Test of transformation mechanism of food waste and its impacts on sulfide and methane production in the sewer system

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ABSTRACT

Food waste (FW) management has become an important issue worldwide. Diverting FW into the sewer system is considered promising to tackle the FW issue. However, the transformation of FW in sewers and its impact on the sewer process have not received adequate attention due to the overlooked sewer networks. In this study, a laboratory-scale sewer reactor system was established to investigate the transformation of FW and the production of sulfide and methane under anaerobic conditions. The transformation of FW in the sewer reactor could result in an increase in the substrate level through hydrolyzing and converting biodegradable substances into preferred substrates. Moreover, the generated substrates from the addition of FW were preferable for the metabolism of key microbes in sewer biofilms. As a result, methane production from the sewer reactor could be enhanced from the addition of FW, whereas sulfide production was not affected at a low sulfate concentration. The findings of this study suggest that the diversion of FW may exert an adverse impact on sewers and the environment in terms of greenhouse gas emission. Hence, more research is necessary to clarify the detailed impacts on FW management and wastewater treatment.

Key words | food waste, methane, sewer, sulfide, wastewater

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INTRODUCTION

Food waste (FW) management has drawn increasing attention worldwide due to the enormous generation and uneconomic treatment (Yasin *et al.* 2013; Xue *et al.* 2017). Each year, nearly 1.3 billion metric tons of FW were discarded globally, accounting for about one-third of food produced for human consumption (Gustavsson *et al.* 2011). Conventionally, landfill and incineration are commonly used to dispose of FW, but both treatment means are considered unsustainable, uneconomical and detrimental to the environment (Katami *et al.* 2004; Iqbal *et al.* 2019). Landfilling FW occupies huge land resources and requires complex post-treatment, while combusting FW may increase the potential of dioxins production due to the high moisture content of FW (Lee *et al.* 2009; Uçkun Kiran *et al.* 2014). To this end, diversion of FW away from the solid waste stream into the wastewater stream is promising through the use of food waste disposers (FWDs) (Iacovidou *et al.* 2012; Maalouf & El-Fadel 2017; Zan *et al.* 2019a). This technique cannot only separate FW at source but also take advantage of the existing sewer system for transporting the FW slurry. To date, numerous efforts have been taken on assessing the impact of FW addition on wastewater treatment (NYEPD 1997; CECED 2003; Battistoni *et al.* 2007; Evans *et al.* 2010). However, the knowledge of the transformation of FW in sewers is still lacking, especially for the impacts on sewer processes.

In sewer management, the production and emission of sulfide and methane have been a leading concern for decades (Sharma *et al.* 2008; Zhang *et al.* 2008; Hvitved-Jacobsen *et al.* 2013). The build-up of sulfide in sewers is primarily mediated by sulfate-reducing bacteria (SRB) in the biofilms, which leads to adverse effects such as malodors, pipe corrosion and human hazards (Halkjaer Nielsen 1987; Jiang *et al.* 2009; Pikaar *et al.* 2014). Methane is generated by the function of methanogenic archaea (MA) also in biofilms, which has a high greenhouse gas potential and may pose occupational safety risks in sewers (Guisasola *et al.* 2008; Sun *et al.* 2014). Moreover, the presence of SRB and MA in the sewer biofilm may compete for substrate available in wastewater, which can determine their abundance and

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distribution (Auguet *et al.* 2015; Zan *et al.* 2020). The addition of FW into sewers can change the characteristics of wastewater, thus affecting sewer processes. This could be achieved by high solid contents (0.16–0.34 g/g FW) and large biodegradable organic fractions (80–94%) contained in FW (Fisgativa *et al.* 2017; Zan *et al.* 2018). A recent study indicated that the addition of FW could facilitate a thick and dense biofilm, limit oxygen diffusion, increase SRB population and enhance sulfide production potential in a pilot-scale gravity sewer (Zan *et al.* 2019a). However, during the transportation of FW in sewers, there are several key issues that need to be clarified: (1) How is FW in wastewater transformed in the sewer? And (2) What is the consequence of the transformation of FW on sewer processes under anaerobic conditions, e.g. the production of sulfide and methane?

Hence, the objective of this study was to test the hydrolysis of FW and evaluate its impacts on sulfide and methane production in a laboratory-scale sewer reactor system under anaerobic conditions. After the sewer system became stable, batch tests were conducted to monitor the changes in FW within 4 h by inhibiting the activity of sulfate reduction and methanogenesis. Subsequently, changes in sulfide and methane in the system were examined with and without FW addition. Potential implications were discussed to elucidate the diversion of FW into the sewer system. The findings of this study can enable the understanding of the transformation mechanism of FW as well as its impacts on sewer processes.

MATERIALS AND METHODS

Set-up of the laboratory-scale sewer reactor system

The laboratory-scale sewer reactor system (i.e. R1 and R2) was set up with an inner diameter of 80 mm and a height of 120 mm, creating a ratio of area to volume of 58 m^2/m^3 (Figure 1). R1 was fed with synthetic wastewater only, and R2 was fed with FW and synthetic wastewater. Synthetic wastewater was prepared according to our previous study, except for sulfate concentration (Zan *et al.* 2019a). The level of sulfate in the sewer reactors was maintained at 40 mg S/L by using a prepared sodium sulfate stock. The addition of FW was controlled at 1 g/L with the composition as follows: 50% fruits, 20% starchy food, 20% vegetables and 10% meat, as detailed characteristics shown in Table 1 (Zan *et al.* 2018). The sewer system was intermittently fed with the prepared synthetic wastewater through a peristaltic pump. In total, 12 feeding events were provided in a day with each feed pumping event supplying 0.3 L of prepared synthetic wastewater into each reactor. This could lead to a hydraulic retention time of 4 h for the sewer reactor. The sewer reactor system was mixed by magnetic stirrers during the feeding phase to mimic the real operational condition in pressure sewers (Gutierrez *et al.* 2008; Zan *et al.* 2020). The sewer reactor system was placed at a temperature of 20 ± 2 °C for several months to develop a stable performance. pH, dissolved organic carbon (DOC), sulfide and methane were determined as the baseline.

Batch tests on hydrolysis of FW in sewer reactors

After the sewer reactors reached the pseudo-steady-state conditions, batch tests were carried out to assess the hydrolysis of FW under different conditions, namely, the blank reactor without biofilm (as the control), and R2 (mature biofilm developed at a concentration of 40 mg SO_4^--S/L with FW addition). The sewer reactors were first emptied of mixed wastewater and then filled with the concentrated FW solution. During the feeding phase, the reactors were mixed by magnetic stirrers to mimic the real condition. The concentrated FW solution (10 g/L) was

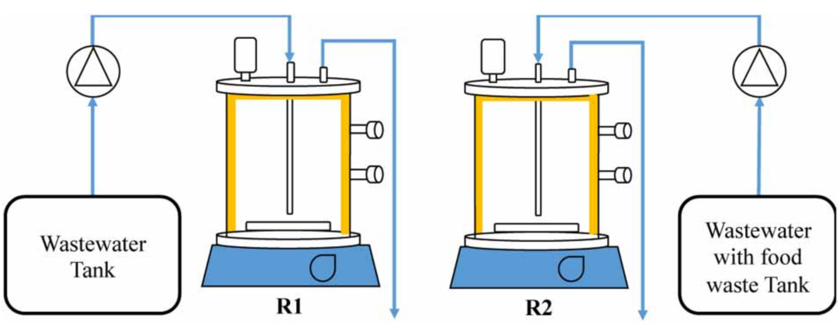

Figure 1 | Schematic of the laboratory-scale sewer reactor system. R1 without FW addition, R2 with FW addition.

Table 1 | Characteristics of food waste used in this study

Parameters	Value	Parameters	Value
TS (mg/g ww)	160 ± 17	SN (mg N/g TS)	12 ± 1
VS (mg/g TS)	910 ± 100	TP (mg P/g TS)	7.6 ± 0.4
TCOD (mg/g TS)	1,440 ± 151	SP (mg P/g TS)	4.2 ± 0.3
SCOD (mg/g TS)	870 ± 96	Polysaccharides (g/g TS)	232 ± 37
TN (mg N/g TS)	21 ± 1	Protein (g/g TS)	186 ± 101

Note: TS: total solids; VS: volatile solids; TCOD: total chemical oxygen demand; SCOD: soluble chemical oxygen demand; TN: total nitrogen; ww: wet weight.

prepared with FW slurry and deionized water. Meanwhile, no additional sulfate was present during the batch tests to avoid sulfate reduction, while sodium 2-bromoethanesulfonate (BES) with 10 mM was added to exclude the influences of methanogenesis. In the 4-h batch tests, changes in particulate protein and polysaccharides were insignificant. During the tests, samples for the measurement of pH, ammonium, volatile fatty acids (VFAs = acetate + propionate + butyrate), soluble protein and soluble polysaccharides were collected to evaluate the hydrolysis of FW under different conditions.

During the experiment, the hydrolysis efficiencies of soluble protein and polysaccharides were calculated by the following equation (Zhao *et al.* 2018).

$$Hydrolysis\ efficiency\ (\%) = \frac{C_0 - C_t}{C_0} \times 100\%$$

where C_0 represents the initial concentration, and C_t represents the residual concentration at time t of protein and polysaccharides during the tests.

Anaerobic batch tests in sewer reactors

To investigate the production of sulfide and methane in the sewer reactors, a 4-h batch test was conducted to monitor the variations of sulfide and methane with and without FW addition. Prior to the experiment, the sewer reactors were emptied of the mixed wastewater. Subsequently, influent containing synthetic wastewater with sulfate of 40 mg SO_4^--S/L was pumped into the sewer reactors: (1) R1 without FW addition; and (2) R2 with FW addition (1 g/L). The magnetic stirrers were used to provide a 1-min stir at 200 rpm to homogenize the solution pumped before sampling. In the batch test, around 5 mL of samples were collected to measure methane and sulfide at an interval of 30 min.

Analytical methods

Samples of DOC, acetate, propionate, butyrate, soluble protein and polysaccharides, sulfate and ammonium were collected and pretreated through disposable Millipore filters (a pore size of 0.45 μm). The DOC was determined by using a total organic carbon/total nitrogen analyzer (TOC-5000A, Shimadzu, Japan). Soluble chemical oxygen demand (SCOD) was calculated with a theoretical ratio of 2.67 (i.e. COD/C = 2.67) (Zan *et al.* 2019b). The filtered samples were immediately filled into a 2-mL sample bottle for the determination of acetate, propionate and butyrate by using a high-performance liquid chromatograph (HIC-20A super, Shimadzu, Japan) equipped with an IC-SA3 analytical column and a conductivity detector. Soluble polysaccharides were measured by using the colorimetric method (Dubois *et al.* 1956), while soluble proteins were determined by the bicinchoninic acid assay with bovine serum albumin as the standard (Smith *et al.* 1985). Ammonium was determined using a flow injection analyzer (QuikChem FIA+ 8000, Lachat, USA). SO_4^{2-} was measured using an ion chromatograph (HIC-20A Super, Shimadzu, Japan) equipped with a conductivity detector and an IC-SA2 analytical column. HS^-/H_2S was measured with the methylene blue method (APHA 2005).

Dissolved methane was determined based on previous studies (Alberto *et al.* 2000; Guisasola *et al.* 2008). A 10-mL plastic syringe was used to collect around 5 mL of fresh samples from the reactors, and then the samples were injected into the vacuumed BD vacutainer tubes using a hypodermic needle connected with the syringe. Samples in the tubes were placed overnight in a shaker to reach the equilibration at a temperature of 25 °C. Over 97% of methane can be released from the liquid phase to the gas phase through this process. Methane in the gas phase was analyzed by using an Agilent 7890B gas chromatograph equipped with an electron capture detector. In the end, the overall amount of methane in the sample was calculated by mass balance and Henry's law.

RESULTS AND DISCUSSION

Operation of the laboratory-scale sewer reactor system

The average results of laboratory-scale sewer reactors, R1 and R2, are shown in Table 2, in terms of pH in effluent and production rates of sulfide and methane in sewer reactors with and without FW addition. pH in the sewer reactors was maintained at about 7.5 in all cases, whereas adding FW could slightly reduce the pH due to the organic acids released

Table 2 | Average pH in effluent, sulfide and methane production rate in R1 and R2

	pH	Sulfide production rate (g S/(m^2·day))	Methane production rate (g/(m^2·day))
R1	7.57 ± 0.17	2.14 ± 0.34	0.18 ± 0.02
R2	7.44 ± 0.18	2.07 ± 0.29	0.29 ± 0.02

from FW (Fisgativa *et al.* 2016; Zan *et al.* 2018). In the sewer reactors, the majority of the consumed COD was used for sulfide production. The difference in sulfide production in R1 and R2 was insignificant at a low sulfate concentration (i.e. 40 mg S/L). However, methane production in R2 was around 1.6 times higher than that in R1. This indicates that the addition of FW can enhance methane production in the sewer reactor with a sulfate concentration of 40 mg S/L. Moreover, the limited sulfate concentration may potentially facilitate methane production with the adequate substrates provided by FW. It is thus necessary to verify the changes in substrate levels after the addition of FW in the sewer reactors.

Hydrolysis of food waste

Hydrolysis of FW may affect the composition of organic substances in sewer reactors through the release and conversion of SCOD, protein, polysaccharides and VFA (Zan *et al.* 2018). To eliminate the effects of MA and SRB on the hydrolysis, the experiment was conducted with the addition of the methanogenesis inhibitor, i.e. BES and no addition of sulfate. Figure 2 depicts the variations of characteristics

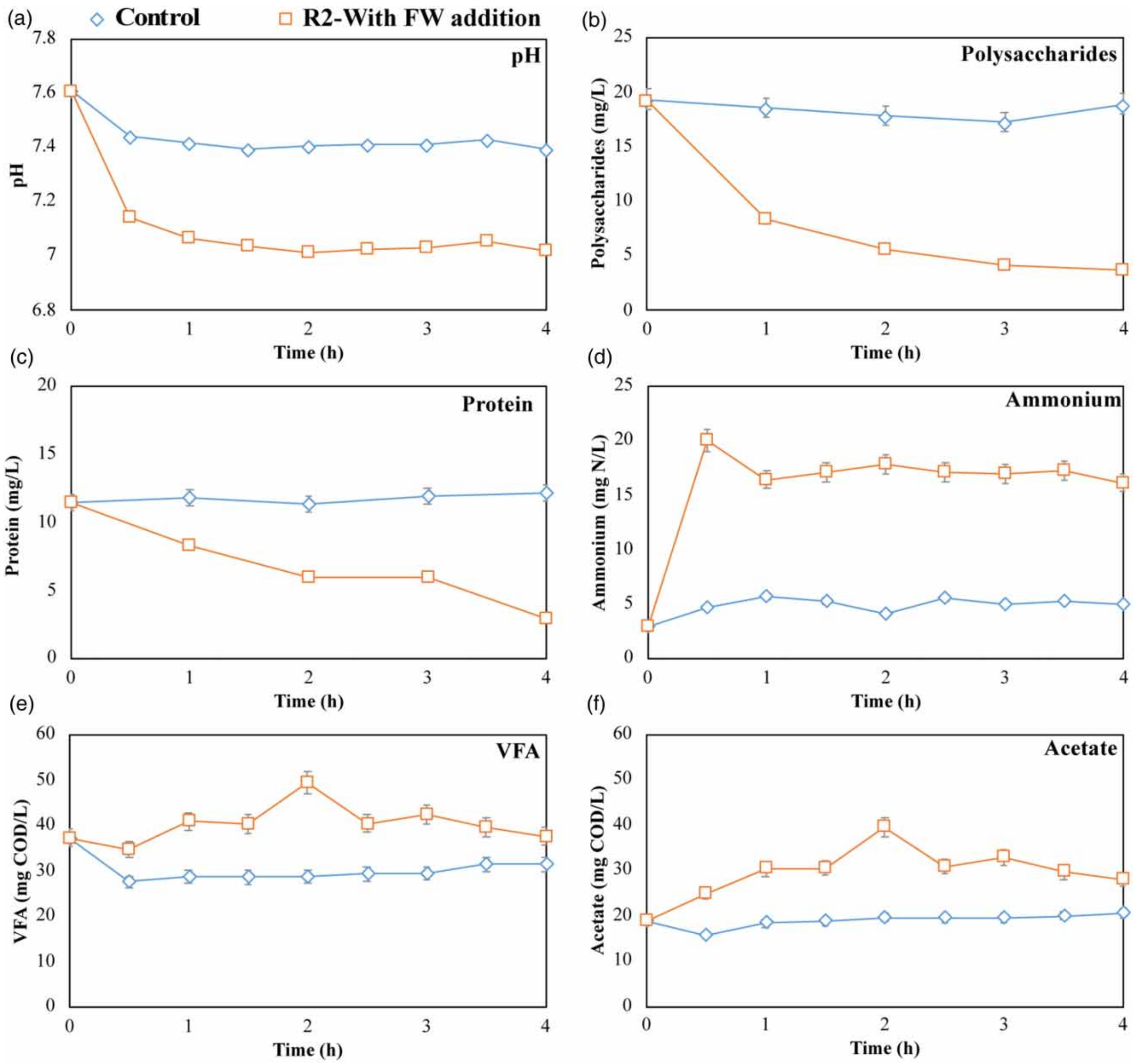

Figure 2 | Hydrolysis of food waste under different conditions. Control: No biofilm attached; R2: Biofilm cultivated with FW addition at sulfate concentration of 40 mg S/L.

under two conditions: (i) blank reactor with no biofilm attached (as control); and (ii) R2 that biofilm cultivated with FW addition at sulfate concentration of 40 mg S/L. In the control reactor, no significant changes of different characteristics occurred during the 4-h batch tests, which attributes to the absence of hydrolytic enzymes excreted from the microorganisms (Bott *et al.* 2014). Furthermore, the addition of FW induced substantial amounts of biodegradable organic substances present in the reactor. Therefore, the net difference of characteristics in R2 mainly resulted from the function and activity of biofilm attached onto the sewer reactors.

In the experimental tests of R2, the hydrolysis mediated by sewer biofilm inevitably caused a decrease in pH from 7.6 to 7.1. Changes in particulate protein and polysaccharides were reported to be negligible (Raunkjær *et al.* 1995; Bolzonella *et al.* 2003). This is because the organic matters in the particulate are mainly slowly biodegraded (Henze *et al.* 2008), and the particulate organics, including particulate protein and polysaccharides, may not be transformed within the 4-h test. In this study, the hydrolysis of soluble polysaccharides in R2 was much higher than that in the control reactor, resulting in the hydrolysis efficiency of 81% (Figure 3(a)). The hydrolysis efficiency of soluble protein in R2 reached 74% after a 4-h test (Figure 3(b)). This is further confirmed by the release of ammonium during the tests since ammonium is mainly produced from amino acids converted from protein (Bott *et al.* 2014). As for VFA and acetate, the concentrations continually fluctuated within a narrow range throughout the 4-h tests. This indicates that FW addition not only provided adequate substrates in sewer reactors but also hydrolyzed and further converted into easily biodegradable organics that were stimulated by sewer biofilm.

Anaerobic sewer batch tests for sulfide and methane production

Batch tests were conducted to monitor the changes in methane and sulfide from the sewer reactors with and without FW addition (Figure 4). In the test, methane and sulfide were produced in both sewer reactors simultaneously, but the sulfate reduction almost completed showing as the stable sulfide concentration in bulk liquid in the final hour of the experiment, and methane production continuously increased. Specifically, there is limited influence on sulfide production with nearly 30 mg S/L of sulfide at the end of the 4-h experiment regardless of the impact of the FW addition, whereas the addition of FW enhanced methane production by up to 59%. This indicates that the addition of FW promoted methane production in the sewer reactor.

Influences on sulfide generation from the addition of FW has been a controversial issue (Wainberg & Nielssen 2000; Iacovidou *et al.* 2012; Zan *et al.* 2019a). The majority of the previous studies show no direct correlation between the formation of sulfide and the addition of FW in the sewer (Iacovidou *et al.* 2012). Moreover, in a pilot-scale gravity sewer, the addition of FW can increase biofilm thickness, enlarge the anaerobic zone and enhance sulfide formation in biofilms (Zan *et al.* 2019a). With FW addition, the produced sulfide (9.75 mg S/m^2/h) was rapidly oxidized by dissolved oxygen in the gravity sewer. However, in this study, sulfide production was not affected by the addition of FW in an anaerobic sewer system. This may ascribe to the distribution of SRB and MA in sewer biofilms, in which MA were mainly accumulated in the inner layer of the biofilm and SRB mainly inhabited the outer layer (Sun *et al.* 2014). It is likely that substrates in sewage are abundant for the metabolism of SRB, whereas mass transfer

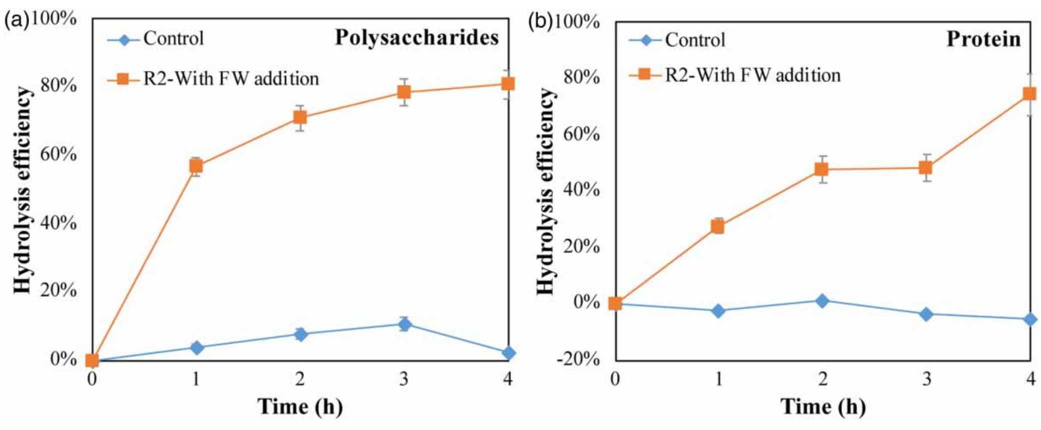

Figure 3 | Hydrolysis efficiency of protein and polysaccharides under different conditions.

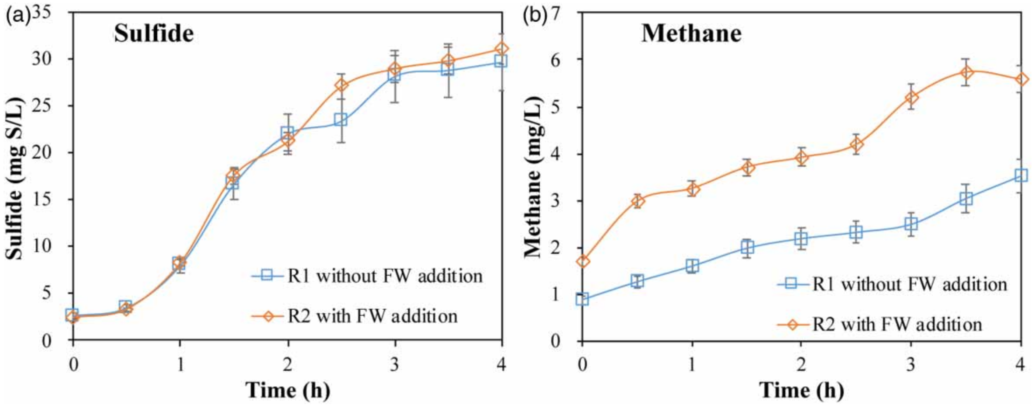

Figure 4 | Changes in sulfide and methane in the sewer reactors with and without FW addition during the batch test.

of substrates is required for the growth of MA. The addition of FW could enhance the mass transfer, provide additional substrates penetrating the biofilm for methanogenesis.

Potential implications

This study has evaluated the transformation of FW and the impacts on the production of sulfide and methane in a well-developed sewer reactor system. The addition of FW into the sewer reactor could be hydrolyzed and converted into easily biodegradable organics by the mediation of sewer biofilms (Figures 2 and 3). The substrate level present in the reactor with FW addition was boosted, which further facilitated the metabolism of various microbes such as SRB and MA. However, the sulfate concentration in this study (i.e. 40 mg S/L) limited sulfide production, while methane production benefited from the increased substrate level due to the addition of FW (Figure 4). In this context, a potential pathway was proposed to elucidate the transformation of FW and its impact on the production of sulfide and methane, as profiled in Figure 5. During the transformation of FW in the sewer reactor, the hydrolysis could promote the content of biodegradable COD. Subsequently, rapidly biodegradable COD was converted into acetate and/or hydrogen, which are preferred substrates for SRB and MA (Yoda *et al.* 1987; Chou *et al.* 2008; Zan & Hao 2020). As a result, the adequate substrate in the sewer reactor promoted methane production. However, methane can render a significant greenhouse effect with a lifespan of nearly 12 years and a global warming potential of about 23 times higher than carbon dioxide (IPCC 2006; Guisasola *et al.* 2008). Moreover, the formed methane in sewers could release to the atmosphere from the liquid phase where the pressure drops. This may cause an increased risk since it forms an explosive mixture in the air at a low concentration (Foley *et al.* 2009). Therefore, the production and emission of methane from the sewers should draw more attention, particularly diverting FW into the sewers. In addition, the transformation of FW in sewers may be dependent on the characteristics of FW, which can vary notably by region, by source and even by season (Fisgativa *et al.* 2016; Zan *et al.* 2018). This could alter the products of hydrolysis and further affect the sewer process. Moreover, the amount of FW, sulfate concentration and the characteristics of wastewater need to be further evaluated to gain insights into the underlying impacts of FW on sewer biofilms and sewer processes.

CONCLUSION

This study has employed a laboratory-scale sewer reactor system to investigate the transformation of FW, and the production of sulfide and methane with and without FW addition. The addition of FW into the sewer reactor could

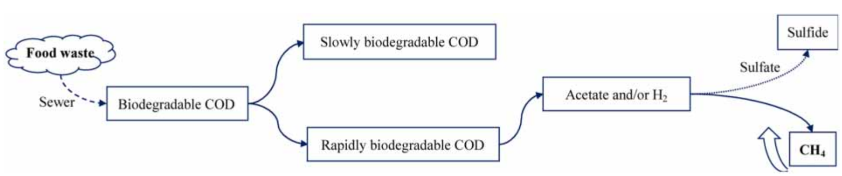

Figure 5 | Proposed pathway of the transformation of food waste and production of sulfide and methane.

be hydrolyzed and converted into easily biodegradable organics. The adequate substrates from FW available in the sewer reactor enhanced methane production, whereas sulfide production was not affected. The results of this study indicate that the addition of FW into sewers may render a detrimental effect on the environment. However, more research, such as the impacts of the FW amounts, sulfate concentration and wastewater characteristics on sewer processes, need to be evaluated.

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