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Frontiers in Membrane Technology

7th IWA-RMTC 2024

Springer

Lecture Notes in Civil Engineering 525

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Giorgio Mannina · How Yong Ng
Editors

Frontiers in Membrane Technology

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ISSN 2366-2557 ISSN 2366-2565 (electronic)
Lecture Notes in Civil Engineering
ISBN 978-3-031-63356-0 ISBN 978-3-031-63357-7 (eBook)
https://doi.org/10.1007/978-3-031-63357-7

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Preface

In recent decades, advanced technologies have received increased attention as interest in sustainable water resources has grown.

Membrane technologies have become of paramount importance in enhancing human life, specifically, membrane technologies for water and wastewater treatment (e.g., novel membrane materials and configurations, energy recovery from water and wastewater, fouling mechanisms and control, membrane process development and optimization, drinking water and wastewater treatment, desalination, etc.) by focusing the attention on the interrelationship among the entire water cycle, environment, and society.

The book contains contributions presented during the 7th International Water Association (IWA) Regional Membrane Technology Conference (IWA-RMTC 2024), which was held on 18–21 June 2024 in Palermo, Italy. This was the seventh in the series of IWA-RMTC events and is a joint effort of the IWA Specialist Group on Membrane Technology and the EU project: Achieving Wider-Uptake of water smart solutions – Wider-Uptake.

The IWA-RMTC's final aim was to create a forum for promoting the discussion among scientists, professionals, and academia in different areas of the broader themes.

The conference was organized in nine parallel sessions, and for each of them, a keynote by a referral researcher was presented. Specifically, the keynotes were held by the following professors, whose contributions were highly inspiring: Damià Barceló, Menachem Elimelech, Xia Huang, Yongmei Li, Eberhard Morgenroth, How Yong NG, Ana Soares, Eveline Volcke, Zhiwei Wang, and Zhiguo Yuan.

The wealth of information exchanged during IWA-RMTC was of great benefit to all involved in the urgent need of developing advanced and sustainable solutions for water and wastewater treatment.

The book is organized into six parts: Part I – Resource recovery from wastewater, Part II – Domestic/industrial wastewater treatment, Part III – Membrane bioreactors, Part IV – Novel membrane materials and hybrid membrane processes, Part V – Membrane fouling mechanisms and control, and Part VI – Desalination.

Each contribution of the conference has been peer-reviewed by at least two members of the scientific committee. Their efforts have contributed to the high quality of the final book contributions, and therefore, their reviewing activity is acknowledged and appreciated.

Finally, I express my thanks to Mr. Pierpaolo Riva, publishing editor at Springer, for his suggestions during the finalization of the book.

I do hope that the reader will find the book a source of inspiration for both research and professional life.

Giorgio Mannina
How Yong Ng

Members of the Scientific Committee of the 7th International Water Association Regional Membrane Technology Conference – IWA-RMTC 2024

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Can Water Conserving Toilet be a Solution to Achieve Higher Energy Recovery from Co-digestion of Toilet Waste and Kitchen Waste?

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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. However, septic tank does not favour the recovery of resources such as energy and nutrients.

In an era of climate change, a circular economy is vital. Separating black water from greywater at the source and treating them with specialized technologies enhances water, energy, and nutrient recovery from domestic wastewater. Anaerobic co-digestion efficiently extracts bioenergy and biofertilizers from organic waste like toilet waste and food residues.

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 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.

Keywords: Toilet waste · Kitchen waste · Anaerobic co-digestion · Decentralised systems · Water efficiency

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G. Mannina and H. Y. Ng (Eds.): IWA-RMTC 2024, LNCE 525, pp. 3–7, 2024.
https://doi.org/10.1007/978-3-031-63357-7_1

1 Introduction

Approximately 21% of New Zealand's population, which mainly live in rural areas, is not connected to a centralized sewer system, relying on septic tanks for onsite wastewater treatment (Beca et al., 2020). 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 and decarbonization, there has been a growing focus on the circular economy approach to recover resources from wastewater (Neczaj and Grosser, 2018). 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 (Zhang et al., 2019). By collecting toilet waste separately, a concentrated stream can be obtained. This concentrated stream contains organic content and nutrients which could be recovered (Zhang et al., 2019).

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 (Elsayed et al., 2020). 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 (Elsayed et al., 2020). 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 (Ministry for the Environment, 2023). By adopting co-digestion and implementing more efficient waste management practices, we can promote sustainability. In this context, this study aimed to use co-digestion strategy to simultaneously recover resources from toilet waste (TW) and kitchen waste (KW).

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 (Gao et al., 2019). However, no study investigated the impact of water content in the gas production of toilet waste.

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. The 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. The serum bottles were inoculated with digested sludge. 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.

All samples were prepared with substrate to inoculum (S/I) ratio of 0.5 g VS/g 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 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

As can be seen in Fig. 1, 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 findings suggested that the co-digestion of toilet waste with reduced water content (here TW1 + KW) may enable a better access to nutrients by the methanogens leading to a higher methane yield. Furthermore, since the amount of methane dissolved in water for each treatment would be different, favoring the test with lower water content (TW1 + KW).

Based on the available data regarding the annual kitchen and toilet waste quantities per person including 145 kg (wet weight) of TW (Kim et al., 2019) and 61.2 kg (wet weight) of KW [9], co-digestion of TW1 + KW could potentially yield around 15.7 m^3 of CH_4 per household per year (i.e., 2.6 people per household) (Stats, 2018)(Table 1). This amount of methane, equivalent to 157 kWh of energy, is derived from considering the calorific value of 1 m^3 of methane as 10 kWh (Suhartini et al., 2019). By considering power usage of daily 1.2 kWh for a fridge or freezer with avarage size, 157 kWh of energy can keep the fridge or freezer on for about 4 months.

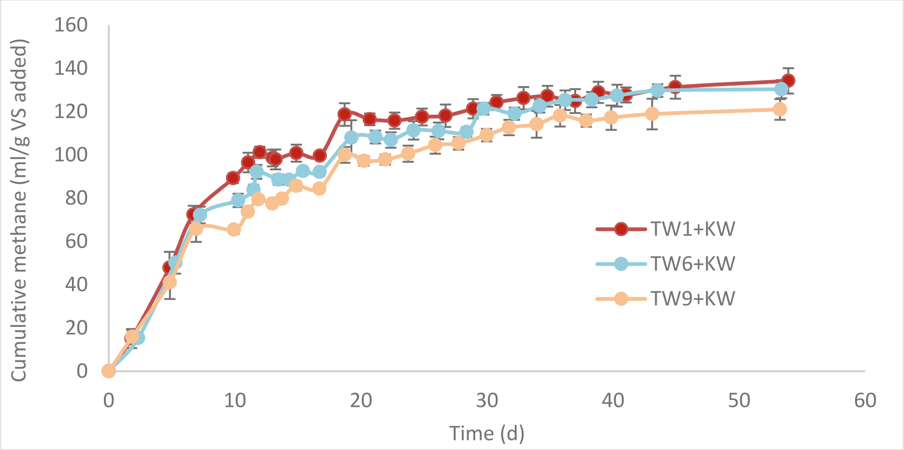

Fig. 1. Cumulative methane production during co-digestion of different types of toilet wastes with kitchen waste

Table 1. 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 ($m^3\ CH_4\ a^{-1}\ household^{-1}$)
TW1 + KW	443 ± 5.5	15.7
TW6 + KW	433 ± 3.4	15.4
TW9 + KW	400 ± 5.8	14.3

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. Further research should be conducted in New Zealand to identify other suitable substrates (e.g. animal manures or green wastes) 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_2eq. Would be avoided on a daily basis (Duan et al., 2020).. This will reduce required costs and energy to operate a conventional wastewater treatment plant.

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

The amount of water in the toilet waste was recognized as a limiting factor affecting the methane yield from co-digestion of toilet waste with kitchen waste. 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. Hence, 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. Collected toilet and kitchen waste from various households or communal spaces (e.g. schools), can be combined and processed within a single anaerobic digester, subsequently producing sustainably energy for the entire community.

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Mechanisms of Biochar-Mediated Promotion of Acidogenic Fermentation in Waste Activated Sludge and Acetic Acid Production Pathways

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Abstract. The conversion of organic matter in waste activated sludge (WAS) into high value-added chemicals of volatile fatty acids (VFAs) has become a focus of attention. However, the direct conversion of WAS to a certain acid in VFAs is difficult. Herein, for the first time, biochar was used to promote sludge solubilization, hydrolysis and acidogenic fermentation directing the production of acetic acid. The results illustrated that biochar was able to promote the oxidation of NADH and maintain the appropriate level of NADH/NAD$^+$ ratio, thus increasing the acetic acid production. The promotion effect was directly proportional to the content of oxygen-containing functional groups (OFGs) in the biochar, and the maximum content of OFGs was found in the CT/Ni_2O_3@SBC, which had the lowest NADH/NAD$^+$ ratio in the anaerobic fermentation system, acetic acid accounted for the largest percentage (52.30%), which was 1.99 times higher compared to the blank. OFGs in the biochar were involved in the electron transfer between electroactive microorganisms in the fermentation system, which compete with the methanogenic microorganisms for the electrons and thereby inhibit the production of methane. This study reveals that biochar could promote sludge solubilization, hydrolysis and promote acetic acid production, providing a new strategy for directional acid production in the future.

Keyword: Biochar · Acetic acid · NADH/NAD$^+$

1 Introduction

The conversion of organic matter in waste activated sludge (WAS) to value-added chemicals such as volatile fatty acids (VFAs) has become a focus of attention (Dyksma et al., 2020). However, most of the current studies have focused on the increase of the total amount of VFAs, and there are fewer studies on the targeted conversion of VFAs to specific acids.

Nicotinamide adenine dinucleotide hydrogen (NADH) and nicotinamide adenine dinucleotide (NAD$^+$) control the production direction of acid, which have to do with electron transport (Martins et al., 2018). Many studies have shown that porous biochar can provide attachment sites for microorganisms and key enzymes in sludge anaerobic

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G. Mannina and H. Y. Ng (Eds.): IWA-RMTC 2024, LNCE 525, pp. 8–13, 2024.
https://doi.org/10.1007/978-3-031-63357-7_2

fermentation systems (Rajendran et al., 2020). In addition, biochar contains oxygen-containing functional groups (OFGs, including quinone groups, phenol groups, and environmentally persistent free radicals (EPFRs)), which have some redox capacity and can transfer electrons.

The main purpose of this study thus was to use biochar to promote WAS solubilization and hydrolysis and directionally promote desired acid production. This study, for the first time, provided deep insights into the feasibility of using biochar to promote WAS solubilization, hydrolysis and acidogenic fermentation directed to acetic acid production.

2 Materials and Methods

2.1 Modified Sludge-based Biochar Preparation

The pyrolysis method was used as follows: firstly, dry sludge, dry sludge + 5% catechol, dry sludge + 5% catechol + 5% ferric oxide, dry sludge + 5% catechol + 5% nickel trioxide were put into a quartz boat and pyrolyzed at 450 °C for 90 min, and then cooled to room temperature. They were named SBC,CT@SBC,CT/Fe_2O_3@SBC and CT/Ni_2O_3@SBC, respectively.

2.2 Acid Production Batch Experiment Under Modified Biochar Pretreatment

The serum bottles for batch fermentation were AF1, AF2, AF3, AF4, AF5, and AF6, with a capacity of 550 mL. Biochar was not added to AF1 and AF2 bottles, in which pH was not adjusted in AF1; pH was adjusted to 10 in AF2 bottles; and SBC, CT@SBC, and CT/Fe_2O_3@SBC with 1.17g were added to AF3, AF4, AF5, and AF6, respectively, and the fermentation time was 7 days.

3 Results and Discussion

3.1 Characterization of Modified Biochar

As can be seen from the Fig. 1, the modified biochar CT/Ni_2O_3@SBC has higher –OH and C = O functional groups, EPFRs, the reduction peaks in the CV curves of the modified biochar are more obvious, and the ability to gain electrons has been improved, and the maximum O/C value (0.52) in CT/Ni_2O_3@SBC indicates that at this time, the biochar contains a higher content of OFGs, which is conducive to the promotion of the electron transfer of the reaction.

3.2 Effect of Modified Biochar on Acid Production

As shown in Fig. 2a and b, at pH 10, the changes of supernatant SCOD with the addition of different biochars (SBC, CT@SBC, CT/Fe_2O_3@SBC, and CT/Ni_2O_3@SBC) firstly increased and then decreased, and then reached the maximum value on the second day (4680.56mg/L, 4820.67mg/L, 5200.45 mg/L and 5540.32 mg/L).The changes of protein

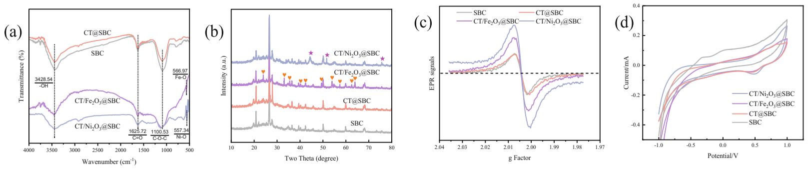

Fig. 1. Modified biochar characterization. (a) FTIR, (b) XRD, (c) EPR and (d) CV.

firstly increasing and then decreasing, and then reaching the maximum on the second day (2024.61 mg/L, 2100.27 mg/L, 2200.19 mg /L and 2386.26 mg/L).

As can be seen in Fig. 2c, the total VFAs production of the AF3, AF4, AF5, and AF6 groups increased with the increase of the electron-gaining capacity in biochar. As can be seen in Fig. 2d, the content of acetic acid was increased with the addition of biochar and the production of acetic acid with the addition of the different biochars SBC, CT@SBC, CT/Fe_2O_3@SBC, and CT/Ni_2O_3@SBC, was 1365.38mgCOD/L, 1701.98mgCOD/L, 1918.33mgCOD/L and 2160.52mgCOD/L, accounting for 42.59%, 47.84%, 50.91% and 52.30%, respectively, which were higher than the AF2 (1085.62mgCOD/L), which were 1.26, 1.56, 1.77 and 1.99 times, respectively.

As can be seen from the Fig. 2e, the maximum gas production was 25.06% on the seventh day in AF2, which was 9.99% higher than that of the AF1 group (15.07%), and the methane production when different biochar SBC, CT@SBC, CT/Fe_2O_3@SBC, and CT/Ni_2O_3@SBC were added was 13.56%, 12.80%, 11.42%, and 10.82%, respectively. Suggesting that the addition of biochar suppressed the anaerobic methanogenesis process of WAS, which was elevated with the increase of OFGs in biochar.

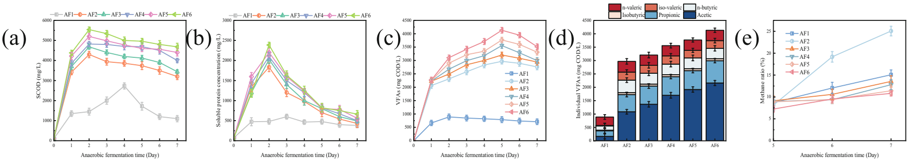

Fig. 2. Effect of modified biochar on acid production from anaerobic fermentation of sludge. (a) SCOD, (b) protein, (c) VFAs, (d) Individual VFAs and (e) Methane ratios.

3.3 Enzyme Activity Analysis

As shown in Fig. 3a, the protease and α-glucosidase activities of the experimental group dosed with CT/Ni_2O_3@SBC biochar were the largest, which were 1.67 times and 1.56 times of those of the AF2 group.

As can be seen in Fig. 3b, PTA enzyme activities were 1.24, 1.38, 1.50 and 1.62 times higher than those of the AF2, and AK enzyme activities were 1.17, 1.21, 1.31 and 1.52 times higher than those of the AF2, respectively. And F420 enzyme activities were 0.81, 0.71, 0.69 and 0.62 times higher than those of the AF2 group.