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Lab-scale co-digestion of kitchen waste and brown water for a preliminary performance evaluation of a decentralized waste and wastewater management

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ABSTRACT

An overall interaction is manifested between wastewater and solid waste management schemes. At the Laboratory of Environmental Engineering (LISA) of the University of Padova, Italy, the scientific and technical implications of putting into practice a decentralized waste and wastewater treatment based on the separation of grey water, brown water (BW – faecal matter) and yellow water (YW – urine) are currently undergoing investigation in the Aquanova Project. An additional aim of this concept is the source segregation of kitchen waste (KW) for subsequent anaerobic co-digestion with BW. To determine an optimal mixing ratio and temperature for use in the treatment of KW, BW, and eventually YW, by means of anaerobic digestion, a series of lab-scale batch tests were performed. Organic mixtures of KW and BW performed much better (max. 520 ml CH_4/g VS) in terms of methane yields than the individual substrates alone (max. 220 ml CH_4/g VS). A small concentration of urine proved to have a positive effect on anaerobic digestion performance, possibly due to the presence of micronutrients in YW. When considering high YW concentrations in the anaerobically digested mixtures, no ammonia inhibition was observed until a 30% and 10% YW content was added under mesophilic and thermophilic conditions, respectively.

1. Introduction

An overall interaction is manifested between wastewater and solid waste management schemes. Solid waste treatment generates liquids (such as landfill leachate), which are often sent to wastewater treatment plants. Wastewater treatment plants produce sludge, sand and screened materials requiring landfill disposal. In recent decades, numerous research studies have been performed to close the co-management cycle of the two systems through co-stabilization, by composting and/or anaerobic digestion of the sludge with the organic fraction of municipal solid waste (Lim and Wang, 2013; Lim et al., 2014; Rajagopal et al., 2013, 2014; Lagerkvist et al., 2015).

In the wastewater sector, there is a tendency to define a systematic approach for the different wastewater fractions and to analyse the effects of different scenarios on the control and source segregation of the different streams, with characterization of the components: black water (urine and faecal matter), grey water, and rainwater (Krebs and Larsen, 1997). The decentralized treatment of municipal wastewater, based on the separation between grey and black waters, and even between brown water (faecal matter) and yellow water (urine), represents a sustainable and future solution for waste(water) treatment (Elmitwalli et al., 2006).

Ongoing discussion surrounding the sustainable co-management of domestic wastewater and organic solid waste is focused on the concepts of avoidance, source separation, recycling and reuse (Henze, 1997). At the Laboratory of Environmental Engineering (LISA) of the University of Padova, Italy, the scientific and technical implications of putting into practice these concepts are currently undergoing investigation as part of the Aquanova Project (Fig. 1). This project focuses on the source separation of domestic wastewater into three main streams: yellow water (YW – urine), brown water (BW – faecal matter), and grey water (i.e. wastewater coming from the washbasin, shower, bath). The purpose of separate management of these fractions is to facilitate water reuse and minimize energy requirements for wastewater treatment (YW and GW) to be performed in a phytotreatment unit (Lavagnolo et al., 2016). An additional aim of this concept is the source segregation of kitchen waste (KW) for subsequent anaerobic co-digestion with BW and recovery

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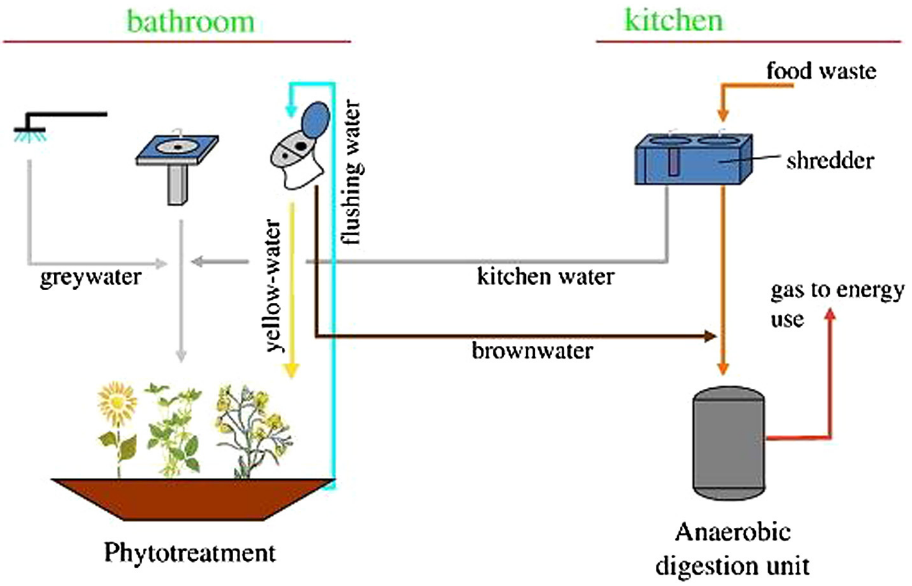

Fig. 1. Aquanova Project. Based on the source separation of various domestic sewage components and on the integrated management of domestic solid and liquid wastes (Lavagnolo et al., 2016).

of energy in the form of methane. The Aquanova Project establishes that kitchen waste should be shredded in a mill installed in the kitchen sink and sent, together with the faecal stream, to an anaerobic digestion (AD) unit.

In recent decades very few studies have investigated the co-digestion of black water and kitchen waste in anaerobic systems (Kujawa-Roeleveld et al., 2003, 2005, 2006; Elmitwalli et al., 2006; Wendland et al., 2007). To avoid the concerns raised over ammonia accumulation, the addition of brown water alone (without urine) to kitchen waste prior to AD was also investigated (Zeeman et al., 2008; Curry and Pillay, 2012; Rajagopal et al., 2013; Lim et al., 2014). BW is capable of improving stability of the anaerobic digestion process by providing additional nutrients and maintaining buffer capacity (Lim et al., 2014). The benefits of co-digesting BW and KW were described by Rajagopal et al. (2013) – higher biogas production and biodegradation efficiencies were observed when BW was added as a co-substrate to the anaerobic degradation of KW, likely due to the adequate buffering capacity provided by BW to KW digestion (Rajagopal et al., 2013). Production of methane via anaerobic co-digestion of KW and BW not only provides a cheaper and greener alternative to disposal, but may help to reduce the use of fossil fuel-derived energy and, consequently, the impact on global warming (Abbasi et al., 2012).

The aim of this research was to compare the specific methane yield of single substrates and of their mixtures under mesophilic and thermophilic conditions.

Tests to assess the specific methane yield of kitchen waste (KW), brown waters (BW), yellow waters (YW), and a series of different mixtures, are summarized in Table 1, and can be grouped into the following three experimental phases:

I. specific bio-methane production batch tests (BMP tests) were performed on the three individual substrates, KW, BW, and YW, under mesophilic (35 ± 1 °C) and thermophilic (55 ± 1 °C) conditions;
II. the three substrates were mixed according to different percentages and BMP tests were performed under mesophilic conditions, varying YW at a maximum concentration of 6% in the mixture;
III. BMP tests were fed with substrate mixtures prepared with increasing percentages of YW up to 50%, to evaluate the anaerobic bacteria inhibition caused by high ammonia content.

Table 1
Sequence of experiments performed.

Experimental batch tests phase	Feeding	Substrates	Temperature during the AD process
I	Single matrix	KW	Mesophilic (35 ± 1 °C)
		BW	
		YW	
		KW	Thermophilic (55 ± 1 °C)
		BW	
		YW	
II	Mixture	KW + BW	Mesophilic (35 ± 1 °C)
		KW + BW + $YW_{(\text{up to }6\%)}$	
III		KW + BW + $YW_{(\text{up to }50\%)}$	Mesophilic (35 ± 1 °C)
		KW + BW + $YW_{(\text{up to }50\%)}$	Thermophilic (55 ± 1 °C)

Mixture percentages are reported in terms of wet basis.

2. Materials and methods

On the basis of Aquanova Project concepts (Fig. 1), a pilot plant for domestic sewage separation was set up at the LISA Laboratory of the University of Padova, Italy, and a purpose-designed toilet (Otterpohl et al., 1999) for the separation of YW and BW was installed.

Grey water from the sink and toilet flows were conveyed separately to three different stainless steel tanks, each with a 100 l capacity. The tanks were equipped with a sampling system, an agitator and a sensor for level control, connected to a motorized valve for tank emptying. At the entrance to the bathroom two photocells were installed to monitor inputs. The whole system was controlled by purpose-designed LabView software, which allowed continuous measurement of flow, calculation of pro-capita production, control of mixers and electric valves for discharging to the sewer system.

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2.1. Substrate characterization

Yellow water (YW) and brown water (BW) obtained from the pilot plant installed at the University of Padova, Italy, were collected from the sampling tanks as substrates to be tested. Kitchen waste (KW) was collected from Padova University canteen and shredded using a kitchen mill.

Prior to anaerobic digestion, the individual substrates (KW, YW, and BW) were tested to measure the following parameters: total solids (TS), volatile solids (VS), pH, alkalinity (Alk), BOD_5, COD, ammonia nitrogen ($N\text{-}NH_3$), TKN, total phosphorus (P_{tot}), volatile fatty acids (VFAs), and heavy metals, as reported in Table 2. In order to better discuss the results of experimental phase III, free ammonia concentration (mg/l) inside the mixed substrates was calculated using the following Eq. (1) (Anthonisen et al., 1976):

$$\text{free ammonia} = 1.214 * NH_4^+ * 10^{pH} / [e^{6344/(273+T)} + 10^{pH}] \tag{1}$$

where NH_4^+ is the total ammonia concentration as nitrogen (mg N/l), and T is the temperature (°C).

Anaerobic sludge, used as inoculum, was collected from a full-scale wastewater treatment plant (Ca'Nordio) located in Padova, Italy.

2.2. Bio-methane production tests

Lab-scale BMP tests were performed to evaluate the specific bio-methane yield of KW, BW, and YW as individual substrates (I phase) and as mixtures in a series of combinations (see Table 1) subsequent to anaerobic digestion (II phase).

Throughout experimental phase II the mixtures were characterized by different KW concentrations, namely 7%, 11%, 20%, 27%, and 33%, initially combined with BW alone, and then with a percentage of YW ranging from 4% to 6%.

During phase III, YW concentrations were increased up to 50% to evaluate the effect of ammonia and the mixed substrates compositions can be seen in Tables 3 and 4.

In phases I, II, and mesophilic III, tests were carried out in 120 ml serum bottles under both mesophilic (35 ± 1 °C) and thermophilic (55 ± 1 °C) conditions. Reactors were hermetically closed using 20 mm aluminium crimp caps (Agilent). Substrate concentration and substrate to inoculum ratio (S/I) were 5 g VS/l and 0.5 g VS/g VS, respectively. The liquid volume in each reactor, consisting of the substrate, and inoculum, was 80 ml. Each vial was fed with 2.7 g inoculum (characterized by 37% of total solids) and 0.8 g of buffer ($NaHCO_3$) was added to maintain neutral pH conditions.

Table 3
Substrate composition for anaerobic digestion batch tests under mesophilic conditions (experimental phase III).

Sample	%KW	%BW	%YW
A	10.0	90.0	0.0
B	9.4	84.6	6.0
C	8.0	72.0	20.0
D	7.0	63.0	30.0
E	5.0	45.0	50.0

Table 4
Substrate composition for anaerobic digestion batch tests under thermophilic conditions (experimental phase III).

Sample	%KW	%BW	%YW
F	10.0	90.0	0.0
G	9.4	84.6	6.0
H	8.0	72.0	20.0
I	7.0	63.0	30.0
L	5.0	45.0	50.0

In phase thermophilic III, larger 12 l reactors were used and filled with the same substrate to inoculum ratio as the serum bottles.

After preparation, the reactors were flushed with N_2 gas for 3 min and incubated under static conditions in a thermostatic chamber. Blank tests using the inoculum alone were also conducted to measure the quantity of methane produced by the biomass. All tests were performed in triplicate.

Biogas volume produced during BMP tests was measured by means of the water displacement method in phases I, II, and mesophilic III. Methane volumes produced in the time interval between each measurement $[t - (t - 1)]$ were calculated using a model taking into consideration the gas concentration at time t and time $t - 1$, together with the total volume of biogas produced at time t, the concentration of specific gas at times t and $t - 1$, and the volume of head space of reactors (Van Ginkel et al., 2005). The following Eq. (2) was applied:

$$V_{C,t} = C_{C,t} * V_{G,t} + V_H * (C_{C,t} - C_{C,t-1}) \tag{2}$$

where $V_{C,t}$ – volume of methane produced in the interval between t and $t - 1$; $C_{C,t}$, $C_{C,t-1}$ – methane concentrations measured at times t and $t - 1$; $V_{G,t}$ – volume of biogas produced between time t and $t - 1$; V_H – volume of the headspace of reactors.

In phase thermophilic III, biogas generated from each reactor was collected using a 10 l Tedlar® sampling bag connected to the upper gas port, and biogas volume was measured daily by means of a volumetric flow meter (Cossu et al., 2016).

Table 2
Chemical characteristics of kitchen waste, brown water, and yellow water used as substrates for anaerobic digestion tests.

Parameter	KW		BW		YW	
	Range	Average	Range	Average	Range	average
TS (mg/l)	106,678–19,555	168,851	2359–4587	3445	4350–8125	6485
VS (mg/l)	87,035–154,108	119,997	1676–3978	2845	755–2380	1450
pH	5.2–5.5	5.3	6.7–8.3	7.5	8.5–8.7	8.6
Alk (mg/l)	–	–	440–720	527	5080–7660	5777
BOD_5 (mg/l)	–	–	267–1135	874	610–1700	1257
COD (mg/l)	122,559–18,660	154,156	5090–7660	5905	2320–4600	3048
$N\text{-}NH_3$ (mg/l)	870–1242	1080	38–132	52	1530–2394	2034
TKN (mg/l)	6778–9544	8830	59–173	125	2296–3458	2766
P_{tot} (mg/l)	–	–	3.2–24.8	12	14.5–96.5	61
VFAs (mg/l)	2755–2992	2802	56–120	78	–	–
Cr (mg/l)	–	–	–	–	0–0.48	0.12
Cu (mg/l)	–	–	0.16–0.31	0.24	0.06–0.15	0.11
Fe (mg/l)	–	–	0.58–2.4	1.15	0.15–0.93	0.53
Mn (mg/l)	–	–	0–0.19	0.07	0–0.05	0.01
Ni (mg/l)	–	–	0.02–0.21	0.09	0.02–0.07	0.04
Pb (mg/l)	–	–	0.02–0.06	0.04	0–0.4	0.02
Zn (mg/l)	–	–	1.17–3.1	2.14	0.42–1.36	0.97

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Methane and carbon dioxide composition in the gas were determined using a gas chromatographer (Hewlett Packard 5820).

To have an empirical evaluation of the lag phase only visually hypnotized from the methane production curves obtained during the batch tests, data were interpolated on the basis of the Gompertz model (Van Ginkel et al., 2001). The Gompertz mathematical expression is described in the following Eq. (3):

$$P(t) = P_{max} \exp\left\{-\exp\left[\frac{R * e}{P_{max}}\right](\lambda - t) + 1\right\} \tag{3}$$

where P(t) is the cumulated methane production at time t; P_{max} is the maximum methane production, R is the maximum production rate and λ is the lag phase.

Data on methane productions are expressed at a temperature of 0 °C and pressure of 1 atm (Normal conditions).

3. Results and discussion

3.1. Biochemical methane production tests – phase I

As expected, the amount of methane recoverable from YW was virtually imperceptible both under mesophilic and thermophilic conditions. YW was characterized by high ammonia concentration (around 2000 mg/l), which inhibited the metabolism of anaerobic bacteria. Yenigün and Demirel (2013) reported that, although ammonia is an essential nutrient for bacterial growth, the presence of high concentrations (1700–5000 mg/l) may inhibit methanogenesis during the anaerobic digestion process, particularly when dealing with complex type of substrates such as manure or the organic fraction of municipal solid waste.

Under mesophilic conditions, KW and BW allowed recovery of 260 and 160 ml CH_4/g VS, respectively. Using Eq. (3) it was possible to highlight that the lag phase for KW (8 days) was 1.5 times shorter than that for BW. The KW sample featured a COD and VS removal rate of 55.1% and 73.7%, respectively, whilst in BW they were 15.9% and 6.1%, respectively.

Under thermophilic conditions, methane productions were 310 and 240 ml CH_4/g VS from KW and BW, respectively. Lag phase was the same (6 days) for KW and BW. In this case, COD and VS removal rates for KW were 56.5% and 69.9%, respectively, and for BW they were 83.2% and 65.6%, respectively.

In agreement with Clarke and Alibardi (2010) and Girotto et al. (2015), KW is clearly a more suitable substrate for anaerobic digestion although, as temperature increases, methanogenesis also performed well in the presence of BW alone. Thermophilic anaerobic digestion is capable of improving mass transport and increasing reaction speed (Krebs and Larsen, 1997). Furthermore, this process contributes towards ensuring improved substrate sanitation.

3.2. Biochemical methane production tests – phase II

Anaerobic co-digestion resulted in higher methane yields than KW and BW alone, in agreement with Rajagopal et al. (2013). Tests were carried out by mixing different percentages of KW, namely 7%, 11%, 20%, 27%, and 33% initially with BW alone, and subsequently with a percentage of YW ranging from 6% to 4%.

Fig. 2 illustrates the biogas production measured under mesophilic conditions.

The process carried out with YW percentage varying between 0 and 6% displayed a complete absence of inhibition.

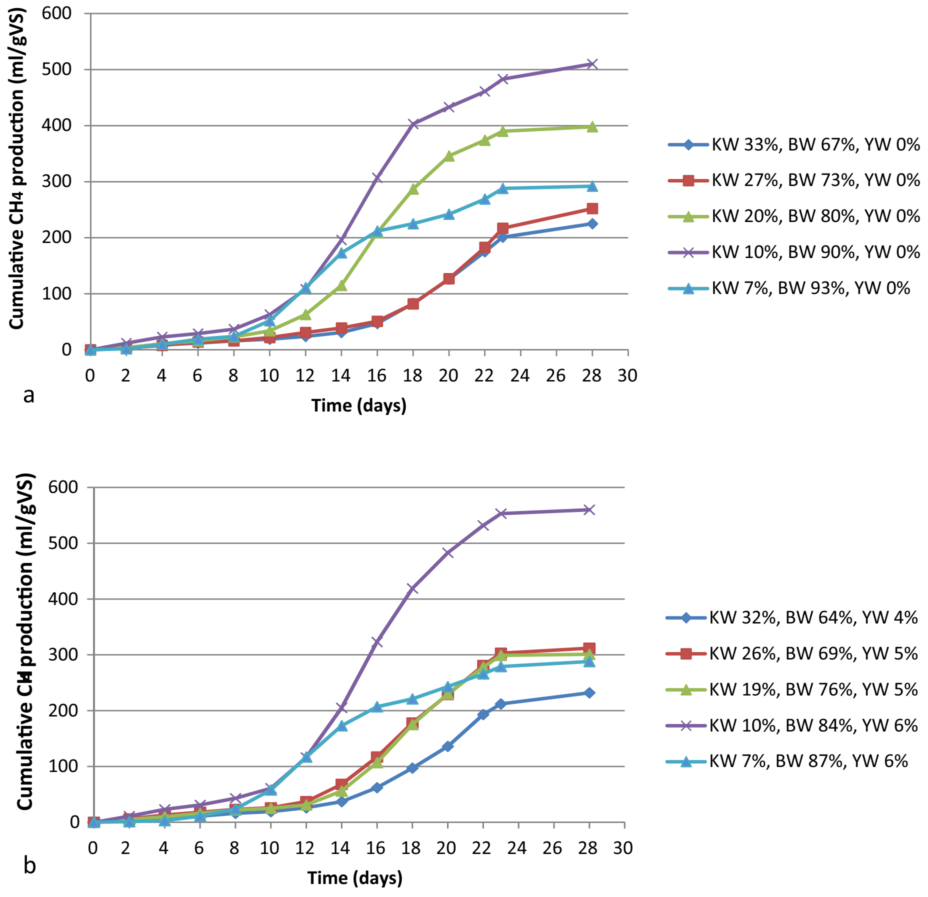

Fig. 2. Cumulative methane production from different mixtures of kitchen waste (KW) and brown water (BW), under mesophilic conditions without (a) and with (b) urine (YW) addition up to 6% (experimental phase II).

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Mixtures with a percentage of KW ranging from 7 to 20% featured a much higher methane production than that observed with individual substrates. The best degree of mixing was obtained with approximately 10% KW, both with and without addition of low YW content. The addition of 6% YW elicited an increased biogas production and improved kinetics. Methane production increased from 510 ml CH_4/g VS to 560 ml CH_4/g VS, and a plateau was reached after 22 days instead of 28. This is probably due to the fact that bacteria benefit from the presence of nutrients both in BW and YW (e.g. N, P, K, Cu). When anaerobically digesting faeces with urine up to a ratio of 1:1, Creamer et al. (2008) reported that the substrate did not inhibit the anaerobic inoculum and provided a good biogas yield.

Both with and without YW addition, lag phases are directly proportional to the increasing concentration of KW (from 7% to 33%) changing between 8 and 13 days.

3.3. Biochemical methane production tests – phase III

On the strength of the promising results obtained with the addition of YW in phase II, a new set of BMP tests were performed with the aim of investigating the impact of ammonia on methane production yielded by the different mixtures. As the anaerobic digestion process is particularly sensitive to ammonia content, a maximum concentration of 1700 mg/l (Yenigün and Demirel, 2013) and larger reactors were adopted to avoid a scale effect on the results of thermophilic phase III.

The results of the BMP tests performed under mesophilic and thermophilic conditions with a higher YW concentration up to 50% in the mixed substrates (see Tables 3 and 4) are shown in Figs. 3 and 4, respectively.

Methane production for samples A and B (YW concentration is 0% and 6%, respectively) is virtually identical (Fig. 3) with values around 210 ml CH_4/g VS. On increasing YW concentration up to 30%, methane production likewise increases (samples C and D). A production peak is observed in D, corresponding to 280 ml CH_4/g VS. By mixing KW and BW with 50% YW (sample E), methane production dropped to 160 ml CH_4/g VS and terminated after 48 days. High ammonia concentration undoubtedly influenced the AD process, resulting in a lower methane production.

Under thermophilic conditions (Fig. 4) the lowest methane production of 170 ml CH_4/g VS was yielded by the sample containing 50% YW (sample L) and a long lag phase time of 20 days, whilst the highest methane production of 370 ml CH_4/g VS was observed with sample G (6% YW). Methane yield from sample G exceeded that produced by sample F in the absence of YW addition (334 ml CH_4/g VS). All samples, with the exception of L, reached a maximum methane production by the 25th day of AD.

Data relating to free ammonia concentrations calculated using Eq. (1) in the different samples on the basis of chemical composition of individual substrates (Table 2), revealed a decrease in methane production under mesophilic conditions up to values of around 100 mg/l of free ammonia; in this specific case study, these values corresponded to approximately 1000 mg/l of ammonia nitrogen and to a percentage of more than 30% YW. Under

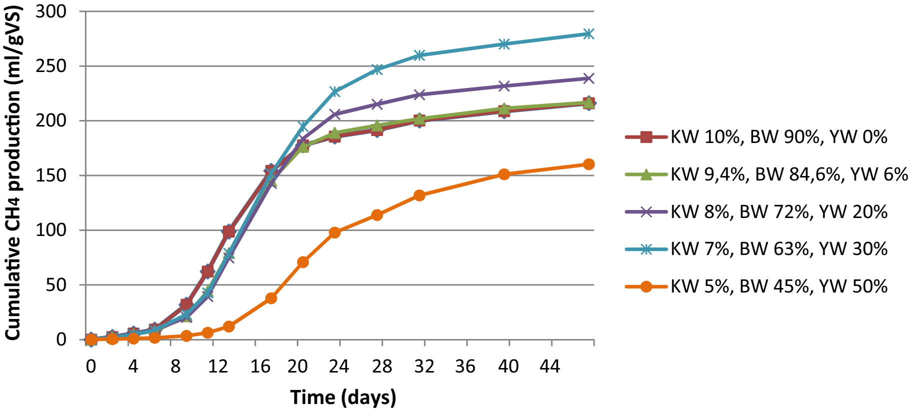

Fig. 3. Cumulative methane production from different mixtures of kitchen waste (KW), brown water (BW), and urine (YW) under mesophilic conditions (experimental phase III).

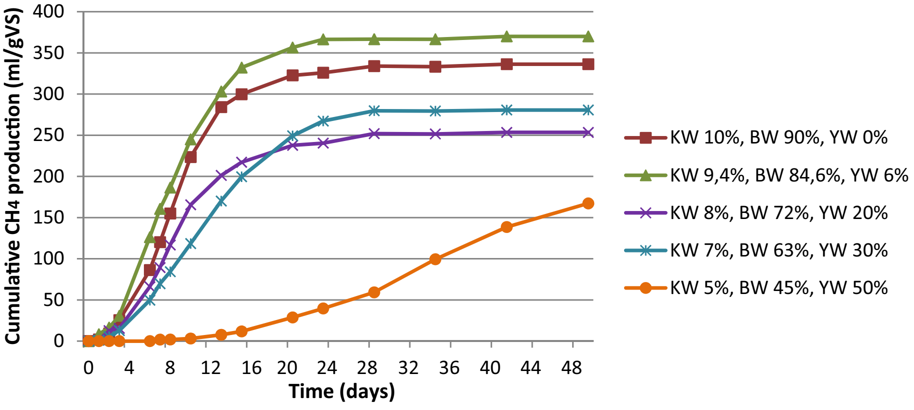

Fig. 4. Cumulative methane production from different mixtures of kitchen waste (KW), brown water (BW), and urine (YW) under thermophilic conditions (experimental phase III).

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thermophilic conditions however, peak methane production was obtained by mixing KW and BW with 6% YW, corresponding to 59 mg/l of free ammonia, while it began to decrease at values exceeding 150 mg/l. Not taking into account the sample with a 50% YW content, the lag phase time during the thermophilic run (max. 3 days) was shorter than that monitored under mesophilic conditions (max. 7 days). This suggests that bacteria were able to adapt very well under thermophilic conditions, although the finding was not confirmed when comparing sample E and sample L. In sample L methane production commenced after 20 days compared to the previously observed 15 days (sample E). An excessively high ammonia concentration inhibits methanogenesis (Angelidaki and Ahring, 1994), with several Authors reporting how methane fermentation is more easily inhibited at thermophilic rather than mesophilic temperatures (Braun et al., 1981; Van Velsen and Lettinga, 1981; Angelidaki and Ahring, 1994).

Moreover, yellow waters likely contribute to bacterial growth due to the high micronutrient concentration. Indeed, peak methane production was achieved in sample G (6% YW) under thermophilic conditions; conversely, under mesophilic conditions, the best yield was achieved by the sample containing 30% YW (sample D).

4. Conclusions

The production of methane from the anaerobic co-digestion of kitchen waste and brown waters was tested both with and without the addition of yellow water under both mesophilic and thermophilic conditions.

BMP batch tests showed that when KW and BW were digested separately, they performed much better under thermophilic rather than mesophilic conditions. Moreover, in terms of methane yields, organic mixtures performed much better (max. 520 ml CH_4/g VS) than the individual substrates alone (max. 220 ml CH_4/g VS). Interesting results have been obtained on the influence of YW, and numerous studies have acknowledged the inhibitory effect of ammonia on bacterial activity. Nevertheless, in the experiments conducted, a small concentration of urine exerted a positive effect on the methanogenic phase, possibly due to the presence of micronutrients in yellow waters. In the presence of higher YW concentrations in the anaerobically digested mixtures, no inhibition was observed prior to reaching a 30% YW content under mesophilic conditions (30% YW corresponds to an optimum under mesophilic conditions, whilst under thermophilic conditions optimal YW content is 6%).

The anaerobic co-digestion of KW, BW, and a small amount of YW, may be further optimized to ensure that each decentralized scenario is rendered autonomous from the point of view of energy supply. Since the characteristics of kitchen waste vary significantly from one country to the next, optimal composition rate should be specifically tested prior to installation of an anaerobic digestion system.

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