2003) reported that industrial wastewater co-disposal in landfills is feasible through theoretical simulations and calculations, but recommended more laboratory- and large-scale studies of industrial wastewater disposal in landfills to validate the models. Diamantis et al. (2013) investigated the feasibility of treating olive oil mill wastewater via disposal into closed landfills. They suggested that comprehensive guidelines to wastewater co-disposal are currently lacking and called for more field studies to establish reliable design data for wastewater disposal in landfills.

2.2.2 Co-Disposal of MSW with Sludge Waste

Co-disposal of sludge waste with MSW is another method of interest to enhance waste degradation. Sludge wastes provide a source of supplemental moisture as well as potential revenue to a landfill owner via disposal fees. Research regarding the co-disposal of MSW with industrial sludge is limited. Studies have been conducted in laboratory-scale reactors to investigate co-disposal of MSW with heavy metal sludge (Pohland and Gould 1986), dye industry sludge (Agdag and Sponza 2005), and mixed sludge from textile, metal plating, electronic, chemical, and plastic industries (Agdag and Sponza 2007). Pohland and Gould (1986) found that higher loading rates of heavy metal sludge inhibited landfill microbial processes, but landfills were able to acclimate at low sludge loading levels. Agdag and Sponza (2005) reported that high concentrations of dye industry sludge containing metals showed toxic effects, but low concentrations of trace metals provided nutrients that positively influenced methanogenic growth. Overall leachate quality was improved with sludge co-disposal but CH_4 generation decreased (Agdag and Sponza 2005). In a follow-up study investigating a mixed source of industrial sludge, Agdag and Sponza (2007) reported that industrial sludge co-disposal improved leachate quality and had a stimulatory effect on CH_4 generation, which suggested co-disposal of MSW with mixed industrial sludge was a viable management technique.

The co-disposal of sewage sludge with MSW has been researched to a greater extent and is the most commonly proposed sludge for co-disposal applications. There is some reluctance from landfill operators to co-dispose sewage solids due to operational difficulties (mixing and compacting), odors, and health risks associated with pathogenic organisms (Townsend et al. 2015). However, when co-disposed with MSW, sewage sludge provides moisture, CH_4 potential, nutrients and a source of anaerobic microorganisms (Watson-Craik and Sinclair 1995; Bae et al. 1998; Townsend et al. 2015). A laboratory-scale study investigating co-disposal of anaerobically digested sludge with MSW indicated that the continuous addition of active methanogens was significantly more effective in waste stabilization than leachate recirculation. In that study, the reactor receiving anaerobic sludge produced 78 times more CH_4 than the reactor recirculating landfill leachate (Bae et al. 1998).

2.2.3 Co-Disposal of MSW with Industrial Solid Waste

Industrial solid waste streams disposed in MSW landfills can also influence biochemistry of the landfill and impact CH_4 generation and leachate quality. Construction and demolition (C&D) waste is one of the larger fractions of solid waste (Townsend et al. 1999; USEPA 2014a), and has been reported to be approximately 20% of total solids (MSW plus C&D) discarded in landfills (Staley and Barlaz 2009). The primary components include concrete, asphalt, wood, metal, gypsum board, cardboard, plastic, soil, and vegetation. Gypsum ($CaSO_4$) is the most biologically relevant component of C&D waste and is a major source of corrosion and hydrogen sulfide (H_2S)

production (Fairweather and Barlaz 1998). Hydrogen sulfide gas is toxic and poses a health threat in confined spaces. High H_2S concentrations can cause rapid corrosion of gas handling equipment, and flared H_2S converts to SO_2 in the atmosphere, which is regulated (Xu et al. 2011). Sulfate reduction and methanogenesis can occur concurrently, and in fact, sulfate reduction can create reduced environments more suitable for methanogenesis, whereby the onset of CH_4 production is accelerated (Rahim and Watson-Craik 1997; Fairweather and Barlaz 1998).

Foundry waste and automobile shredder residue were identified as highly absorbent waste materials for moisture retention during liquid waste co-disposal (Bareither et al. 2017). Foundries use high-quality, size-specific silica sands for use in their molding and casting processes. Waste foundry sand typically consists of silica sand and a binder to form molds for ferrous and nonferrous metal castings. The chemical composition of the waste foundry sand depends on the type of metal and binder, but leachate generated from waste foundry sand generally consists of various organic compounds, polyaromatic compounds, phenols, formaldehyde, metals (Pb, Ni, Cu, Zn, and Hg), and mineral oils (Siddique et al. 2010).

Automobile shredder residue is waste that remains from vehicles after recovery of metals and dismantled parts. The shredder residue typically consists of plastics, metals, rubber, textile, foam, glass, and wood. Metals contained in shredder residue (Fe, Al, Zn, and Cu) can influence gas production. Studies conducted by Aghdam et al. (2016) found that iron and copper in shredder residue inhibited CH_4 generation, but aluminum and zinc contributed to higher CH_4 percentages and lower CO_2 percentages than typically observed in landfills. Hydrogen production from bio-corrosion of aluminum and zinc can be utilized by methanogens to convert CO_2 to CH_4 (Aghdam et al. 2016).

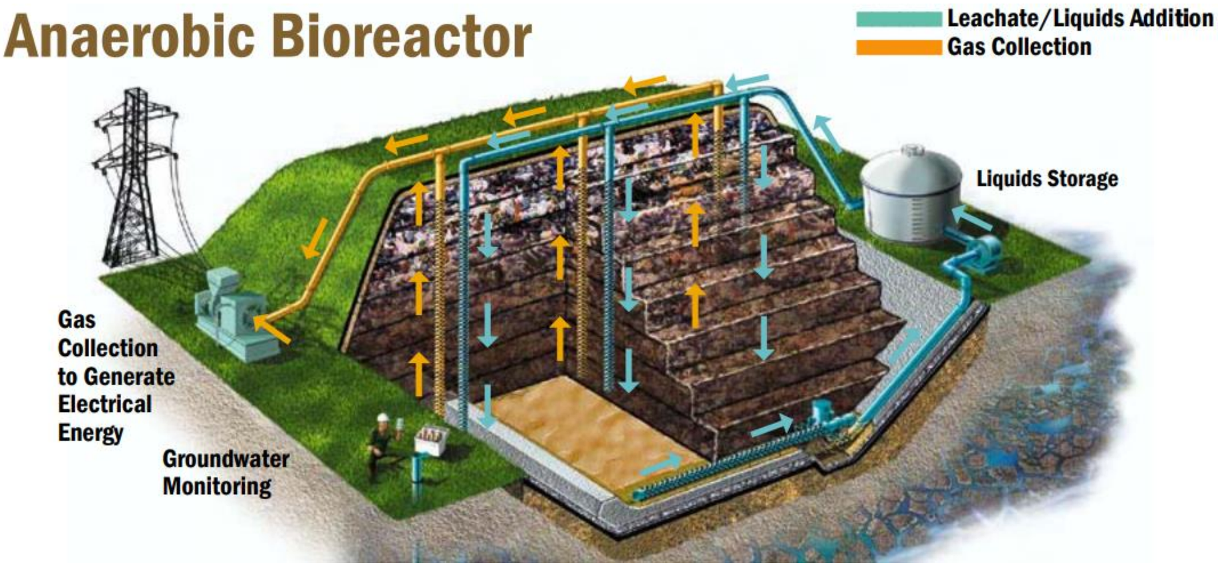


Figure 1. Schematic of an anaerobic bioreactor (Waste Management 2004).

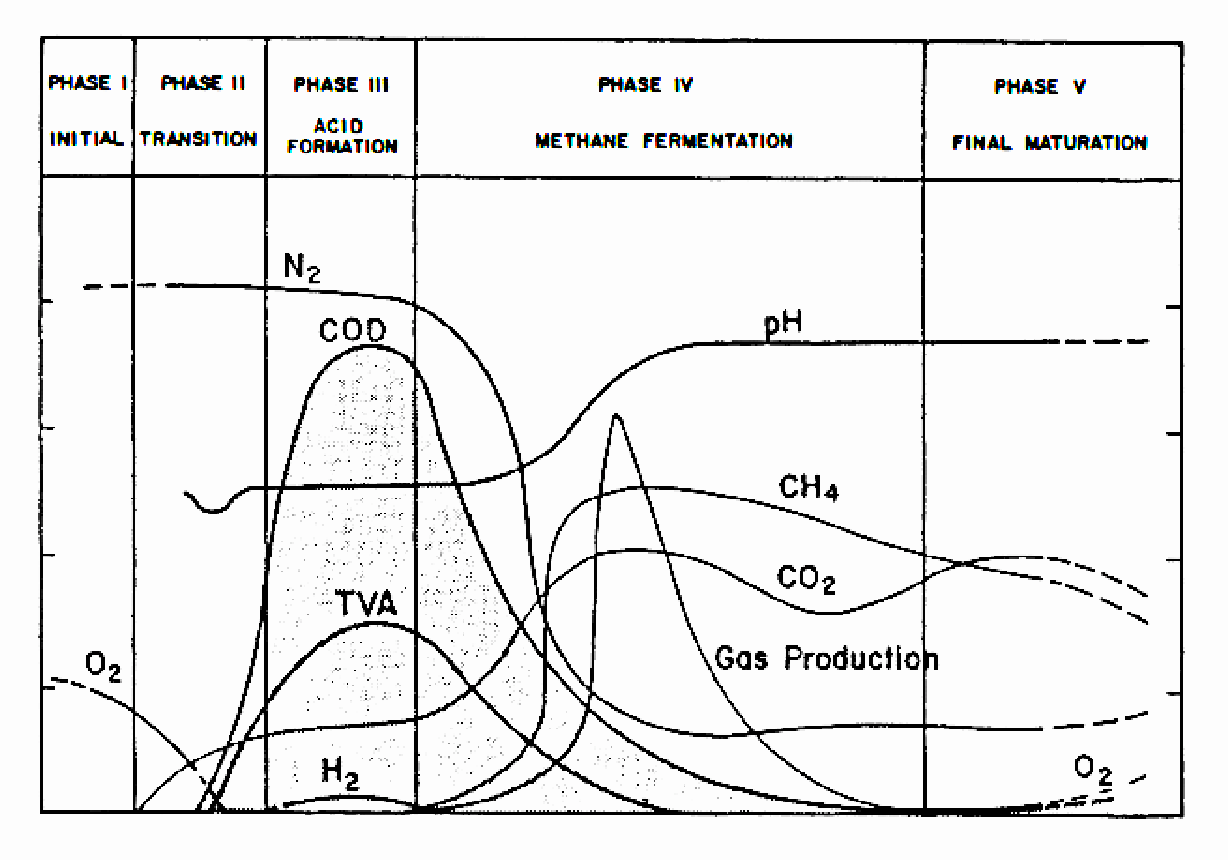


Figure 2. Changes in selected indicator parameters during the phases of landfill stabilization (Pohland and Gould 1986).

CHAPTER 3: METHODOLOGY

3.1 Experimental Overview

Laboratory-scale column reactors were designed and constructed to study the co-disposal of solid and liquid waste that could occur in MSW landfills. Reactors were designed to facilitate gas collection and leachate recirculation during experimental operation. Wastes used in this study included MSW, three types of industrial solid waste, two types of sludge waste, and six types of liquid waste. The specific wastes were selected to represent common wastes co-disposed in landfills based on a study of ten solid waste landfills (Bareither et al. 2017). A compilation of reactor photographs is included in Appendix D.

3.2 Materials

3.2.1 Municipal Solid Waste

A summary of the percent composition of the target MSW as well as the MSW composition used for experiments conducted in this study is in Table 1. The target MSW was based on summaries of the U.S. national average reported in literature (Staley and Barlaz 2009; USEPA 2014a). The actual MSW composition for this study was adjusted to simplify two waste categories (paper and plastics) and omit the “other” waste category reported in literature. The USEPA (2014) did not distinguish between paper and cardboard or rigid plastic and film plastic, so these percentages were further refined based on Staley and Barlaz (2009).

The MSW was collected from a local landfill, separated into individual components, air dried, shredded using a motorized shredder (Model 1-SHRED-H-0800 Sludge Grinder, JWC Environmental, Santa Ana, CA), and passed through a 19-mm sieve. The processed waste was stored in sealed containers at room temperature, with the exception of food waste. Pre-consumer, pulped produce was collected fresh from Colorado State University dining facilities and stored at 4 °C prior to creating an MSW mixture for experimentation. Individual waste components were recombined proportionately to achieve the initial waste composition reported in Table 1. All waste fractions were added based on aid-dried mass, except food waste, which was added based on total (wet) mass to add moisture to the initial MSW mixture.

Characterization of the solid wastes included dry-weight water content (w_d), volatile solids (VS), and biochemical methane potential (BMP) (analytical procedures for solid waste characterization described subsequently). The initial w_d, VS, and BMP of the MSW used for all reactor experiments is in Table 2. The w_d after food waste addition was approximately 33%, which is typical for fresh MSW disposed in landfills (Hanson et al. 2010; Bareither et al. 2012a; Bareither et al. 2013). The BMP for MSW was 95.3 mL-CH_4/g MSW (95.3 m^3-CH_4/Mg-MSW), on a dry mass basis. This methane yield is similar to ranges reported in literature for MSW (Chickering et al. 2018).

3.2.2 Industrial Solid Waste

Representative industrial solid wastes selected for this study included construction and demolition (C&D) waste, automobile shredder residue (ASR), and foundry waste. The C&D waste was represented using gypsum board (GB), which is the most biologically important component in C&D waste. The ASR consisted of shredded non-metallic, non-recyclable components of vehicles and was collected from a local vehicle salvage facility. The foundry waste (FW) was collected from a local bronze casting facility and consisted primarily of non-reusable casting shell. The casting shell was made from a mixture of silica flour and water. The industrial solid wastes were shredded, sieved, and stored in sealed containers at room temperature until used.

The initial w_d, VS, and BMP of the three industrial solid wastes are in Table 2. The high VS content (76%) and high BMP (20 mL-CH_4/g-waste) of the ASR indicate that the material may be beneficial for co-disposal. Low VS content for FW (0.0%) and GB (3.5%), and the negative BMP values (FW = -0.2 and GB = -3.0 mL-CH_4/g-waste), suggest that FW and GB waste streams could perform poorly or even inhibit anaerobic biodegradation if co-disposed with MSW. The negative BMP indicates that the BMP assays for the FW and GB yielded less CH_4 relative to the inoculum alone. The w_d of the industrial solids was low ($w_d < 21$ %) due to the air-drying step during waste processing.

3.2.3 Liquid Waste

Representative liquid wastes selected for this study included landfill leachate (LL), brewery wastewater (BW), cheese production wastewater (CW), automobile wash water (AWW), high-strength manufacturing plant wastewater (MW-H), and low-strength manufacturing plant wastewater (MW-L). High-strength manufacturing plant wastewater consisted of degreasers, coolants, and other industrial chemicals. The low-strength manufacturing plant wastewater was high-strength wastewater that had been filtered and treated for oils and grease and then mixed with plant cleaning water. Landfill leachate was collected from a local MSW landfill and the other liquid wastes were collected directly from the local wastewater generators. Liquids were stored in collapsible containers with minimal headspace at 4 °C until used. Deionized water (DIW) was used as a control liquid.

The initial characteristics of the liquid wastes are in Table 3. Characterization of the liquid wastes included total solids, VS, COD, ammonia, pH, electrical conductivity (EC), oxidation-reduction potential (ORP), and BMP (analytical procedures for liquid characterization described subsequently). Most of the liquid wastes, except MW-H, had a pH less than neutral. The MW-H and BW wastewaters had the greatest COD (367,140 and 57,750 mg O_2/L, respectively), and the greatest BMP yields (23 and 19 mL-CH_4/mL-liquid waste, respectively). These relatively high COD and BMP levels indicate high organic loading and suggest that these high strength wastewaters could potentially enhance CH_4 generation in co-disposal applications relative to MSW alone. The liquid wastes with lower COD (< 2,500 mg O_2/L) corresponded to low BMP (< 0.6 mL-CH_4/mL-liquid waste). The liquid wastes generally had low EC and ammonia levels, suggesting that increased ammonia or salinity inhibition from their addition to MSW should not occur.

3.2.4 Sludge Waste

The sludge wastes selected for this study include anaerobic digester (AD) sludge from the anaerobic digester of a local wastewater treatment plant and industrial sludge (IS) from the fracking industry. The AD sludge had low solids content and was characterized similar to the liquid wastes (Table 3), whereas the industrial sludge had higher solids content and was characterized similar to the solid wastes (Table 2). The industrial sludge was fracking sludge waste provided by a manufacturer. Although this material had a very high water content (w_d = 760%), the industrial sludge would classify as "solidified waste" based on passing the paint filter test (EPA Method 9095B). In contrast, the AD sludge was more liquid-like than the industrial sludge, but trial experiments resulted in clogging of the filter (photograph included in Appendix D) and tubing and indicted that the AD sludge could not be treated similar to the other liquid wastes. Thus, the AD sludge was viewed similar to the industrial sludge to provide further distinction between the wastes used in this study (i.e., solid, liquid, and sludge).

Both IS and AD sludge were expected to perform well in co-disposal experiments. The industrial and anaerobic sludge wastes both had high VS contents (VS > 73%) and high w_d to serve as a moisture source. The IS sludge showed relatively high BMP compared to the other solid wastes (Table 2). The AD sludge was not evaluated for BMP because the sludge was used as inoculum in the assays. The anaerobic sludge was a good source of methanogenic organisms and the sludge yielded the lowest ORP (-56.5 mV) of all of the liquid wastes.

The AD sludge was collected from the digesters of a local wastewater treatment plant in collapsible storage containers and stored at 4 °C with minimal headspace in the container. The fracking sludge was received in sealed 5-gallon buckets and stored at 4 °C until use.

3.3 Reactor Design

A summary of the 24 reactors operated for this study is in Table 4. The 24 reactors included 12 unique combinations of wastes, and each waste combination was evaluated in duplicate. The waste combinations represented MSW plus solid waste co-disposal (MSW-SW), MSW plus sludge waste co-disposal (MSW-Sludge), and MSW plus liquid waste co-disposal (MSW-LW). All 12 waste combinations include MSW that was mixed with a unique solid, sludge, or liquid waste. The MSW-SW reactors included mixtures prepared with gypsum board, auto shredder residue, or foundry waste. The MSW-Sludge reactors included MSW mixed with industrial sludge or anaerobic digestion sludge. The MSW-LW reactors included MSW mixed with auto wash water, brewery wastewater, cheese production wastewater, the high- and low-strength manufacturing plant wastewaters, and landfill leachate. A set of control reactors was operated only with MSW and DIW.

Effluent from each reactor was recirculated during reactor operation. In the MSW-LW reactors, effluent was generated from the liquid waste addition and these reactors were constrained to only MSW and a single liquid waste. In the MSW-SW and MSW-Sludge reactors, leachate collected from an MSW landfill (LL in Table 3) was used to help generate effluent, which was subsequently recirculated in a given reactor (Table 4). The MSW-LW reactor that received landfill leachate also served as a control for these solid and sludge co-disposal combinations.

A schematic for a laboratory reactor is shown in Fig. 3. Each reactor included a 457-mm-tall by 203-mm-diameter polycarbonate cylinder. The cylinder was fitted with an effluent port installed in the base cap for leachate collection and an influent port installed in the top cap for liquid addition and leachate recirculation. Each port was fitted with a two-way valve to maintain a gas tight system and allow effluent collection or recirculation as needed. The top cap of the cylinder was also fitted with a gas line connected to a 10-L flexfoil gas collection bag (SKC Inc., Eight Four, PA). The gas line was fitted with a four-way valve (with a “closed” position) to facilitate gas sampling and detachment of the collection bag during volume measurement. The reactor base was epoxied to the cylinder and the reactor lid was secured to the cylinder using silicon sealant to create a gas-tight system. After each reactor was filled with waste, they were flushed with nitrogen gas to promote anaerobic conditions. All reactors were operated in a temperature controlled room maintained at 37°C to create mesophilic conditions.

The waste specimens in each reactor were sandwiched between layers of nonwoven geotextiles and gravel (Fig. 3). A 50-mm-thick layer of washed gravel was placed at the base of the reactor to allow for drainage and effluent storage between recirculation intervals. A gravel layer was placed on top of the waste specimen to evenly distribute recirculated liquid to the surface of a waste specimen. The surface gravel provided a 2-kPa surface stress on the waste specimens that represented interim landfill cover (Bareither et al. 2013). Settlement of each waste specimen was measured via a measuring tape adhered to the outside of the clear cylinder. Nonwoven geotextiles were placed between the gravel layers and the waste to provide separation between the materials and prevent clogging of the drainage layer and effluent port.

Initial waste specimen thickness and density in each reactor are tabulated in Table 4. Each specimen was prepared with a 2.4-kg solid waste mixture. A total mass of 2.4 kg was selected because this mass of MSW approximated the target specimen thickness of 203 mm when compacted via hand tamping in four equal layers. All MSW-LW reactors included similarly prepared MSW specimens (Table 4) that included an initial total MSW mass of 2.4 kg. In contrast, the MSW-SW and MSW-Sludge specimens were mixed with MSW at a ratio of 60:40 MSW to solid waste or MSW to sludge waste, by total mass; this ratio was selected based on data from a study of 10 solid waste landfills (Bareither et al. 2017).

The individual MSW components combined to create the MSW for each reactor were thoroughly mixed to ensure each reactor include a similar MSW composition. Special solid and sludge wastes were also thoroughly mixed with MSW to achieve as homogenous of a waste mixture as possible in these select reactors. Food waste, and sludge when applicable, was added to the mixture 24 h prior to starting an experiment to hydrate the waste specimen. The initial specimen thicknesses in all reactors ranged from 121 mm to 208 mm, resulting in a total density range between 0.35 and 0.61 g/cm^3 (Table 4).

3.4 Reactor Leachate Recirculation and Sampling

A summary of the initial liquid dose volume, initial recirculation volume, and w_d after dosing is in Table 4. The initial liquid dose volume was added in increments during the first week of reactor operation via injection into the top influent port of the reactor (Fig. 3). Dosing began on Day 1 of each experiment, and liquid was added incrementally to promote liquid retention within a given waste specimen. The initial dose volumes ranged from 450 to 1800 mL (188 to 750 L/Mg-waste), with a target volume of 1500 mL to represent typical liquid dosing rates of liters of liquid added per mass of total waste (L/Mg-waste) in full-scale landfills (Bareither et al. 2010; Nwaokorie et al. 2017). Smaller dose volumes were added to the MSW-Sludge specimens since the as-prepared waste mixtures with sludge had high initial w_d. Initial dose volumes in the MSW-SW were adjusted based on observed effluent generation. The overarching goal of liquid addition in all reactors was to exceed moisture holding capacity of the waste and generate sufficient effluent liquid for recirculation.

Dry-weight water contents after dosing ranged from 60% to 150% (Table 4) and initial recirculated volumes ranged from 130 to 330 mL (53 to 139 L/Mg-waste). The greatest w_d after initial dosing were in the MSW-Sludge reactors due to the high initial water contents of the sludge. In contrast, the lowest w_d after dosing were in the MSW-SW reactors, which varied between 59% and 94% based on initial dose volume and moisture retention capacity of the solid waste. The w_d after initial dosing in all MSW-LW reactors and the MSW reactor with DIW were similar, and ranged between 97% and 108%, indicating that moisture retention of the MSW was similar for the six different liquid wastes and DIW.

Effluent was extracted from the drainage layer via syringe once per week and recirculated (Fig. 3). Recirculated liquid was buffered using a 2M sodium hydroxide solution to raise the pH above 7 to mitigate against acidic conditions in the waste that can inhibit methanogenesis. The entire volume of liquid collected from the drainage layer, minus a small amount extracted to assess liquid chemistry, was recirculated each week. Recirculated liquid was injected into the top influent port via a syringe.

Effluent samples were collected weekly and analyzed immediately for pH, EC, ORP, and ammonia. The effluent samples were then preserved via acidification to pH ≤ 2 using sulfuric acid (approximately 4 drops per 5 mL sample) and stored at 4 °C for COD analysis. Select effluent samples were filtered using a 0.45-μm syringe filter and preserved with nitric acid (approximately 1 drop per 5 mL sample) for elemental analysis. Since the weekly effluent volumes extracted for liquid chemistry were not replaced, additional fresh liquid was added, as needed, to generate effluent. Additional dose volumes of 200 mL were added when effluent generation was needed, and similar dose volumes were always added to the duplicate reactors to maintain consistency between duplicates.

3.5 Analytical Methods

3.5.1 Solids Analysis

Solid waste was analyzed for w_d and VS. Water contents were determined by oven drying samples for a minimum of 24 h at 105 °C, or until the change in mass was negligible with continued oven drying. Volatile solids were measured as the mass loss on ignition at 550 °C. The VS specimens were ignited for a minimum of 2 h, or until the change in mass loss was negligible.

3.5.2 Liquid Analysis

The as-collected liquid wastes were analyzed for total solids, VS, pH, EC, ORP, COD, ammonia, metals, and other elements. The total solids content was determined by evaporating samples in a steam bath and then oven drying the remaining solids at 105 °C until the change in mass was negligible. Volatile solids were determined as previously described for solid wastes. The pH, EC, and ORP were measured using a portable multi-parameter meter (Hach Sension+ MM150) with a multi-sensor probe (Sension+ 5048). Chemical oxygen demand was measured using a Hach 0-1500 mg/L test kit. The COD samples were digested using a Hach DRB200 heating block and results were read using a Hach DR2500 spectrophotometer. Five-point calibration curves covering the entire concentration range of the test kit for COD were generated with a potassium hydrogen phthalate solution. Ammonia was measured using a Hach 0.4-50 mg NH_3-N/L test kit. Measurements were conducted on the Hach DR2500 spectrophotometer and five-point calibration curves were generated with an ammonium sulfate solution. Metals and elemental analysis were conducted using an inductively coupled plasma-optical emission spectrometer (Optima 7300, PerkinElmer, Waltham, MA).

3.5.3 Gas Collection and Analysis

Biogas generated during reactor operation was collected in 10-L flexfoil bags. Gas volume was measured via water displacement. Gas was evacuated from a collection bag into the measuring device using a vacuum pump. The measuring device was an inverted 1-L graduated cylinder submerged in water acidified to $pH \approx 3$ with hydrochloric acid. Gas volume measurements were recorded after the displaced cylinder equilibrated with atmospheric conditions.

Biogas was sampled for composition analysis each time a gas bag was evacuated for volume measurement. Gas was extracted from the gas line sampling port using a syringe and was injected into gas-tight evacuated glass vials. Gas samples were then extracted from the glass vials using a 100 µL gas tight syringe (Hamilton GASTIGHT #1730, Reno, NV) and were injected into a gas chromatograph (GC). Samples were analyzed for CO_2 and CH_4 using an HP6890 GC (Hewlett-Packard, Palo Alto, CA) equipped with a thermal conductivity detector (TCD) and RT-Q-Bond column (Restek Corporation, Bellefonte, PA). OpenLAB chromatography data system software (Agilent Technologies, Santa Clara, CA) was used as the data interface for the GC. A program was created within OpenLAB to achieve separation between nitrogen, CH_4, and CO_2. Deviations from the software defaults include a 30 °C inlet and oven temperature, 200 °C TCD temperature, 50 cm/s linear velocity in the column, 40:1 split flow, and hydrogen was used as the carrier gas. Percentages of CO_2 and CH_4 were determined relative to calibration curves generated from chemically pure CO_2 and CH_4 gas (Airgas, Radnor, PA).

3.5.4 Biochemical Methane Potential Assay

The BMP assays were conducted to determine the maximum amount of CH_4 generated per mass of VS or COD of a given substrate under ideal anaerobic degradation conditions. A compilation of BMP photographs is included in Appendix D. Biochemical methane potential assays were conducted using a modified procedure based on protocols described in the literature (Owen et al. 1979; Wang et al. 1994; Moody et al. 2011; Wilson et al. 2013). Solid wastes for BMP tests were ground using a Wiley mill (Standard Model No. 3, Arthur H. Thomas Co., Philadelphia, PA) and passed through a 2-mm screen. Solid waste masses were selected to achieve a target value of 5 g-VS/L in the assay bottle. An arbitrary mass of 5 g was selected for the drywall and foundry waste assays because these wastes contained negligible VS. Liquid samples for BMP tests were prepared to target a concentration of 5 g-COD/L. The MSW leachate, automobile wash water, and cheese processing wastewaters all had initial COD concentrations < 5 g COD/L; therefore, these liquids were tested as-received.

Active anaerobic bacteria and sufficient nutrients were supplied to each BMP assay to ensure ideal conditions for anaerobic biodegradation. Nutrient media was created following the protocol described in Owen et al. (1978). Concentrated stock solutions were mixed and stored at 4 °C. Nutrient media was mixed fresh the day a BMP test was initiated. In assays containing liquid samples, the liquid waste was used as the diluent water to make the media solution in lieu of DIW to conserve specimen volume in the assay bottles. Anaerobically digested sludge from the local wastewater treatment plant was collected fresh and was used as the inoculum. Media and inoculum were supplied to test bottles at a 1:1 ratio (Wilson et al. 2013). Assays were prepared in 165-mL serum bottles with 50 mL of media and 50 mL of inoculum. Negative controls containing inoculum and media with no substrate were created to measure background CH_4 production from the inoculum and to adjust measured gas volumes of the other assays. For quality assurance purposes, positive controls were also created using readily degradable glucose to ensure inoculum and media were not limiting CH_4 production. All BMP tests were run in triplicate for a given waste.

The BMP tests were carried out at 37 °C and bottles were continuously mixed using a shaker table operating at 150 rpm. Serum bottles were sealed with a rubber septum and aluminum crimp caps. The headspace in the assay bottles was flushed with nitrogen gas for several minutes after sealing the caps and then the bottles were vented to atmospheric conditions using a wetted 10-mL glass syringe. Gas volume was measured periodically using a wetted 10-mL glass syringe. Samples were analyzed for CH_4 composition each time gas volume was measured. Samples for gas analysis were extracted directly from the serum bottle using a 100-μL gas tight syringe and immediately injected into the GC for composition analysis (as previously described).

Table 1. Target municipal solid waste (MSW) composition based on literature and the adjusted MSW composition used in this study.

Individual MSW Component	Target Composition (%)	Adjusted Composition used in This Study (%) [a]
Paper and cardboard	14.3	
Paper[b]	10.9	11.4
Cardboard[b]	3.4	3.5
Yard trimmings	7.9	8.2
Metals	9.4	9.8
Glass	5.2	5.4
Plastics	18.5	
Rigid[b]	14.9	15.5
Film[b]	3.6	3.8
Wood	8.1	8.5
Food [c]	21.6	22.5
Rubber/leather/textiles	10.8	11.3
Other	4.2	

[a] Percentages adjusted to exclude “other” category reported by the U.S. EPA.

[b] USEPA (2014a) does not distinguish between paper and cardboard, or between rigid and film plastic; target compositions for these categories were established using data reported in Staley and Barlaz (2009).

[c] Food waste added on wet basis to achieve a total mixture water content of approximately 33%.

Table 2. Initial dry weight water content (w_d), volatile solids (VS), and 60 day biochemical methane potential (BMP) for the solid wastes and industrial sludge.

Solid Waste	w_d [%]	VS [%]	BMP [mL-CH_4 /g-solid waste]	BMP [mL-CH_4 /g-VS]
MSW	32.6	74.0	95.3	128.8
GB	21.1	3.5	-3.0	-[a]
ASR	2.5	76.2	20.0	26.9
FW	0.3	0.0	-0.2	-[a]
IS	759.3	73.2	9.2	12.5

Notes: MSW = municipal solid waste; GM = gypsum board; ASR = automobile shredder residue; FW = foundry waste; and IS = industrial sludge.

[a] GB and FW volatile solids were too low for BMP on a VS-basis to be conducted.

Table 3. Initial characteristics of the liquid wastes and anaerobic digester sludge, including total solids content (TS), volatile solids (VS), chemical oxygen demand (COD), ammonia, pH, electrical conductivity (EC), oxidation-reduction potential (ORP), and 60-day biochemical methane potential (BMP).

Liquid Waste	TS [%]	VS [%]	COD [mg O_2 /L]	Ammonia [mg/L NH_3-N]	pH	EC [mS/ cm]	ORP [mV]	BMP [mL-CH_4/mL-liquid waste]	BMP [mL-CH_4/ g-COD]
LL	2.5	9.3	1,460	86.4	6.8	3.2	7.5	0.3	213.6
BW	2.3	96.8	57,750	58.0	4.6	1.6	228.5	18.7	324.6
CW	0.2	55.4	2,530	9.0	3.9	2.0	234.5	0.6	234.3
AWW	0.1	38.4	230	0.6	6.2	0.2	232.6	0.0	-22.9
MW-H	8.6	96.4	367,140	275.8	7.7	2.2	127.3	22.6	61.6
MW-L	0.4	83.4	22,110	24.8	6.5	0.7	-7.3	1.2	54.3
AD	1.8	77.0	20,990	1129.9	7.2	7.5	-56.5	-[a]	-[a]

Notes: LL = landfill leachate; BW = brewery wastewater; CW = cheese production wastewater; AWW = automobile wash water; MW-H = manufacturing plant high-strength wastewater; MW-L = manufacturing plant low-strength wastewater; and AD = anaerobically digested sludge.

[a] Anaerobic sludge served as the inoculum in BMP assays and was therefore not analyzed for a BMP yield.

Table 4. Summary of the laboratory reactors, including waste components of each reactor, initial specimen thickness and density, initial liquid dose volume, initial liquid recirculation volume, and dry-weight water content (w_d) after initial dosing.

Reactor	Solid Waste	Liquid Source	Thickness [cm]	Density [g/cm^3]	Initial Dose [L/Mg-waste]	Initial Recirculated Volume [L/Mg-waste]	w_d after Dosing [%]
DIW-1	MSW	DIW	20.6	0.36	625	95	103
DIW-2	MSW	DIW	20.8	0.36	625	124	99
LL-1	MSW	LL	20.6	0.36	625	109	101
LL-2	MSW	LL	20.0	0.37	625	113	100
CW-1	MSW	BW	20.6	0.36	625	120	108
CW-2	MSW	BW	20.6	0.36	625	91	105
AWW-1	MSW	CW	20.0	0.37	625	123	100
AWW-2	MSW	CW	20.2	0.37	625	139	103
MW-H-1	MSW	AWW	20.0	0.37	625	87	99
MW-H-2	MSW	AWW	20.8	0.36	625	60	97
MW-L-1	MSW	MW-H	20.3	0.36	625	104	104
MW-L-2	MSW	MW-H	20.6	0.36	625	109	108
GB-1	MSW	MW-L	20.3	0.36	750	114	102
GB-2	MSW	MW-L	21.1	0.35	750	95	101
ASR-1	MSW + GB	LL	18.4	0.40	458	102	92
ASR-2	MSW + GB	LL	20.0	0.37	458	53	94
FW-1	MSW + ASR	LL	18.7	0.40	458	70	59
FW-2	MSW + ARR	LL	18.4	0.40	458	59	65
AD-1	MSW + FW	LL	15.2	0.49	188	109	63
AD-2	MSW + FW	LL	16.0	0.46	188	110	64
AD-1	MSW + AD	LL	14.0	0.53	333	93	135
AD-2	MSW + AD	LL	12.7	0.58	333	75	135
IS-1	MSW + IS	LL	12.7	0.58	547	95	149
IS-2	MSW + IS	LL	12.1	0.61	188	53	152
Average			18.5	0.41	750	139	102
Minimum			12.1	0.35	625	95	59
Maximum			21.1	0.61	625	124	152

Notes: DIW = deionized water; MSW = municipal solid waste; LL = landfill leachate; BW = brewery wastewater; CW = cheese production wastewater; AWW = automobile wash water; MW-H = manufacturing plant high-strength wastewater; MW-L = manufacturing plant low-strength wastewater; GB = gypsum board; ASR = automobile shredder residue; FW = foundry waste; IS = industrial sludge; and AD = anaerobically digested sludge.

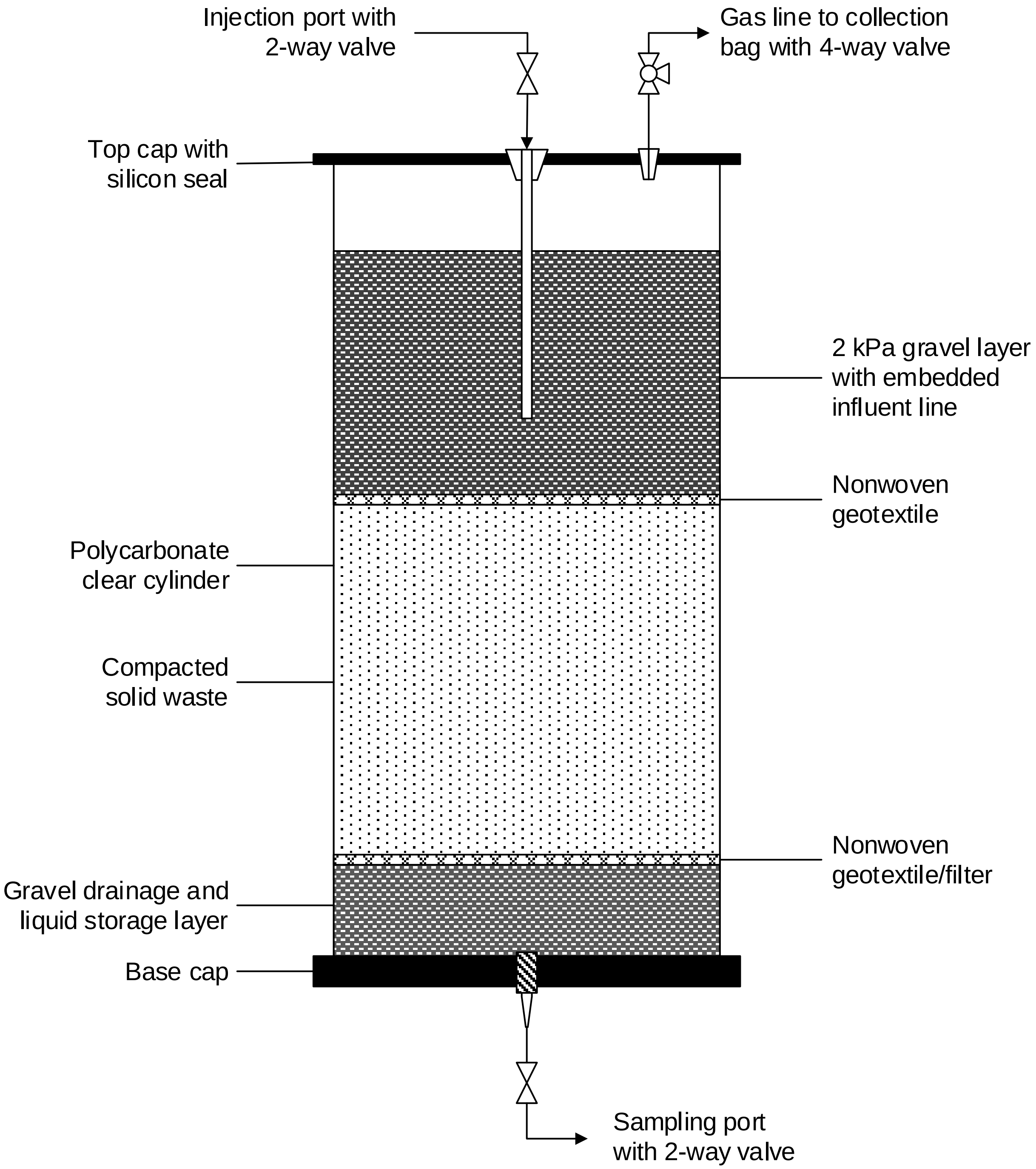


Figure 3. Schematic of a laboratory reactor.

CHAPTER 4: RESULTS AND DISCUSSION

A summary of the co-disposal reactors, at the end of each reactor time (105 to 140 d), is in Table 5, and includes the experiment duration, cumulative liquid recirculated per mass of waste, average weekly does rate, % settlement, pH, peak COD, COD reduction, total CH_4 generation, peak percent contribution of CH_4, and peak CH_4 flow rate. Reactor effluent was recirculated and sampled weekly, whereas gas was analyzed as needed (e.g., higher sampling rates were adopted for reactors that generated more gas). Parameters monitored in the reactors and included in this analysis were effluent recirculation volumes, % settlement, pH, EC, ORP, COD, ammonia, select heavy metals and other inorganic elements, and CH_4 generation. Complete data sets for the 24 reactor experiments are included in Appendix A (plots and summary data) and Appendix B (tabulated data).

Results from the reactors were grouped by reactor type: controls (DIW and LL reactors), MSW-LW (BW, CW, AWW, MW-H, and MW-L), MSW-SW (GB, ASR, and FW), and MSW-Sludge (AD and IS). Results are also discussed in terms of degradation phase. In general, the control and liquid waste reactors remained in the acid formation phase throughout the duration of reactor operation, the sludge reactors all reached methanogenesis, and there were varied results for the solid waste reactors. Six of the 24 reactors generated CH_4 during the duration of the experiment reported herein.

Duplicate reactors showed repeatable results prior to the onset of CH_4 generation. Once CH_4 generation began in one of the duplicates, differences observed in leachate and gas data were likely attributed to the biological activity. Control and liquid waste reactors did not produce CH_4, and therefore data between duplicates was repeatable. In these cases where the duplicates yielded comparable data, the data were averaged for clarity when preparing summary graphs. Several of the solid waste reactors and all of the sludge waste reactors produced CH_4 and exhibited variations in temporal monitoring data due to differences in the onset and extent of biological activity. Reactors that generated CH_4 are discussed individually below.

4.1 Physical Reactor Characteristics

4.1.1 Recirculation Volumes

Cumulative recirculation volumes, excluding the initial dosing, and average weekly dose rates for the reactors are in Table 5. Liquid was added to each reactor with a series of initial doses intended to hydrate the waste and generate enough effluent for subsequent sampling and recirculation. Weekly recirculation rates after initial dosing ranged between 37 and 109 L/Mg-waste. These rates were comparable to recirculation rates used in similar laboratory-scale bioreactor experiments (Bareither et al. 2012a; Bareither et al. 2013) and are representative of aggressive recirculation operations implemented in full-scale bioreactor landfills (Benson et al. 2007; Bareither et al. 2010; Barlaz et al. 2010). Cumulative liquid recirculated into the reactors ranged from 517 to 1530 L/Mg- waste. These cumulative amounts agree with the higher range of both cumulative leachate recirculation and liquid addition reported in literature for full-scale bioreactor landfills (e.g., Bareither et al. 2010).

Reactors received supplemental dosing of fresh liquid (e.g., liquid waste) when sampling depleted the quantity of effluent available to an amount that prohibited further sampling. The DIW control, brewery wastewater, high-strength manufacturing wastewater, and automobile shredder residue (recirculated with landfill leachate) reactors received an additional 200 mL of liquid during reactor operation.

4.1.2 Settlement

Waste settlement was aided in each reactor via a gravel layer placed above the waste specimens, exerting a 2 kPa vertical stress. Waste settlement strain ranged from 0.9 to 9.1% (Table 5). The average settlement observed in the reactors (3.3%) was at the low range relative to settlement observed in bioreactor landfills (3-25%) (Benson 2007). The low magnitudes of settlement observed in the reactors were likely attributed to compaction of the waste specimens, the small surface stress applied by the gravel layer (Bareither et al. 2012b), and incomplete waste decomposition.

4.2 Leachate Quality

Leachate from full-scale MSW landfills contains four types of pollutants: dissolved organic matter, inorganic macrocomponents, heavy metals, and xenobiotic organic compounds (Kjeldsen et al. 2002). In this study, reactor leachate chemistry was analyzed to investigate the first three types of pollutants. Leachate composition and presence of select contaminants are dependent on the waste decomposition phase. Indicator parameters (pH, COD, ORP) were used to determine the decomposition phase in each reactor. Leachate strength was assessed via COD, ammonia, and EC, which also were used to assess effectiveness of the waste to provide leachate treatment. Heavy metals and inorganic macrocomponents were quantified to assess ability of the waste to mobilize or release potential pollutants.

4.2.1 Leachate Composition – Bulk Parameters

Temporal trends of reactor leachate pH, ORP, COD, and ammonia are shown in Figs. 4, 5, and 6 for MSW-LS, MSW-SW, and MSW-Sludge reactors, respectively. Electrical conductivity trends were similar to COD and were not included in the summary figures (EC data are in Appendix A). Leachate chemistry at the end of the experiments generally agreed with ranges of pH, COD, EC, and ammonia for full-scale MSW landfills (e.g., Kjeldsen et al. 2002; Barlaz et al. 2010).

The pH of the reactor leachate was monitored to determine if acidic conditions were present in the waste. Landfill leachate typically has pH ranging between 4.5 and 9.0 (Kjeldsen et al. 2002). The final pH ranged from 5.6 to 5.8 in the LL and DIW reactors, from 5.5 to 6.1 in the

MSW-LW reactors, from 5.3 to 7.0 in the MSW-SW reactors, and from 7.3 to 8.3 in the MSW-Sludge reactors (Table 5). The GB, AD, and IS reactors were the only reactors to achieve neutral pH during the experiment.

Oxidation reduction potential was monitored to determine if a reducing environment suitable for CH_4 generation was achieved (ORP < -200 mV). Similar to trends in pH, OPR < -200 mV was only measured in the GB, AD and IS reactors. These three reactors also generated CH_4 (described in section 4.3.2, below), which supports the leachate chemistry trends in pH and ORP.

Reactor leachate COD was monitored to determine leachate strength and when organic acids were generated (increasing COD) and either buffered or mineralized to biogas (decreasing COD). Landfill leachate COD can encompass a broad range in full-scale landfills, from 140 to 152,000 mg O_2/L (Kjeldsen et al. 2002). The COD measured in the reactor experiments was within the range reported for full-scale landfills, with the greatest COD achieved in the brewery wastewater reactors (peak COD = 65,720 mg O_2/L in BW-1, Table 5). The DIW, LL, and all MSW-LW reactors as well as the FW and ASR (solid waste) reactors appeared to exhibit increasing or constant COD trends during reactor operation, whereas the MSW-Sludge and GB reactors appeared to exhibit decreasing COD trends during reactor operation. In the reactors where COD appeared to continue to increase, acid generating microorganisms were likely the dominant microbial community.

Ammonia was measured in all reactors to evaluate if elevated ammonia concentrations were established and whether these could be linked to potential reactor inhibition. Ammonia inhibition of methanogenesis has been reported at concentrations as low as 1,700 mg NH_3-N/L (Chen et al. 2008), but concentrations up to 2,200 mg NH_3-N/L are typical in landfill leachate (Kjeldsen et al. 2002). The brewery wastewater (BW in Fig. 4d) and the industrial sludge reactors (IS-1 and IS-2 in Fig. 6d) generated ammonia concentrations that exceeded the low-end inhibition threshold of 1,700 mg NH_3-N/L. The brewery wastewater did not exceed the typical landfill leachate range for ammonia, and inhibition in the BW reactors, as well as all of the other liquid waste reactors, was most likely due to acidic conditions rather than ammonia concentrations. Although both industrial sludge reactors exceeded ammonia concentrations of 2,500 mg NH_3-N/L, ammonia did not inhibit CH_4 generation, as CH_4 generation was observed in both of the IS reactors.

The electrical conductivity of the reactor leachate is presented with the complete reactor data sets in Appendix A. Typical leachate EC reported for landfills ranges from 2.5 to 35 mS/cm (Kjeldsen et al 2002). Approximately half of the reactors (DIW-1 & 2, LL-1 & 2, BW-1 & 2, AWW-1 & 2, MW-H-1, MW-L-1 & 2, FW-2, and IS-2) exceeded the 35 mS/cm threshold at some point during the experiment, but all values were within the range reported by Kjeldsen et al. (2002) at the final day of leachate sampling. Temporal trends in EC were similar to COD trends, whereby EC increased with COD generation and decreased with COD removal.

4.2.2 Leachate Composition – Elemental Analysis

Liquid wastes and reactor leachate samples were analyzed for heavy metals and other common elements found in landfill leachate. Results from the ICP analysis for the liquid wastes sources, the initial recirculated volume of leachate generated, and the final volume of leachate generated are discussed briefly here. The complete data set is reported in Appendix C. Results were compared to typical landfill leachate concentrations as well as federal drinking water maximum contaminant levels (MCL – 40CFR 141.11) and non-enforceable secondary MCL concentrations (40CFR 143.3). Heavy metals and other elements generally did not exceed typical concentrations reported for landfills (Kjeldsen et al. 2002), but several MCL and secondary MCL concentrations were exceeded.

With few exceptions, heavy metal and inorganic component concentrations increased with one recirculation through the waste mass relative to concentrations measured in the initial wastewater source. Final concentrations in the recirculated reactor leachate did not exceed typical landfill leachate concentrations in literature (Kjeldsen et al. 2002). Phosphorus was the exception, whereby the concentration in most reactors exceeded 23 mg/L at the initial measurement and after the duration of the experiment. In the majority of reactors, Ca, Fe, K, Mn, Na, Ni, Pb, and Zn concentrations increased with recirculation. In all of the reactors, the concentration of Al, Cd, Cu, and P decreased with recirculation.

Maximum contaminant levels for Cd, Cr, and Pb were exceeded in several reactors at the end of the experiment. Secondary MCL concentrations were exceeded for Mn in all reactors, Fe in all but one reactor, and Al and Zn in several reactors at the end of the experiment. However, none of these concentrations exceeded limits typical of landfill leachate.

Increases in Na concentrations were observed in most of the reactors. The increase in Na concentration was attributed to the use of NaOH to buffer the reactor leachate and increase pH prior to recirculation. Sodium can be inhibitory at concentrations as low as 3,500 mg/L (Chen et al. 2008), but concentrations in the reactor leachate did not exceed this threshold.

4.3 Transition To Methanogenesis

4.3.1 Leachate Indicator Parameter Trends

In the reactor experiments, pH, OPR, and COD were used as leachate indicator parameters to determine if a reactor was transitioning from the acid formation phase to methanogenesis. Concurrent increasing pH and decreasing COD trends are indicative of the conversion of organic acids to biogas. A decrease in ORP to negative values indicates development of a reduced environment suitable for CH_4 generation.

Leachate chemistry data for the liquid waste co-disposal reactors, previously presented in Fig. 4, suggest that the control reactors and all liquid waste reactors were still generating acid and potentially stuck in the acid formation phase. The pH decreased in all control and liquid waste reactors until approximately 60 d, and subsequently similar increasing trends were observed. The slow increase in pH from Day 60 onwards was likely attributed to leachate buffering with NaOH, which was used to help prevent stagnant acidic conditions. Oxidation reduction potential for the control and liquid waste reactors converged to approximately -100 mV (Fig. 4b), which typically is not low enough for a favorable methanogenic environment. In the majority of the liquid waste reactors, COD showed an increasing trend, indicating generation and subsequent accumulation of organic acids. The two greatest strength liquid wastes (BW and MW-H) showed high but fairly constant COD throughout the experiments. Methane generation was not observed in any of the liquid waste reactors or in the control reactor with DIW. However, minor CH_4 generation was observed in the control reactor with leachate, which may suggest future transition to the methane generating phase.

Leachate chemistry trends in the MSW-SW (Fig. 5) and MSW-Sludge (Fig. 6) reactors exhibited more pronounced variability during operation as compared to the liquid waste reactors. The main factor influencing temporal variability in leachate chemistry in the solid waste and sludge reactors was likely the development of methanogenesis in select reactors. For example, leachate chemistry trends in the industrial sludge reactors (IS-1 and IS-2) and anaerobic digestion sludge reactors (AD-1 and AD-2) exhibited increasing pH, ORP < -200 mV, and decreasing COD, which are all coincident with active methanogenesis (e.g., Pohland and Gould 1986; Reinhart and Al-Yousfi 1996). The solid waste reactors with gypsum board (GB-1 and GB-2) also exhibited similar temporal trends of leachate chemistry that coincided with methanogenesis. The FW reactors showed trends in leachate chemistry consistent with the acid generation phase, however, these reactors did produce measureable volumes of methane. The ASR reactors were the only set of MSW-SW reactors that did not achieve a neutral pH, low ORP, or decreasing COD concentration and also did not produce measurable CH_4 flow rates (biogas discussed in section 4.3.2 below).

4.3.2 Biogas Generation

Total CH_4 generation, peak percent CH_4 composition, and peak CH_4 generation rate are tabulated for each reactor in Table 5. Methane generation was observed in six reactors (AD-1, AD-2, IS-1, IS-2, FW-1, and GB-1) during the experiment. As discussed previously with regard to leachate chemistry, the MSW-LW reactors remained in the acid formation phase and had not produced CH_4. In addition, neither of the two sets of control reactors operated with DIW and LL produced considerable amounts of CH_4. However, the LL control reactors produced more CH_4 relative to the DIW controls (1.3 L compared to 0.0 L, on average), and headspace sampling of the reactors indicated higher percent CH_4 composition present in the LL control relative to the DIW control (27% compared to 2%, on average). The LL control, MSW-SW, and MSW-Sludge reactors were initially dosed with landfill leachate, which could have contained a source of methanogenic microorganisms. The industrial liquid wastes and the fresh MSW likely did not contain sources of methanogenic microorganisms, which could explain the inactivity in the liquid waste reactors relative to the solid waste and sludge reactors.

Temporal trends of cumulative CH_4 generation in the MSW-Sludge reactors are shown in Fig. 7. The sludge reactors were the four reactors that generated the most CH_4 from the 24 reactors operated for this study. The anaerobic digester sludge reactors, AD-1 and AD-2, produced 61 L and 31 L, respectively, and the industrial sludge reactors, IS-1 and IS-2, produced 31 L and 22 L, respectively. The AD reactors also achieved the greatest CH_4 generation rates, with AD-1 producing 1.9 L/d and AD-2 producing 1.5 L/d. The development of active CH_4 generation in the AD sludge reactors was probably aided by an active anaerobic microbial community present in the sludge. The industrial sludge reactors achieved the quickest onset of CH_4 generation.

Temporal trends of leachate chemistry (pH and COD) and cumulative CH_4 generation that highlight the transition to methanogenesis for the anaerobic digestion sludge reactors (AD-1 and AD-2) and the industrial sludge reactors (IS-1 and IS-2) are shown in Fig. 8. As noted previously, methanogenesis developed in all of the sludge reactors, which coincided with an increase in pH, decrease in COD, and increase in CH_4 generation that occurred simultaneously. These observations suggest that the sludge wastes used for the co-disposal experiments in this study did not inhibit anaerobic biodegradation. Furthermore, in comparison to the landfill leachate control reactor, the industrial sludge and anaerobic digestion sludge appeared to have accelerated the onset of methanogenesis.

Temporal trends of cumulative CH_4 generation in the MSW-SW reactors are shown in Fig. 9. The solid wastes that generated considerable amounts of CH_4 (i.e., GB-1 and FW-1) produced 4.5 L and 17.3 L, respectively. Their counterpart reactors, GB-2 and FW-2, only generated 1.2 L and 1.4 L, respectively. The range of CH_4 generation observed and the delay in onset of methanogenesis between duplicates is likely a result of the heterogeneous nature of the waste.

Leachate chemistry trends in the GB reactors, presented in Fig. 10, corresponded with an increase in pH and decrease in COD, as well as a decrease in ORP (Fig 5b). These chemical trends were indicative of the reactors transitioning into methanogenesis; however, only small amounts of CH_4 were generated in both of the GB reactors. The coupled trends of leachate chemistry and CH_4 generation for GB-1 and GB-2 in Fig. 10 identify lower COD concentrations relative to the other reactors that generated CH_4 (peak COD < 30,000 mg O_2/L). While GB-1 generated more methane than GB-2, the low COD concentrations in both of the GB reactor leachates may have been due to the low initial organic content of the MSW mixed with gypsum board (VS of GB = 3.5%, Table 2). Low COD concentrations were observed in similar MSW-gypsum board reactor experiments conducted by Fairweather and Barlaz (1998).

The FW reactors had atypical results relative to what would be anticipated for reactors with active anaerobic biodegradation. As shown in Fig. 10, pH decreased to < 5.5 and COD continued to increase after Day 100 of the experiment. Additionally, the ORP stabilized at approximately +50 mV (Fig. 5b). However, both reactors generated some CH_4, and reactor FW-1 generated the largest amount of CH_4 among the solid waste reactors (FW-1 = 17.3 L and FW-2 = 1.4 L, Table 5). The foundry waste experiments demonstrate that pH and ORP may not necessarily have to be in the ideal ranges for CH_4 generation. A study on spatial variability of microorganisms and pH in waste conducted by Staley et al. (2011) suggested that there may be the presence of pH neutral pockets within the waste mass that serve as methanogenesis initiation centers or that low pH tolerant methanogens could be responsible for this observation.

4.3.3 Biogas Composition

Temporal trends in biogas composition for the MSW-SW and MSW-Sludge reactors are shown in Figure 11. Typical CH_4 composition in landfills undergoing active anaerobic decomposition ranges from 50-60% (Amini et al. 2012). The peak CH_4 composition in the sludge reactors reached 62% in reactor AD-1, 49% in reactor AD-2, 61% in reactor IS-1, and 56% in reactor IS-2. The CH_4 composition observed in these reactors was consistent with typical landfills and indicative of established methanogenesis. Reactor FW-1 achieved a CH_4 fraction of 51%, also falling in the range typical for landfills. Reactor FW-2, however, has not yet achieved peak CH_4 generation, and has only achieved a peak CH_4 composition of 31% during the study period. The elevated methane content in FW-2 suggests that this reactor could be on the verge of transitioning to methanogenic conditions.

The GB-1 reactor exhibited decreasing CH_4 composition with time compared to the other reactors generating CH_4, and only achieved a peak CH_4 composition of 34%. GB-2 also exhibited low CH_4 content, and only achieved a peak composition of 12%. Gypsum board has high sulfate content, and potential sulfate reduction was noted in the GB reactors by the black coloration that developed (photograph included in Appendix D) (Rahim and Watson-Craik 1996) and the observed odors of H_2S gas. Although sulfate reduction can create favorable conditions for CH_4 generation (i.e., negative ORP), the low and decreasing trend of CH_4 content in GB-1 was likely due to competition between sulfate reducing bacteria and methanogens. This trend is consistent with similar MSW-gypsum board reactor experiments that observed decreased CH_4 content, which was attributed to organic carbon being diverted to sulfate reducers (Fairweather and Barlaz 1998).

Methane was detected in the reactor headspace for some of the reactors that did not generate sufficient biogas for volumetric measurements (Table 5). For example, headspace samples from the high- and low-strength manufacturing wastewater reactors contained between 4 and 13% CH_4. Furthermore, the leachate control reactors reached CH_4 contents of 22 to 32%, which were measured towards the end of the experiment and documented an increasing CH_4 contribution in the biogas. These reactors may have been on the verge of transitioning from the acid formation phase to the methanogenesis phase.

4.4 Liquid Waste Treatment Implications

In addition to development of active methanogenesis, waste treatment was also evaluated via reductions in leachate COD. Reactors that reached the CH_4 generation phase showed consumption of organic acids and a reduction in COD (Table 5). For example, COD removal ranging from 27,290 to 47,230 mg O_2/L (52 to 88% removal of the peak COD) was computed for the MSW-Sludge reactors, which achieved the greatest CH_4 generation. These reactors showed improved leachate quality relative to the initial recirculation of leachate and demonstrated leachate treatment that exists in landfills with active CH_4 generation. The majority of the reactors that remained in the acid formation phase exhibited increasing COD during operation as the generation and accumulation of organic acids continued. The COD concentration of the leachate in the acid stuck reactors was greater than the initial liquid added to the reactors based on the higher COD concentrations. Although a reduction in COD was computed for all reactors (Table 5), the lower COD reductions, especially in the MSW-LW and control reactors, were likely due to variations in the temporal trend of COD as compared to actual leachate treatment and reduction in COD.

High-strength wastewater treatment by the MSW was observed in the MW-H reactors. High-strength manufacturing wastewater had an initial COD concentration of approximately 370,000 mg O_2/L (Table 3). After initial dosing of the reactor with high-strength manufacturing wastewater, COD of the reactor leachate reduced to less than 50,000 mg O_2/L in both MW-H reactors with the first recirculation through the waste body (Fig. 4c). This immediate reduction in liquid waste COD was likely attributed to adsorption of metals and manufacturing chemicals to MSW waste components. The high-strength manufacturing wastewater was a cloudy white color and had a relatively high initial solids content (TS = 8.6%, Table 3), which was not observed in the translucent brown leachate after percolation through the waste mass (photographs included in Appendix D). Adsorption of phenolic compounds was observed during initial recirculation in similar reactor experiments studying phenolic wastewater co-disposal (Percival and Senior 1998).

Ammonia reduction was observed in the MSW-Sludge reactors (Fig. 6d), which demonstrated a potential ability of the industrial and anaerobic digestion sludge to treat ammonia. The concentration of ammonia initially increased, and subsequently decreased in all four sludge reactors upon transition from acidic to methanogenic conditions (i.e., between Days 50 to 70 in Fig. 6d). This potential removal of ammonia in the reactors is an interesting observation considering there is no known mechanism for ammonia degradation under methanogenic conditions. Kjeldsen et al. (2002) stated that the only reported removal mechanism of ammonia in solid waste landfills was through leaching, which suggests an alternative mechanism may have occurred in the sludge reactors to decrease ammonia. Additional research is needed to evaluate potential ammonia treatment in solid waste reactors mixed with industrial sludge or anaerobic digestion sludge.

4.5 Biochemical Methane Potential Assays

Biochemical methane potential assays were conducted for 60 d to obtain ultimate CH_4 yields for all of the solid, liquid, and sludge wastes. These relative CH_4 yields (previously reported in Tables 2 and 3) were used to assess the applicability of the BMP test as a co-disposal selection tool for solid and liquid wastes. Plots for CH_4 generation and CH_4 composition are in shown in Fig. 12 for solid wastes and Fig. 13 for liquid wastes. Methane yield was normalized to amount of waste disposed, on a total mass basis, to compare to default values reported for MSW in literature. Methane yield was also normalized on a g-VS basis for solid wastes (Fig. 12b) and on a g-COD basis for liquid wastes and the glucose control (Fig 13b).

A glucose positive control was used to ensure that an active inoculum was present and that there were no limiting nutrients. At the end of 60 days the glucose BMP assays generated 187.8 mL-CH_4/g-COD, which was relatively low compared to the theoretical value of 395 mL CH_4 generated/g COD reduced (Moody et al. 2011). The glucose assay was still increasing in gas generation at 60 d and likely would have achieved a CH_4 yield closer to the theoretical value had the test continued longer than 60 d. The BMP assays on MSW also provided a check on the MSW blend prepared for this study with respect to potential CH_4 yield. At the end of the 60-d BMP test, the CH_4 yield for MSW was 95.3 mL-CH_4/g-MSW. This CH_4 yield was close to values reported in literature. The USEPA AP-42 (1998) default value for methane generation potential is 100 m^3-CH_4/Mg-MSW (100 mL-CH_4/g-MSW) and more recent BMP experiments yielded an average value of 80 m^3-CH_4/Mg-MSW (90 mL-CH_4/g-MSW) (Chickering et al. 2018).

Liquid waste BMP assays ranged from 0.0 to 22.6 mL-CH_4/mL-liquid waste. The undiluted liquid wastes used for the BMP assays (LL, CW, and AWW) had COD concentrations less than 5 g-COD/L. These low strength liquid wastes did not yield much CH_4 (LL = 0.3, CW = 0.6, and AWW = 0.0 mL-CH_4/mL-liquid waste). The high variability observed in the AWW data in Fig 13b was potentially attributed to the low COD (0.2 g O_2/L) and its influence after the data was normalized to g-COD. The high strength liquid wastes (BW = 57.7 and MW-H = 367.1 g COD/L) that were diluted down to 5 g-COD/L produced much higher CH_4 yields (BW = 18.7 and MW-H = 22.6 mL-CH_4/mL-liquid waste). These higher CH_4 yields suggest that high strength liquid wastes can potentially increase CH_4 yields in co-disposal applications. However, the liquid waste reactors remained in the acid formation phase of decomposition for the extent of the experiment duration; thus, no performance comparisons can yet be made between liquid waste co-disposal and BMP assay results.

The solid and sludge waste BMP assays showed greater variation than the BMP assays on liquid waste, with CH_4 yields ranging from -3.0 to 95.3 mL-CH_4/g-solid waste. The GB and FW hindered CH_4 generation relative to the blank control assays, as indicated by negative CH_4 yields (GB = -3.0 and FW = -0.2 mL CH_4/g solid waste). The finding that GB and FW waste inhibited CH_4 generation in the BMP assays contradicts results from the reactor experiments. Reactors GB-1 and FW-1 exhibited relatively high CH_4 generation relative to the other MSW-SW reactors, and their counterpart reactors, GB-2 and FW-2, did generate small amounts of methane.

The BMP assays on ASR and IS indicate that these two wastes have potential benefit in co-disposal applications based on a CH_4 yields of 20.0 and 9.2 mL-CH_4/g-solid waste, respectively. Industrial sludge results from the BMP assays were corroborated with CH_4 generated in the reactor experiments; however, the potential for IS as a seed source is uncertain based on the addition of MSW landfill leachate to generate effluent in the reactor for subsequent recirculation. The ASR reactors were still in the acid formation phase and cannot be compared to the BMP results. Anaerobic digestion sludge was not tested for CH_4 yield because the sludge was used as the inoculum source in the BMP assays. The use of AD sludge as a concentrated methanogenic community in the BMP assays, combined with the observation of healthy methanogenic conditions in the reactor experiments (Fig. 8), suggests that addition of AD sludge to a landfill can aid solid waste decomposition and CH_4 generation.

Biogas composition for the BMP assays is reported in Figures 11c and 12c. Regardless of the volume of CH_4 generated, most of the solid and liquid waste BMP assays converged to a methane content between 62 and 72%, which is greater than the typical CH_4 composition of 50-60% reported for landfills (Amini et al. 2012). The greater observed CH_4 composition was potentially due to the ideal decomposition conditions created in the BMP assays. The gypsum board BMP assays showed decreased CH_4 content, which only reached 41%. This decreased CH_4 content was also observed in the gypsum board reactors. The gypsum board had high sulfate content, such that the decreased CH_4 was likely due to competition with sulfate reducers.

Hydrogen sulfide generation was noted in the BMP assays on gypsum board by olfactory observation.

Table 5. Summary of reactor experiment duration, cumulative and weekly recirculation volumes, settlement, chemical oxygen demand (COD) peak strength and removal, methane (CH_4) generation and rate, and CH_4 composition.

Reactor Type	Reactor Name	Experiment Duration [days]	Cumulative Liquid Recirculated[a] [L/Mg-Waste[b]]	Average Weekly Dose[a] [L/Mg-Waste[b]]	Settlement [%]	pH	Peak COD [mg O_2/L]	COD Reduction [mg O_2/L]	Total CH_4 Generation [L]	Peak CH_4 [%]	Peak CH_4 Rate [L/d]
Control	DIW-1	140	852	45	4.6	5.8	45,780	2,530	0.0	1	0.0
	DIW-2	140	1189	63	3.1	5.8	46,150	2,210	0.1	3	0.0
MSW-LW	LL-1	125	1165	69	3.1	5.6	49,180	1,650	1.4	32	0.1
	LL-2	125	1300	76	2.4	5.6	52,900	370	1.2	22	0.0
	BW-1	126	696	41	3.1	5.5	65,720	8,160	0.0	0	0.0
	BW-2	126	1162	68	3.1	5.7	61,540	3,610	0.0	1	0.0
	CW-1	126	965	57	2.4	5.8	44,680	3,490	0.0	5	0.0
	CW-2	126	666	39	3.9	5.9	43,810	2,990	0.0	0	0.0
	AWW-1	126	1194	70	2.4	5.7	48,490	320	0.5	13	0.0
	AWW-2	126	1256	74	2.3	6.1	44,400	1,330	0.0	2	0.0
	MW-H-1	125	1128	66	3.1	6.0	46,350	4,250	0.1	7	0.0
	MW-H-2	125	716	42	2.3	6.1	50,970	9,370	0.0	4	0.0
	MW-L-1	125	900	53	1.6	5.8	42,660	180	0.0	13	0.0
	MW-L-2	125	1125	66	2.3	5.9	46,240	6,250	0.1	12	0.0
MSW-SW	GB-1	105	1120	80	1.7	7.0	24,140	15,120	4.5	34	0.3
	GB-2	105	751	54	1.6	7.0	29,980	18,420	1.2	12	0.0
	ASR-1	105	964	69	1.7	6.3	28,190	4,600	0.1	11	0.0
	ASR-2	105	580	41	0.9	6.1	29,660	2,440	0.1	15	0.0
	FW-1	105	560	40	2.1	5.4	45,140	3,080	17.3	51	0.7
	FW-2	105	517	37	5.0	5.3	44,860	740	1.4	31	0.0
MSW-Sludge	AD-1	105	1530	109	9.1	7.7	32,320	27,290	60.5	62	1.9
	AD-2	105	1465	105	7.5	8.1	41,370	36,480	30.5	49	1.5
	IS-1	105	1138	81	6.8	8.3	56,190	47,230	31.1	61	1.1
	IS-2	105	898	64	2.5	7.3	57,750	30,140	22.2	56	1.0
Average		118	993	63	3.3	6.2	44,940	9,680	6.9	21	0.3
Min		105	517	37	0.9	5.3	24,140	180	0.0	0	0.0
Max		140	1530	109	9.1	8.3	65,720	47,230	59.5	62	1.9

Notes: DIW = de-ionized water; LL = landfill leachate; BW = brewery wastewater; CW = cheese production wastewater; AWW = automobile wash water; MW-H = high-strength manufacturing wastewater; MW-L = low-strength manufacturing wastewater; GB = gypsum board; ASR = automobile shredder residue; FW = foundry waste; AD = anaerobic digestion sludge; and IS = industrial sludge.

[a] Cumulative liquid recirculated and average weekly dose values do not include the initial dosing of the waste.

[b] Rates based on initial waste mass.

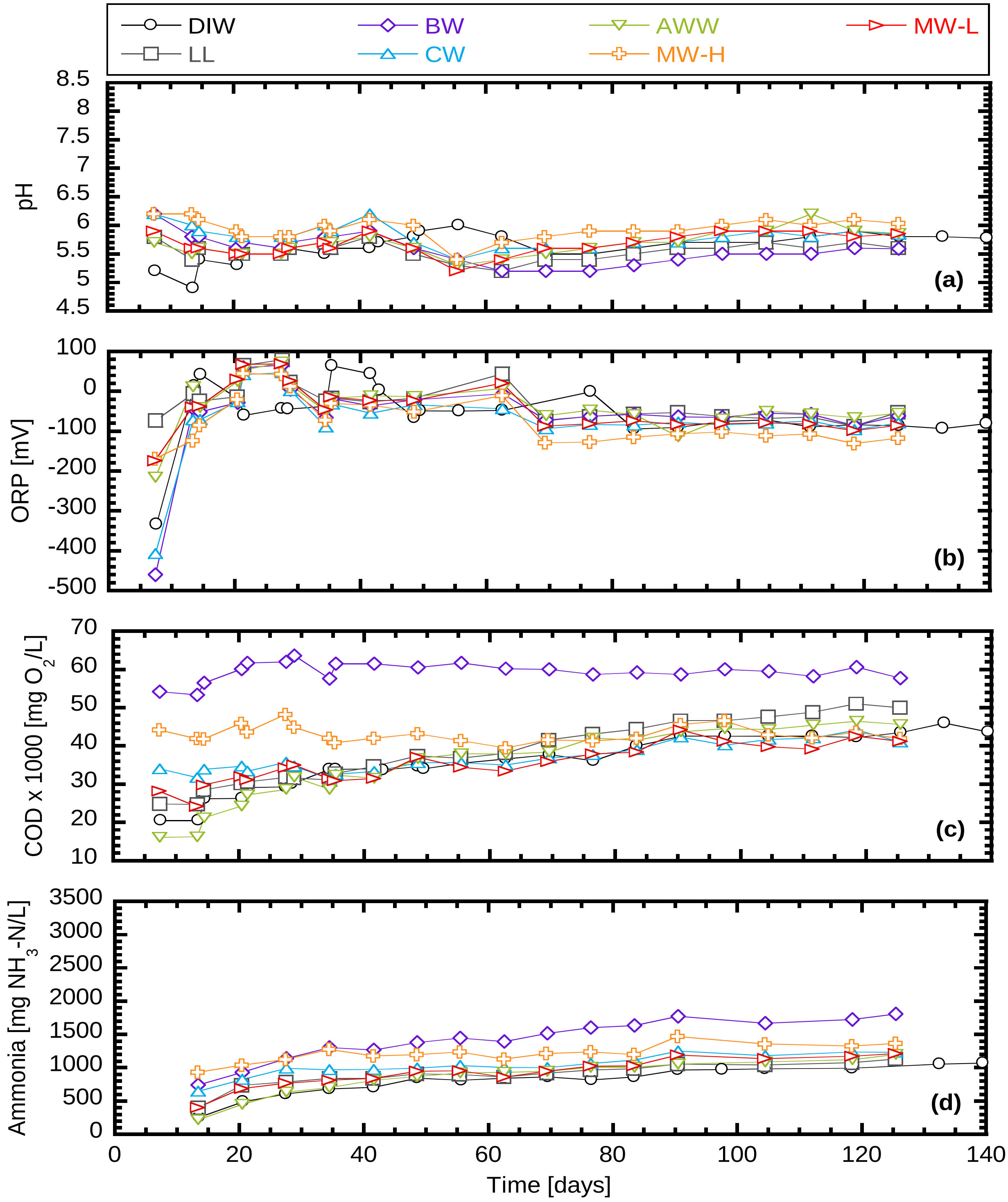


Figure 4. Temporal trends in reactor leachate (a) pH, (b) oxidation reduction potential (ORP), (c) chemical oxygen demand (COD), and (d) ammonia in the liquid waste reactors. Notes: DIW = de-ionized water; LL = landfill leachate; BW = brewery wastewater; CW = cheese processing wastewater; AWW = automobile wash water; MW-H = high-strength manufacturing wastewater; and MW-L = low-strength manufacturing wastewater.

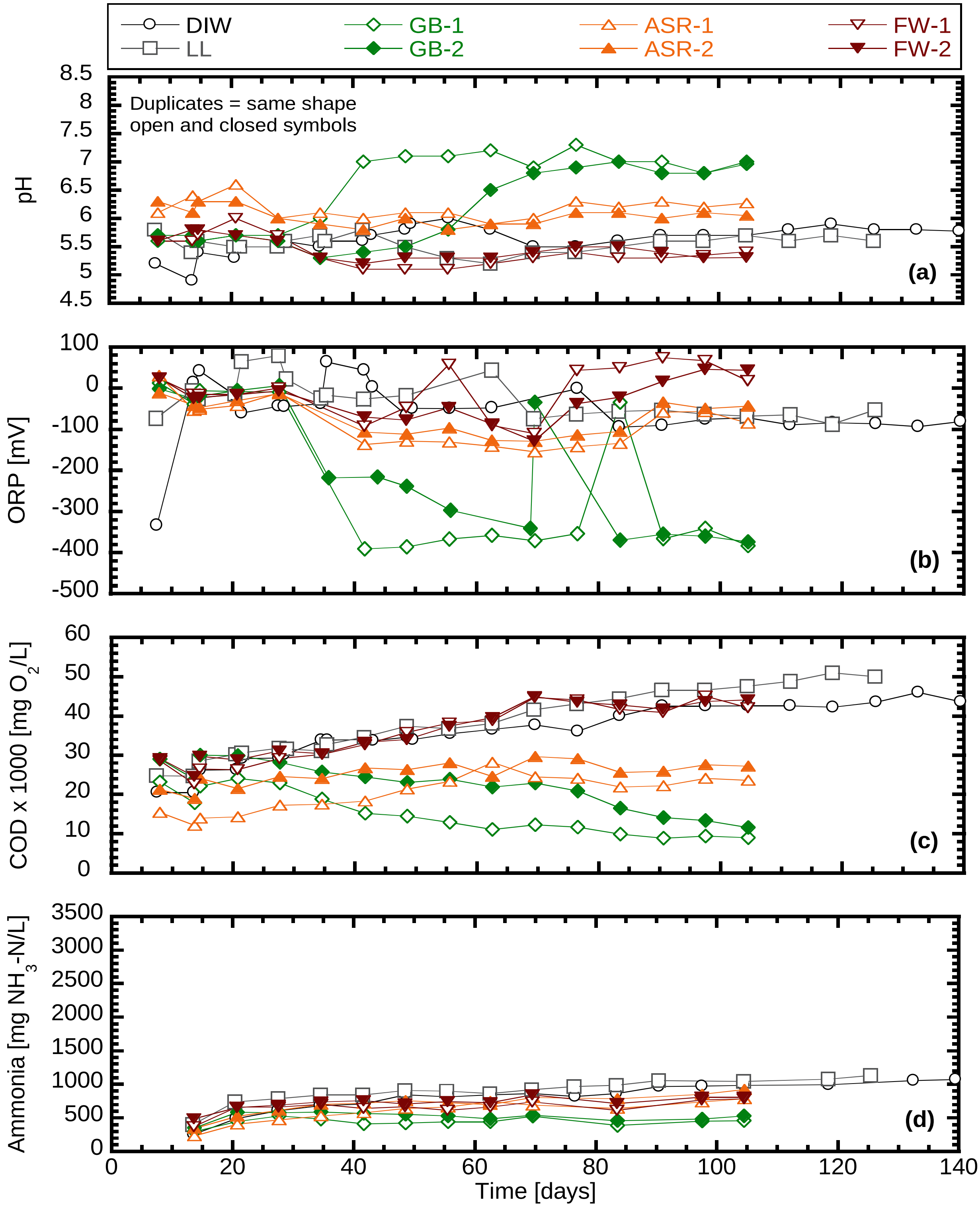


Figure 5. Temporal trends in (a) pH, (b) oxidation reduction potential (ORP), (c) chemical oxygen demand (COD), and (d) ammonia in the solid waste reactors. Notes: DIW = de-ionized water; LL = landfill leachate; GB = gypsum board; ASR = automobile shredder residue; and FW = foundry waste.

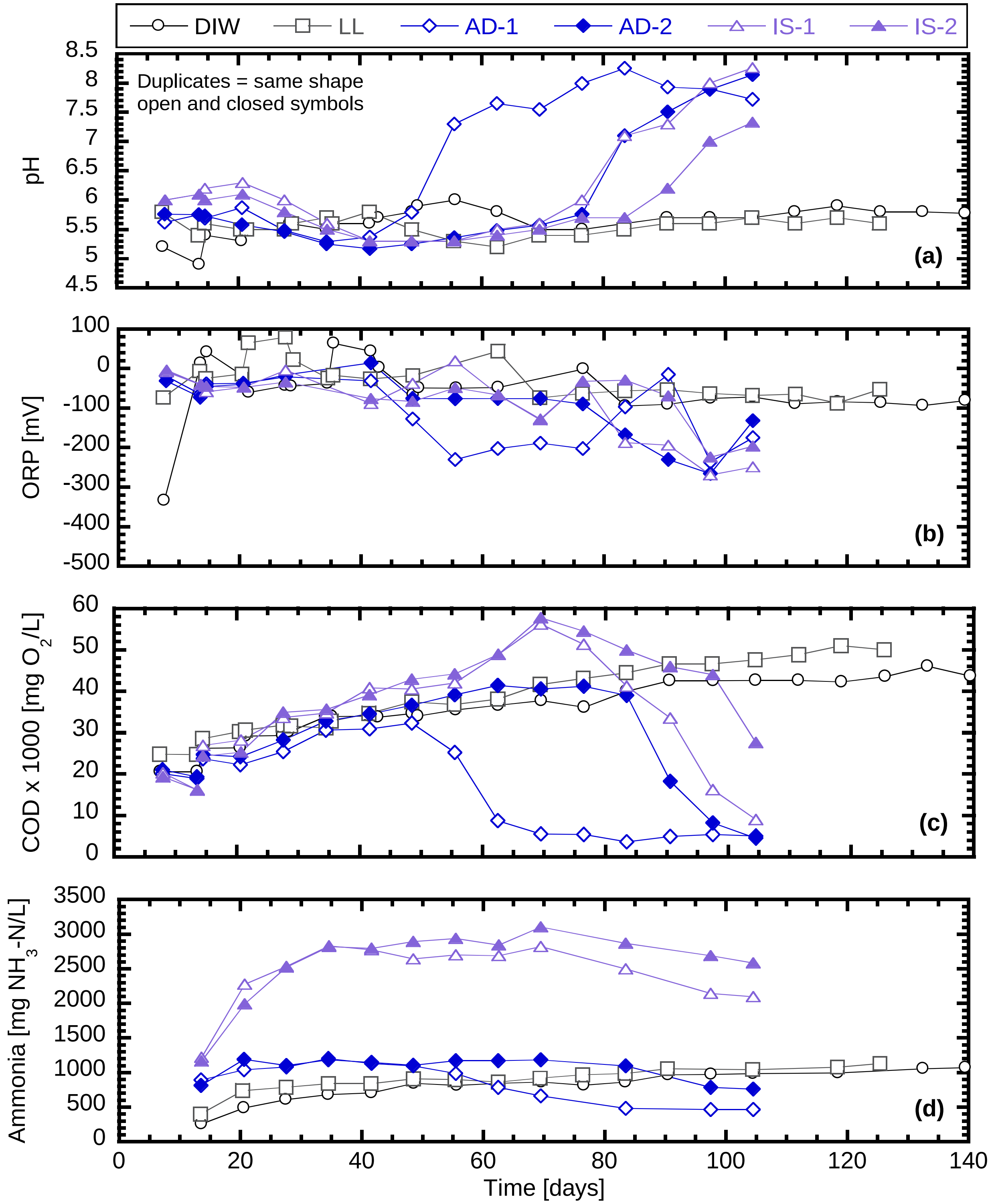


Figure 6. Temporal trends in leachate (a) pH, (b) oxidation reduction potential (ORP), (c) chemical oxygen demand (COD), and (d) ammonia in the sludge waste reactors. Notes: DIW = de-ionized water; LL = landfill leachate; AD = anaerobic digestion sludge; and IS = industrial sludge.

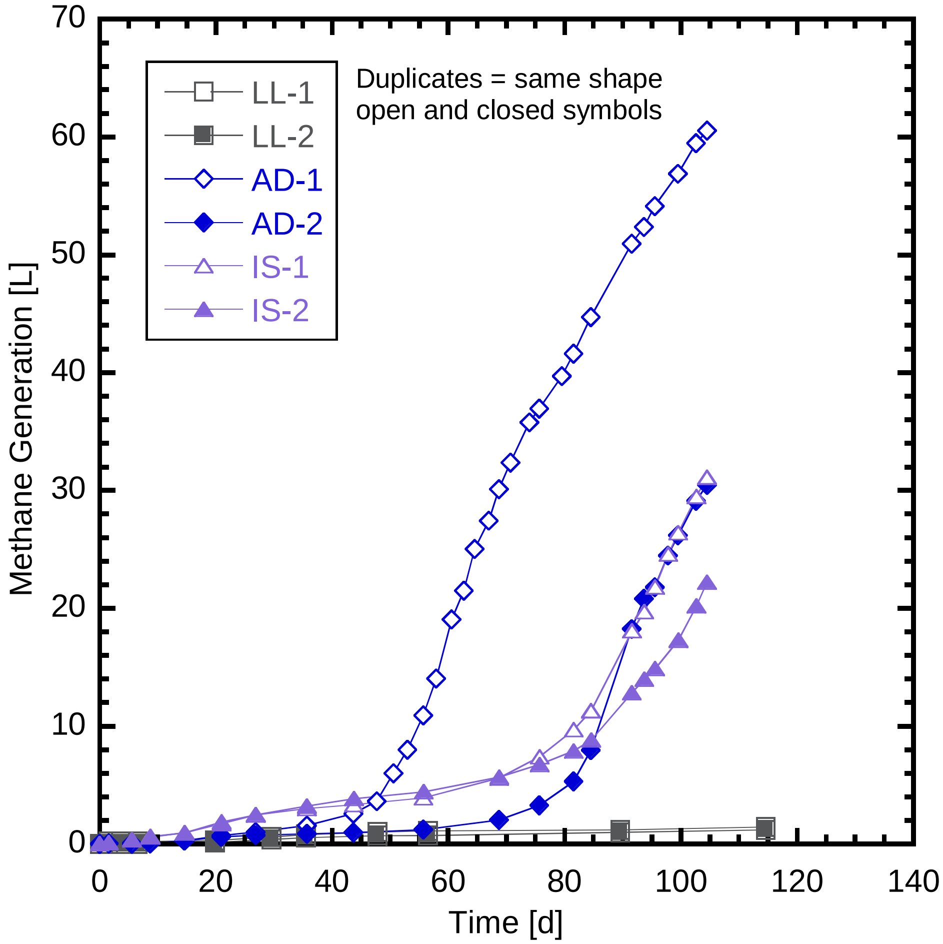


Figure 7. Temporal trends in methane generation in sludge waste reactors. Notes: LL = landfill leachate; AD = anaerobic digestion sludge; and IS = industrial sludge.

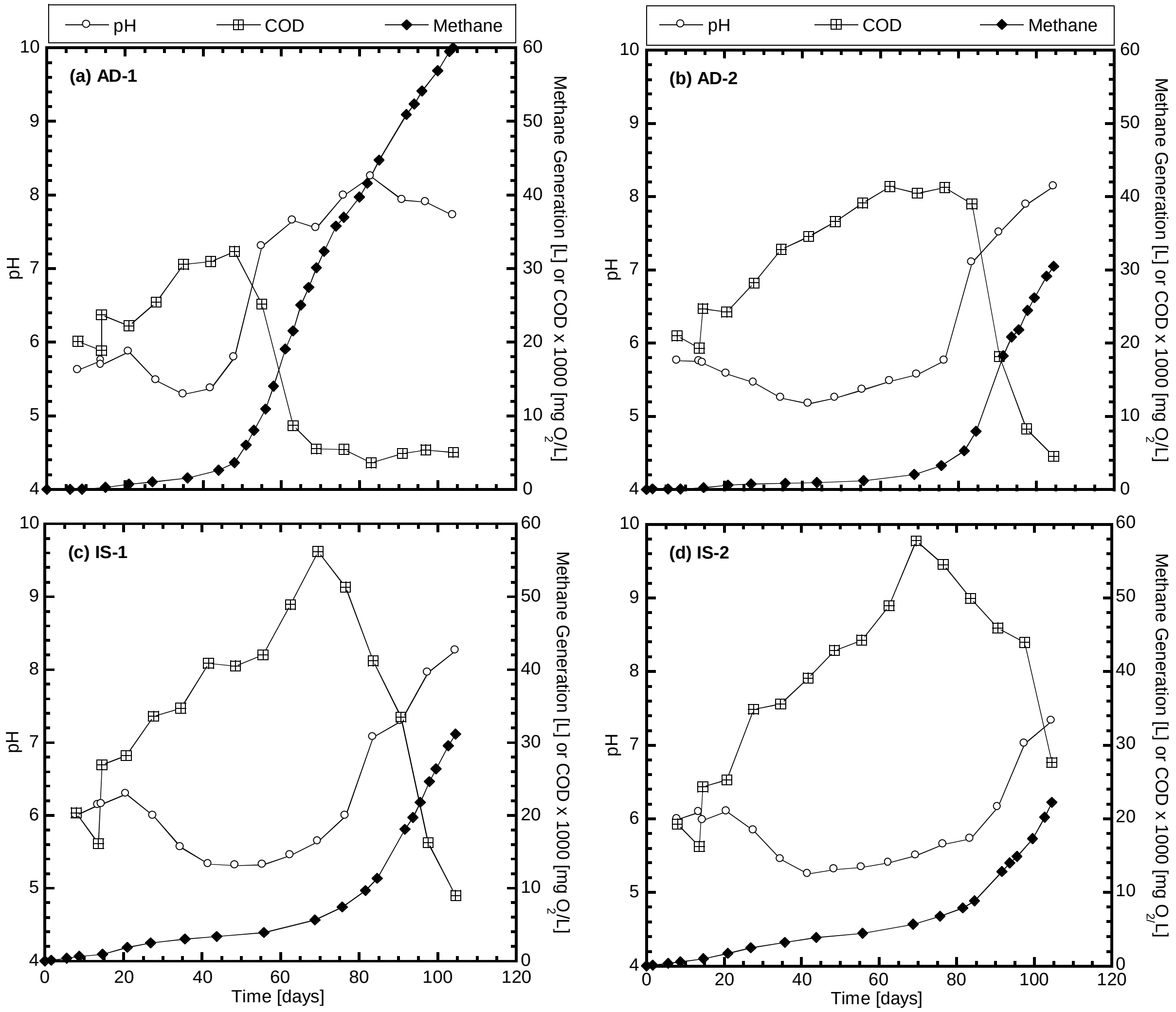


Figure 8. Temporal trends of pH and chemical oxygen demand (COD) in reactor leachate and methane generation of the sludge reactors actively generating biogas: (a) anaerobic digestion sludge reactor 1 (AD-1), (b) anaerobic digestion sludge reactor 2 (AD-2), (c) industrial sludge reactor 1 (IS-1), and (d) industrial sludge reactor 2 (IS-2).

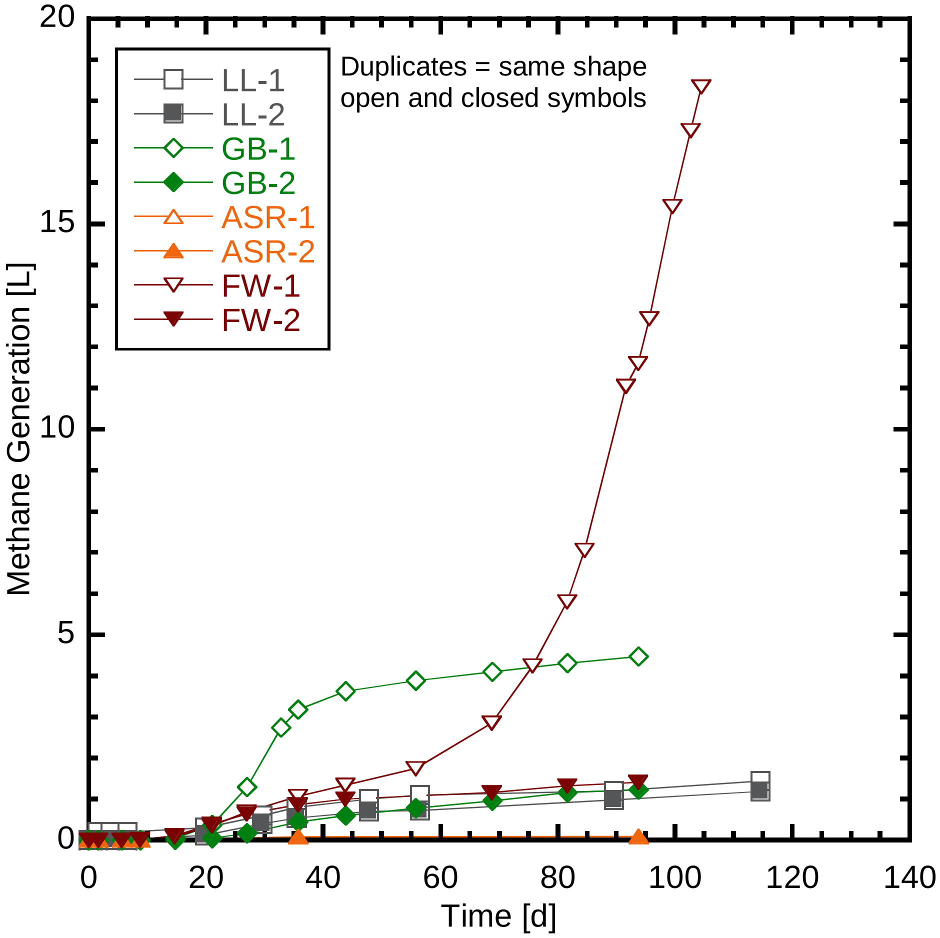


Figure 9. Temporal trends in methane generation in solid waste reactors. Notes: LL = landfill leachate; GB = gypsum board; ASR = automobile shredder residue; and FW = foundry waste.

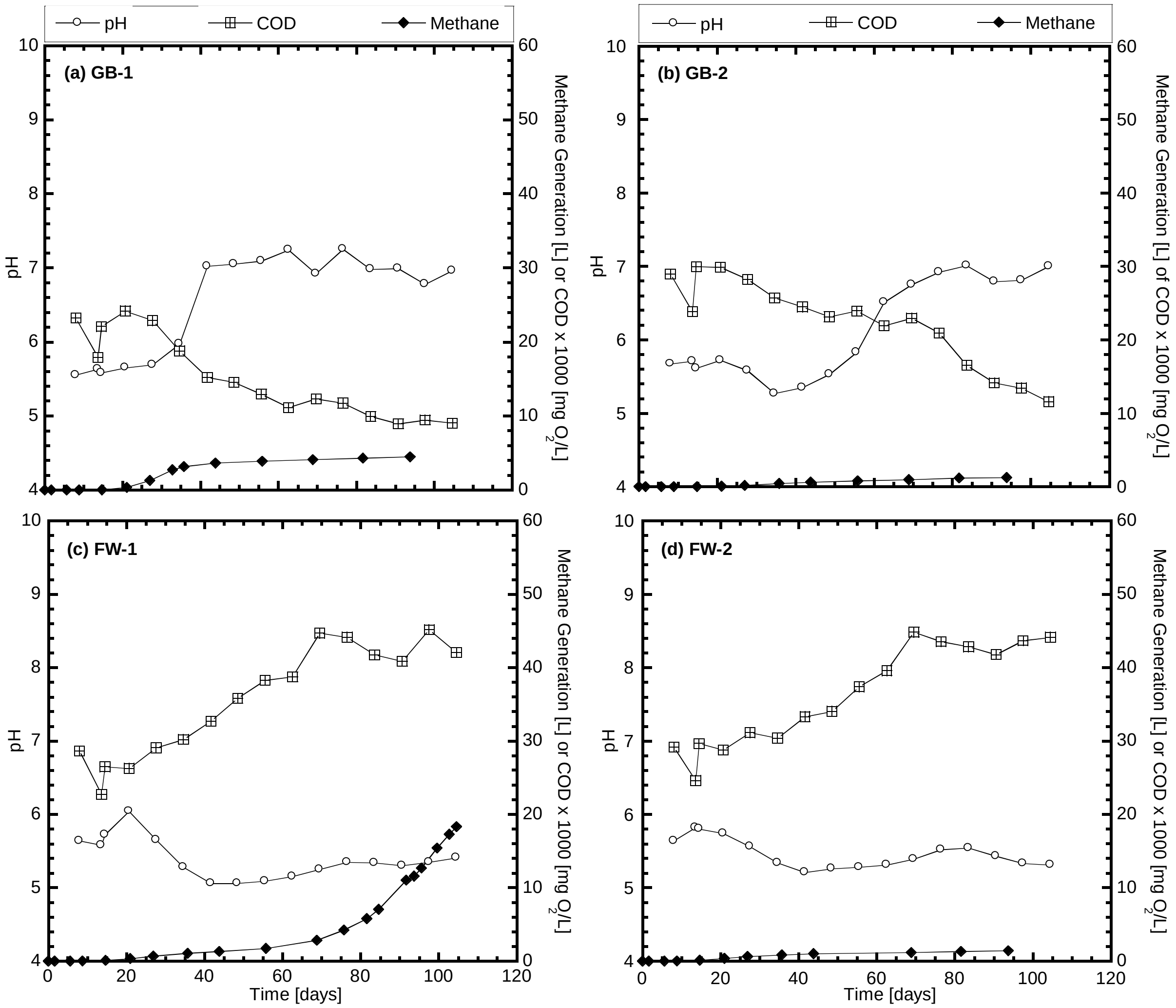


Figure 10. Temporal trends of pH and chemical oxygen demand (COD) in reactor leachate and methane generation of the solid waste reactors actively generating biogas: (a) gypsum board reactor 1 (GB-1), (b) gypsum board reactor 2 (GB-2), (c) foundry waste reactor 1 (FW-1), and (d) foundry waste reactor 2 (FW-2).

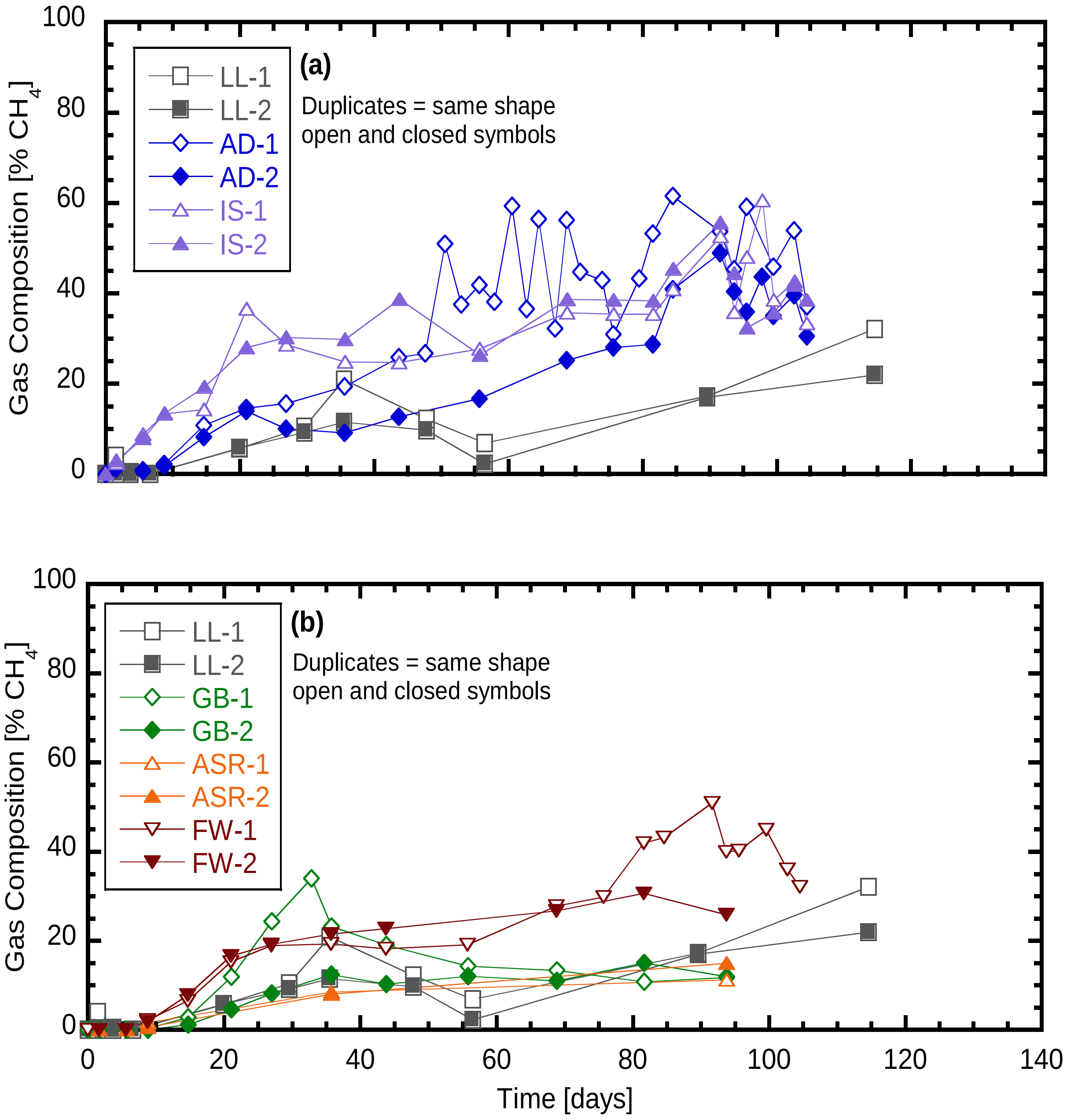


Figure 11. Gas composition in (a) sludge waste reactors and (b) solid waste reactors. Notes: LL = landfill leachate; AD = anaerobic digestion sludge; IS = industrial sludge, GB = gypsum board; ASR = automobile shredder residue; and FW = foundry waste.

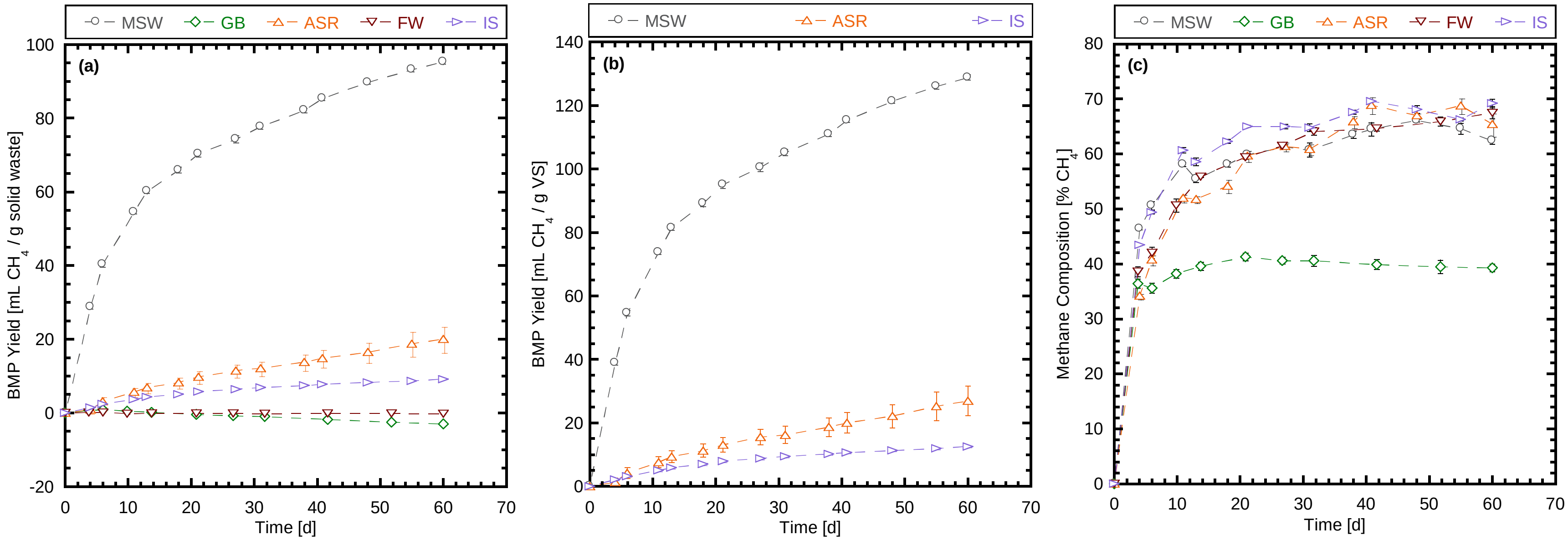


Figure 12. Solid waste biochemical methane potential (BMP) results for (a) methane (CH4) yield normalized to mass of waste, (b) CH4 yield normalized to volatile solids (VS) and, (c) CH4 composition. Notes: MSW = municipal solid waste; ASR = automobile shredder residue; FW = foundry waste; GB = gypsum board; and IS = industrial sludge

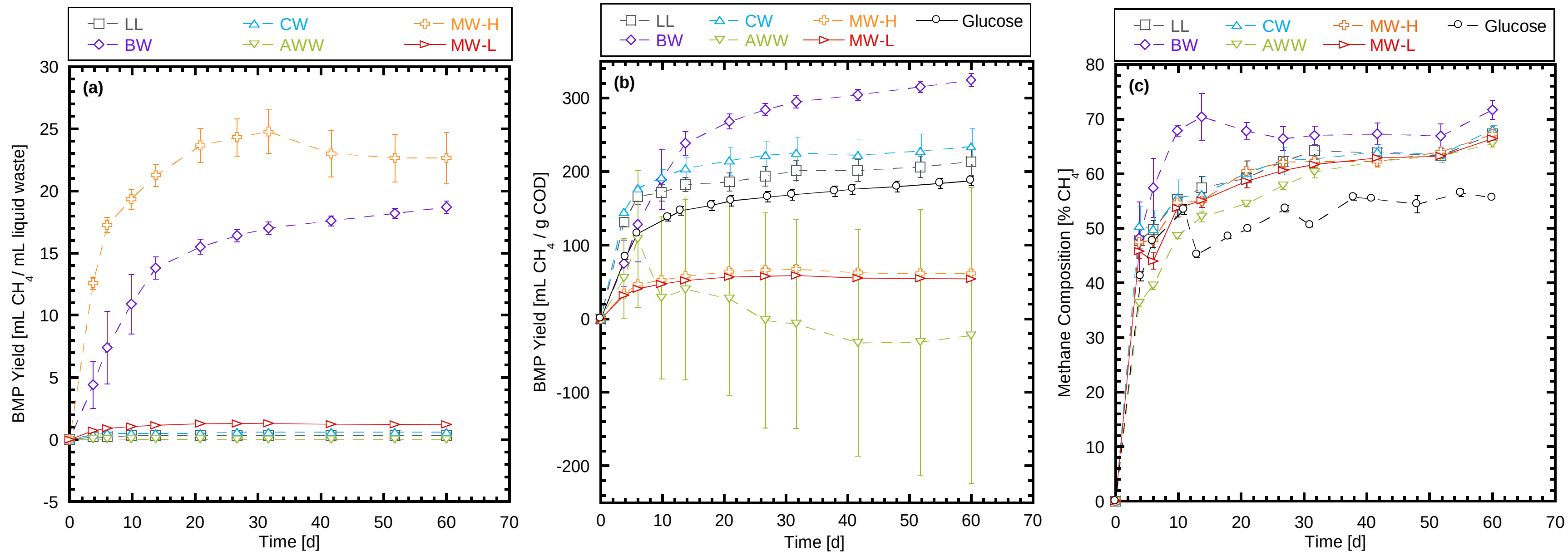


Figure 13. Liquid waste and glucose biochemical methane potential (BMP) results for (a) methane (CH_4) yield normalized to volume of waste, (b) CH_4 yield normalized to chemical oxygen demand (COD) and, (c) CH_4 composition. Notes: LL = landfill leachate; BW = brewery wastewater; CW = cheese processing wastewater; AWW = automobile wash water; MW-L = high strength manufacturing wastewater; and MW-H = high strength manufacturing wastewater.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Guidance on Co-disposal

The objective of this research was to evaluate the impacts of co-disposal of diverse solid, liquid, and/or sludge wastes in MSW on biodegradation and biochemical compatibility. Several key observations and conclusions regarding co-disposal were made from the laboratory study. These observations and conclusions were also used to develop suggested guidance for the practice of co-disposal in solid waste landfills.

- Early and aggressive addition of commercial liquid wastes during reactor startup did not promote accelerated anaerobic decomposition of fresh MSW. Liquid waste reactors were stuck in the acid formation phase and had leachate with pH values < 6 and COD values approaching or exceeding 50,000 mg O_2/L.
- The MSW exhibited the ability to buffer and potentially treat liquid waste when not in an anaerobic degradation phase. Pronounced reduction of COD was measured in the high-strength manufacturing wastewater reactors following a single recirculation dose. In addition, the BMP assays indicated that high-strength manufacturing wastewater had relatively high methane yield, which suggests high-strength liquid wastes are treatable and have potential benefit in co-disposal applications.
- The anaerobic digestion sludge and industrial sludge appeared to have been beneficial for accelerating anaerobic biodegradation. Increased methane production and improved leachate quality were observed in the MSW-Sludge reactors relative to the landfill leachate control reactors and all other waste combinations evaluated in the reactors.
- Anaerobic biodegradation and methane generation were observed in reactors operated with foundry waste or gypsum board co-disposed with MSW. Despite BMP results that indicated methane generation would be inhibited with these two waste streams, co-

disposing with MSW did not completely inhibit anaerobic degradation, and appeared to have promoted generation in one of the two duplicates for both foundry waste and gypsum board.

- The high sulfate content of gypsum board appeared to have led to sulfate reduction, which likely created a reduced environment favorable for methane generation in the reactors, as was observed by low ORP values. Materials with an elevated sulfate content may generate H_2S gas and potentially corrode reactor components.
- The more methanogenically active of the two foundry waste reactors demonstrated that a solid waste stream that appeared to be inhibitory for methane generation, based on leachate chemistry (low pH, high OPR, high COD), still promoted biodegradation. Components specific to the foundry waste may have been beneficial to methane generation, but were not identified as part of the study. Spatial variability in landfilled waste could also be important in explaining discrepancies between indicator parameter trends in the leachate and the onset of biogas generation.
- The BMP assays only provided methane yield from organic substrate degradation under ideal conditions and did not capture other benefits of co-disposal (e.g., impacts of moisture addition). A potential co-disposal waste source should not be ruled out by BMP results alone.
- The BMP results for solid wastes did not show good agreement with reactor data; e.g., negative BMP results corresponded to some of the best-performing solid waste reactors. The BMP assay would not have been a good selection tool in these cases.

The following guidance for co-disposal of solid, liquid, and sludge wastes in full-scale landfills was developed from the reactor experiments and BMP assays conducted in this study.

- Given the bioreactor conditions used in this study, liquid wastes were not observed to be effective inoculums to establish methane generation in fresh MSW and would not be recommended as the sole moisture source for bioreactor landfills. Although full-scale landfills have a higher buffering capacity than reactor-scale experiments that may mitigate high acid accumulation and potential anaerobic inhibition, a source of anaerobic microorganisms (e.g., mature landfill leachate or anaerobic digestion sludge) should be considered with liquid waste co-disposal to promote biodegradation of organic waste.

- Treatment of high-strength wastewater is possible in MSW. However, addition of high-strength liquid waste should be implemented following established methane generation, which has been shown to be an effective moisture enhancement technique in full-scale MSW landfills.
- Sludge wastes appear to have been beneficial to anaerobic biodegradation and should be considered as potential sources of moisture and organic loading for waste decomposition. The anaerobic digestion sludge likely provided active methanogenic microorganisms to accelerate methane generation and may be a beneficial seed source in full-scale landfills. There are several operational considerations for sludge waste co-disposal: (i) early gas collection is needed to manage accelerated production of biogas; (ii) the amount of sludge that can be added while maintaining the observed benefits remains undetermined; and (iii) clogging of liquid and gas infrastructure due to sludge may be an issue (e.g., tubing and filters were prone to clogging in MSW-Sludge reactor experiments).
- Recirculation coupled with certain waste types (e.g., brewery wastewater and industrial sludge) showed increases in ammonia trends that exceeded concentrations known to be inhibitory. Ammonia accumulation can negatively impact anaerobic degradation and wastes that lead to ammonia accumulation should be used cautiously.
- Biochemical methane potential assays on the individual solid, liquid, and sludge wastes did not yield consistent data that were useful for inferring anticipated behavior in the co-disposal reactors. Thus, BMP assays that simulate ideal anaerobic conditions do not

appear to be an effective screening tool that can be used alone to determine compatibility of co-disposal waste streams.

5.2 Future Work

Reactor operation will continue for several months to continue monitoring the reactors, with particular interest in the reactors that have yet to generate methane. This extended study will provide a better understanding of liquid waste addition and confirm if the liquid waste reactors are perpetually stuck in the acid generation phase. Future co-disposal experiments should consider the following:

- Inoculation prior to liquid addition to ensure reactors have a methanogenic community and evaluate subsequent influence of the liquid waste on methanogenesis;
- Addition of liquid wastes of varying strength to mature methanogenic reactors to evaluate treatment capacity of the waste body;
- Investigation of potential ammonia treatment in sludge co-disposal applications;
- Evaluation of the amount of sludge waste that can be added to MSW and still maintain beneficial attributes of enhanced anaerobic biodegradation;
- The applicability of a BMP assay as a selection tool in which the BMP assay creates non-ideal anaerobic conditions more representative of a landfill and evaluates co-disposal combinations of wastes rather than individual waste streams; and,
- Three or greater replicates to conduct a statistical analysis of the results.

REFERENCES

Agdag, O., and Sponza, T. (2005). Co-digestion of industrial sludge with municipal solid wastes in anaerobic simulated landfilling bioreactors. *Process Biochemistry,* 40, 1871-1879.

Agdag, O., and Sponza, T. (2007). Co-digestion of mixed industrial sludge with municipal solid wastes in anaerobic simulated landfilling bioreactors. *Journal of Hazardous Materials,* 140, 75-85.

Aghdam, E., Scheutz, C., and Kjeldsen, P. (2017). Assessment of methane production from shredder waste in landfills: The influence of temperature, moisture, and metals. *Waste Management,* 63, 226-237.

Al Yaqout, A. (2003). Assessment and analysis of industrial liquid waste and sludge disposal at unlined landfill sites in arid climate. *Waste Management,* 23, 817-824.

Amini, H., Reinhart, D., and Mackie, K. (2012). Determination of first-order landfill gas modeling parameters and uncertainties. *Waste Management*, 32, 305-316.

Bae, J., Cho, K., Lee, S., Bum, B., and Yoon, B. (1998). Effects of leachate recycle and anaerobic digester sludge recycle on the methane production from solid wastes. *Water Science Technology,* 38(2) 159-168.

Bareither, C., Benson, C., Barlaz, M., Edil, T., and Tolaymat, T. (2010). Performance of North American bioreactor landfills. I: Leachate hydrology and waste settlement. *Journal of Environmental Engineering,* 136(8), 824-838.

Bareither, C., Benson, C., and Edil, T. (2012a). Effects of waste composition and decomposition on the shear strength of municipal solid waste. *Journal of Geotechnical and Geoenvironmental Engineering*, 138(10), 1161-1174.

Bareither, C., Benson, C., and Edil, T. (2012b). Comparison of waste settlement parameters for bioreactor landfills derived from physical, chemical, and biological processes, *Proc. Global Waste Management Symposium*, Penton Media, 1-5.

Bareither, C., Benson, C., and Edil, T. (2013). Compression of municipal solid waste in bioreactor landfills: Mechanical creep and biocompression. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(7), 1007-1021.

Bareither, C., Barlaz, M., Doran, M., and Benson, C. (2017). Retrospective analysis of Wisconsin's landfill organic stability rule. *Journal of Environmental Engineering,* 143(5).

Barlaz, M., Chanton, J., and Green, R. (2009). Controls on landfill gas collection efficiency: Instantaneous and lifetime performance. *Journal of the Air & Waste Management Association,* 59, 1399-1404.

Barlaz, M., Bareither, C., Hossain, A., Saquing, J., Mezzari, I., Benson, C., Tolaymat, T., and Yazdani, R. (2010). Performance of North American bioreactor landfills. II: Chemical and biological characteristics. *Journal of Environmental Engineering,* 136(8), 839-853.

Behera, S., Kim, D., Shin, H., Cho, S., Yoon, S., and Park, H. (2011). Enhanced methane recovery by food waste leachate injection into a landfill in Korea. *Waste Management,* 31, 2126-2132.

Benson, C., Barlaz, M., Lane, D., and Rawe, J. (2007). Practice review of five bioreactor/recirculation landfills. *Waste Management,* 27, 13-29.

Chen, Y., Cheng, J., and Creamer, K. (2008). Inhibition of anaerobic digestion process: A review. *Bioresource Technology,* 99, 4044-4064.

Chickering, G. Krause, M., and Townsend, T. (2018). Determination of as-discarded methane potential in residential and commercial municipal solid waste. *Waste Management.*

Cossu, R., Blakey, N., and Cannas, P. (1993). Influence of codisposal of municipal solid waste and olive vegetation water on the anaerobic digestion of a sanitary landfill. *Water Science Technology,* 27(2), 261-271.

Dhesi, P. (2003). *Study of addition of non-hazardous industrial and municipal wastewater to bioreactor landfills,* MS Thesis, University of Central Florida, Orlando, FL, USA.

Diamantis, V., Erguder, T., Aivasidis, A., Verstraete, W., and Voudrias, E. (2013). Wastewater disposal to landfill-sites: A synergistic solution for centralized management of olive mill wastewater and enhanced production of landfill gas. *Journal of Environmental Management,* 128, 427-434.

Fairweather, R., and Barlaz, M. (1998). Hydrogen sulfide production during decomposition of landfill inputs. *Journal of Environmental Engineering,* 124(4), 353-361.

Griffin, M., McMahon, K., Mackie, R., and Raskin, L. (1998). Methanogenic population dynamics during start-up of anaerobic digesters treating municipals solid waste and biosolids. *Biotechnology and bioengineering,* 57(3), 342-355.

Hanson, J., Yesiller, N., Von Stockhausen, S., and Wong, W. (2010). Compaction characteristics of municipal solid waste. *Journal of Geotechnical and Geoenvironmental Engineering,* 136(8), 1095-1102.

Kjeldsen, P., Barlaz, M., Rooker, A., Baun, A., Ledin, A., and Christensen, T. (2002). Present and long-term composition of MSW landfill leachate: A review. *Environmental Science and Technology,* 32(4), 297-336.

Knox, K. (1983). Treatability studies on leachate from a co-disposal landfill. *Environmental Pollution,* 5 (Series B), 157-174.

Ko, J., and Townsend, T. (2012). Evaluation of the potential methane yield of industrial wastewaters used in bioreactor landfills. *Journal of Material Cycles Waste Management,* 14, 162-168.

Lee, D., Behera, S., Kim, J., and Park, H. (2009). Methane production potential of leachate generated from Korean food waste recycling facilities: A lab-scale study. *Waste Management,* 29, 876-882.

Moody, L., Burns, R., Bishop, G., Sell, S., and Spajic, R. (2011). Using biochemical methane potential assays to aid in co-substrate selection for co-digestion. *Applied Engineering in Agriculture,* 27(3), 433-439.

Nwaokorie, K. (2017). *Phase-based analysis to determine first-order decay rates for a bioreactor landfill.* MS Thesis, Colorado State University, Fort Collins, CO, USA.

Owen, W., Stuckey, D., Healy, J., Young, L., and McCarty, P. (1979). Bioassay for monitoring biochemical methane potential and anaerobic toxicity. *Water Research,* 13(6), 473-560.

Percival, L., and Senior, E. (1998). An assessment of the effects of the dual co-disposal of phenol and waste activated sewage sludge with refuse on the refuse anaerobic fermentation and leachate quality. *Water SA,* 24(1), 57-70.

Pohland, F., and Gould, J. (1986). Co-disposal of municipal refuse and industrial waste sludge in landfills. *Water Science Technology,* 18(12). 177-192.

Rahim, R., and Watson-Craik, I. (1997). The co-disposal of a model brewery wastewater with domestic refuse. *Letters in Applied Microbiology,* 24, 281-285.

Reinhart, D., and Al-Yousfi, A. (1996). The impact of leachate recirculation on municipal solid waste landfill operating characteristics. *Waste Management and Research,* 14, 337-346.

Reinhart, D., McCreanor, P., and Townsend, T. (2002). The bioreactor landfill: Its status and future. *Waste Management & Research.* 20, 172-186.

Sanphoti, N., Towprayoon, S., Chaiprasert, P., and Nopharatana, A. (2006). The effects of leachate recirculation with supplemental water addition on methane production and waste decomposition in a simulated tropical landfill. *Journal of Environmental Management,* 81, 27-35.

Siddique, R., Kaur, G., and Rajor, A. (2010). Waste foundry sand and its leachate characteristics. *Resources, Conservation and Recycling,* 54, 1027-1036.

Sosnowski, P., Wieczorek, A., and Ledakowicz, S. (2003). Anaerobic co-digestion of sewage sludge and organic fraction of municipal solid wastes. *Advances in Environmental Research,* 7, 609-616.

Sponza, T., and Agdag, O. (2004). Impact of leachate recirculation and recirculation volume on stabilization of municipal solid wastes in simulated anaerobic bioreactors. *Process Biochemistry,* 39, 2157-2165.

Staley, B., and Barlaz, M. (2009). Composition of municipal solid waste in the united states and implications for carbon sequestration and methane yield. *Journal of Environmental Engineering*, 135(10), 901-909.

Staley, B., de los Reyes III, S., and Barlaz, M. (2011). Effect of special differences in microbial activity, pH, and substrate levels on methanogenesis initiation in refuse. *Applied and Environmental Microbiology,* 77(7), 2381-2391.

Townsend, T., Jang, Y., and Thurn, L. (1999). Simulation of construction and demolition waste leachate. *Journal of Environmental Engineering,* 125(11), 1071-1081.

Townsend, T., Powell, J., Jain, P., Xu, Q., Tolaymat, T., and Reinhart, D. (2015). Moisture Supply and Conveyance. *Sustainable Practices for Landfill Design and Operation,* 133-150.

USEPA (2014a). Advancing sustainable materials management: 2014 fact sheet. United States Environmental Protection Agency, Washington, DC.

USEPA (2014b). Permitting of landfill bioreactor operations: Ten years after the RD&D rule. United States Environmental Protection Agency, Washington, DC.

Wang, Y., Byrd, C., and Barlaz, M. (1994). Anaerobic biodegradability of cellulose and hemicellulose in excavated refuse samples using a biochemical methane potential assay. *Journal of Industrial Miocrobioigy,* 13(3), 147-153.

Waste Management (2004). The bioreactor landfill: Next generation landfill technology. *Bioreactor Program.* Waste Management, Cincinnati, OH, USA.

Watson-Craik, I., and Senior, E. (1989). Treatment of phenolic wastewaters by co-disposal with refuse. *Water Resources,* 23(10). 1293-1303.

Watson-Craik, I., and Sinclair, K. (1995). Co-disposal of industrial wastewaters and sludge. *Microbiology of Landfill Sites*, 91-130.

Wilson, P., Loetscher, L., Sharvelle, S., and De Long, S. (2013). Microbial community acclimation enhances waste hydrolysis rates under elevated ammonia and salinity conditions. *Bioresource Technology,* 146, 15-22.

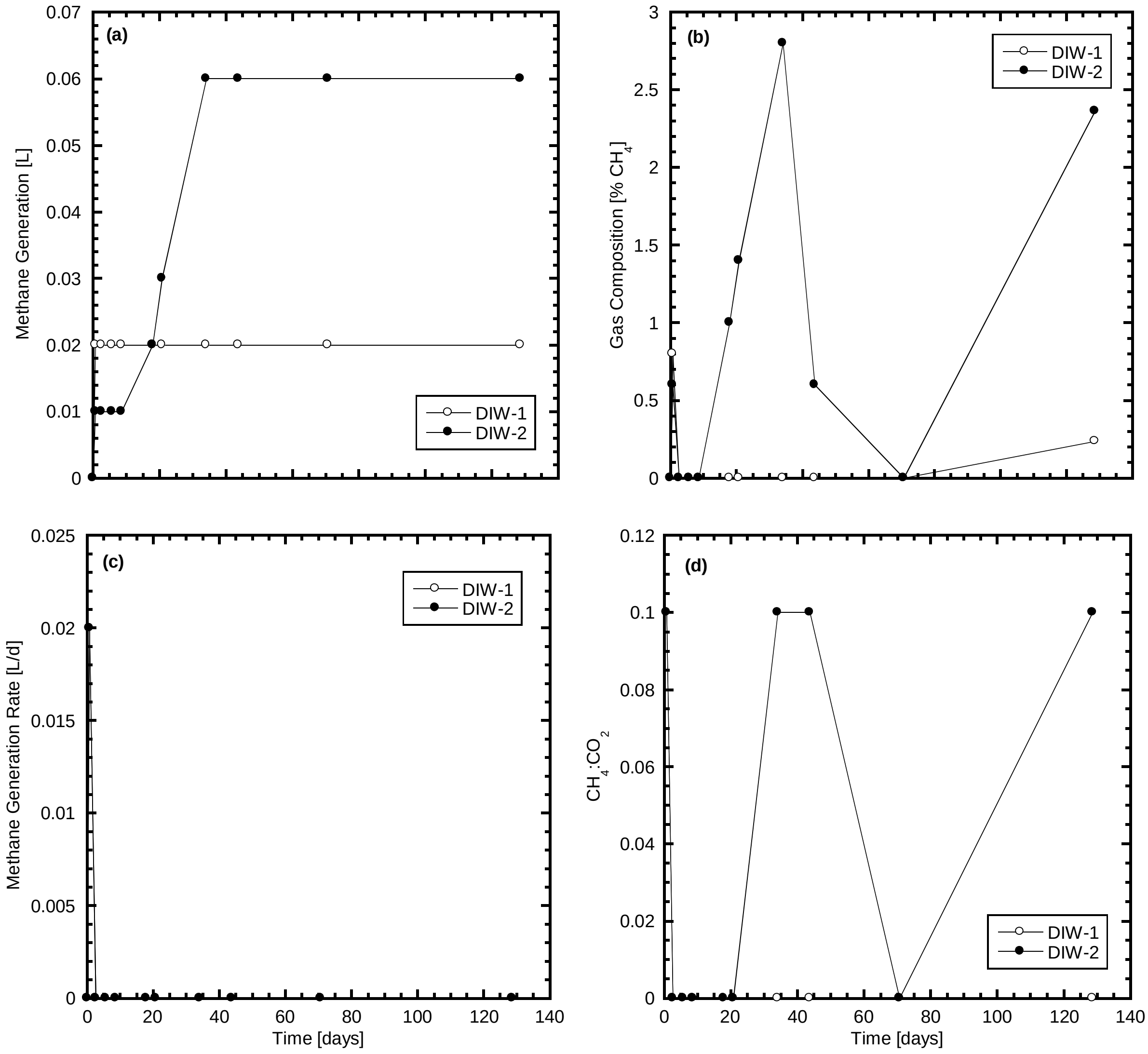
Xu, Q., Townsend, T., and Bitton, G. (2011). Inhibition of hydrogen sulfide generation from disposed gypsum drywall using chemical inhibitors. *Journal of Hazardous Materials,* 191, 204-211.

Zhang, Y., Zhang, H., Jia, B., Wang, W., Zhu, W., Huang, T., and Kong, X. (2012). Landfill CH4 oxidation by mineralized refuse: Effects of NH4+-N incubation, water content and temperature. *Science of the Total Environment,* 426, 406-413.

APPENDIX A: Compilation of Reactor Data

Table A-1. Reactor information, initial conditions, and final conditions for the de-ionized water (DIW) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**DIW-1**	**DIW-2**
Reactors:	DIW-1 & DIW-2	*Specimen thickness [cm]:*	20.6	20.8
Startup date:	1/10/2018	*Specimen density [g/cm^3]:*	0.36	0.36
Experiment duration [days]:	140	*Initial recirculated volume [L/Mg-waste]:*	95	124
Solid waste fraction:	Municipal Solid Waste	*Initial w_d after dosing [%]:*	103	99
MSW [g]:	2400			
Liquid waste fraction:	De-ionized Water	**FINAL CONDITIONS**		
Initial liquid dose [L/Mg-waste]:	625	*Cumulative recirculated liquid [L/Mg-waste]:*	852	1189
		Average weekly recirculated liquid [L/Mg-waste]:	45	63
		Settlement Strain [%]:	4.6	3.1



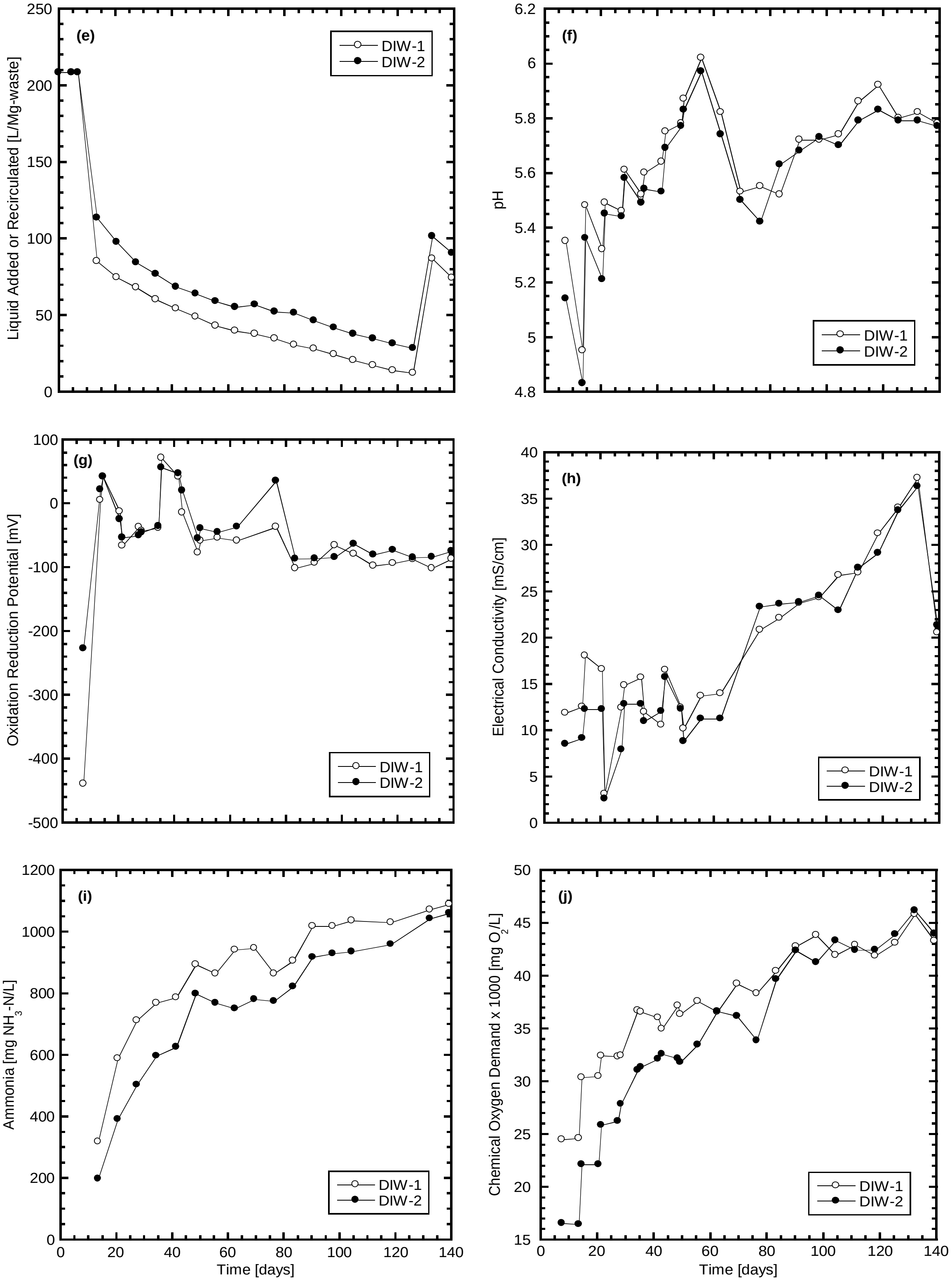
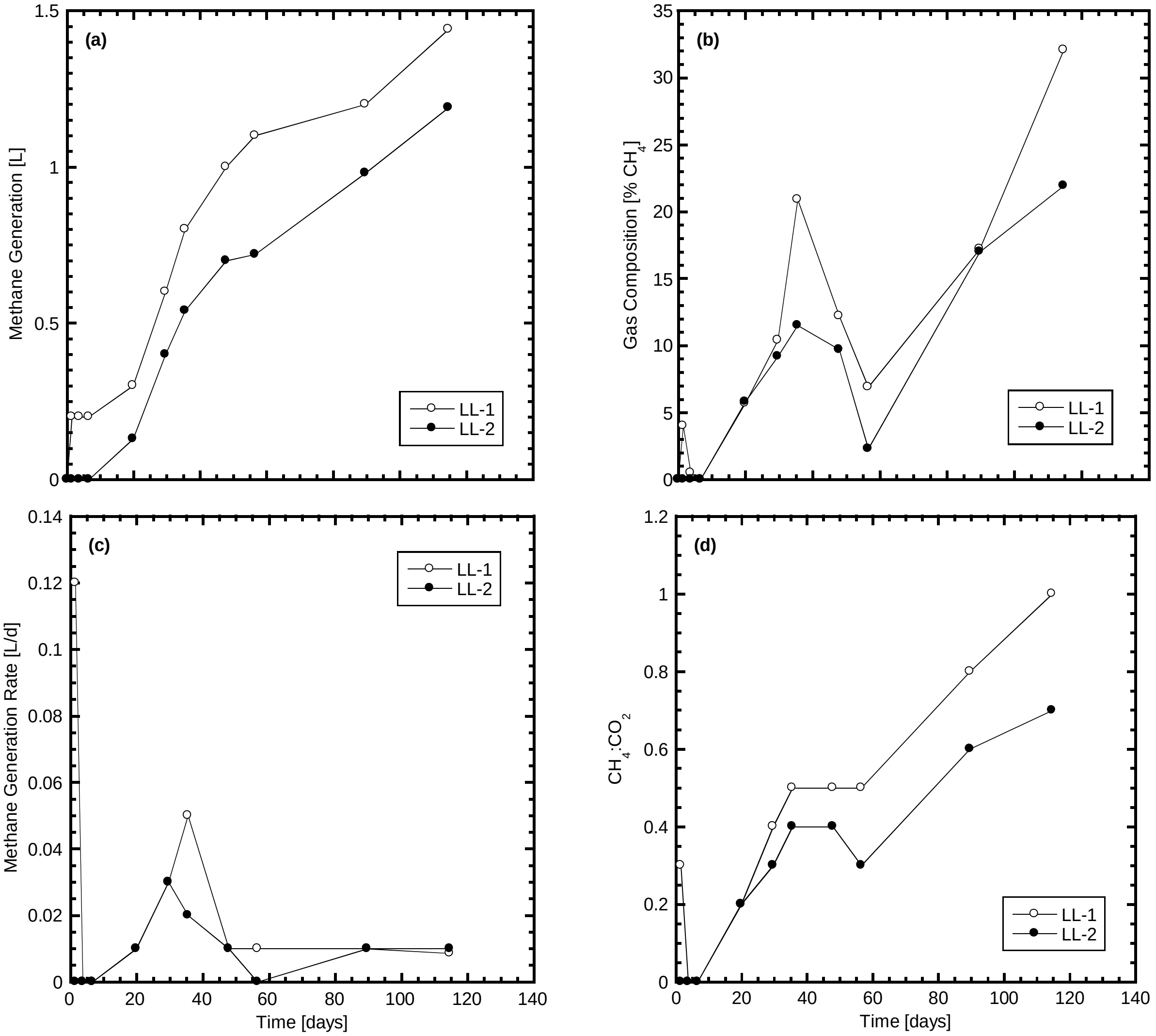


Figure A-1. Summary data, including (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand for the de-ionized water (DIW) reactor duplicates.

Table A-2. Reactor information, initial conditions, and final conditions for the landfill leachate (LL) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**LL-1**	**LL-2**
Reactors:	LL-1 & LL-2	*Specimen thickness [cm]:*	20.6	20.0
Startup date:	1/24/2018	*Specimen density [g/cm^3]:*	0.36	0.37
Experiment duration [days]:	125	*Initial recirculated volume [L/Mg-waste]:*	109	113
Solid waste fraction:	Municipal Solid Waste	*Initial w_d after dosing [%]:*	101	100
MSW [g]:	2400			
Liquid waste fraction:	Landfill Leachate	**FINAL CONDITIONS**		
Initial liquid dose [L/Mg-waste]:	625	*Cumulative recirculated liquid [L/Mg-waste]:*	1165	1300
		Average weekly recirculated liquid [L/Mg-waste]:	69	76
		Settlement Strain [%]:	3.1	2.4



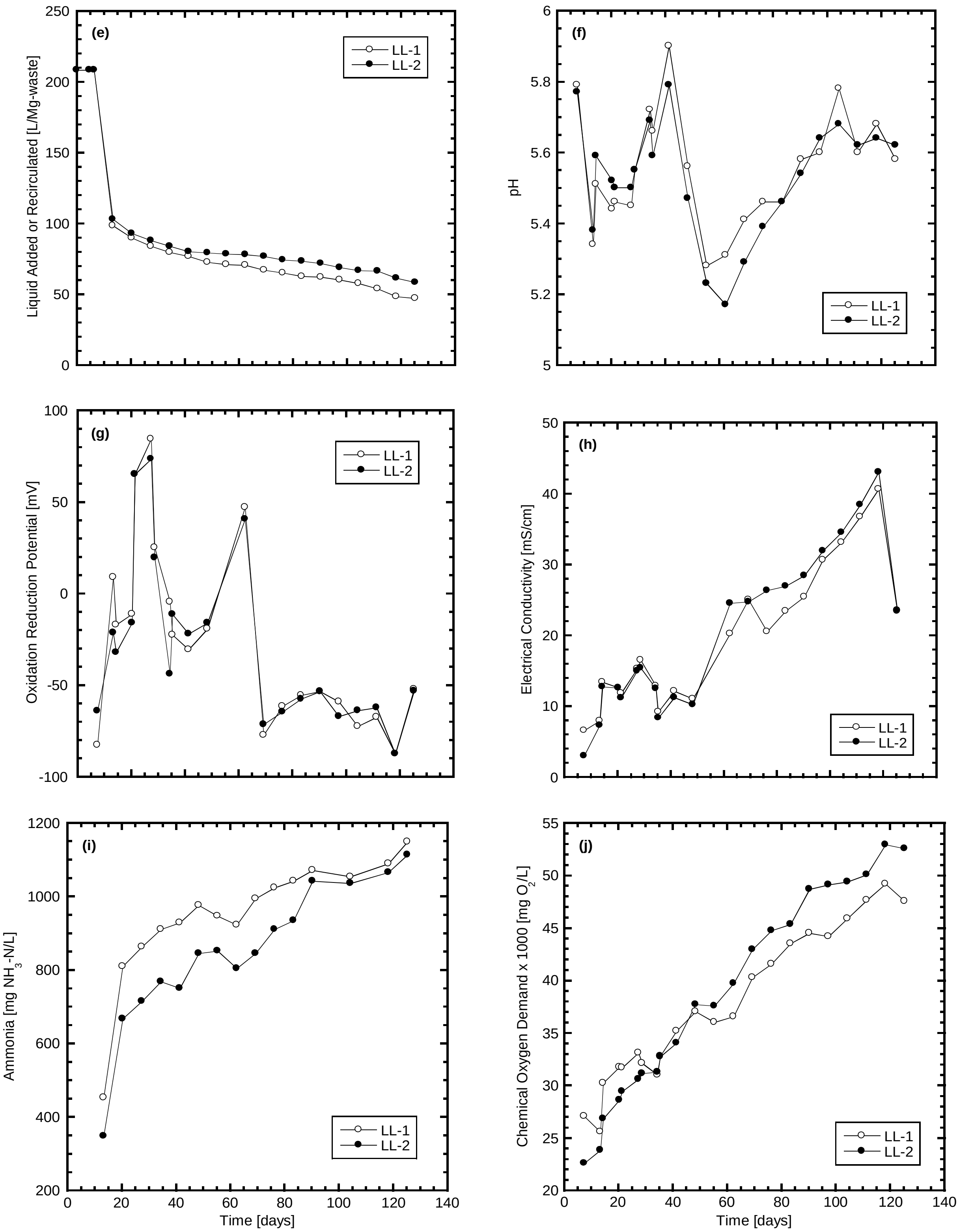
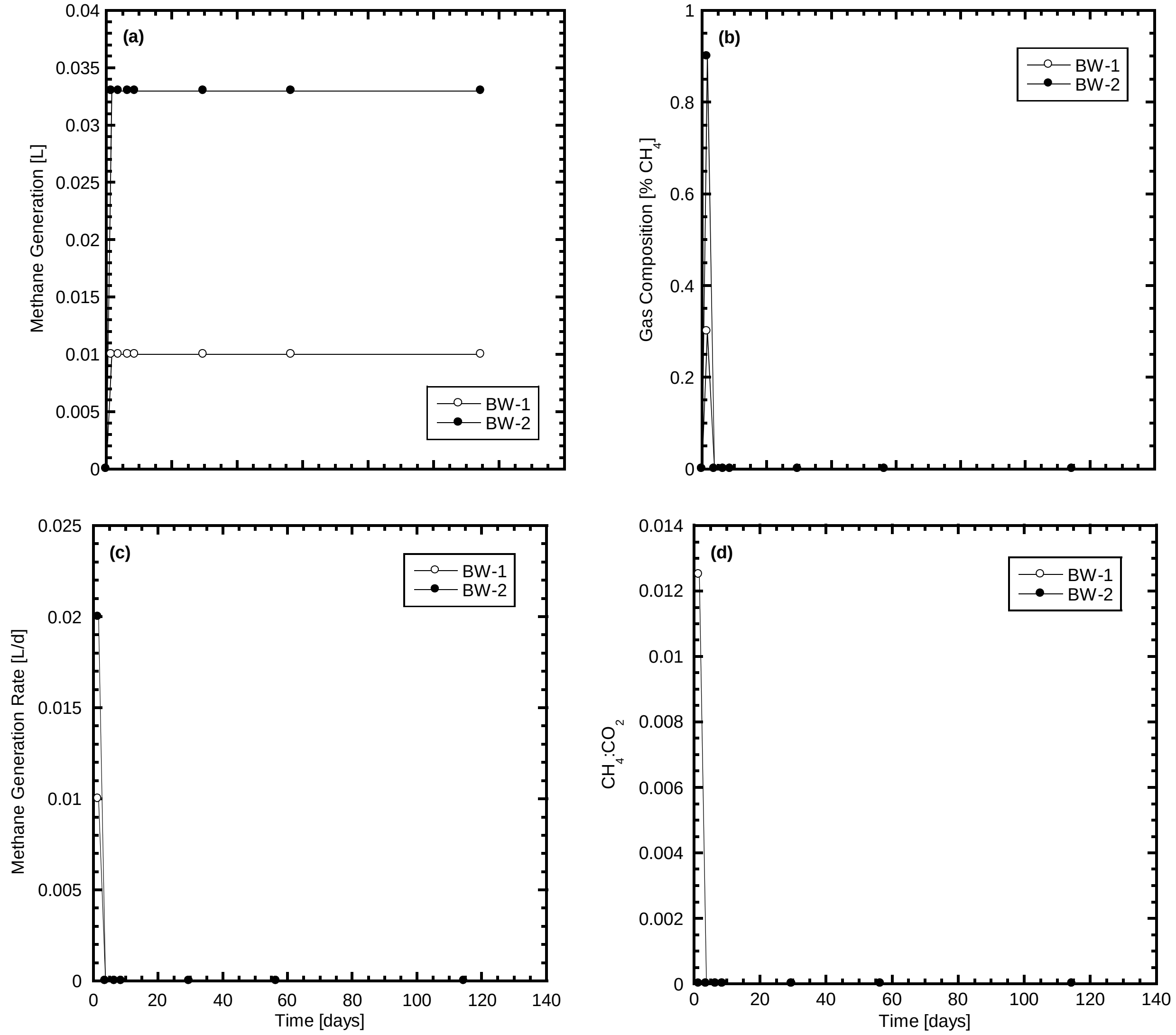


Figure A-2. Summary data for the landfill leachate (LL) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

Table A-3. Reactor information, initial conditions, and final conditions for the brewery wastewater (BW) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**BW-1**	**BW-2**
Reactors:	BW-1 & BW-2	*Specimen thickness [cm]:*	20.6	20.6
Startup date:	1/24/2018	*Specimen density [g/cm^3]:*	0.36	0.36
Experiment duration [days]:	126	*Initial recirculated volume [L/Mg-waste]:*	55	76
Solid waste fraction:	Municipal Solid Waste	*Initial w_d after dosing [%]:*	108	105
MSW [g]:	2400			
Liquid waste fraction:	Brewery Wastewater	**FINAL CONDITIONS**		
Initial liquid dose [L/Mg-waste]:	625	*Cumulative recirculated liquid [L/Mg-waste]:*	696	1162
		Average weekly recirculated liquid [L/Mg-waste]:	41	68
		Settlement Strain [%]:	3.1	3.1



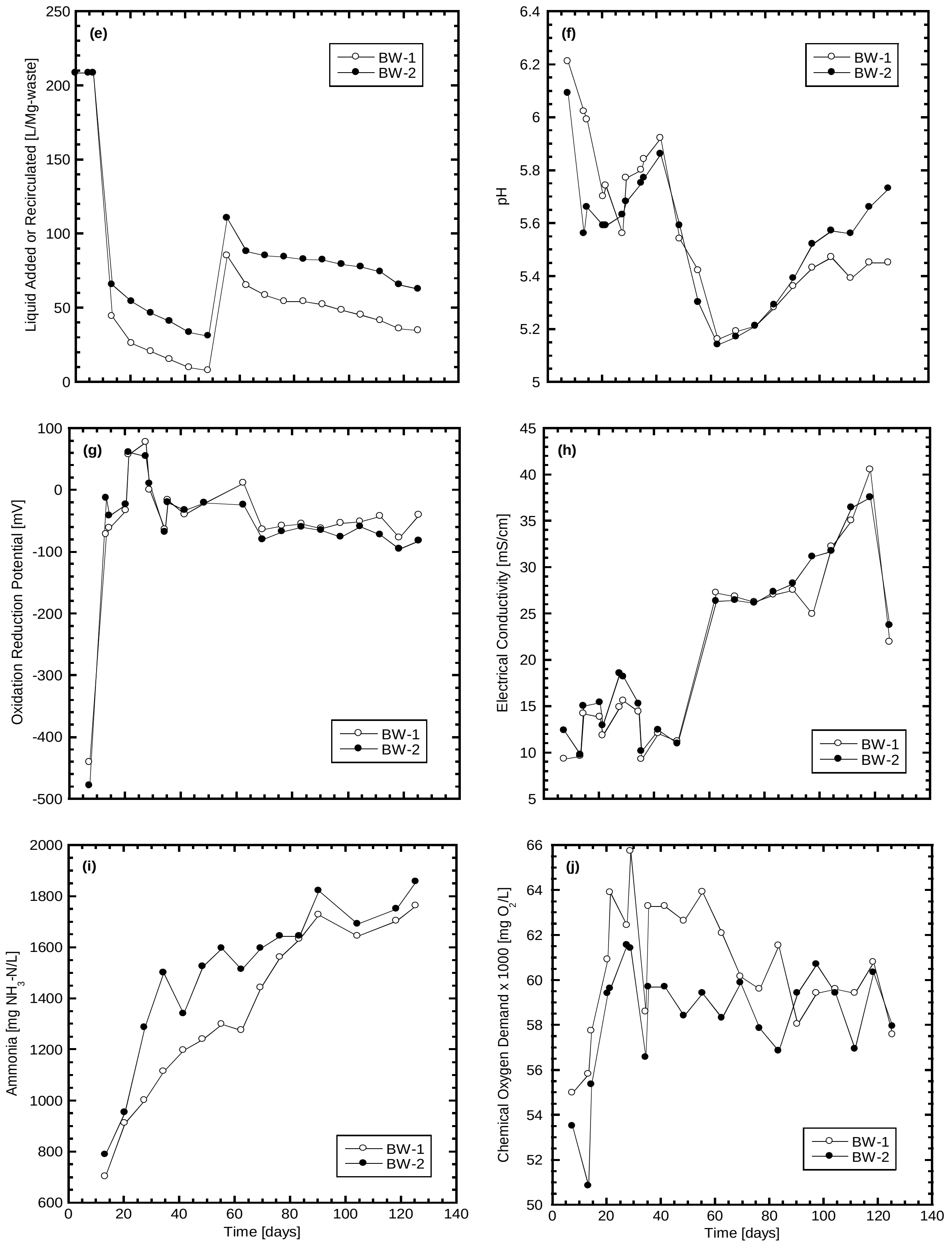
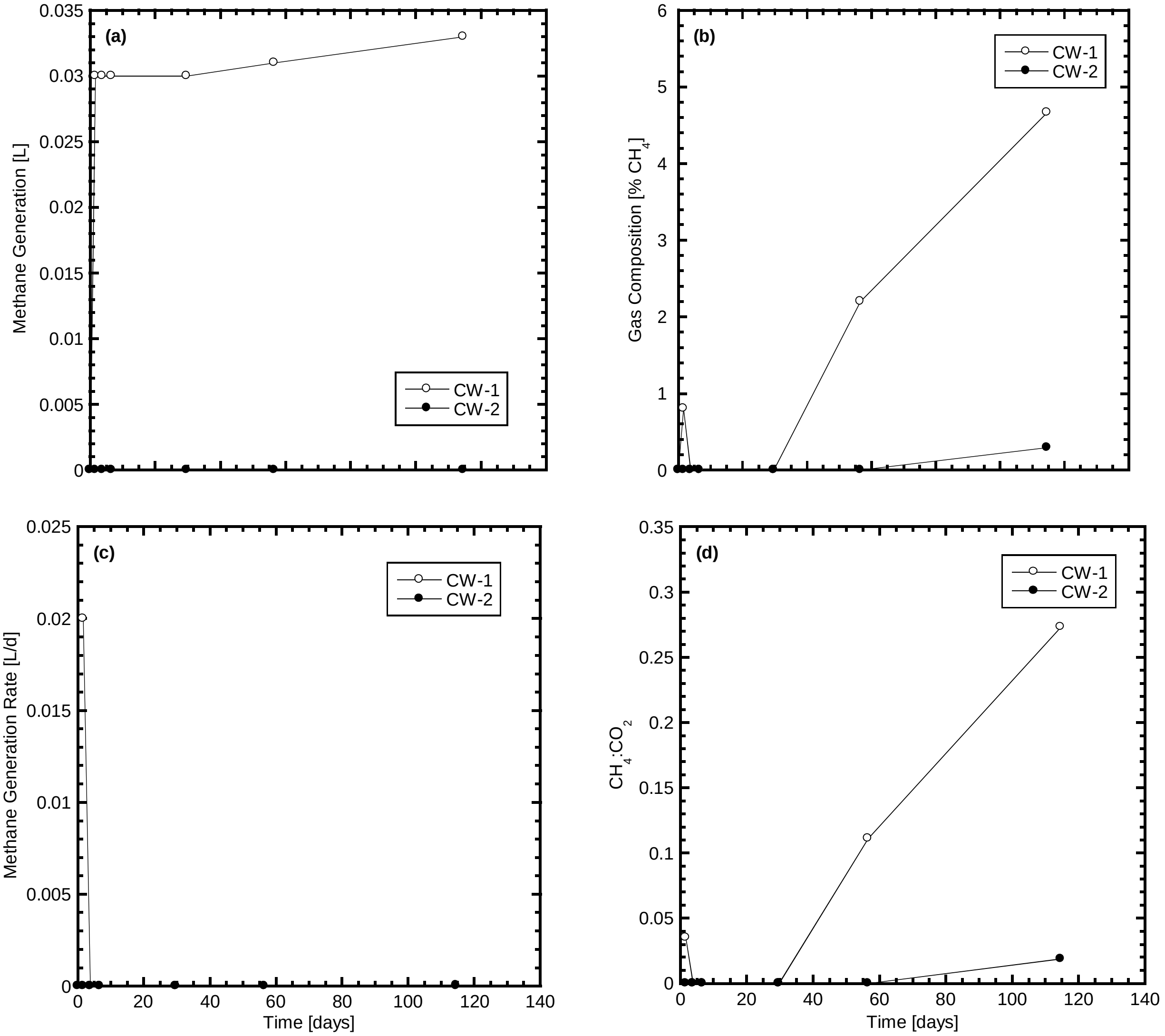


Figure A-3. Summary data for the brewery wastewater (BW) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

Table A-4. Reactor information, initial conditions, and final conditions for the cheese processing wastewater (CW) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**CW-1**	**CW-2**
Reactors:	CW-1 & CW-2	*Specimen thickness [cm]:*	20.0	20.2
Startup date:	1/24/2018	*Specimen density [g/cm^3]:*	0.37	0.37
Experiment duration [days]:	126	*Initial recirculated volume [L/Mg-waste]:*	120	91
Solid waste fraction:	Municipal Solid Waste	*Initial w_d after dosing [%]:*	100	103
MSW [g]:	2400			
		FINAL CONDITIONS		
Liquid waste fraction:	Cheese Processing Wastewater	*Cumulative recirculated liquid [L/Mg-waste]:*	965	666
Initial liquid dose [L/Mg-waste]:	625	*Average weekly recirculated liquid [L/Mg-waste]:*	57	39
		Settlement Strain [%]:	2.4	3.9



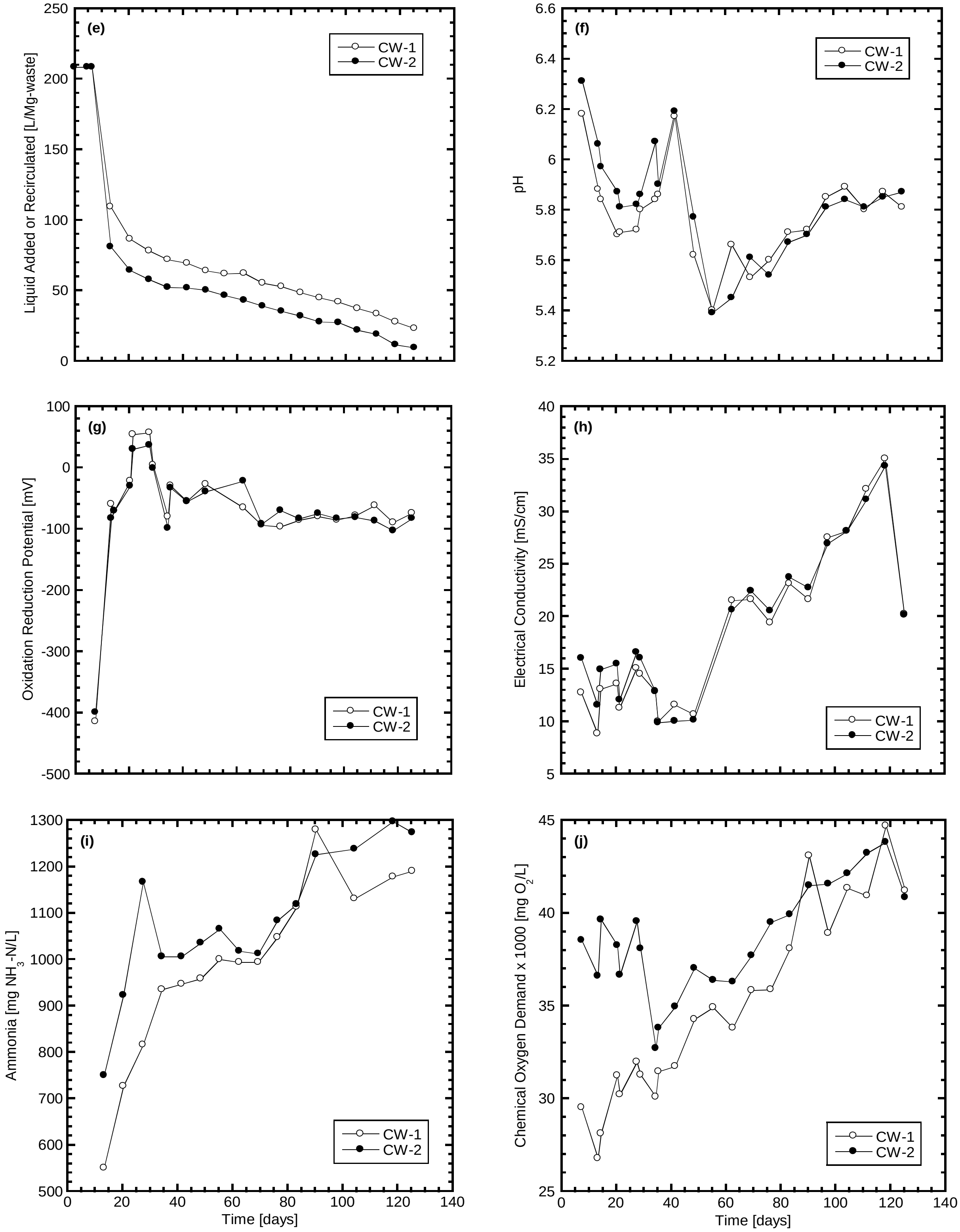
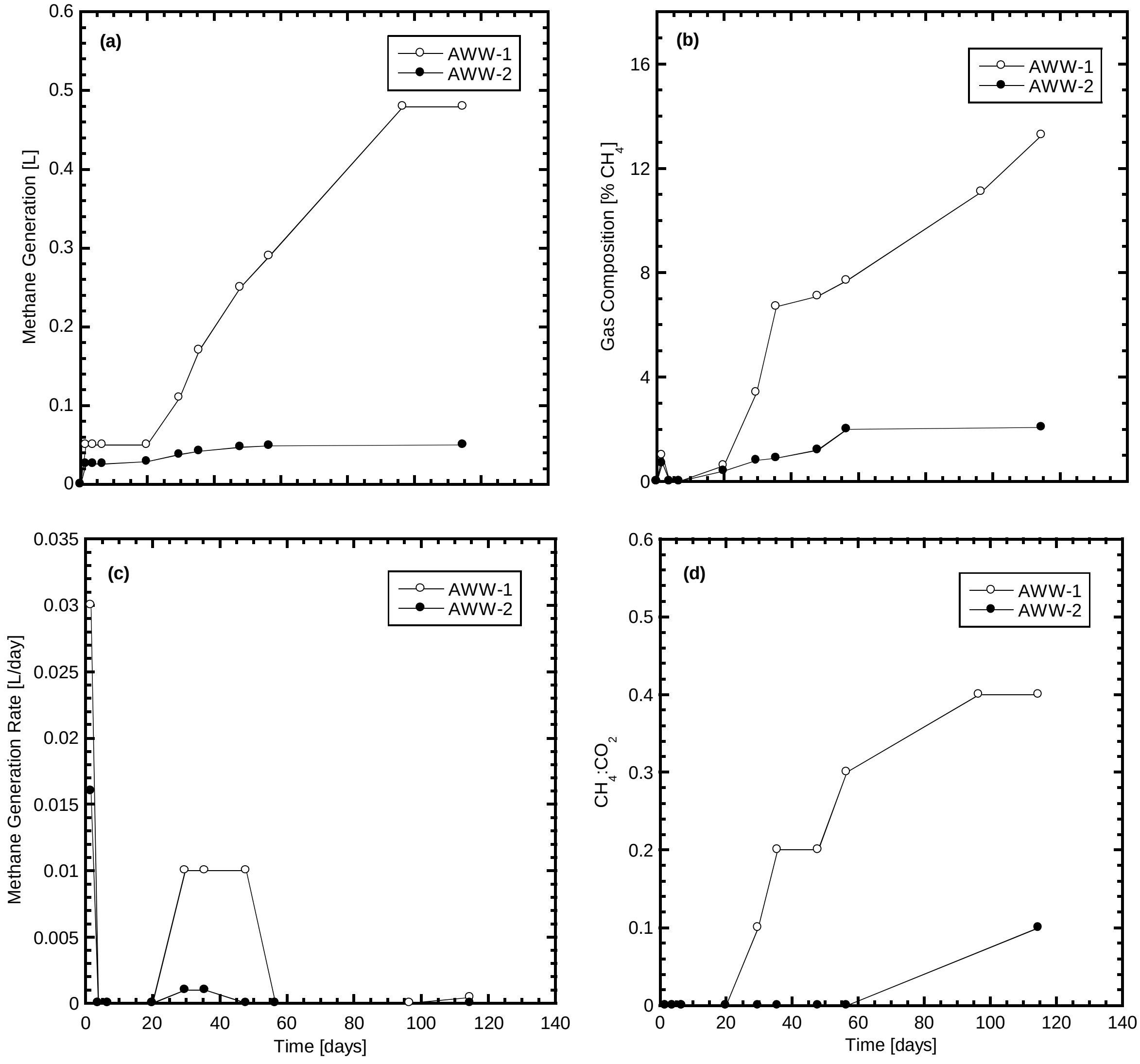


Figure A-4. Summary data for the cheese processing wastewater (CW) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

Table A-5. Reactor information, initial conditions, and final conditions for the automobile wash water (AWW) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**AWW-1**	**AWW-2**
Reactors:	AWW-1 & AWW-2	*Specimen thickness [cm]:*	20.0	20.8
Startup date:	1/24/2018	*Specimen density [g/cm^3]:*	0.37	0.36
Experiment duration [days]:	126	*Initial recirculated volume [L/Mg-waste]:*	123	139
Solid waste fraction:	Municipal Solid Waste	*Initial w_d after dosing [%]:*	99	97
MSW [g]:	2400			
		FINAL CONDITIONS		
Liquid waste fraction:	Automobile Wash Water	*Cumulative recirculated liquid [L/Mg-waste]:*	1194	1256
Initial liquid dose [L/Mg-waste]:	625	*Average weekly recirculated liquid [L/Mg-waste]:*	70	74
		Settlement Strain [%]:	2.4	2.3



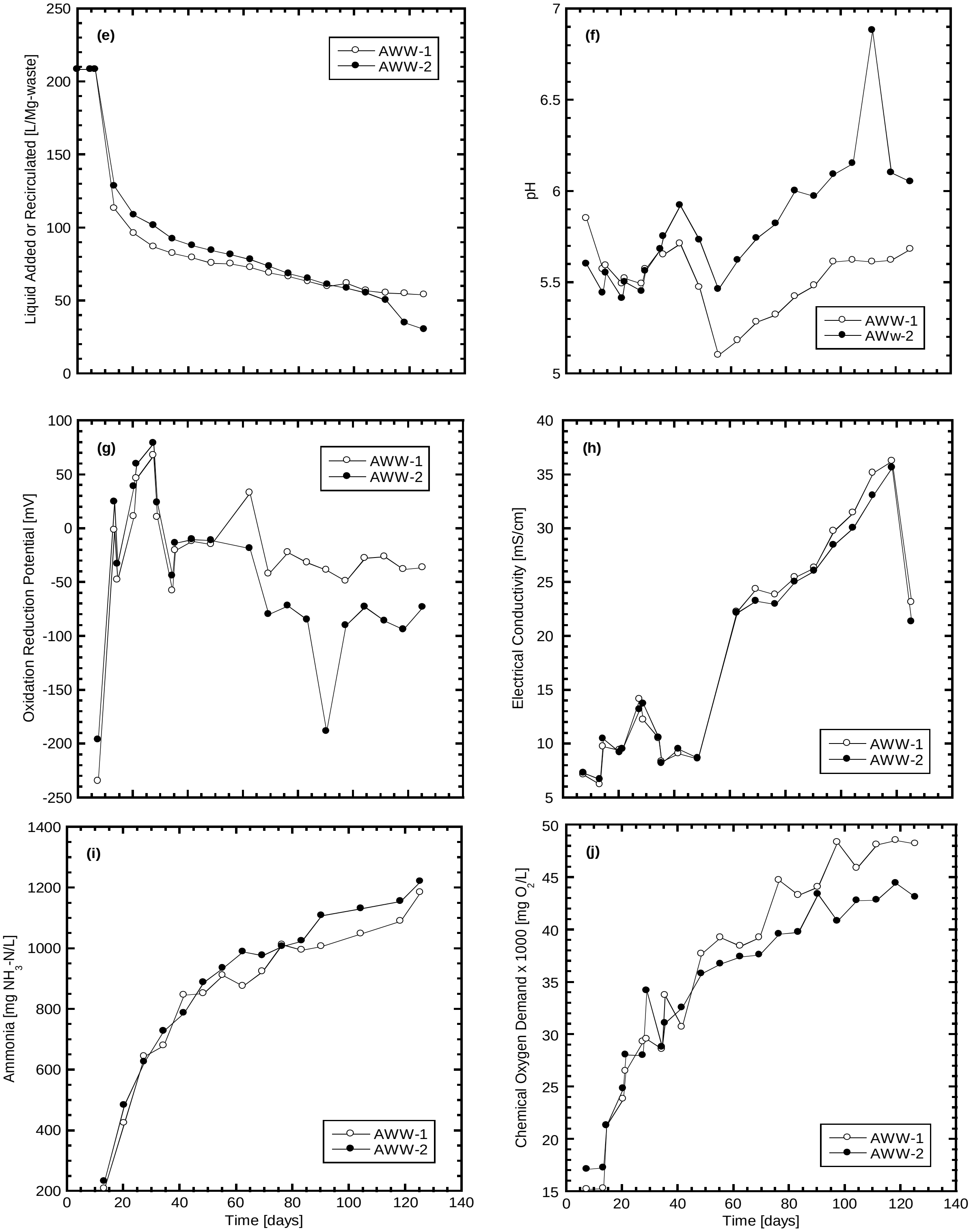
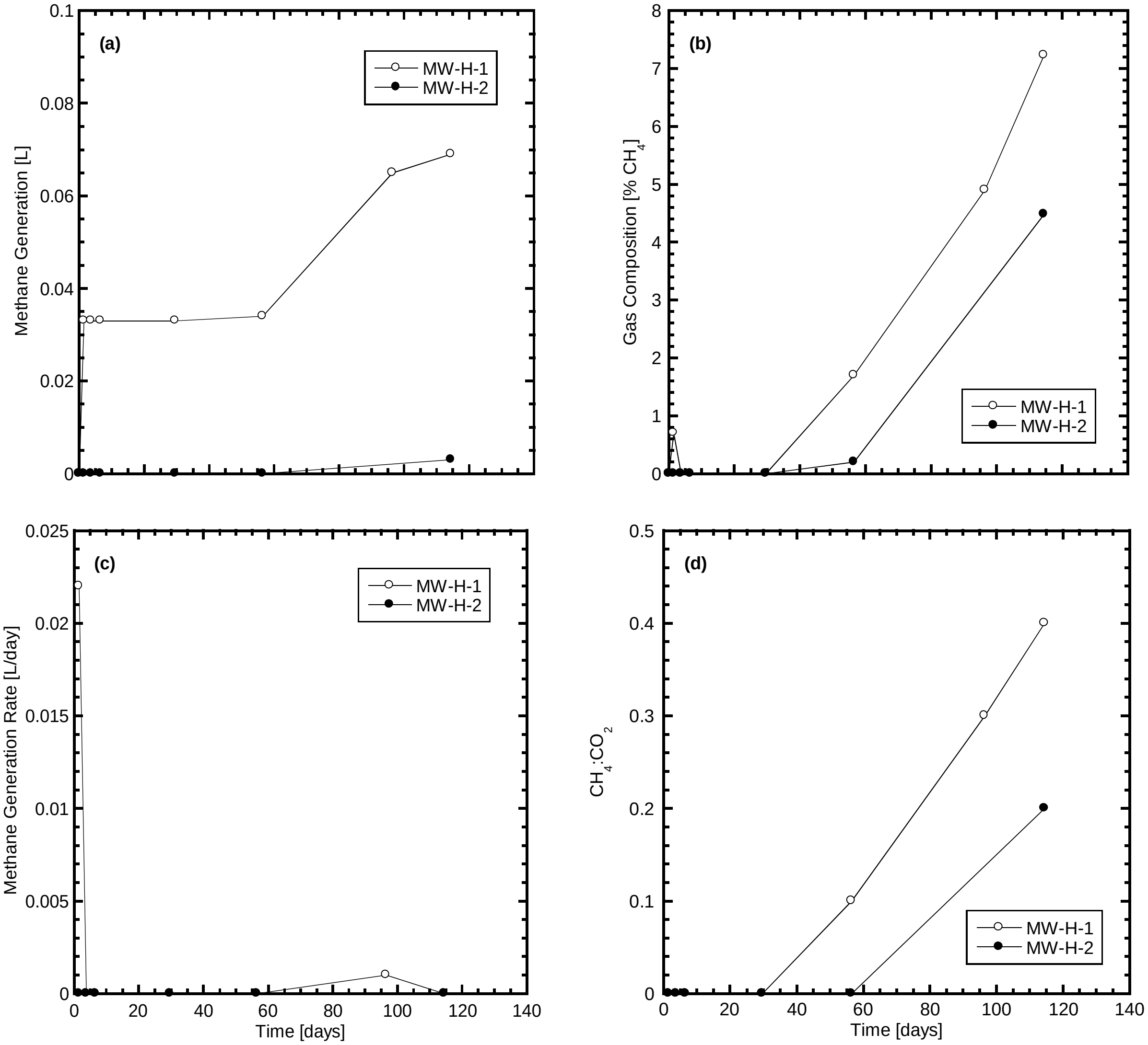


Figure A-5. Summary data for the automobile wash water (AWW) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

Table A-6. Reactor information, initial conditions, and final conditions for the high strength manufacturing wastewater (MW-H) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**MW-H-1**	**MW-H-2**
Reactors:	MW-H-1 & MW-H-2	*Specimen thickness [cm]:*	20.3	20.6
Startup date:	1/24/2018	*Specimen density [g/cm^3]:*	0.36	0.36
Experiment duration [days]:	125	*Initial recirculated volume [L/Mg-waste]:*	87	60
Solid waste fraction:	Municipal Solid Waste	*Initial w_d after dosing [%]:*	104	108
MSW [g]:	2400			
Liquid waste fraction:	High Strength Manufacturing Wastewater	**FINAL CONDITIONS**		
		Cumulative recirculated liquid [L/Mg-waste]:	1128	716
Initial liquid dose [L/Mg-waste]:	625	*Average weekly recirculated liquid [L/Mg-waste]:*	66	42
		Settlement Strain [%]:	3.1	2.3



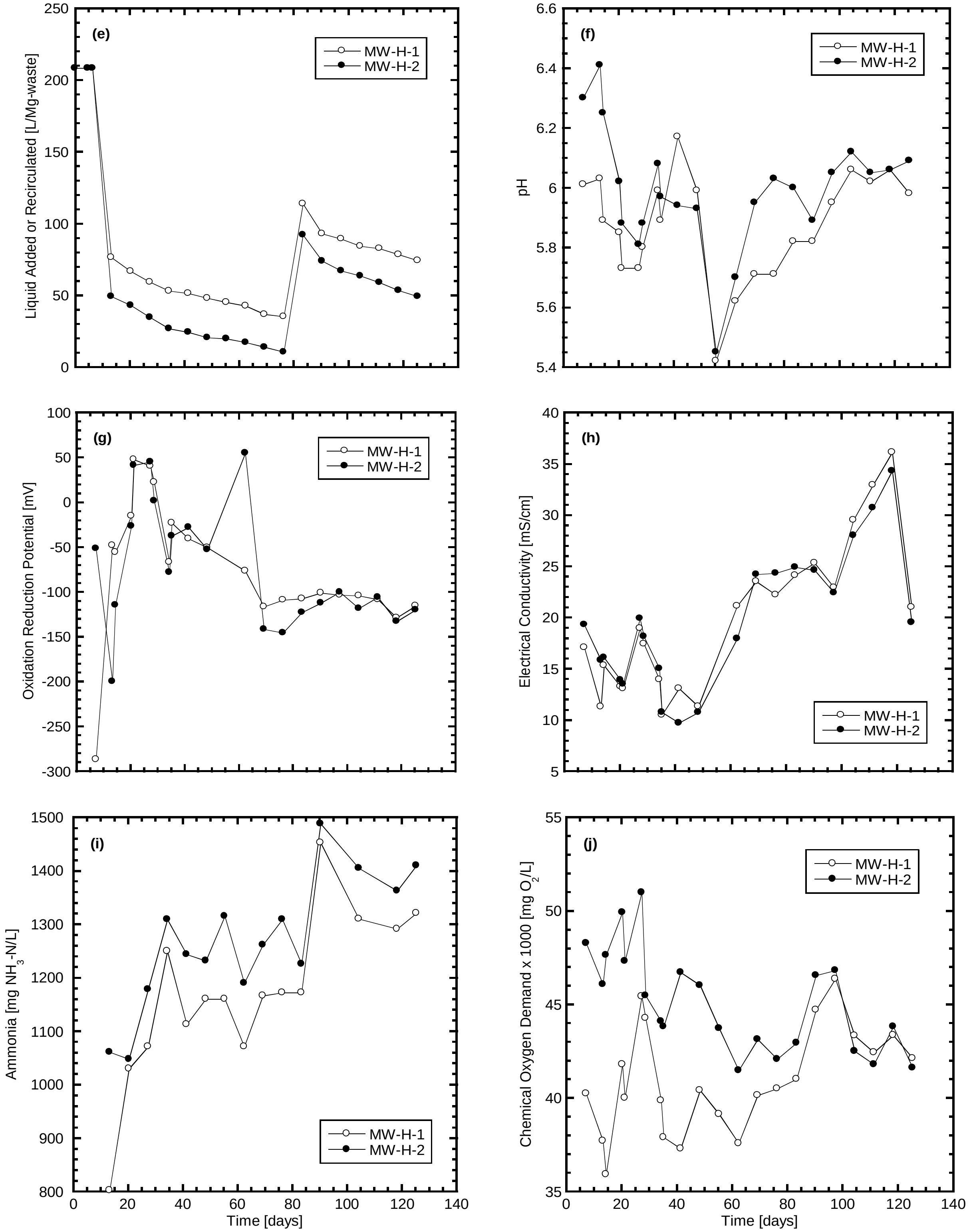
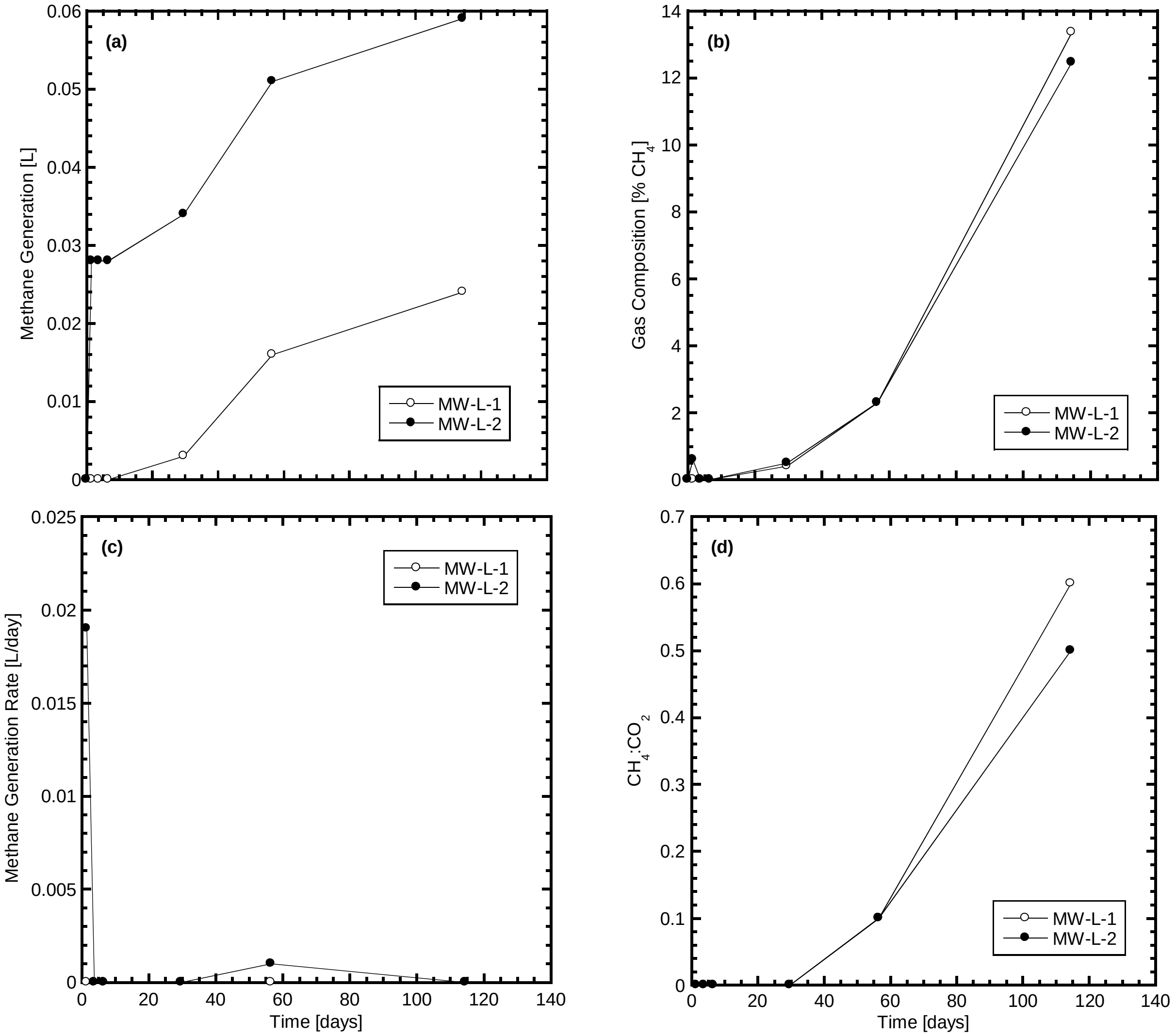


Figure A-6. Summary data for the high-strength manufacturing wastewater (MW-H) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

Table A-7. Reactor information, initial conditions, and final conditions for the low strength manufacturing wastewater (MW-L) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**MW-L-1**	**MW-L-2**
Reactors:	MW-L-1 & MW-L-2	*Specimen thickness [cm]:*	20.3	21.1
Startup date:	1/24/2018	*Specimen density [g/cm^3]:*	0.36	0.35
Experiment duration [days]:	125	*Initial recirculated volume [L/Mg-waste]:*	104	109
Solid waste fraction:	Municipal Solid Waste	*Initial w_d after dosing [%]:*	102	101
MSW [g]:	2400			
Liquid waste fraction:	Low Strength Manufacturing Wastewater	**FINAL CONDITIONS**		
		Cumulative recirculated liquid [L/Mg-waste]:	900	1125
Initial liquid dose [L/Mg-waste]:	625	*Average weekly recirculated liquid [L/Mg-waste]:*	53	66
		Settlement Strain [%]:	1.6	2.3



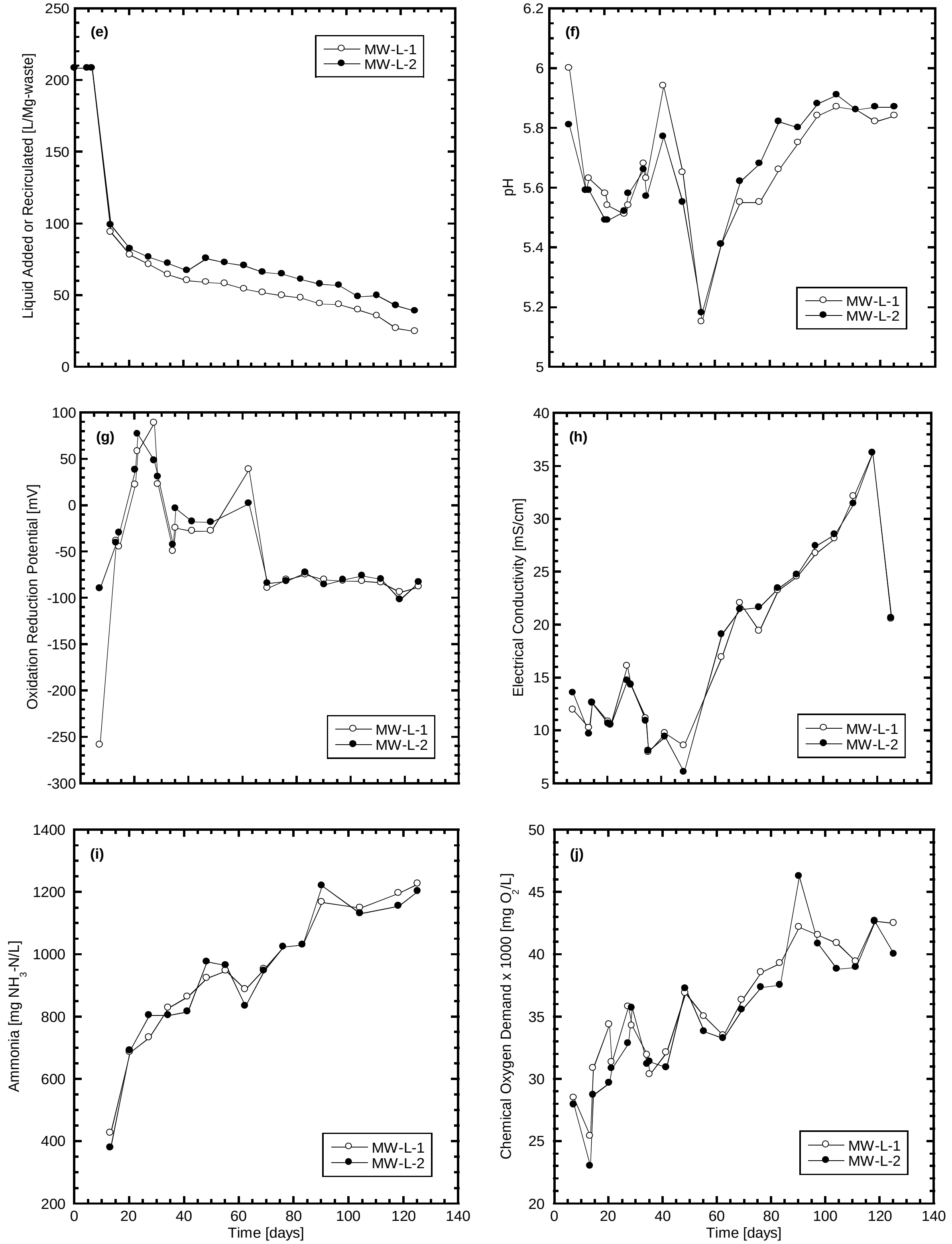
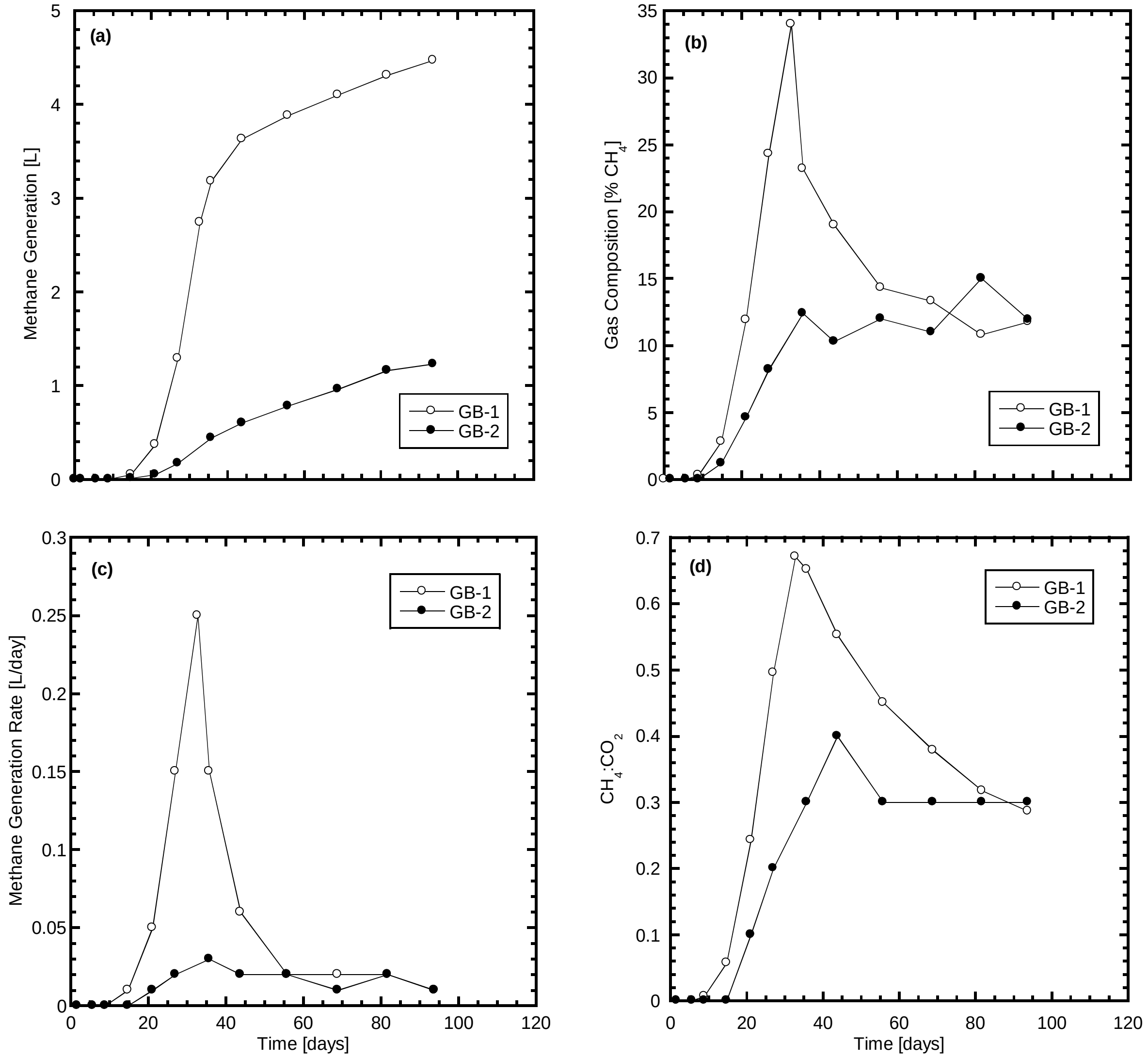


Figure A-7. Summary data for the low-strength manufacturing wastewater (MW-L) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

Table A-8. Reactor information, initial conditions, and final conditions for the gypsum board (GB) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**GB-1**	**GB-2**
Reactors:	GB-1 & GB-2	*Specimen thickness [cm]:*	18.4	20.0
Startup date:	2/14/2018	*Specimen density [g/cm^3]:*	0.40	0.37
Experiment duration [days]:	105	*Initial recirculated volume [L/Mg-waste]:*	114	95
Solid waste fraction:	Municipal Solid Waste and Gypsum Board	*Initial w_d after dosing [%]:*	92	94
MSW [g]:	1440	**FINAL CONDITIONS**		
Gypsum Board [g]:	960	*Cumulative recirculated liquid [L/Mg-waste]:*	1120	751
Liquid waste fraction:	Landfill Leachate	*Average weekly recirculated liquid [L/Mg-waste]:*	80	54
Initial liquid dose [L/Mg-waste]:	750	*Settlement Strain [%]:*	1.7	1.6



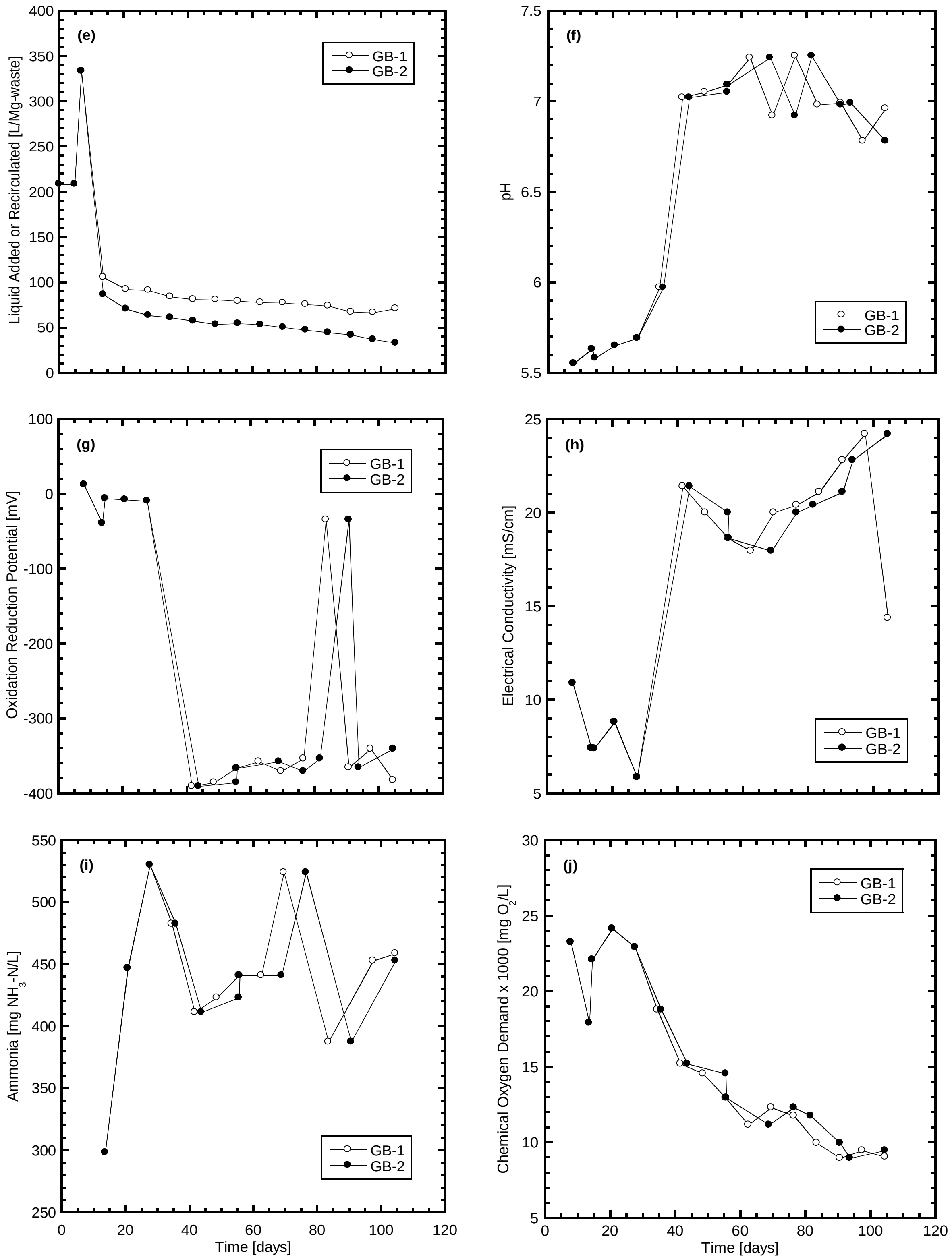
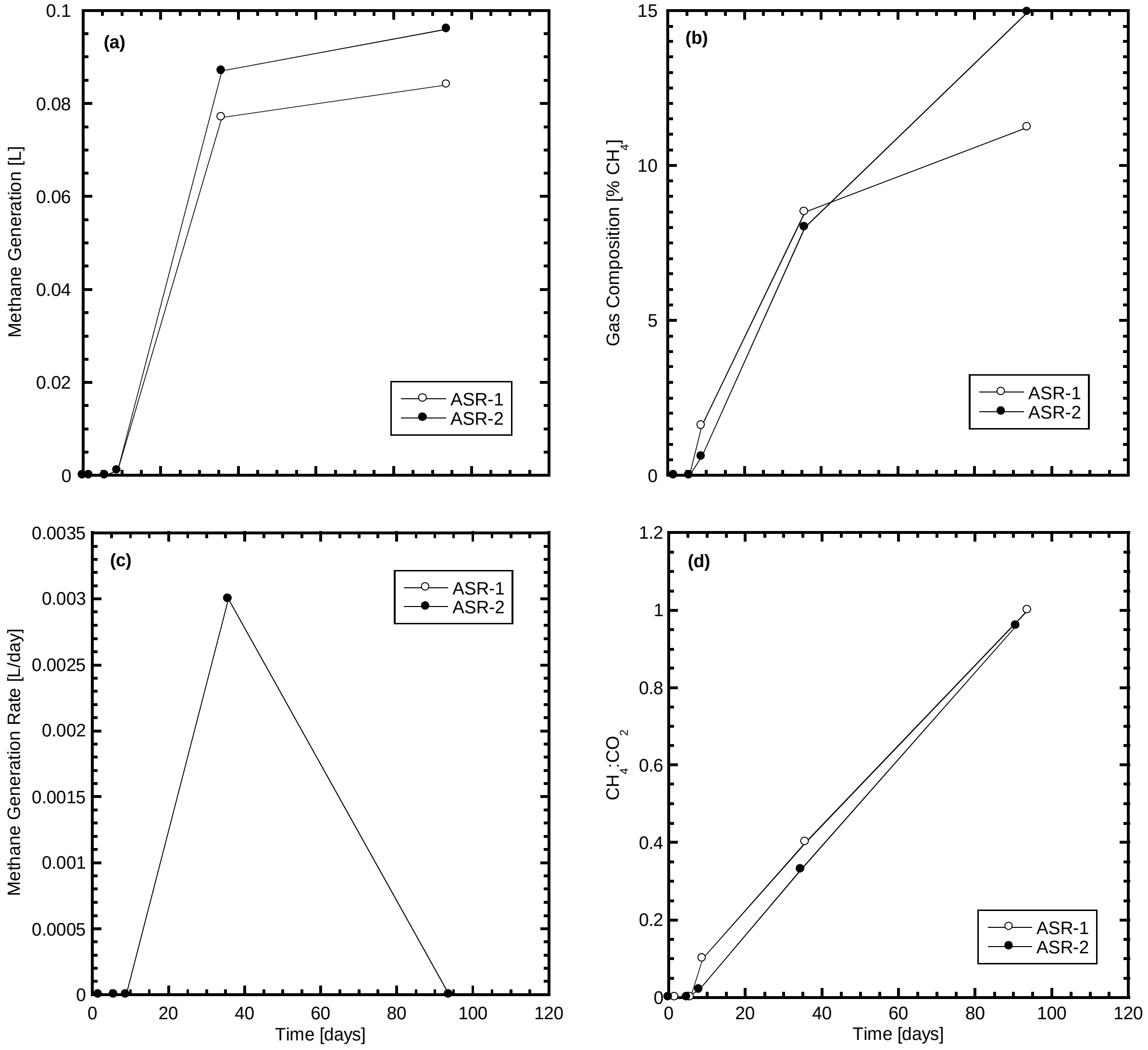


Figure A-8. Summary data for the gypsum board (GB) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

Table A-9. Reactor information, initial conditions, and final conditions for the automobile shredder residue (ASR) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**ASR-1**	**ASR-2**
Reactors:	ASR-1 & ASR-2	*Specimen thickness [cm]:*	18.7	18.4
Startup date:	2/14/2018	*Specimen density [g/cm^3]:*	0.40	0.40
Experiment duration [days]:	105	*Initial recirculated volume [L/Mg-waste]:*	102	53
Solid waste fraction:	Municipal Solid Waste and Auto Shredder Residue	*Initial w_d after dosing [%]:*	59	65
MSW [g]:	1440	**FINAL CONDITIONS**		
Auto Shredder Residue [g]:	960	*Cumulative recirculated liquid [L/Mg-waste]:*	964	580
Liquid waste fraction:	Landfill Leachate	*Average weekly recirculated liquid [L/Mg-waste]:*	69	41
Initial liquid dose [L/Mg-waste]:	458	*Settlement Strain [%]:*	1.7	0.9



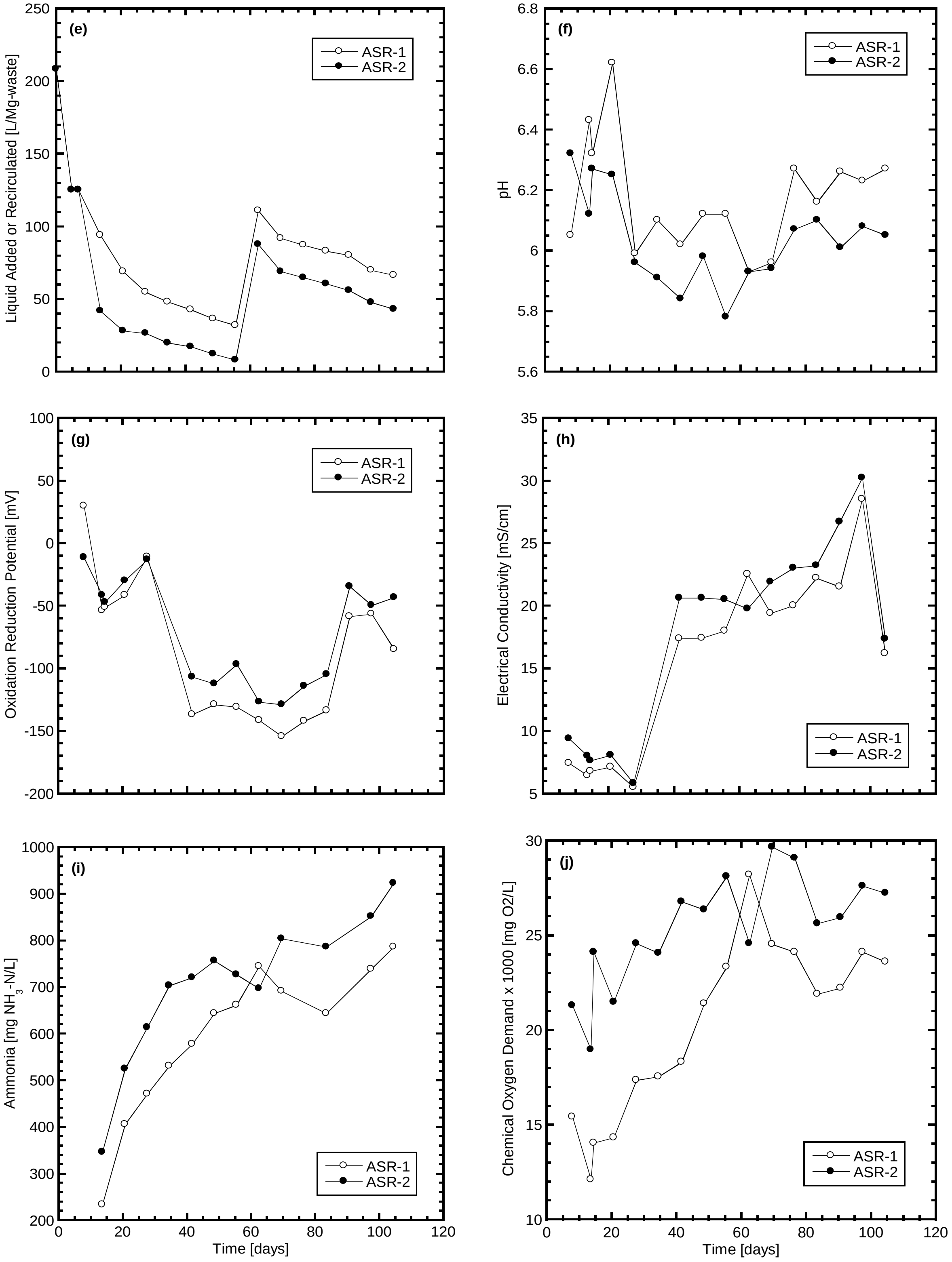
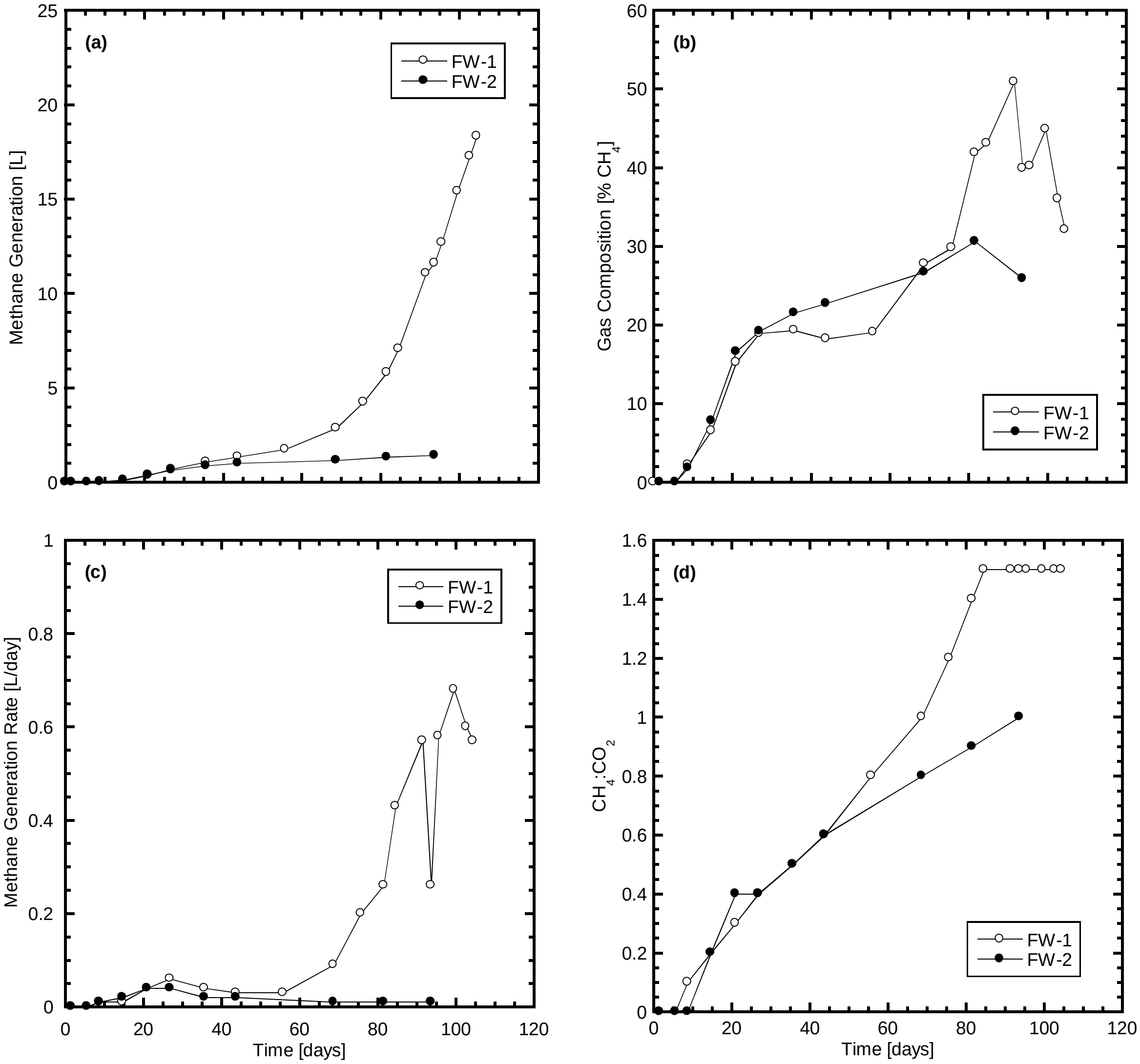


Figure A-9. Summary data for the automobile shredder residue (ASR) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

Table A-10. Reactor information, initial conditions, and final conditions for the foundry waste (FW) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**FW-1**	**FW-2**
Reactors:	FW-1 & FW-2	*Specimen thickness [cm]:*	15.2	16.0
Startup date:	2/14/2018	*Specimen density [g/cm^3]:*	0.49	0.46
Experiment duration [days]:	105	*Initial recirculated volume [L/Mg-waste]:*	70	59
Solid waste fraction:	Municipal Solid Waste and Foundry Waste	*Initial w_d after dosing [%]:*	63	64
MSW [g]:	1440	**FINAL CONDITIONS**		
Foundry Waste [g]:	960	*Cumulative recirculated liquid [L/Mg-waste]:*	560	517
Liquid waste fraction:	Landfill Leachate	*Average weekly recirculated liquid [L/Mg-waste]:*	40	37
Initial liquid dose [L/Mg-waste]:	458	*Settlement Strain [%]:*	2.1	5.0



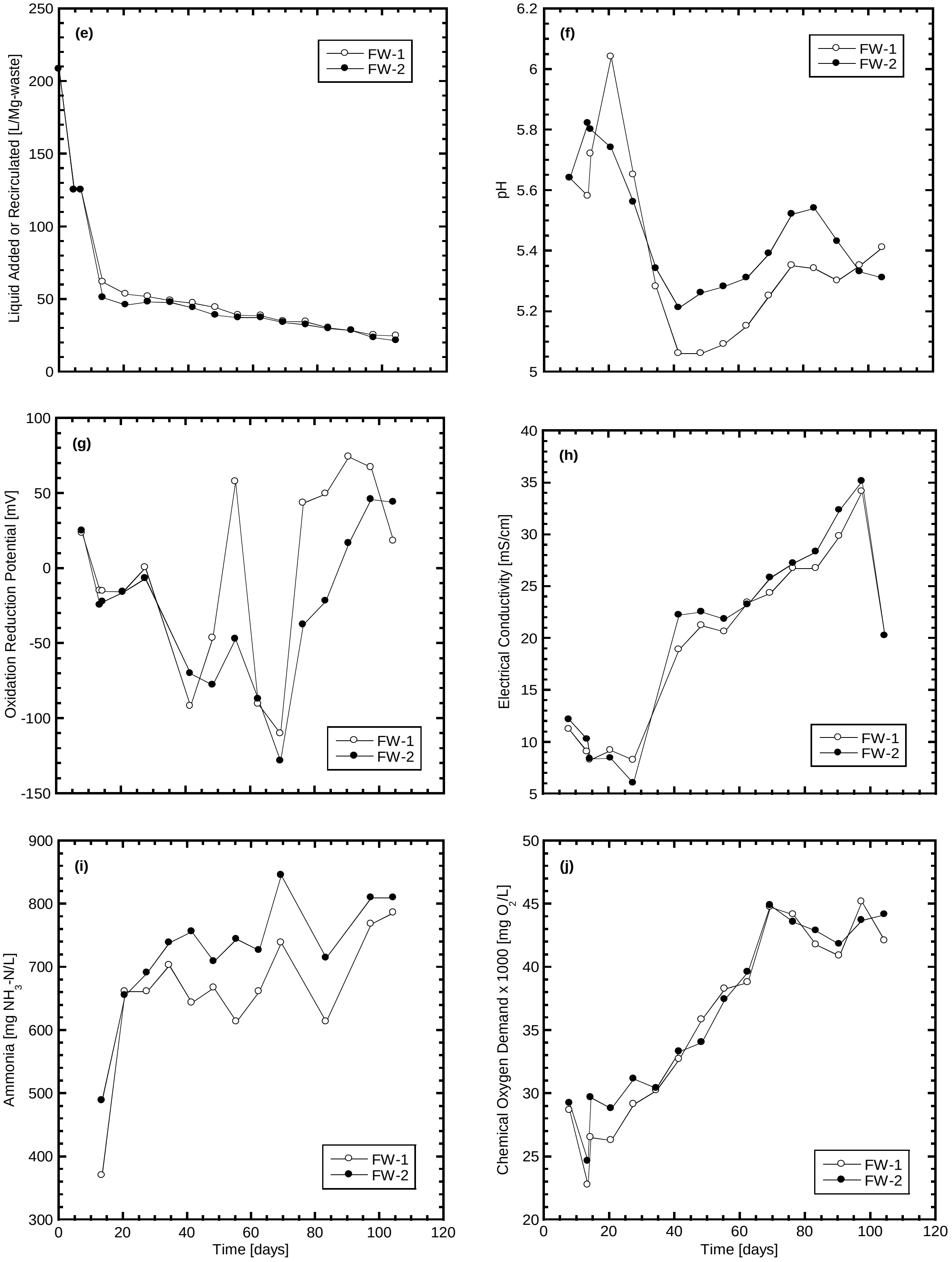
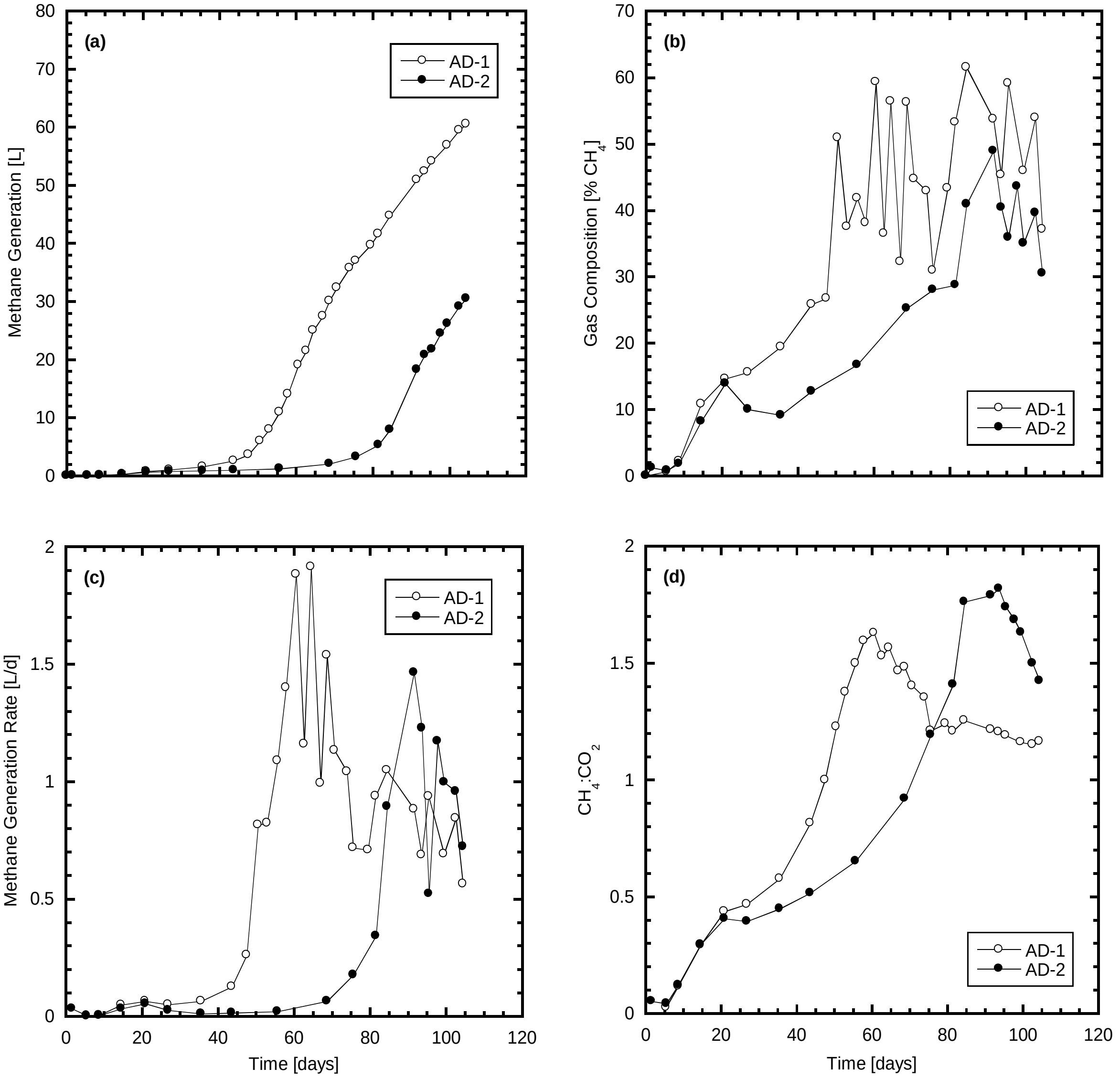


Figure A-10. Summary data for the foundry waste (FW) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

Table A-11. Reactor information, initial conditions, and final conditions for the anaerobic digestion sludge (AD) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**AD-1**	**AD-2**
Reactors:	AD-1 & AD-2	*Specimen thickness [cm]:*	14.0	12.7
Startup date:	2/14/2018	*Specimen density [g/cm^3]:*	0.53	0.58
Experiment duration [days]:	105	*Initial recirculated volume [L/Mg-waste]:*	109	110
Solid waste fraction:	Municipal Solid Waste and Anaerobic Sludge	*Initial w_d after dosing [%]:*	135	135
MSW [g]:	1440	**FINAL CONDITIONS**		
Anaerobic Sludge [g]:	960	*Cumulative recirculated liquid [L/Mg-waste]:*	1530	1465
Liquid waste fraction:	Landfill Leachate	*Average weekly recirculated liquid [L/Mg-waste]:*	109	105
Initial liquid dose [L/Mg-waste]:	188	*Settlement Strain [%]:*	9.1	7.5



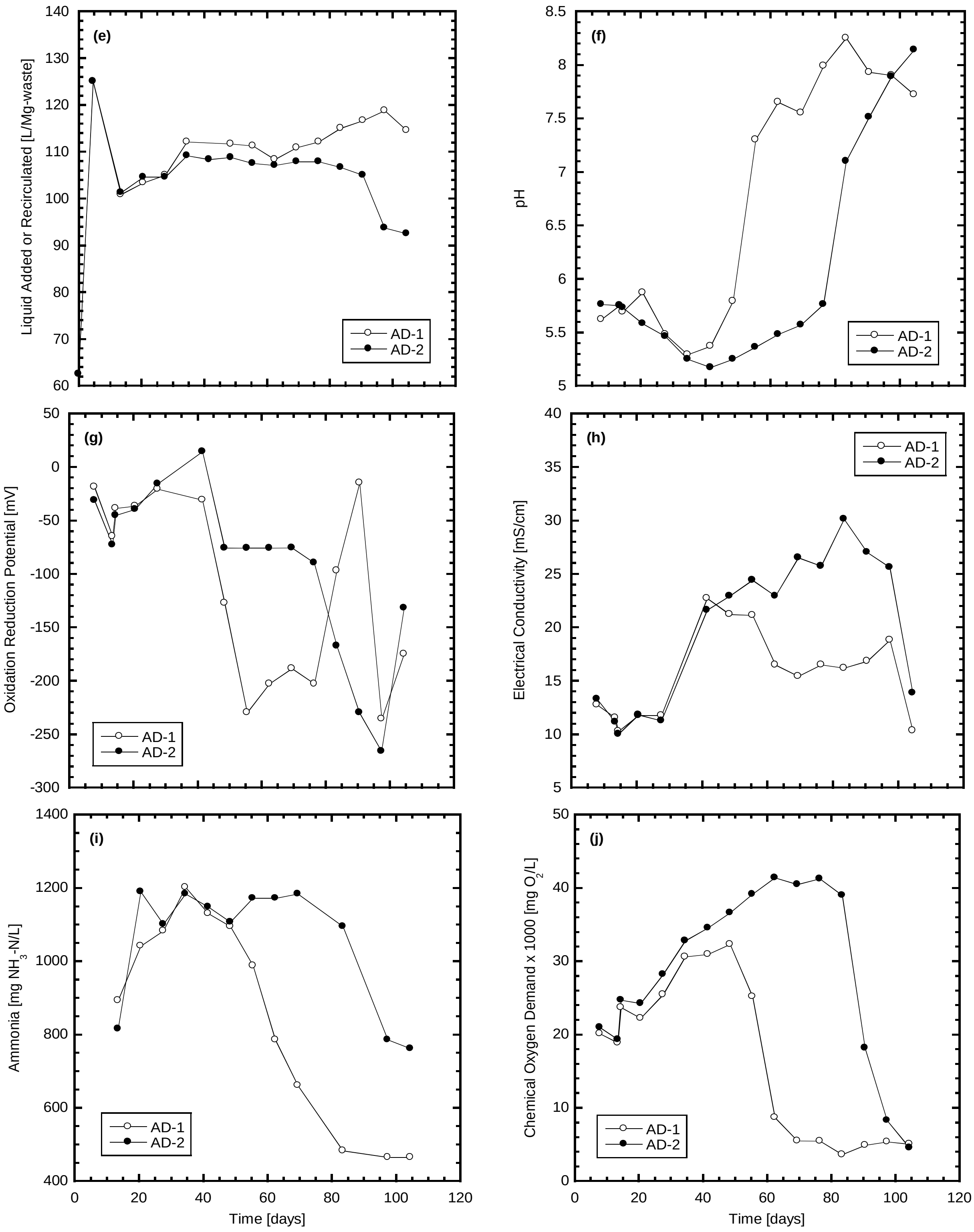
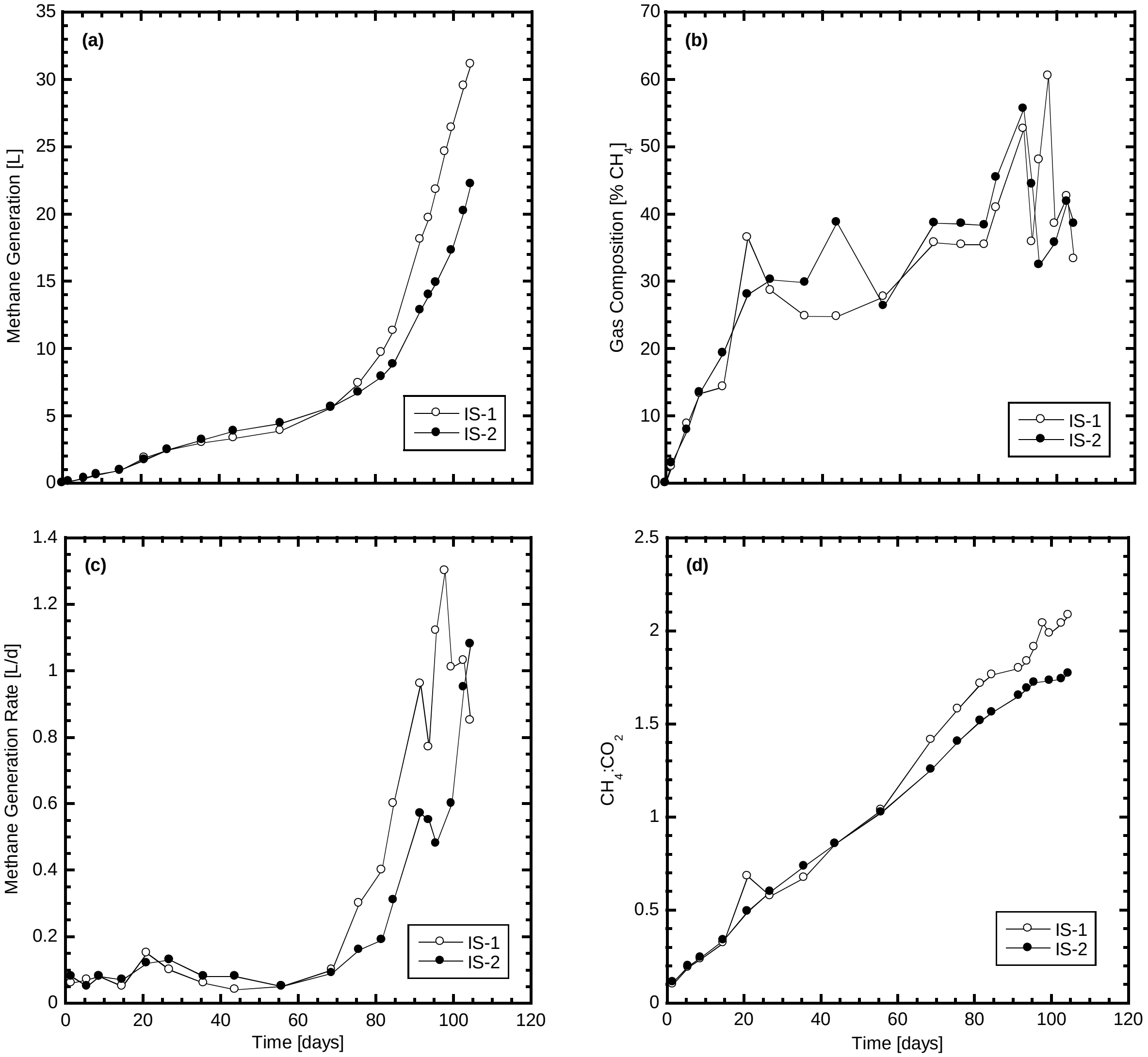


Figure A-11. Summary data for the anaerobic digestion sludge (AD) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

Table A-12. Reactor information, initial conditions, and final conditions for the industrial sludge (IS) reactor duplicates.

REACTOR INFORMATION		**INITIAL CONDITIONS**	**IS-1**	**IS-2**
Reactors:	IS-1 & IS-2	*Specimen thickness [cm]:*	12.7	12.1
Startup date:	2/14/2018	*Specimen density [g/cm^3]:*	0.58	0.61
Experiment duration [days]:	105	*Initial recirculated volume [L/Mg-waste]:*	93	75
Solid waste fraction:	Municipal Solid Waste and Industrial Sludge	*Initial w_d after dosing [%]:*	149	152
MSW [g]:	1440	**FINAL CONDITIONS**		
Industrial Sludge [g]:	960	*Cumulative recirculated liquid [L/Mg-waste]:*	1138	898
Liquid waste fraction:	Landfill Leachate	*Average weekly recirculated liquid [L/Mg-waste]:*	81	64
Initial liquid dose [L/Mg-waste]:	333	*Settlement Strain [%]:*	6.8	2.5



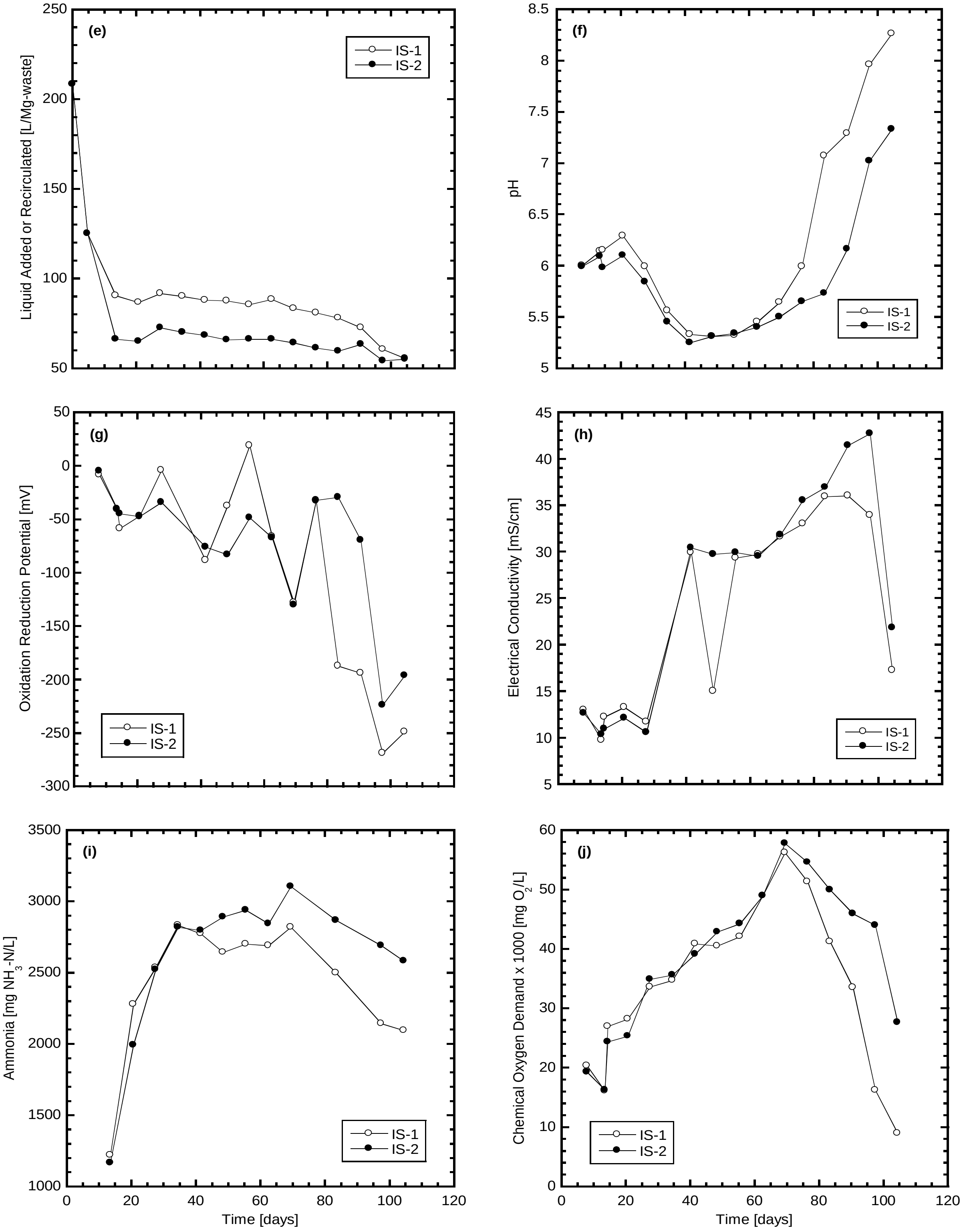


Figure A-12. Summary data for the industrial sludge (IS) reactor duplicates: (a) methane generation, (b) gas composition, (c) methane generation rate, (d) methane to carbon dioxide ratio, (e) liquid addition or recirculation, (f) pH, (g) oxidation reduction potential, (h) electrical conductivity, (i) ammonia, and (j) chemical oxygen demand.

APPENDIX B: Compilation of Tabulated Reactor Data

Table B-1. Tabulated data for DIW-1 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00		208.3	20.6					
0.7	2.2	0.8	8.4	0.1	0.02	0.02							
2.6	6.8	0.0	39.3	0.0	0.02	0.00							
4.6							208.3						
5.7	8.5	0.0	52.9	0.0	0.02	0.00							
6.8							208.3	20.0					
7.6									5.4	-440.0	11.8		24451
8.6	9.4	0.0	57.3	0.0	0.02	0.00							
13.6							85.0	20.0	5.0	4.6	12.5	317.6	24580
14.6									5.5	41.7	18.0		30341
17.9	10.5	0.0	51.9	0.0	0.02	0.00							
20.6							74.6	19.8	5.3	-12.9	16.6	587.4	30451
20.8	11.0	0.0	40.6	0.0	0.02	0.00							
21.5									5.5	-66.8	3.1		32399
27.5							67.9	19.8	5.5	-37.5	12.4	711.2	32321
28.5									5.6	-43.7	14.8		32412
34.1	11.8	0.0	34.2	0.0	0.02	0.00							
34.5							60.0	19.8	5.5	-38.9	15.7	767.7	36685
35.5									5.6	70.9	12.0		36547
41.6							54.2	19.8	5.6	41.2	10.6	785.5	35996
43.0									5.8	-14.9	16.5		34939
43.8	12.2	0.0	29.2	0.0	0.02	0.00							
48.6							48.8	19.8	5.8	-77.6	12.4	892.5	37145
49.5									5.9	-58.9	10.1		36318
55.7							42.9	19.7	6.0	-54.3	13.7	862.8	37558
62.6							39.6	19.7	5.8	-59.0	14.0	940.0	36547
69.6							37.5	19.7	5.5			946.0	39212
70.7	12.2	0.0	21.3	0.0	0.02	0.00							
76.6							34.6	19.7	5.6	-37.4	20.8	862.8	38293
83.5							30.4	19.7	5.5	-102.1	22.1	904.4	40407
90.5							27.9	19.7	5.7	-94.2	23.7	1017.3	42750
97.6							24.2	19.7	5.7	-66.2	24.3	1017.3	43807
104.5							20.4	19.7	5.7	-79.6	26.7	1035.1	41923
111.5							17.1	19.7	5.9	-98.1	27.0		42888
118.5							13.8	19.7	5.9	-94.5	31.2	1029.2	41877
125.6							12.1	19.7	5.8	-87.9	34.0		43072
128.7	12.3	0.2	33.4	0.0	0.02	0.00							
132.5							86.7	19.7	5.8	-102.0	37.2	1070.8	45782
139.5							74.2	19.7	5.8	-87.4	20.5	1088.6	43255

Table B-2. Tabulated data for DIW-2 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00		208.3	20.8					
0.7	2.2	0.6	9.3	0.1	0.01	0.02							
2.6	6.1	0.0	33.9	0.0	0.01	0.00							
4.6							208.3						
5.7	8.6	0.0	50.0	0.0	0.01	0.00							
6.8							208.3	20.5					
7.6									5.1	-228.0	8.5		16530
8.6	9.9	0.0	59.1	0.0	0.01	0.00							
13.6							113.3	20.5	4.8	21.4	9.1	196.8	16420
14.6									5.4	40.8	12.2		22080
17.9	11.0	1.0	60.9	0.0	0.02	0.00							
20.6							97.5	20.3	5.2	-25.2	12.2	390.1	22080
20.8	11.7	1.4	41.6	0.0	0.03	0.00							
21.5									5.5	-54.1	2.6		25811
27.5							84.2	20.3	5.4	-50.8	7.9	502.0	26210
28.5									5.6	-46.0	12.8		27818
34.1	12.5	2.8	34.7	0.1	0.06	0.00							
34.5							76.7	20.3	5.5	-36.2	12.8	595.3	31034
35.5									5.5	55.9	10.9		31310
41.6							68.3		5.5	46.3	12.0	625.0	32091
43.0									5.7	19.6	15.7		32550
43.8	12.8	0.6	10.6	0.1	0.06	0.00							
48.6							63.8	20.3	5.8	-55.4	12.3	797.4	32137
49.5									5.8	-39.3	8.8		31769
55.7							58.8		6.0	-45.5	11.2	767.7	33423
62.6							55.0	20.2	5.7	-37.1	11.2	749.8	36593
69.6							56.7	20.2	5.5			779.6	36134
70.7	12.8	0.0	4.1	0.0	0.06	0.00							
76.6							52.1	20.2	5.4	34.9	23.3	773.6	33837
83.5							51.3	20.2	5.6	-87.2	23.6	821.2	39626
90.5							46.3	20.2	5.7	-86.9	23.8	916.3	42337
97.6							41.7	20.2	5.7	-84.8	24.5	928.2	41234
104.5							37.5	20.2	5.7	-64.2	22.9	934.1	43301
111.5							34.6	20.2	5.8	-80.7	27.5		42382
118.5							31.3	20.2	5.8	-73.6	29.1	957.9	42428
125.6							28.3	20.2	5.8	-85.4	33.7		43899
128.7	12.9	2.4	16.3	0.1	0.06	0.00							
132.5							101.3	20.2	5.8	-84.3	36.3	1041.1	46150
139.5							90.4	20.2	5.8	-75.3	21.3	1058.9	43945

Table B-3. Tabulated data for LL-1 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00		208.3	20.6					
1.5	4.4	4.0	14.8	0.3	0.18	0.12							
3.7	6.6	0.5	43.4	0.0	0.19	0.00							
4.7							208.3						
6.4							208.3	20.3					
6.6	8.4	0.0	46.1	0.0	0.19	0.00							
7.4									5.8	-82.8	6.6		27061
13.4							98.3	20.3	5.3	8.8	7.9	452.1	25567
14.4									5.5	-17.2	13.4		30207
19.9	10.4	5.7	26.6	0.2	0.30	0.01							
20.4							89.6	20.3	5.4	-11.3	12.6	809.3	31723
21.4									5.5	65.1	11.8		31677
27.5							83.8	20.3	5.5	84.3	15.3	862.8	33102
28.8									5.6	25.0	16.5		32091
29.6	12.8	10.4	26.3	0.4	0.56	0.03							
34.5							79.6	20.3	5.7	-4.7	12.9	910.3	30988
35.4									5.7	-22.7	9.2		32780
35.5	14.2	20.9	44.3	0.5	0.84	0.05							
41.5							76.7	20.3	5.9	-30.7	12.1	928.2	35169
47.8	15.6	12.2	23.0	0.5	1.01	0.01							
48.5							72.5	20.2	5.6	-19.4	11.0	975.7	37007
55.4							70.8	20.0	5.3			946.0	35996
56.5	16.2	6.9	13.8	0.5	1.05	0.01							
62.5							70.4	20.0	5.3	47.0	20.2	922.2	36547
69.4							67.1	20.0	5.4	-77.4	25.0	993.5	40269
76.4							65.0	20.0	5.5	-61.7	20.5	1023.2	41555
83.4							62.5	20.0	5.5	-55.7	23.4	1041.1	43485
89.6	17.2	17.2	21.9	0.8	1.22	0.01							
90.4							62.1	20.0	5.6	-53.6	25.4	1070.8	44496
97.4							60.0	20.0	5.6	-59.2	30.6		44174
104.4							57.5	20.0	5.8	-72.6	33.1	1053.0	45874
111.5							53.8	20.0	5.6	-67.6	36.7		47620
114.6	17.9	32.1	32.7	1.0	1.44	0.01							
118.4							48.3	20.0	5.7	-87.6	40.6	1088.6	49182
125.4							47.1	20.0	5.6	-52.4	23.4	1148.1	47528

Table B-4. Tabulated data for LL-2 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00		208.3	20.0					
1.5	3.7	0.0	23.6	0.0	0.00	0.00							
3.7	7.5	0.0	43.8	0.0	0.00	0.00							
4.7							208.3						
6.4							208.3	19.7					
6.6	9.4	0.0	31.9	0.0	0.00	0.00							
7.4									5.8	-64.2	3.0		22577
13.4							102.9	19.7	5.4	-21.5	7.3	347.5	23821
14.4									5.6	-32.3	12.7		26807
19.9	11.6	5.8	30.5	0.2	0.13	0.01							
20.4							92.9	19.7	5.5	-16.1	12.6	666.6	28599
21.4									5.5	65.0	11.2		29426
27.5							87.9	19.7	5.5	73.4	15.0	714.2	30575
28.8									5.6	19.5	15.4		31126
29.6	14.5	9.2	28.8	0.3	0.40	0.03							
34.5							83.8	19.7	5.7	-44.0	12.5	767.7	31264
35.4									5.6	-11.5	8.3		32734
35.5	15.8	11.5	29.0	0.4	0.54	0.02							
41.5							80.0	19.5	5.8	-22.1	11.2	749.8	34021
47.8	17.5	9.7	23.9	0.4	0.70	0.01							
48.5							79.2	19.5	5.5	-16.1	10.2	844.9	37696
55.4							78.3	19.5	5.2			850.9	37558
56.5	18.4	2.3	7.4	0.3	0.72	0.00							
62.5							77.9	19.5	5.2	40.5	24.5	803.3	39718
69.4							76.7	19.5	5.3	-71.6	24.7	844.9	42934
76.4							74.2	19.5	5.4	-64.7	26.3	910.3	44726
83.4							73.3	19.5	5.5	-57.7	26.9	934.1	45323
89.6	19.9	17.0	28.1	0.6	0.98	0.01							
90.4							71.7	19.5	5.5	-53.6	28.4	1041.1	48677
97.4							68.8	19.5	5.6	-67.2	31.9		49090
104.4							66.7	19.5	5.7	-64.0	34.5	1035.1	49366
111.5							66.3	19.5	5.6	-62.4	38.4		50055
114.6	20.9	21.9	31.3	0.7	1.19	0.01							
118.4							61.3	19.5	5.6	-87.7	43.0	1064.9	52904
125.4							58.3	19.5	5.6	-53.3	23.5	1112.4	52536

Table B-5. Tabulated data for BW-1 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00		208.3	20.6					
1.6	3.8	0.3	27.7	0.0	0.01	0.01							
3.8	7.2	0.0	39.7	0.0	0.01	0.00							
4.8							208.3						
6.5							208.3	20.5					
6.7	13.2	0.0	40.3	0.0	0.01	0.00							
7.4									6.2	-441.0	9.3		54971
8.8	15.9	0.0	38.7	0.0	0.01	0.00							
13.4							44.2	20.3	6.0	-72.0	9.6	701.7	55798
14.5									6.0	-62.1	14.2		57728
20.5							25.8	20.3	5.7	-33.6	13.8	910.3	60898
21.4									5.7	57.1	11.8		63885
27.6							20.4	20.3	5.6	76.9	14.9	999.5	62415
28.9									5.8	-0.2	15.6		65723
29.7	16.1	0.0	18.1	0.0	0.01	0.00							
34.5							15.0	20.3	5.8	-64.7	14.4	1112.4	58576
35.5									5.8	-17.1	9.2		63263
41.6							9.6	20.2	5.9	-39.9	12.0	1195.6	63263
48.6							7.5	20.2	5.5	-21.8	11.2	1238.2	62619
55.5							85.0	20.2	5.4			1297.6	63906
56.6	16.1	0.0	8.7	0.0	0.01	0.00							
62.6							65.0	20.2	5.2	10.9	27.2	1273.8	62068
69.5							58.3	20.2	5.2	-64.4	26.8	1440.3	60138
76.5							54.2	20.0	5.2	-58.2	26.2	1559.1	59587
83.5							54.2	20.0	5.3	-54.9	27.0	1630.5	61517
90.5							52.1	20.0	5.4	-62.8	27.5	1725.5	58025
97.5							48.3	20.0	5.4	-54.2	24.9		59403
104.5							45.0	20.0	5.5	-51.3	32.2	1642.3	59587
111.6							41.3	20.0	5.4	-42.7	35.0		59403
114.6	16.2	0.0	14.1	0.0	0.01	0.00							
118.5							35.8	20.0	5.5	-77.7	40.5	1701.8	60782
125.5							34.6	20.0	5.5	-40.9	21.9	1761.2	57566

Table B-6. Tabulated data for BW-2 reactor.

Cumulative Time [d]	**Cumulative Gas [L]**	**CH4 [%]**	**CO2 [%]**	**CH4: CO2**	**Cumulative CH4 [L]**	**Rate [L/d]**	**Liquid In [L/Mg]**	**Waste Height [cm]**	**pH**	**ORP [mV]**	**EC [mS/cm]**	**Ammonia [mg NH3-N/L]**	**COD [mg O2/L]**
0.0	0.0	0.0	0.0		0.00		208.3	20.6					
1.6	3.8	0.9	31.6	0.0	0.03	0.02							
3.8	8.0	0.0	44.2	0.0	0.03	0.00							
4.8							208.3						
6.5							208.3	20.6					
6.7	13.0	0.0	61.6	0.0	0.03	0.00							
7.4									6.1	-479.0	12.3		53501
8.8	14.3	0.0	50.4	0.0	0.03	0.00							
13.4							65.4	20.6	5.6	-13.4	9.7	787.3	50836
14.5									5.7	-42.0	15.0		55339
20.5							54.2	20.5	5.6	-23.8	15.4	951.9	59382
21.4									5.6	60.9	12.9		59612
27.6							46.3	20.5	5.6	54.2	18.5	1284.8	61542
28.9									5.7	9.9	18.2		61404
29.7	14.5	0.0	27.1	0.0	0.03	0.00							
34.5							40.8	20.5	5.8	-68.5	15.2	1498.7	56555
35.5									5.8	-20.4	10.1		59679
41.6							33.3	20.3	5.9	-33.2	12.4	1338.3	59679
48.6							30.8	20.3	5.6	-21.0	10.9	1523.5	58393
55.5							110.4	20.3	5.3			1594.8	59403
56.6	14.5	0.0	17.5	0.0	0.03	0.00							
62.6							87.9	20.3	5.1	-24.4	26.3	1511.6	58301
69.5							85.0	20.3	5.2	-80.6	26.4	1594.8	59863
76.5							84.2	20.3	5.2	-67.8	26.1	1642.3	57841
83.5							82.5	20.3	5.3	-60.5	27.3	1642.3	56830
90.5							82.1	20.3	5.4	-65.4	28.2	1820.6	59403
97.5							79.2	20.2	5.5	-76.3	31.1		60690
104.5							77.5	20.2	5.6	-59.5	31.7	1689.9	59403
111.6							74.2	20.2	5.6	-72.7	36.4		56922
114.6	14.6	0.0	13.4	0.0	0.03	0.00							
118.5							65.4	20.0	5.7	-95.7	37.5	1749.3	60322
125.5							62.5	20.0	5.7	-82.7	23.7	1856.3	57933

Table B-7. Tabulated data for CW-1 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00		208.3	20.0					
1.6	3.6	0.8	24.4	0.0	0.03	0.02							
3.8	7.7	0.0	45.6	0.0	0.03	0.00							
4.8							208.3						
6.5							208.3	19.8					
6.7	11.5	0.0	49.8	0.0	0.03	0.00							
7.4									6.2	-415.0	12.7		29505
13.4							109.2	19.8	5.9	-60.3	8.8	549.6	26761
14.5									5.8	-70.8	13.0		28094
20.5							86.3	19.8	5.7	-22.3	13.6	726.1	31218
21.4									5.7	53.6	11.3		30207
27.6							77.9	19.8	5.7	56.4	15.0	815.2	31953
28.9									5.8	3.7	14.5		31264
29.7	12.5	0.0	40.3	0.0	0.03	0.00							
34.5							71.7	19.7	5.8	-80.6	12.8	934.1	30069
35.5									5.9	-30.2	10.0		31448
41.6							69.2	19.7	6.2	-54.9	11.6	946.0	31723
48.6							63.8	19.7	5.6	-27.8	10.6	957.9	34250
55.5							61.7	19.5	5.4			999.5	34893
56.6	12.5	2.2	19.7	0.1	0.03	0.00							
62.6							62.1	19.5	5.7	-65.9	21.5	993.5	33791
69.5							55.0	19.5	5.5	-94.4	21.6	993.5	35812
76.5							52.5	19.5	5.6	-96.9	19.4	1047.0	35858
83.5							48.3	19.5	5.7	-86.1	23.1	1112.4	38064
90.5							44.6	19.5	5.7	-80.1	21.6	1278.8	43072
97.5							41.7	19.5	5.9	-86.0	27.5		38891
104.5							37.1	19.5	5.9	-78.8	28.1	1130.2	41326
111.6							33.3	19.5	5.8	-62.7	32.1		40912
114.6	12.6	4.7	17.1	0.3	0.03	0.00							
118.5							27.5	19.5	5.9	-90.2	35.0	1177.8	44680
125.5							22.9	19.5	5.8	-75.0	20.2	1189.7	41188

Table B-8. Tabulated data for CW-2 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00	0.00	208.3	20.2					
1.6	3.6	0.0	25.3	0.0	0.00	0.00							
3.8	8.2	0.0	42.6	0.0	0.00	0.00							
4.8							208.3						
6.5							208.3	20.0					
6.7	12.5	0.0	29.4	0.0	0.00	0.00							
7.4									6.3	-400.0	16.0		38523
13.4							80.8	20.0	6.1	-83.2	11.5	749.3	36593
14.5									6.0	-71.2	14.9		39626
20.5							64.2	20.0	5.9	-30.6	15.5	922.2	38247
21.4									5.8	29.6	12.0		36639
27.6							57.5	19.8	5.8	36.1	16.6	1165.9	39534
28.9									5.9	-1.4	16.0		38064
29.7	13.6	0.0	31.2	0.0	0.00	0.00							
34.5							52.1	19.7	6.1	-99.3	12.8	1005.4	32688
35.5									5.9	-33.6	9.9		33791
41.6							51.7	19.7	6.2	-56.0	10.0	1005.4	34939
48.6							50.0	19.7	5.8	-39.7	10.1	1035.1	37007
55.5							46.3	19.4	5.4			1064.9	36364
56.6	13.6	0.0	22.8	0.0	0.00	0.00							
62.6							42.9	19.4	5.5	-22.4	20.6	1017.3	36272
69.5							38.8	19.4	5.6	-92.7	22.4	1011.4	37696
76.5							35.0	19.4	5.5	-70.2	20.5	1082.7	39488
83.5							31.7	19.4	5.7	-83.9	23.7	1118.3	39901
90.5							27.5	19.4	5.7	-75.1	22.7	1225.3	41464
97.5							27.1	19.4	5.8	-83.6	26.9		41555
104.5							21.7	19.4	5.8	-81.6	28.1	1237.2	42107
111.6							18.8	19.4	5.8	-87.3	31.1		43210
114.6	13.7	0.3	15.6	0.0	0.00	0.00							
118.5							11.3	19.4	5.9	-103.2	34.3	1296.6	43807
125.5							9.2	19.4	5.9	-83.5	20.1	1272.9	40820

Table B-9. Tabulated data for AWW-1 reactor.

Cumulative Time [d]	**Cumulative Gas [L]**	**CH4 [%]**	**CO2 [%]**	**CH4: CO2**	**Cumulative CH4 [L]**	**Rate [L/d]**	**Liquid In [L/Mg]**	**Waste Height [cm]**	**pH**	**ORP [mV]**	**EC [mS/cm]**	**Ammonia [mg NH3-N/L]**	**COD [mg O2/L]**
0.0	0.0	0.0	0.0		0.00		208.3	20.0					
1.6	4.6	1.0	29.9	0.0	0.05	0.03							
3.8	8.4	0.0	43.4	0.0	0.05	0.00							
4.8							208.3						
6.5							208.3	19.7					
6.7	10.4	0.0	52.7	0.0	0.05	0.00							
7.4									5.9	-235.0	7.1		15152
13.4							112.9	19.8	5.6	-2.0	6.2	207.2	15229
14.5									5.6	-48.3	9.7		21248
20.0	11.1	0.6	33.6	0.0	0.05	0.00							
20.5							95.8	19.8	5.5	10.6	9.4	423.0	23775
21.4									5.5	46.0	9.4		26440
27.6							86.7	19.8	5.5	67.3	14.1	642.9	29242
28.9									5.6	9.9	12.2		29514
29.7	12.9	3.4	30.3	0.1	0.11	0.01							
34.5							82.1	19.7	5.7	-58.3	10.5	678.5	28553
35.5									5.7	-20.9	8.3		33699
35.6	13.7	6.7	37.0	0.2	0.17	0.01							
41.6							79.2	19.7	5.7	-12.4	9.1	844.9	30667
47.9	14.9	7.1	29.4	0.2	0.25	0.01							
48.6							75.4	19.7	5.5	-15.3	8.6	850.9	37650
55.5							75.0	19.5	5.1			910.3	39212
56.6	15.4	7.7	27.3	0.3	0.29	0.00							
62.6							72.5	19.5	5.2	32.5	22.2	874.7	38385
69.5							68.8	19.5	5.3	-42.5	24.3	922.2	39212
76.5							66.3	19.5	5.3	-22.7	23.8	1011.4	44680
83.5							62.9	19.5	5.4	-32.2	25.4	993.5	43255
90.5							59.6	19.5	5.5	-39.2	26.3	1005.4	44037
96.6	17.1	11.1	29.4	0.4	0.48	0.00							
97.5							61.7	19.5	5.6	-49.3	29.7		48309
104.5							56.7	19.5	5.6	-28.1	31.4	1047.0	45828
111.6							55.0	19.5	5.6	-26.6	35.1		48080
114.6	17.1	13.3	30.7	0.4	0.48	0.00							
118.5							54.6	19.5	5.6	-38.4	36.2	1088.6	48493
125.5							53.8	19.5	5.7	-36.9	23.1	1183.7	48172

Table B-10. Tabulated data for AWW-2 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00		208.3	20.8					
1.6	4.0	0.7	28.4	0.0	0.03	0.02							
3.8	7.9	0.0	42.1	0.0	0.03	0.00							
4.8							208.3						
6.5							208.3	20.6					
6.7	9.4	0.0	56.1	0.0	0.03	0.00							
7.4									5.6	-196.7	7.2		17063
13.4							128.3	20.6	5.4	24.2	6.7	231.0	17205
14.5									5.6	-33.5	10.4		21248
20.0	10.2	0.4	56.9	0.0	0.03	0.00							
20.5							108.3	20.6	5.4	38.5	9.2	482.4	24786
21.4									5.5	59.2	9.5		28002
27.6							101.3	20.6	5.5	78.7	13.1	625.0	27956
28.9									5.6	23.4	13.7		34158
29.7	11.3	0.8	50.5	0.0	0.04	0.00							
34.5							92.1	20.6	5.7	-44.5	10.5	726.1	28737
35.5									5.8	-14.0	8.2		31034
35.6	11.8	0.9	41.7	0.0	0.04	0.00							
41.6							87.5	20.5	5.9	-10.8	9.5	785.5	32504
47.9	12.2	1.2	36.3	0.0	0.05	0.00							
48.6							84.2	20.5	5.7	-11.7	8.6	886.5	35766
55.5							81.3	20.3	5.5			934.1	36685
56.6	12.3	2.0	49.0	0.0	0.05	0.00							
62.6							77.9	20.3	5.6	-18.9	22.1	987.6	37374
69.5							73.3	20.3	5.7	-80.2	23.2	975.7	37558
76.5							68.3	20.3	5.8	-72.3	22.9	1005.4	39534
83.5							65.0	20.3	6.0	-85.2	25.0	1023.2	39718
90.5							60.8	20.3	6.0	-188.8	26.0	1106.5	43347
97.5							58.3	20.3	6.1	-90.6	28.4		40774
104.5							55.0	20.3	6.2	-73.4	30.0	1130.2	42750
111.6							50.0	20.3	6.9	-86.4	33.0		42796
114.6	12.3	2.1	31.0	0.1	0.05	0.00							
118.5							34.6	20.3	6.1	-94.3	35.6	1154.0	44404
125.5							30.0	20.3	6.1	-73.8	21.3	1219.4	43072

Table B-11. Tabulated data for MW-H-1 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00		208.3	20.3					
1.5	4.7	0.7	25.6	0.0	0.03	0.02							
3.7	7.7	0.0	47.2	0.0	0.03	0.00							
4.7							208.3						
6.4							208.3	20.2					
6.6	9.2	0.0	27.3	0.0	0.03	0.00							
7.3									6.0	-287.0	17.1		40223
13.3							76.3	20.0	6.0	-48.4	11.3	801.6	37696
14.4									5.9	-56.0	15.3		35904
20.4							66.7	20.0	5.9	-15.5	13.2	1029.2	41785
21.3									5.7	47.4	13.1		39993
27.4							59.2	20.0	5.7	40.1	18.9	1070.8	45415
28.8									5.8	22.0	17.4		44266
29.6	9.8	0.0	30.1	0.0	0.03	0.00							
34.4							52.9	19.8	6.0	-67.2	13.9	1249.1	39856
35.3									5.9	-23.4	10.5		37880
41.5							51.3	19.8	6.2	-40.7	13.1	1112.4	37283
48.5							47.9	19.8	6.0	-50.7	11.3	1159.9	40407
55.4							45.0	19.8	5.4			1159.9	39120
56.5	9.2	1.7	18.1	0.1	0.03	0.00							
62.5							42.5	19.8	5.6	-76.7	21.1	1070.8	37558
69.3							36.7	19.8	5.7	-116.8	23.5	1165.9	40131
76.4							35.0	19.8	5.7	-109.2	22.2	1171.8	40499
83.4							113.8	19.8	5.8	-107.8	24.1	1171.8	41004
90.4							92.9	19.8	5.8	-101.3	25.3	1452.1	44701
96.5	9.8	4.9	17.3	0.3	0.06	0.00							
97.4							89.2	19.8	6.0	-103.6	22.9		46355
104.4							84.2	19.7	6.1	-104.3	29.5	1309.5	43323
111.4							82.5	19.7	6.0	-108.5	32.9		42428
114.5	9.9	7.2	17.5	0.4	0.07	0.00							
118.4							78.3	19.7	6.1	-129.0	36.1	1290.7	43347
125.4							74.2	19.7	6.0	-115.7	21.0	1320.4	42107

Table B-12. Tabulated data for MW-H-2 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00		208.3	20.6					
1.5	4.2	0.0	23.6	0.0	0.00	0.00							
3.7	7.2	0.0	36.4	0.0	0.00	0.00							
4.7							208.3						
6.4							208.3	20.5					
6.6	10.1	0.0	29.2	0.0	0.00	0.00							
7.3									6.3	-51.8	19.3		48263
13.3							49.2	20.5	6.4	-200.0	15.8	1060.7	46058
14.4									6.3	-114.7	16.1		47620
20.4							42.9	20.5	6.0	-26.8	13.9	1047.0	49917
21.3									5.9	41.0	13.5		47299
27.4							34.6	20.5	5.8	44.8	19.9	1177.8	50974
28.8									5.9	1.5	18.2		45461
29.6	10.5	0.0	23.7	0.0	0.00	0.00							
34.4							26.7	20.3	6.1	-78.3	15.0	1308.5	44082
35.3									6.0	-37.7	10.7		43807
41.5							24.2	20.3	5.9	-28.1	9.7	1243.2	46701
48.5							20.4	20.3	5.9	-52.9	10.7	1231.3	46012
55.4							19.6	20.2	5.5			1314.5	43715
56.5	10.5	0.2	15.7	0.0	0.00	0.00							
62.5							17.1	20.2	5.7	54.7	17.9	1189.7	41464
69.3							13.8	20.2	6.0	-141.8	24.2	1261.0	43118
76.4							10.4	20.2	6.0	-145.7	24.3	1308.5	42061
83.4							92.1	20.2	6.0	-123.2	24.9	1225.3	42934
90.4							73.8	20.2	5.9	-112.6	24.6	1487.8	46539
97.4							67.1	20.2	6.1	-100.3	22.4		46814
104.4							63.3	20.2	6.1	-118.5	28.0	1404.6	42496
111.4							58.8	20.2	6.1	-106.2	30.7		41785
114.5	10.6	4.5	18.1	0.2	0.00	0.00							
118.4							53.3	20.2	6.1	-133.2	34.3	1362.0	43807
125.4							49.2	20.2	6.1	-120.2	19.5	1409.6	41601

Table B-13. Tabulated data for MW-L-1 reactor.

Cumulative Time [d]	**Cumulative Gas [L]**	**CH4 [%]**	**CO2 [%]**	**CH2: CO2**	**Cumulative CH4 [L]**	**Rate [L/d]**	**Liquid In [L/Mg]**	**Waste Height [cm]**	**pH**	**ORP [mV]**	**EC [mS/cm]**	**Ammonia [mg NH3-N/L]**	**COD [mg O2/L]**
0.0	0.0	0.0	0.0		0.00		208.3	20.3					
1.5	4.2	0.0	26.1	0.0	0.00	0.00							
3.7	7.7	0.0	38.7	0.0	0.00	0.00							
4.7							208.3						
6.4							208.3	20.3					
6.6	10.2	0.0	46.0	0.0	0.00	0.00							
7.3									6.0	-259.0	11.9		28461
13.3							93.8	20.3	5.6	-38.8	10.2	425.9	25383
14.4									5.6	-45.2	12.6		30850
20.4							77.9	20.3	5.6	21.8	10.8	684.5	34342
21.3									5.5	57.8	10.6		31310
27.4							71.3	20.0	5.5	88.6	16.1	732.0	35766
28.8									5.5	22.2	14.3		34250
29.6	11.0	0.4	32.8	0.0	0.00	0.00							
34.4							64.2	20.0	5.7	-49.8	11.1	827.1	31907
35.3									5.6	-24.8	7.9		30345
41.5							60.0	20.3	5.9	-28.1	9.7	862.8	32091
48.5							58.8	20.0	5.7	-27.9	8.5	922.2	36869
55.4							57.9	20.0	5.2			946.0	34985
56.5	11.5	2.3	21.9	0.1	0.02	0.00							
62.5							54.2	20.0	5.4	38.5	16.9	886.5	33469
69.3							51.7	20.0	5.6	-89.7	22.0	951.9	36318
76.4							49.6	20.0	5.6	-80.6	19.4	1023.2	38523
83.4							47.9	20.0	5.7	-75.2	23.2	1029.2	39258
90.4							43.8	20.0	5.8	-80.6	24.5	1165.9	42153
97.4							43.3	20.0	5.8	-82.0	26.7		41510
104.4							39.6	20.0	5.9	-82.2	28.1	1148.1	40866
111.4							35.4	20.0	5.9	-83.8	32.1		39396
114.5	11.6	13.4	22.6	0.6	0.02	0.00							
118.4							26.7	20.0	5.8	-94.2	36.2	1195.6	42658
125.4							24.6	20.0	5.8	-88.4	20.5	1225.3	42474

Table B-14. Tabulated data for MW-L-2 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0	0.0		0.00		208.3	21.1					
1.5	4.6	0.6	25.7	0.0	0.03	0.02							
3.7	7.5	0.0	41.2	0.0	0.03	0.00							
4.7							208.3						
6.4							208.3	21.0					
6.6	9.2	0.0	30.4	0.0	0.03	0.00							
7.3									5.8	-90.2	13.5		27910
13.3							98.8	20.8	5.6	-40.8	9.6	378.4	22994
14.4									5.6	-29.9	12.6		28691
20.4							82.1	20.8	5.5	37.8	10.6	690.4	29656
21.3									5.5	76.6	10.5		30804
27.4							76.3	20.8	5.5	48.0	14.7	803.3	32826
28.8									5.6	30.5	14.3		35675
29.6	10.3	0.5	28.7	0.0	0.03	0.00							
34.4							72.1	20.8	5.7	-42.9	10.9	803.3	31172
35.3									5.6	-3.8	8.0		31356
41.5							67.1	20.8	5.8	-18.0	9.4	815.2	30896
48.5							75.4	20.8	5.6	-18.8	6.0	975.7	37237
55.4							72.5	20.6	5.2			963.8	33791
56.5	11.1	2.3	19.1	0.1	0.05	0.00							
62.5							70.4	20.6	5.4	1.6	19.0	833.1	33239
69.3							65.8	20.6	5.6	-84.6	21.4	946.0	35537
76.4							64.6	20.6	5.7	-82.3	21.6	1023.2	37329
83.4							60.8	20.6	5.8	-72.9	23.4	1029.2	37512
90.4							57.5	20.6	5.8	-86.0	24.7	1219.4	46242
97.4							56.7	20.6	5.9	-80.5	27.4		40820
104.4							48.8	20.6	5.9	-76.3	28.5	1130.2	38799
111.4							49.6	20.6	5.9	-80.1	31.4		38937
114.5	11.1	12.5	23.5	0.5	0.06	0.00							
118.4							42.5	20.6	5.9	-102.2	36.2	1154.0	42612
125.4							38.8	20.6	5.9	-83.4	20.6	1201.6	39993

Table B-15. Tabulated data for GB-1 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0			0.00		208.3	18.4					
1.7	3.2	0.0	12.1	0.0	0.00	0.00							
4.8							208.3						
5.7	4.9	0.0	26.9	0.0	0.00	0.00							
6.9							333.3	18.4					
8.0									5.6	12.2	10.9		23223
8.9	6.6	0.3	40.9	0.0	0.00	0.00							
13.7							105.4	18.3	5.6	-39.3	7.4	298.1	17894
14.6									5.6	-6.3	7.4		22075
14.8	8.4	2.8	48.9	0.1	0.05	0.01							
20.8							92.1	18.1	5.7	-7.9	8.8	446.7	24142
21.1	11.1	11.9	48.9	0.2	0.37	0.05							
27.0	14.8	24.3	49.1	0.5	1.29	0.15							
27.7							90.8	18.1	5.7	-10.1	5.8	529.9	22902
32.8	19.1	34.0	50.7	0.7	2.74	0.25							
34.6							83.8	18.1	6.0			482.4	18767
35.8	21.0	23.2	35.7	0.7	3.18	0.15							
41.7							80.8	18.1	7.0	-391.0	21.4	411.1	15183
43.8	23.4	19.0	34.3	0.6	3.63	0.06							
48.6							80.4	18.1	7.1	-386.0	20.0	423.0	14540
55.6							79.2	18.1	7.1	-367.0	18.6	440.8	12932
55.8	25.1	14.3	31.7	0.5	3.88	0.02							
62.6							77.5	18.1	7.2	-358.0	18.0	440.8	11140
68.9	26.8	13.3	35.3	0.4	4.10	0.02							
69.6							77.1	18.1	6.9	-371.0	20.0	524.0	12289
76.6							75.4	18.1	7.3	-354.0	20.4		11737
81.7	28.7	10.8	34.0	0.3	4.31	0.02							
83.6							73.8	18.1	7.0	-34.6	21.1	387.3	9945
90.7							67.1	18.1	7.0	-366.0	22.8		8935
93.8	30.1	11.8	41.1	0.3	4.47	0.01							
97.6							66.3	18.1	6.8	-341.0	24.2	452.7	9440
104.6							70.8	18.1	7.0	-383.0	14.4	458.6	9026

Table B-16. Tabulated data for GB-2 reactor.

Cumulative Time [d]	**Cumulative Gas [L]**	**CH4 [%]**	**CO2 [%]**	**CH4: CO2**	**Cumulative CH4 [L]**	**Rate [L/d]**	**Liquid In [L/Mg]**	**Waste Height [cm]**	**pH**	**ORP [mV]**	**EC [mS/cm]**	**Ammonia [mg NH3-N/L]**	**COD [mg O2/L]**
0.0	0.0				0.00		208.3	20.0					
1.7	2.9	0.0	28.6	0.0	0.00	0.00							
4.8							208.3						
5.7	5.6	0.0	22.6	0.0	0.00	0.00							
6.9							333.3	20.0					
8.0									5.7	-1.6	13.2		28967
8.9	7.0	0.0	44.2	0.0	0.00	0.00							
13.7							86.3	19.8	5.7	-25.8	10.1	351.6	23821
14.6									5.6	-19.1	8.6		29977
14.8	8.0	1.2	39.8	0.0	0.01	0.00							
20.8							70.4	19.8	5.7	-5.8	10.0	583.4	29885
21.1	8.9	4.6	45.6	0.1	0.05	0.01							
27.0	10.3	8.2	41.1	0.2	0.17	0.02							
27.7							63.3	19.8	5.6	5.8	6.1	577.5	28231
34.6							60.8	19.8	5.3			589.4	25704
35.8	12.5	12.4	37.6	0.3	0.44	0.03							
41.7							57.1	19.8	5.4	-218.0	20.6	565.6	24510
43.8	14.0	10.3	27.9	0.4	0.60	0.02							
48.6							53.3	19.8	5.5	-216.0	19.5	553.7	23132
55.6							54.2	19.8	5.8	-239.0	20.1	529.9	23913
55.8	15.6	12.0	34.8	0.3	0.78	0.02							
62.6							52.9	19.8	6.5	-297.0	23.0	488.3	21891
68.9	17.1	11.0	34.0	0.3	0.96	0.01							
69.6							50.0	19.7	6.8	-341.0	24.5	541.8	22948
76.6							47.1	19.7	6.9	-34.7	24.8		20926
81.7	18.5	15.0	50.7	0.3	1.16	0.02							
83.6							44.2	19.7	7.0	-370.0	25.8	458.6	16515
90.7							41.7	19.7	6.8	-355.0	27.8		14126
93.8	19.1	11.9	43.2	0.3	1.23	0.01							
97.6							36.7	19.7	6.8	-360.0	29.0	482.4	13437
104.6							32.9	19.7	7.0	-374.0	16.1	529.9	11553

Table B-17. Tabulated data for ASR-1 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0				0.00		208.3	18.7					
1.7	2.9	0.0	10.2	0.0	0.00	0.00							
4.8							125.0						
5.7	4.9	0.0	22.6	0.0	0.00	0.00							
6.9							125.0	18.7					
8.0									6.1	29.7	7.4		15413
8.9	5.0	1.6	26.3	0.1	0.00	0.00							
13.7							93.8	18.7	6.4	-53.9	6.4	232.8	12105
14.6									6.3	-51.4	6.8		14034
20.8							68.8	18.6	6.6	-41.7	7.1	405.1	14310
27.7							54.6	18.4	6.0	-11.1	5.5	470.5	17342
34.6							47.9	18.4	6.1			529.9	17526
35.8	5.9	8.5	22.6	0.4	0.08	0.00							
41.7							42.5	18.4	6.0	-137.1	17.4	577.5	18307
48.6							36.3	18.4	6.1	-129.1	17.4	642.9	21386
55.6							31.7	18.4	6.1	-131.2	18.0	660.7	23315
62.6							110.8	18.4	5.9	-141.6	22.5	743.9	28185
69.6							91.7	18.4	6.0	-154.6	19.4	690.4	24510
76.6							87.1	18.4	6.3	-142.4	20.0		24096
83.6							82.9	18.4	6.2	-134.0	22.2	642.9	21891
90.7							80.0	18.4	6.3	-58.6	21.5		22213
93.8	6.0	11.2	11.4	1.0	0.08	0.00							
97.6							69.6	18.4	6.2	-56.8	28.5	738.0	24096
104.6							66.3	18.4	6.3	-85.1	16.2	785.5	23591

Table B-18. Tabulated data for ASR-2 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0				0.00		208.3	18.4					
1.7	3.3	0.0	10.7	0.0	0.00	0.00							
4.8							125.0						
5.7	5.6	0.0	23.3	0.0	0.00	0.00							
6.9							125.0	18.4					
8.0									6.3	-11.6	9.4		21294
8.9	5.7	0.6	31.5	0.0	0.00	0.00							
13.7							41.7	18.4	6.1	-41.7	8.0	345.7	18951
14.6									6.3	-47.2	7.6		24096
20.8							27.9	18.4	6.3	-30.0	8.1	524.0	21478
27.7							26.3	18.3	6.0	-13.2	5.8	613.1	24556
34.6							19.6	18.3	5.9			702.3	24050
35.8	6.8	8.0	24.0	0.3	0.09	0.00							
41.7							17.1	18.3	5.8	-106.9	20.6	720.1	26761
48.6							12.1	18.3	6.0	-112.4	20.6	755.8	26348
55.6							7.9	18.3	5.8	-96.9	20.5	726.1	28094
62.6							87.5	18.3	5.9	-127.1	19.8	696.4	24556
69.6							68.8	18.3	5.9	-129.2	21.9	803.3	29656
76.6							64.6	18.3	6.1	-114.3	23.0		29058
83.6							60.4	18.3	6.1	-105.0	23.2	785.5	25613
90.7							55.8	18.3	6.0	-34.7	26.7		25934
93.8	6.8	14.9	15.5	1.0	0.10	0.00							
97.6							47.5	18.3	6.1	-49.8	30.2	850.9	27588
104.6							42.9	18.3	6.1	-43.5	17.3	922.2	27221

Table B-19. Tabulated data for FW-1 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0			0.00		208.3	15.2					
1.6	3.5	0.0	17.4	0.0	0.00	0.00							
4.7							125.0						
5.6	4.6	0.0	30.2	0.0	0.00	0.00							
6.8							125.0	15.2					
8.0									5.6	23.3	11.2		28645
8.8	5.3	2.2	36.7	0.1	0.02	0.01							
13.6							61.7	15.2	5.6	-15.2	9.0	369.5	22718
14.5									5.7	-15.6	8.2		26486
14.7	6.4	6.5	37.5	0.2	0.09	0.01							
20.7							53.3	15.2	6.0	-15.9	9.2	660.7	26256
21.0	8.1	15.2	47.2	0.3	0.35	0.04							
26.9	9.9	18.9	43.5	0.4	0.69	0.06							
27.6							51.7	15.1	5.7	0.3	8.2	660.7	29104
34.6							48.8	15.1	5.3			702.3	30207
35.7	11.9	19.3	36.9	0.5	1.07	0.04							
41.6							47.1	15.1	5.1	-92.1	18.9	642.9	32688
43.8	13.4	18.2	28.8	0.6	1.34	0.03							
48.5							44.2	15.1	5.1	-46.7	21.2	666.6	35812
55.5							38.8	15.1	5.1	57.5	20.6	613.1	38247
55.8	15.5	19.1	24.2	0.8	1.74	0.03							
62.6							38.3	15.1	5.2	-90.7	23.4	660.7	38753
68.8	19.5	27.8	26.9	1.0	2.85	0.09							
69.5							34.6	15.1	5.3	-110.4	24.3	738.0	44726
75.7	24.1	29.8	23.9	1.2	4.24	0.20							
76.5							34.2	14.9	5.4	43.3	26.7		44128
81.6	27.8	41.9	29.6	1.4	5.80	0.26							
83.5							30.0	14.9	5.3	49.4	26.7	613.1	41739
84.6	30.8	43.1	29.1	1.5	7.06	0.43							
90.6							28.3	14.9	5.3	74.1	29.8		40866
91.6	38.6	50.9	34.8	1.5	11.05	0.57							
93.7	40.0	39.9	26.3	1.5	11.60	0.26							
95.6	42.7	40.2	26.5	1.5	12.69	0.58							
97.5							25.0	14.9	5.4	67.0	34.1	767.7	45139
99.6	48.8	44.9	29.4	1.5	15.42	0.68							
102.7	53.9	36.0	24.2	1.5	17.27	0.60							
104.5	57.2	32.1	21.9	1.5	18.33	0.57	24.6	14.9	5.4	18.0	20.2	785.5	42061

Table B-20. Tabulated data for FW-2 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0				0.00		208.3	16.0					
1.6	3.3	0.0	16.0	0.0	0.00	0.00							
4.7							125.0						
5.6	4.8	0.0	36.5	0.0	0.00	0.00							
6.8							125.0	16.0					
8.0									5.6	24.8	12.1		29196
8.8	5.8	1.8	37.2	0.0	0.02	0.01							
13.6							50.8	15.9	5.8	-24.7	10.2	488.3	24602
14.5									5.8	-22.6	8.4		29656
14.7	7.0	7.8	41.3	0.2	0.11	0.02							
20.7							45.8	15.6	5.7	-16.2	8.4	654.8	28783
21.0	8.7	16.6	47.5	0.4	0.39	0.04							
26.9	10.0	19.2	43.3	0.4	0.64	0.04							
27.6							47.9	15.6	5.6	-7.0	6.0	690.4	31126
34.6							47.5	15.6	5.3			738.0	30391
35.7	11.0	21.5	42.0	0.5	0.86	0.02							
41.6							43.8	15.6	5.2	-70.3	22.2	755.8	33285
43.8	11.6	22.7	39.5	0.6	1.00	0.02							
48.5							38.8	15.4	5.3	-78.0	22.5	708.2	34021
55.5							37.1	15.4	5.3	-47.4	21.8	743.9	37420
62.6							37.1	15.4	5.3	-87.4	23.2	726.1	39580
68.8	12.2	26.7	33.2	0.8	1.16	0.01							
69.5							33.8	15.4	5.4	-128.6	25.8	844.9	44864
76.5							32.1	15.4	5.5	-37.8	27.2		43531
81.6	12.7	30.6	35.0	0.9	1.32	0.01							
83.5							29.6	15.4	5.5	-22.1	28.3	714.2	42842
90.6							28.3	15.4	5.4	16.4	32.3		41785
93.7	13.1	25.9	26.1	1.0	1.41	0.01							
97.5							23.3	15.2	5.3	45.7	35.1	809.3	43669
104.5							21.3	15.2	5.3	43.9	20.2	809.3	44128

TableB-21. Tabulated data for AD-1 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0			0.00		62.5	14.0					
1.6													
4.6							125.0						
5.5	1.4	0.6	21.7	0.0	0.01	0.00							
6.7								14.0					
7.9									5.6	-19.0	12.8		20099
8.7	2.0	2.2	19.1	0.1	0.02	0.00							
13.5							100.8	13.5	5.8	-65.0	11.5	892.5	18859
14.5									5.7	-38.9	10.3		23683
14.6	4.6	10.8	36.6	0.3	0.30	0.05							
20.6							103.3	13.3	5.9	-36.8	11.8	1041.1	22213
20.9	7.4	14.6	33.5	0.4	0.71	0.06							
26.9	9.3	15.6	33.4	0.5	1.00	0.05							
27.6							105.0	13.3	5.5	-20.8	11.7	1082.7	25429
34.5							112.1	13.2	5.3			1201.6	30575
35.6	12.1	19.4	33.5	0.6	1.56	0.06							
41.6								13.2	5.4	-31.1	22.7	1130.2	30942
43.7	16.1	25.8	31.7	0.8	2.58	0.13							
47.6	20.0	26.7	26.7	1.0	3.61	0.26							
48.5							111.7	13.2	5.8	-127.4	21.2	1094.6	32321
50.6	24.7	50.9	41.5	1.2	6.00	0.82							
53.0	30.0	37.5	27.3	1.4	7.99	0.82							
55.5							111.3	13.2	7.3	-230.0	21.1	987.6	25153
55.7	36.9	41.8	27.9	1.5	10.91	1.09							
57.9	45.1	38.1	23.9	1.6	14.03	1.40							
60.6	53.6	59.3	36.4	1.6	19.05	1.88							
62.5							108.3	13.2	7.7	-203.0	16.5	785.5	8659
62.7	60.3	36.5	23.9	1.5	21.51	1.16							
64.5	66.6	56.4	36.0	1.6	25.02	1.91							
67.0	74.1	32.2	21.9	1.5	27.44	0.99							
68.7	78.8	56.2	37.9	1.5	30.10	1.54							
69.5							110.8	13.2	7.6	-188.7	15.4	660.7	5489
70.7	83.9	44.7	31.9	1.4	32.36	1.13							
74.0	91.8	42.9	31.8	1.4	35.77	1.04							
75.6	95.7	30.9	25.5	1.2	36.96	0.72							
76.5							112.1	13.2	8.0	-203.0	16.5		5443
79.5	102.0	43.3	34.9	1.2	39.71	0.71							
81.5	105.6	53.2	44.0	1.2	41.60	0.94							
83.5							115.0	13.0	8.3	-97.2	16.2	482.4	3605
84.5	110.6	61.5	49.0	1.3	44.72	1.05							
90.6							116.7	13.0	7.9	-15.0	16.8		4891
91.6	122.2	53.7	44.2	1.2	50.93	0.88							
93.6	125.4	45.3	37.6	1.2	52.36	0.69							
95.5	128.3	59.1	49.6	1.2	54.11	0.94							
97.5							118.8	12.9	7.9	-236.0	18.8	464.6	5351
99.5	134.3	45.9	39.6	1.2	56.88	0.69							
102.6	139.2	53.9	46.8	1.2	59.47	0.84							
104.5	142.0	37.1	31.8	1.2	60.53	0.56	114.6	12.7	7.7	-175.2	10.3	464.6	5029

Table B-22. Tabulated data for AD-2 reactor.

Cumulative Time [d]	**Cumulative Gas [L]**	**CH4 [%]**	**CO2 [%]**	**CH4: CO2**	**Cumulative CH4 [L]**	**Rate [L/d]**	**Liquid In [L/Mg]**	**Waste Height [cm]**	**pH**	**ORP [mV]**	**EC [mS/cm]**	**Ammonia [mg NH3-N/L]**	**COD [mg O2/L]**
0.0	0.0	0.0			0.00		62.5	12.7					
1.6	4.1	1.2	23.8	0.1	0.05	0.03							
4.6							125.0						
5.5	5.4	0.8	19.3	0.0	0.06	0.00							
6.7								12.7					
7.9									5.8	-31.3	13.3		20972
8.7	6.1	1.8	14.5	0.1	0.07	0.00							
13.5							101.3	12.2	5.8	-73.0	11.1	815.2	19318
14.5									5.7	-45.5	10.0		24694
14.6	8.4	8.2	27.8	0.3	0.27	0.03							
20.6							104.6	12.1	5.6	-39.9	11.8	1189.7	24234
20.9	10.8	13.9	34.4	0.4	0.60	0.05							
26.9	12.4	10.0	25.3	0.4	0.76	0.03							
27.6							104.6	12.1	5.5	-16.0	11.2	1100.5	28185
34.5							109.2	11.9	5.3			1183.7	32780
35.6	13.4	9.1	20.3	0.4	0.85	0.01							
41.6							108.3	11.9	5.2	14.2	21.6	1148.1	34526
43.7	14.3	12.7	24.6	0.5	0.96	0.01							
48.5							108.8	11.9	5.3	-76.0	22.9	1106.5	36593
55.5							107.5	11.9	5.4	-76.2	24.4	1171.8	39120
55.7	15.8	16.7	25.6	0.7	1.21	0.02							
62.5							107.1	11.9	5.5	-76.1	22.9	1171.8	41372
68.7	19.1	25.2	27.4	0.9	2.05	0.06							
69.5							107.9	11.9	5.6	-75.8	26.5	1183.7	40453
75.6	23.5	28.0	23.5	1.2	3.27	0.18							
76.5							107.9	11.9	5.8	-89.8	25.7		41234
81.5	30.5	28.7	20.4	1.4	5.29	0.34							
83.5							106.7	11.9	7.1	-167.5	30.1	1094.6	38983
84.5	37.0	40.9	23.2	1.8	7.95	0.89							
90.6							105.0	11.9	7.5	-230.0	27.0		18169
91.6	58.1	48.9	27.3	1.8	18.26	1.46							
93.6	64.4	40.4	22.2	1.8	20.82	1.23							
95.5	67.1	35.9	20.6	1.7	21.79	0.52							
97.5							93.8	11.7	7.9	-266.0	25.6	785.5	8245
97.8	73.3	43.6	25.9	1.7	24.48	1.17							
99.5	78.1	35.0	21.5	1.6	26.18	1.00							
102.6	85.6	39.6	26.4	1.5	29.13	0.96							
104.5	90.0	30.5	21.4	1.4	30.48	0.72	92.5	11.7	8.1	-132.1	13.8	761.7	4524

Table B-23. Tabulated data for IS-1 reactor.

Cumulative Time [d]	Cumulative Gas [L]	CH4 [%]	CO2 [%]	CH4: CO2	Cumulative CH4 [L]	Rate [L/d]	Liquid In [L/Mg]	Waste Height [cm]	pH	ORP [mV]	EC [mS/cm]	Ammonia [mg NH3-N/L]	COD [mg O2/L]
0.0	0.0	0.0			0.00		208.3	14.0					
1.6	4.1	2.4	24.2	0.1	0.10	0.06							
4.7							125.0						
5.6	7.3	8.8	46.1	0.2	0.38	0.07							
6.8								14.0					
8.0									6.0	-8.4	13.0		20329
8.8	9.3	13.3	56.6	0.2	0.65	0.08							
13.6							90.4	13.7	6.1	-41.0	9.7	1219.4	16102
14.5									6.2	-58.8	12.2		26945
14.7	11.2	14.3	44.5	0.3	0.93	0.05							
20.7							86.7	13.3	6.3	-47.0	13.3	2277.3	28185
21.0	13.8	36.5	53.5	0.7	1.87	0.15							
26.9	15.9	28.6	49.9	0.6	2.46	0.10							
27.6							91.7	13.3	6.0	-4.2	11.7	2533.9	33582
34.6							90.0	13.3	5.6			2831.0	34685
35.7	18.0	24.8	36.9	0.7	2.99	0.06							
41.6							87.9	13.0	5.3	-88.5	29.9	2771.6	40842
43.8	19.4	24.7	28.9	0.9	3.34	0.04							
48.5							87.5	13.3	5.3	-37.6	15.0	2640.8	40474
55.5							85.4	13.0	5.3	18.8	29.3	2700.3	42036
55.8	21.4	27.7	26.7	1.0	3.89	0.05							
62.6							88.3	13.0	5.5	-66.4	29.7	2688.4	48928
68.8	26.3	35.7	25.2	1.4	5.65	0.13							
69.5							83.3	13.0	5.6	-128.2	31.6	2819.2	56187
75.7	31.3	35.4	22.4	1.6	7.40	0.25							
76.5							80.8	13.0	6.0	-32.9	33.0		51317
81.6	37.7	35.4	20.7	1.7	9.66	0.38							
83.5							77.9	13.0	7.1	-187.4	35.9	2498.2	41209
84.6	41.8	40.9	23.2	1.8	11.33	0.56							
90.6							72.5	13.0	7.3	-194.1	36.0		33490
91.6	54.6	52.6	29.3	1.8	18.07	0.96							
93.7	59.0	35.8	19.5	1.8	19.67	0.77							
95.6	63.4	48.0	25.1	1.9	21.76	1.12							
97.5							60.4	13.0	8.0	-269.0	33.9	2141.6	16215
97.9	68.2	60.5	29.7	2.0	24.63	1.25							
99.6	72.6	38.5	19.4	2.0	26.35	1.01							
102.7	80.1	42.6	20.9	2.0	29.54	1.03							
104.5	84.9	33.3	16.0	2.1	31.14	0.85	55.4	13.0	8.3	-249.0	17.2	2094.0	8956

Table B-24. Tabulated data for IS-2 reactor.

Cumulative Time [d]	**Cumulative Gas [L]**	**CH4 [%]**	**CO2 [%]**	**CH4: CO2**	**Cumulative CH4 [L]**	**Rate [L/d]**	**Liquid In [L/Mg]**	**Waste Height [cm]**	**pH**	**ORP [mV]**	**EC [mS/cm]**	**Ammonia [mg NH3-N/L]**	**COD [mg O2/L]**
0.0	0.0	0.0			0.00		208.3	12.7					
1.6	4.2	3.0	26.4	0.1	0.12	0.08							
4.7							125.0						
5.6	6.9	7.9	40.1	0.2	0.34	0.05							
6.8								12.7					
8.0									6.0	-4.8	12.6		19272
8.8	8.7	13.5	55.2	0.2	0.58	0.08							
13.6							66.3	12.5	6.1	-40.5	10.3	1165.9	16240
14.5									6.0	-45.1	10.9		24326
14.7	10.7	19.3	57.2	0.3	0.97	0.07							
20.7							65.0	12.5	6.1	-47.5	12.1	1992.0	25291
21.0	13.4	28.0	56.9	0.5	1.72	0.12							
26.9	15.9	30.2	50.5	0.6	2.47	0.13							
27.6							72.5	12.5	5.8	-34.3	10.6	2522.0	34869
34.6							70.0	12.5	5.5			2819.2	35604
35.7	18.3	29.8	40.5	0.7	3.20	0.08							
41.6							68.3	12.4	5.3	-76.2	30.4	2795.4	39096
43.8	20.0	38.7	45.3	0.9	3.85	0.08							
48.5							65.8	12.4	5.3	-83.3	29.7	2890.5	42863
55.5							66.3	12.4	5.3	-48.7	29.9	2938.0	44241
55.8	22.2	26.3	25.7	1.0	4.43	0.05							
62.6							66.3	12.4	5.4	-67.4	29.5	2842.9	48928
68.8	25.4	38.6	30.8	1.3	5.66	0.09							
69.5							64.2	12.4	5.5	-130.3	31.8	3104.4	57749
75.7	28.2	38.5	27.4	1.4	6.74	0.16							
76.5							61.3	12.4	5.7	-32.3	35.5		54533
81.6	31.2	38.3	25.3	1.5	7.89	0.19							
83.5							59.6	12.4	5.7	-29.6	36.9	2866.7	49939
84.6	33.2	45.4	29.1	1.6	8.82	0.31							
90.6							63.3	12.4	6.2	-69.6	41.4		45896
91.6	40.5	55.6	33.7	1.6	12.83	0.57							
93.7	43.1	44.4	26.3	1.7	13.98	0.55							
95.6	45.9	32.4	18.8	1.7	14.88	0.48							
97.5							54.2	12.4	7.0	-224.0	42.7	2688.4	43966
99.6	52.6	35.7	20.6	1.7	17.28	0.60							
102.7	59.5	41.8	24.0	1.7	20.19	0.95							
104.5	64.8	38.5	21.7	1.8	22.21	1.08	55.0	12.4	7.3	-196.4	21.8	2581.4	27609

APPENDIX C: Compilation of Select Heavy Metals and Other Inorganic Elements Data

Table C-1. Heavy metals and other inorganic elements data for liquid waste sources.

Liquid Waste	Liquid Waste Concentrations [mg/L]													
	Al	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	P	Pb	Zn
Control Landfill Leachate	0.00	218	0.013	0.00	0.00	24.0	60	78	0.7	423	0.1	1.1	0.000	0.2
Brewery Wastewater	0.00	14	0.041	0.00	0.02	0.4	216	57	0.1	18	0.1	263.8	0.000	0.0
Cheese Processing Wastewater	0.00	245	0.000	0.00	0.00	0.5	236	22	0.0	138	0.1	139.9	0.005	0.2
Automobile Wash Water	0.00	69	0.013	0.00	0.06	0.7	6	3	0.0	8	0.1	1.3	0.000	0.4
Manufacturing High Strength	6.15	377	0.043	0.00	0.30	35.9	55	35	1.3	422	0.2	148.7	0.238	3.0
Manufacturing Low Strength	0.41	102	0.000	0.00	0.02	8.2	13	3	0.3	58	0.2	50.9	0.007	0.4
Landfill Leachate for MSW-SW and MSW-Sludge Reactors	0.15	240	0.009	0.00	0.00	41.0	57	82	0.8	402	0.1	1.6	0.000	0.0

Table C-2. Heavy metals and other inorganic elements data for initial recirculation samples.

Reactor	Initial Recirculation Concentrations [mg/L]													
	Al	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	P	Pb	Zn
Control-1	1.62	922	0.032	0.18	0.43	47.5	1650	221	8.8	469	0.4	85.7	0.000	3.5
Control-2	1.09	851	0.014	0.00	0.10	84.1	1040	167	8.8	314	0.2	73.4	0.087	2.0
LL-1	2.67	720	0.033	1.09	0.13	37.3	1691	227	8.5	711	0.3	83.4	0.000	3.0
LL-2	1.56	841	0.025	0.08	0.07	36.5	1299	212	8.7	650	0.3	69.4	0.000	1.0
BW-1	3.43	745	0.065	0.22	0.11	26.0	1869	256	6.9	589	0.3	91.1	0.000	3.0
BW-2	2.48	617	0.057	0.06	0.08	27.4	2041	256	6.9	573	0.2	120.4	0.000	2.6
CW-1	1.80	725	0.043	0.61	0.04	23.4	1847	231	8.4	583	0.2	95.5	0.000	1.7
CW-2	4.21	953	0.018	1.24	0.08	31.1	2656	293	9.7	733	0.3	75.7	0.000	2.3
AWW-1	1.02	850	0.011	0.68	0.01	32.5	796	152	8.4	316	0.3	49.3	0.063	0.3
AWW-2	0.95	867	0.032	0.00	0.01	58.2	865	164	9.4	331	0.3	64.9	0.030	1.0
MW-H-1	6.11	683	0.047	0.37	0.12	39.3	2623	266	8.0	884	0.4	112.3	0.000	5.9
MW-H-2	9.53	859	0.042	0.59	0.11	41.1	3186	305	9.6	893	0.3	105.2	0.000	7.5
MW-L-1	2.22	811	0.050	0.13	0.06	28.5	1536	216	7.7	502	0.3	87.3	0.000	2.3
MW-L-2	2.84	826	0.051	0.42	0.11	28.2	1414	215	8.7	478	0.3	104.4	0.000	3.2
GB-1	2.09	993	0.037	0.18	0.02	51.7	1159	235	10.5	758	0.3	48.6	0.000	0.7
GB-2	3.06	907	0.056	0.49	0.01	32.9	1655	279	9.9	963	0.4	66.9	0.000	0.2
ASR-1	1.10	692	0.008	0.00	0.14	64.6	628	156	12.3	641	0.9	8.8	0.000	14.3
ASR-2	1.39	807	0.027	0.36	0.14	104.5	1277	214	15.5	785	1.3	13.8	0.011	28.9
FW-1	1.65	886	0.037	0.00	0.04	74.6	1557	229	11.8	856	0.3	67.5	0.000	0.7
FW-2	1.87	809	0.028	0.03	0.05	42.2	1641	233	9.4	850	0.3	75.4	0.000	0.6
AD-1	1.37	854	0.033	0.87	0.05	77.2	1296	220	9.5	481	0.3	222.7	0.000	0.5
AD-2	1.75	866	0.022	3.27	0.08	52.0	1354	220	7.3	477	0.3	248.5	0.000	0.6
IS-1	0.82	951	0.012	0.00	0.05	34.3	774	191	10.0	429	0.5	245.1	0.000	0.2
IS-2	0.80	1076	0.007	0.00	0.04	31.0	770	201	9.3	444	0.5	224.3	0.115	0.0
MCL			0.005	0.1	1.3								0.015	
Secondary MCL	0.05				1	0.3			0.05					5
Typical Leachate (Kjeldsen et al. 2002)		7200	0.4	1.5	10	5500	3700	15000	1400	7700	13	23	5	1000

Table C-3. Heavy metals and other inorganic elements data for final recirculation samples.

Reactor	Final Recirculation Concentrations [mg/L]													
	Al	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	P	Pb	Zn
Control-1	0.00	2002	0.009	0.06	0.00	378.8	2716	190	22.6	1429	0.4	27.1	0.128	5.7
Control-2	0.00	1931	0.000	0.05	0.00	385.5	2748	188	20.6	1733	0.3	25.2	0.102	6.1
LL-1	0.11	1947	0.000	0.48	0.00	416.9	2775	189	23.6	2186	0.3	28.9	0.190	21.6
LL-2	0.11	2000	0.000	0.22	0.00	415.4	2653	183	22.9	2450	0.2	27.4	0.162	4.1
BW-1	0.06	1908	0.006	0.12	0.00	386.1	2740	171	21.7	1016	0.3	53.0	0.050	4.6
BW-2	0.00	1673	0.015	0.05	0.00	324.9	2859	175	19.1	1604	0.3	63.6	0.051	7.7
CW-1	0.00	1624	0.003	0.13	0.00	294.4	2684	183	17.5	1399	0.3	29.1	0.056	6.3
CW-2	0.00	1641	0.000	0.12	0.00	310.9	2556	184	18.9	1077	0.3	31.5	0.090	3.0
AWW-1	0.09	1923	0.000	0.12	0.00	336.4	2428	180	21.2	1691	0.3	25.7	0.065	1.4
AWW-2	0.00	1720	0.006	0.10	0.00	261.8	2502	183	16.3	1594	0.3	23.5	0.034	2.7
MW-H-1	0.17	1280	0.006	0.07	0.00	264.5	2411	183	13.9	1538	0.5	29.1	0.105	1.0
MW-H-2	0.14	1279	0.003	0.07	0.00	231.0	2294	180	12.4	1129	0.5	32.3	0.043	0.5
MW-L-1	0.00	1654	0.004	0.17	0.00	295.6	2300	181	15.7	1323	0.3	29.4	0.104	1.5
MW-L-2	0.12	1620	0.003	0.25	0.00	269.0	2366	184	16.0	1532	0.4	30.0	0.055	1.4
GB-1	0.00	1244	0.012	0.21	0.00	1.9	961	146	1.9	926	0.0	7.0	0.013	0.0
GB-2	0.00	1785	0.020	0.09	0.00	0.2	941	151	2.7	924	0.0	6.2	0.000	0.0
ASR-1	0.00	1236	0.000	0.03	0.00	259.5	1371	187	30.6	1177	1.3	4.1	0.055	34.7
ASR-2	0.05	1287	0.000	0.16	0.00	354.0	1668	190	32.5	1080	1.7	5.0	0.153	47.9
FW-1	0.04	1984	0.009	0.01	0.00	285.9	2202	186	26.2	1587	0.2	26.2	0.065	11.4
FW-2	0.03	1983	0.000	0.09	0.00	323.7	2095	184	24.2	1478	0.2	21.9	0.118	2.1
AD-1	0.19	83	0.000	0.14	0.00	10.9	951	107	0.4	995	0.2	22.4	0.011	0.1
AD-2	0.00	97	0.000	0.13	0.00	13.0	1116	138	0.2	1506	0.1	16.6	0.011	0.1
IS-1	0.00	94	0.000	0.00	0.00	24.1	1151	147	0.1	1074	0.1	16.6	0.013	0.0
IS-2	0.00	1097	0.006	0.00	0.00	230.3	1457	173	4.4	1150	0.1	11.5	0.048	0.1
MCL			0.005	0.1	1.3								0.015	
Secondary MCL	0.05				1	0.3			0.05					5
Typical Leachate (Kjeldsen et al. 2002)		7200	0.4	1.5	10	5500	3700	15000	1400	7700	13	23	5	1000

APPENDIX D: Photos of Reactors and Biochemical Methane Potential Assays

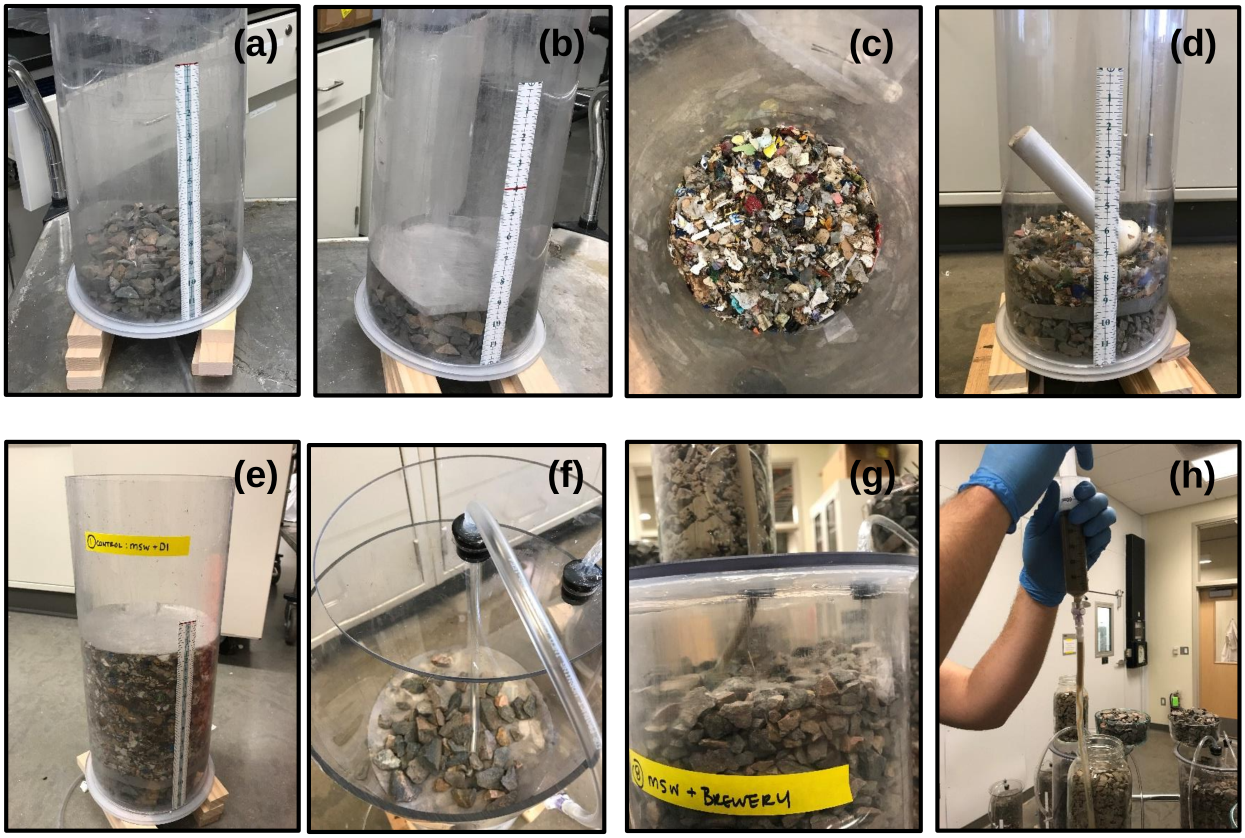


Figure D-1. Reactor construction of (a) drainage layer, (b) geotextile filter, (c) waste lift, (d) hand-tamped waste lift, (e) upper geotextile, (f) influent line buried in upper gravel layer, (g) gravel load and lid secured with silicon, and (h) injecting initial liquid dose.

Figure D-2. (a) Final constructed control reactors and (b) temperature control room with 24 reactor experiments in operation.

Figure D-3. Weekly recirculation: (a) reactor leachate is pulled from the gravel storage layer via syringe, (b) samples are collected and stored in vials, and (c) leachate volume is measured via syringe, collected in a beaker, and buffered before reinjection into the influent port.

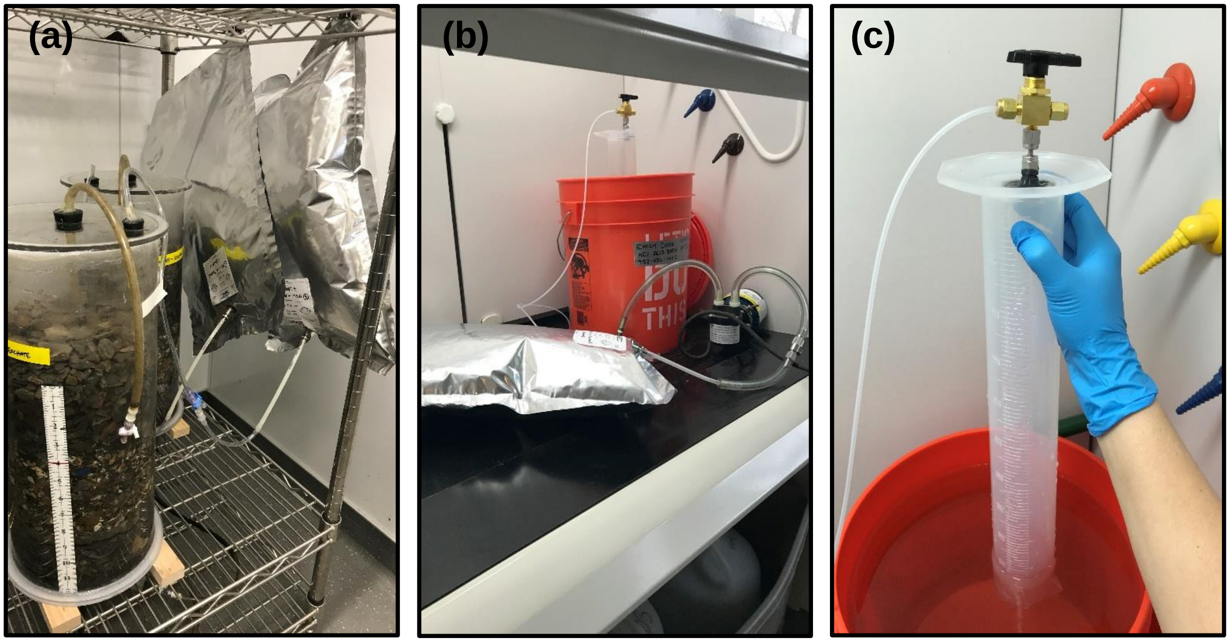


Figure D-4. Reactor gas management: (a) gas is collected in bags, (b) gas bag is connected to vacuum pump for volume measurement, and (c) gas is measured via volume displacement using an inverted 1-L graduated cylinder.

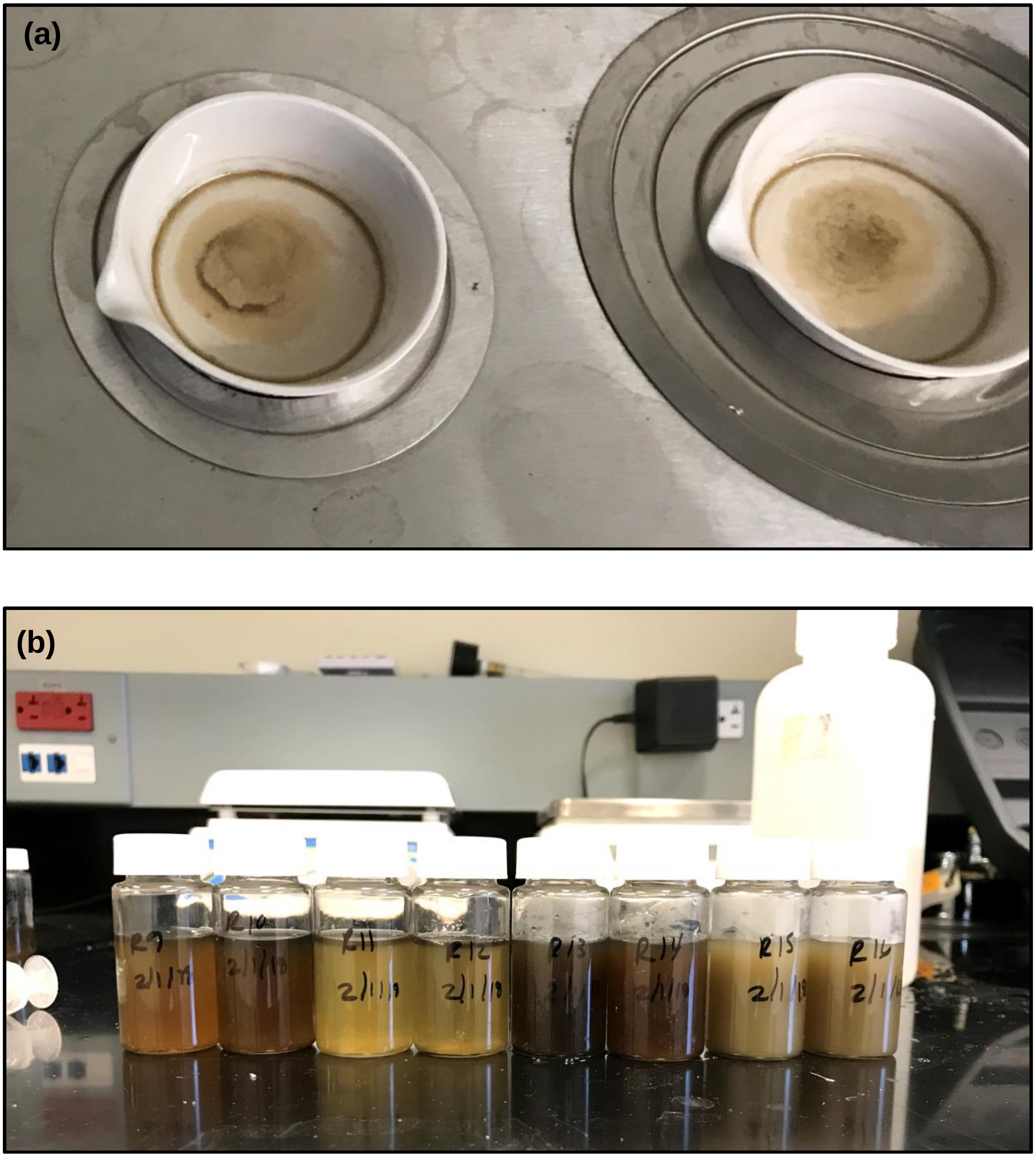


Figure D-5. Treatment of high strength manufacturing wastewater (MW-H) via one recirculation of through the waste mass: (a) initial white/high solids liquid waste prior to recirculation and (b) translucent brown MW-H leachate after first recirculation through the waste mass (“R13” and R14”, 5th and 6th from the left, respectively).

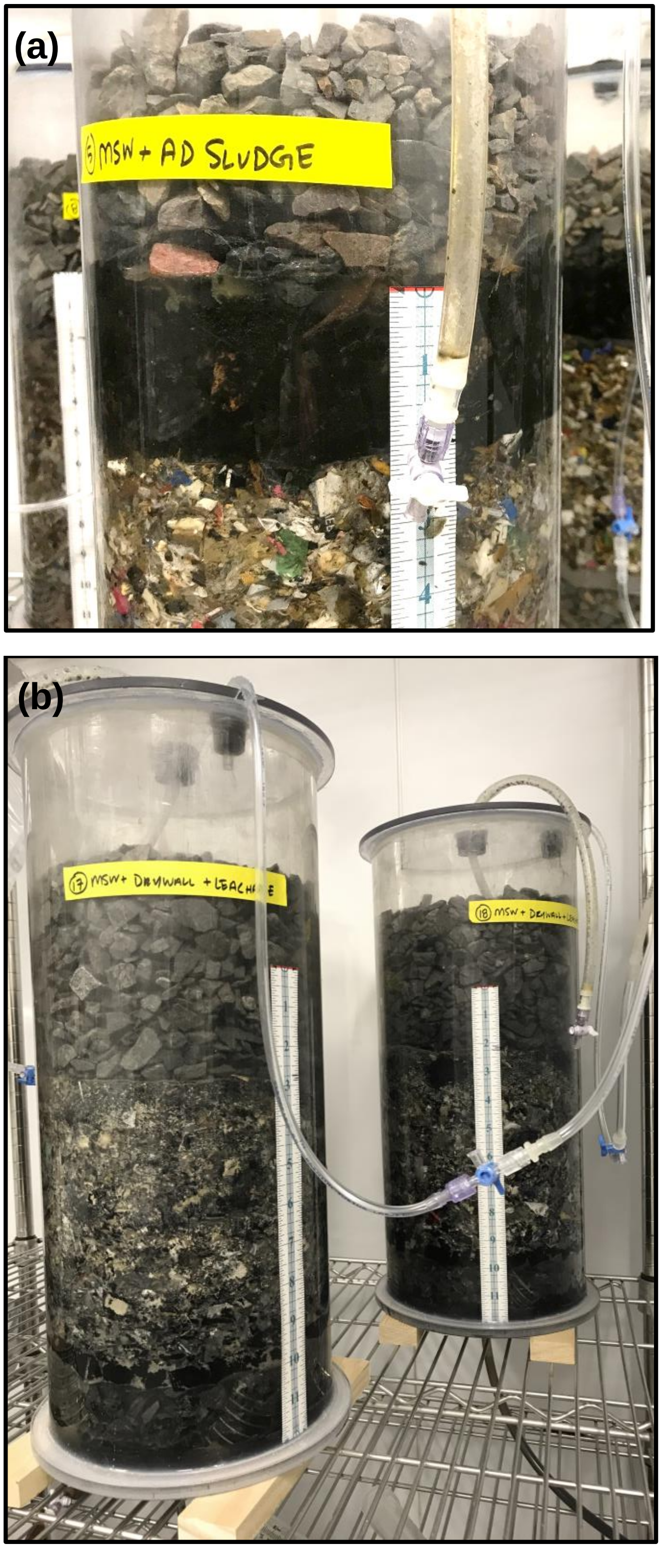


Figure D-6. Operational considerations including (a) reactor clogging due to AD sludge addition and (b) sulfate reduction, indicated by the black coloration in the GB reactors.

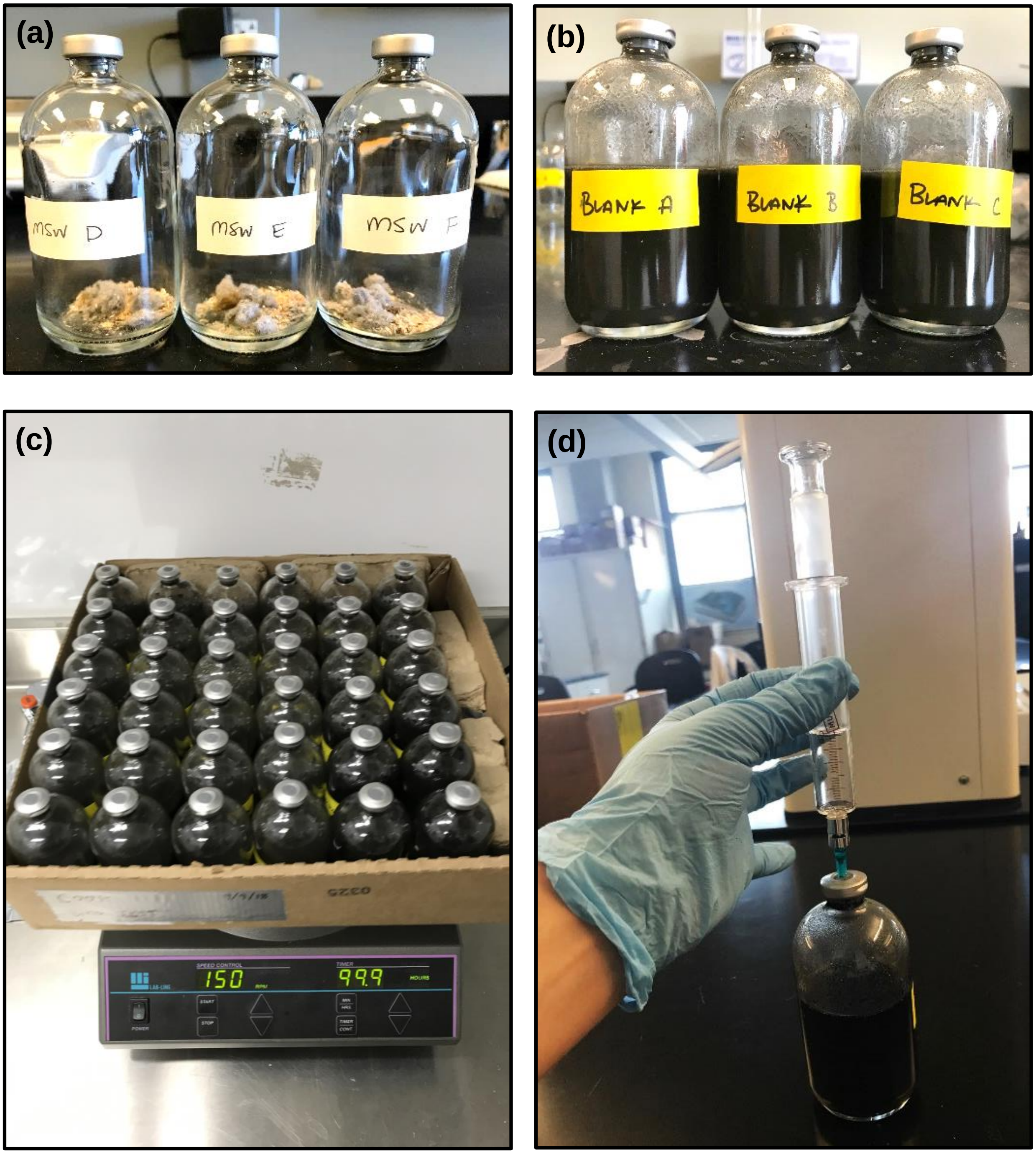


Figure D-7. Biochemical methane potential (BMP) assays: (a) solid waste sample added to assay bottle, (b) BMP control consisting of 50 mL nutrient media and 50 mL anaerobic inoculum, (c) bottles in temperature controlled room on shaker table, and (d) venting gas bottle prior to sampling using a wetted glass syringe.