ENHANCED ENERGY RECOVERY FROM CO-DIGESTION OF TOILET WASTE AND KITCHEN WASTE USING WATER-CONSERVING TOILETS

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ABSTRACT

Approximately 21 % of Aotearoa-New Zealand's population is not connected to a reticulated sewer system. They live in rural areas where households must treat their sewage with onsite wastewater treatment systems, which is commonly a septic tank. Unfortunately, this type of onsite wastewater treatment system does not favour the recovery of resources such as energy and nutrients.

In an era of climate change and worldwide water scarcity, efforts to develop a circular economy approach and recover water, energy and nutrients are necessary. One strategy to improve water, energy and nutrient recovery from domestic wastewater is to separate black water from greywater at source and treat each stream with technologies suited to their characteristics. Anaerobic co-digestion can effectively recover clean bioenergy and biofertilisers from high-strength organic waste streams such as toilet waste and food residues. Co-digestion refers to the simultaneous anaerobic digestion of multiple organic wastes in one digester. The benefits include increased cost-efficiency, the synergistic

degradation of treated materials, optimal moisture and nutrient concentrations, the dilution of inhibitory compounds such as ammonia, and the degradation of products such as lipids.

This work presents the results of a batch experiment to investigate the biogas production by anaerobically co-digesting source separated toilet wastewater and kitchen waste with different amounts of water to represent: a) water conserving toilet waste (e.g., vacuum toilets using 0.5-1.2 L water per flush), b) dual-flush toilet waste (using 6 L water per flush) and c) conventional toilet waste (using 9 L water per flush). The main objective of this research was to evaluate the impact of water content on the biochemical methane production from co-digestion of three different type of toilet wastes with kitchen waste.

The results of this study showed that co-digestion of water conserving toilet waste and kitchen waste accelerated the methane production (443 L CH_4 Kg VS^{-1} in TW1+KW) compared to the toilet waste diluted with higher amount of water. Water diluted waste (for example by using less water efficient toilets) impacted the co-digestion reducing the methane production (400 L CH_4 Kg VS^{-1} in TW9+KW).

KEYWORDS

Toilet waste, Kitchen waste, Anaerobic co-digestion, Decentralised systems, Water efficiency.

PRESENTER PROFILE

Fara (Farideh) is a Senior Technician at the Institute of Environmental Science and Research (ESR). She is a member of the Circular Economy team located at the ESR Christchurch Science Centre. Her role involves contributing to various projects focused on recovering resources such as energy, water, and nutrients from wastewater and other organic waste materials.
One of her primary interests lies in exploring energy recovery through the utilization of anaerobic digestion. Her goal is to enhance the efficiency of anaerobic digestion processes as a means to produce renewable energy and biofertilizers.

1- INTRODUCTION

Approximately 21% of New Zealand's population, which mainly live in rural areas, is not connected to a centralized sewer system, requiring the use of onsite wastewater treatment systems, often in the form of septic tanks [1]. However, the operation and maintenance of such onsite wastewater treatment systems pose challenges and do not effectively recover valuable resources like energy and nutrients. To address this issue, alternative technologies for onsite waste management are being sought.

In response to climate change, decarbonization, and global water scarcity concerns, there has been a growing focus on the circular economy approach to recover resources from wastewater [2]. The concept of decentralized wastewater management with separate collection and treatment of toilet waste and greywater, along with water reuse, is gaining popularity. This approach aims to maximize the recovery of valuable resources from wastewater, including energy, nutrients, and water [3]. By collecting toilet waste separately and using water-conserving toilets like vacuum toilets, a concentrated stream can be obtained, comprising less than 30% of total household wastewater consumption. This concentrated stream contains more than 50% of organic content and 80-95% of the nutrients which could be recovered [3].

Anaerobic digestion (AD) is a waste-to-energy technology that converts organic waste into biogas. AD can be used in both centralised and decentralised systems to manage a wide spectrum of organic wastes, from complex lignocellulosic materials to easily degradable food waste to generate renewable energy [4]. Co-digestion (i.e., simultaneous anaerobic digestion of multiple organic waste products) is often the most suitable way to increase methane production from different sorts of organic waste, especially toilet waste [4]. In New Zealand, reducing the food waste that is sent to landfills and significantly contributes to greenhouse gas emissions, is a priority for the Ministry for the Environment [5]. By adopting co-digestion and implementing more efficient waste management practices, we can promote sustainability and environmental protection. In this context, this study aimed to use co-digestion strategy to simultaneously recover resources from toilet waste (TW) and kitchen waste (KW).

Since the characteristics of the collection system has an impact on the toilet waste composition and, consequently, on biogas production, we aimed to evaluate the impact of water usage on the co-digestion of toilet waste with kitchen waste. The main objective of this study was to evaluate the biochemical methane potential from anaerobically co-digesting source separated toilet wastewater and KW with different amount of water to represent: a) water conserving toilet waste (vacuum toilets using 0.5-1.2 L water per flush), b) dual-flush toilet waste (using 6 L water per flush) and c) conventional toilet waste (using 9 L water per flush).

In this study, the term "water conserving toilet waste" is used interchangeably for toilet waste with 1 L of water (TW1), while "water wasting toilet waste" refers to toilet waste diluted with 6 L (TW6) and 9 L of water (TW9).

2- MATERIALS AND METHODS

Kitchen waste made up mainly of fruit peels, vegetable residue and a lower amount of meat, bread and rice was used. Toilet waste stock (mixture of faeces, urine and toilet paper) was sourced from healthy adult volunteers. To prepare toilet wastes with varying level of water, an equivalent quantity of stock toilet waste (374 g wet weight) was diluted with 1, 6, and 9 L of water to represent water conserving toilet waste (designated as TW1), dual flush toilet waste (designated as TW6) and conventional toilet waste (designated as TW9), respectively. Each group of toilet waste was then mixed with kitchen waste to give a volatile solid ratio of 70% toilet waste and 30% kitchen waste.

The biomethane potential test (BMP) of the prepared mixtures was conducted in sealed serum bottles (162 mL), previously flushed with nitrogen gas to remove air from the headspace, incubated at 37 °C (Fig 1). The serum bottles were inoculated with digested sludge obtained from mesophilic anaerobic digesters at the Christchurch Wastewater Treatment Plant. Five replicates were carried out for each mixture. Gas chromatography was used to determine the gas composition in the serum bottles and gas volume was also measured during the experiment.

The pH, total solid (TS) and total volatile solid (VS) content were determined in initial wastes. pH was measured using pH electrode (RE357Tx Microprocessor pH Meter). TS and VS were measured according to the Standard Methods [6]

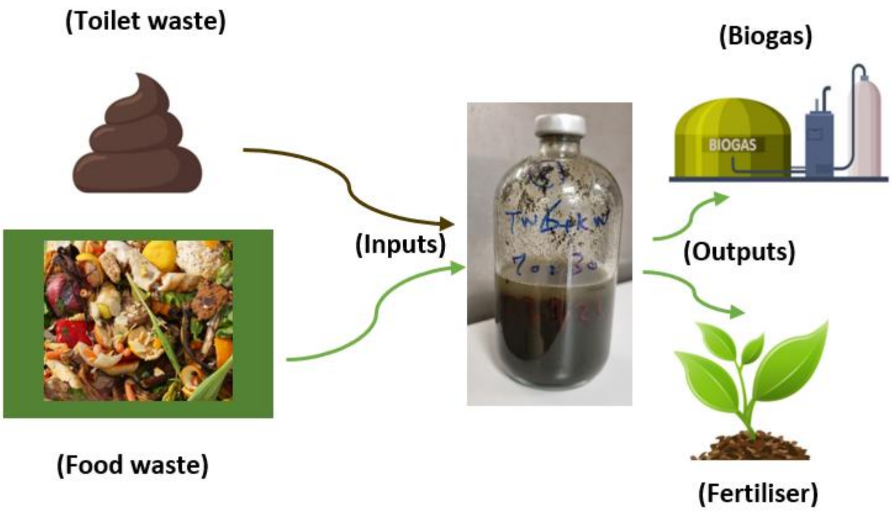

Fig 1. Biomethane potential test in 162 ml serum bottle

It is noteworthy to mention that in this study, ammonia inhibition and volatile acid accumulation were not studied. All samples were prepared with substrate to inoculum (S/I) ratio of 0.5 g VS/g VS and each serum bottle contained the same amount of substrate mixture based on VS. This enabled us to evaluate the maximum methane yield from each type of waste by considering the amount of water as a limiting factor that would impact the biogas production in each treatment.

One-way ANOVA (analysis of variance) method followed by post hoc Tukey's test with a 0.05 significance level was used to determine whether the various treatments were statistically different from each other or not.

3- RESULTS AND DISCUSSION

3-1 Characterisation of wastes

The waste characteristics are presented in Table 1. KW exhibited an acidic pH, whereas the pH of toilet wastes was basic. These results aligned with the pH values reported in previous literature for toilet waste and kitchen waste samples [3, 7]. The VS/TS ratio for various waste samples fell within the range of 0.85 to 0.95.

This indicates that these samples contained a high proportion of organic matter, which suggests a significant level of biodegradability in the wastes [7]

Table 1 Characteristics of initial wastes (Units are g/kg for KW, and g/L for TW)

	KW	TW with 1 L water	6 L flushing toilet waste	9 L water flushing toilet waste	Seed sludge
pH	4.5	8.4	8.3	8.2	8.5
VS	130 ± 0.01 g/Kg	21 ± 0.57 (g/L)	4.0 ± 0.65 (g/L)	2.7 ± 0.25 (g/L)	21 ± 2.7 (g/L)
TS	140 ± 0.01 g/Kg	24 ± 1.2 (g/L)	4.7 ± 0.85 (g/L)	3.1 ± 0.54 (g/L)	31 ± 3.6 (g/L)

3-2 Methane yield

As can be seen in Fig 2, co-digestion of TW1+KW resulted in the highest methane yield of 443 L CH_4 kg VS^{-1}, which was 10% higher than the co-digestion of TW9+KW (400 L CH_4 kg VS^{-1}). One-way ANOVA test showed that there was a significant difference among three treatments (P value of < 0.05). The reduced methane yield suggests that the methanogens' ability to produce methane was hindered, possibly due to the alteration in their habitat caused by the higher water content.

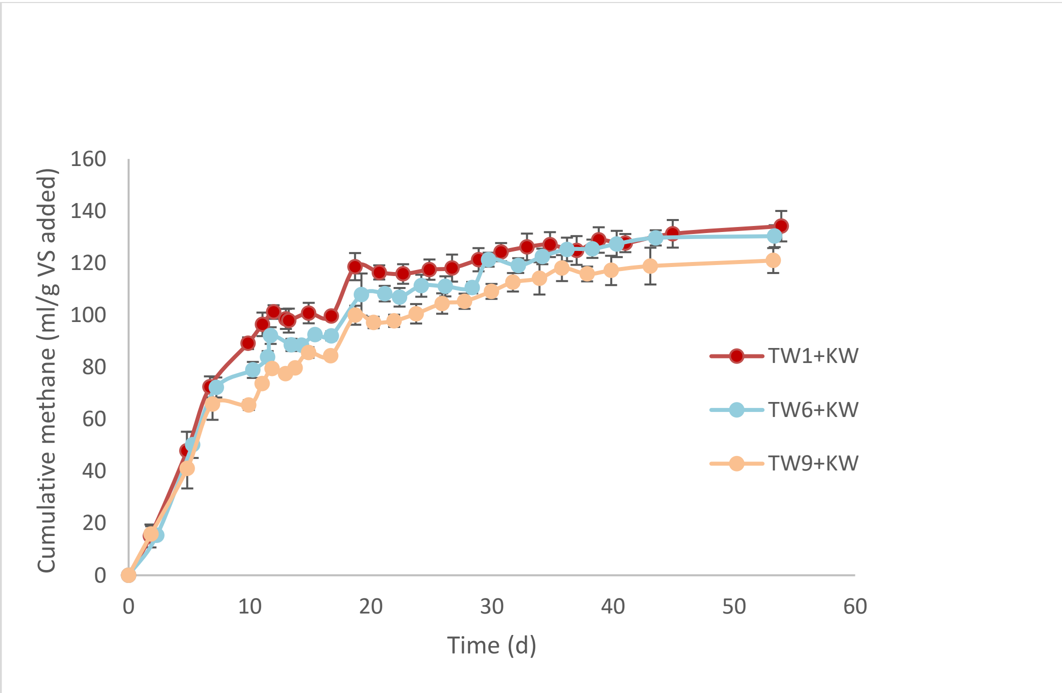

Fig 2 Cumulative methane production during co-digestion of different types of toilet wastes with kitchen waste

Table 2. Biochemical methane potential (BMP) of toilet waste and kitchen waste with different levels of dilution and estimate potential methane production per household.

Substrate	**BMP (L CH_4 kg VS^{-1})**	***Methane yield (*** **m^3 CH_4 a^{-1} household^{-1})**	***Quantity available of TW*** **(Kg a^{-1} household^{-1})**	***Required amount of KW*** **(Kg a^{-1} household^{-1})**
TW1+KW	*443±5.5*	*32.4*	*725*	*169.2*
TW6+KW	*433±3.4*	*31.6*	*725*	*169.2*
TW9+KW	*400±5.8*	*29.2*	*725*	*169.2*

Furthermore, the findings suggested that the co-digestion of water conserving toilet waste with KW (TW1+KW) led to better accessibility of microbial community to food and as a result, a higher methane yield generated. Previous studies investigated the co-digestion of blackwater sourced from different collection systems. Their findings showed that the characteristics of the blackwater contributed to the large variance in the reported methane production [7]. However, no study investigated the impact of water content in the gas production in different toilet waste collection system. More detailed research regarding changes in microbial community would help to understand the specific mechanisms behind this observation and draw definitive conclusions about the relationship between water content, methanogen activity, and methane production in the system.

In summary, characteristics of toilet waste (i.e., amount of water diluted with waste) can affect the biogas production. When employing anaerobic co-digestion, selecting the appropriate substrate becomes crucial to achieving the highest methane yield. Identifying various factors that could influence gas production is vital. In this study, the amount of water was recognized as a limiting factor affecting the process.

Based on the available data regarding the annual kitchen and toilet waste quantities per person including 145 Kg (wet weight) of TW [8] and 61.2 Kg (wet weight) of KW [9], co-digestion of TW1+KW could potentially yield around 32 m^3 of CH_4 per household per year (i.e., 5 people per household [10]) (Table 2). This amount of methane, equivalent to 320 kWh of energy, is derived from considering the calorific value of 1 m^3 of methane as 10 kWh [11]. It should be noted that the biogas production in an anaerobic digester heavily relies on the specific properties of the substrate employed as was shown in this study (refer to Table1). For instance, individuals' dietary choices influence both the types of food they eat and the characteristics of the toilet waste. So, the gas production can be varied among different households and communities. For example, the VS of kitchen waste in this study was lower than the VS of kitchen waste in previous studies (i.e. reported 230 g/kg of wet weight)[12]. It's important to note that greater VS content in waste tends to correspond with increased gas production[13].

To enhance efficiency of biogas production within household digesters in rural regions, the crucial factor is identifying diverse substrates available in decentralized areas. Other potential substrates in rural areas could be animal manures, green wastes, etc. These substrates can be integrated as potential inputs into anaerobic digesters, effectively enhancing system efficiency and biogas generation. Anaerobic co-digestion exhibits remarkable adaptability, enabling the incorporation and management of various waste streams within the system. So, there would be opportunities to co-digest different organic wastes in a single household digestor in rural areas in New Zealand. Bukauskas et al., [14] reported an experiment in Cambodia, where an anaerobic digester was directly connected to a household's toilet. This, when combined with the traditional input of animal manures like cow, buffalo, or pig waste, yielded sufficient gas to fulfil all cooking requirements of the household. This approach underscores the flexibility of anaerobic co-digestion and its capability to harness different waste resources for meaningful energy production. Further research should be conducted in New Zealand to identify other suitable substrates available in decentralised areas for the anaerobic co-digestion and their potential for enhancing energy recovery.

Furthermore, when this technology is expanded to a larger scale, such as at the community or city level, the cumulative production of biogas can be significant. A rough estimation based on daily human waste production in China showed that, the electricity production from human waste could reach 257 GWh/day. If this electricity substitutes coal-based electricity, −142 kt $CO_{2,eq}$. would be avoided on a daily basis[13]. This will reduce required costs and energy to operate a conventional wastewater treatment plant. Studies have reported that conventional wastewater treatment plants, excluding sludge incineration, typically consume energy ranging from 0.30 to 1.89 kWh per cubic meter[13]. The implementation of water conserving toilet waste to co-digest toilet waste with kitchen waste is a viable solution for effectively handling the wastes in rural communities across New Zealand. By collecting waste from various households, these toilet and kitchen wastes can be combined and processed within a single anaerobic digester, subsequently producing energy for the entire community. Furthermore, this technology has the potential to extend its application to communal spaces like Marae, schools, restaurants, thereby offering a versatile and sustainable waste management solution.

Finally, it is noteworthy to mention that the estimations given in this study regarding the methane yield generated is based on the biomethane potential test. However, BMP does not give information on the continuous operation of an anaerobic digester, and this require more research to evaluate the methane yield in a continuous anaerobic co-digestion digestor.

4- CONCLUSIONS

Amount of water in the toilet waste was recognized a limiting factor affecting the methane yield from co-digestion of toilet waste with kitchen waste (i.e., 443 L CH_4 Kg VS^{-1} in TW1+KW versus 400 L CH_4 Kg VS^{-1} in TW9+KW).

It is suggested that toilet waste generated from water conserving toilet waste (toilet with 0.5 to 1.2 L of water per flush) and kitchen waste can be a good substrate to be applied in anaerobic co-digestion systems for obtaining higher energy recovery, while the amount of water for toilet flushing can hugely be minimised.

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