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Anaerobic batch digestion of solid potato waste alone and in combination with sugar beet leaves

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Abstract

The objective of this study was to characterise anaerobic batch biodegradation of potato waste alone and when co-digested with sugar beet leaves. The effects of increasing concentration of potato waste expressed as percentage of total solids (TS) and the initial inoculum-to-substrate ratio (ISR) on methane yield and productivity were investigated. The ISRs studied were in the range 9.0–0.25 and increasing proportions of potato waste from 10% to 80% of TS. A maximum methane yield of 0.32 l CH_4/g $VS_{degraded}$ was obtained at 40% of TS and an ISR of 1.5. A methane content of up to 84% was obtained at this proportion of potato waste and ISR. Higher ISRs led to faster onset of biogas production and higher methane productivity. Furthermore, co-digestion of potato waste and sugar beet leaves in varying proportions was investigated at constant TS. Co-digestion improved the accumulated methane production and improved the methane yield by 31–62% compared with digestion of potato waste alone.

Keywords: Anaerobic digestion; Biogas production; Batch; Co-digestion; Potato waste; Sugar beet leaves; Inoculum–substrate ratio; Methane yield

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1. Introduction

Biomass and agricultural waste represent a large potential renewable energy source, which could benefit society with a clean fuel in the form of methane [1–3]. A policy has been adopted by Zimbabwe's Department of Energy to develop biogas technology from agricultural and other organic wastes and to encourage its use [4]. In Zimbabwe, as in any other developing country, conventional energy supplies such as electricity, coal, gas and petroleum products are either not available, too capital intensive to install, are unjustifiable due to low population densities in some semi-arid regions, or are simply unaffordable for the target population [4,5]. The general overproduction of food products by the agricultural sector in Europe and the steady rise in environmental taxes on fossil fuels is spurring efforts to find new non-food utilisation possibilities for agricultural products, for example, energy production. Anaerobic digestion may lead to environmental benefits with regard to waste treatment, pollution reduction, energy production and improvements in agricultural practices [2,6].

Anaerobic digestion of waste and wastewater can be performed in batch, or in continuous processes. In normal batch digestion, reactors are filled once with fresh waste, with or without the addition of inoculum, and allowed to go through the degradation process leading to the formation of biogas. Anaerobic batch digestion experiments are useful because they can be performed quickly with simple, inexpensive equipment, and are useful in assessing the rate at which a material can be digested [7,8]. There is significant potential for anaerobic batch digestion in developing countries, which have substantial amounts of biomass. However, African nations are not the only ones with such resources. In Europe, particularly Denmark and Germany, large amounts of waste biomass are being utilised for energy production. Anaerobic fermentation could be particularly attractive for the more than 3000 tonnes of potato waste and thousands of tonnes of sugar beet leaves produced in southern Sweden every year. There is considerable effort in southern Sweden to increase the energy contribution from biogas from the current 1.5 TWh per year to a predicted value of 14 TWh per year [9]. According to Stewart et al. [8], the gross energy of potato is 16.4 MJ/kg total solids (TS) and the energy in methane produced from potato is 15.5 MJ/kg TS of potato, giving an energy conversion efficiency of 95% with the assumption that biogas yields 410 l/kg TS potato and has a methane content of 50%. The energy content of methane is 37.7 kJ/l. Materials like potato, with a high content of soluble carbohydrate, are usually regarded as more suitable feedstocks for the production of ethanol rather than conversion to biogas. The yield of ethanol that can be obtained from potato is approximately 0.4 l/kg TS with a total energy content of 9.8 MJ/kg TS. The corresponding energy conversion efficiency is thus only about 60%, well below that obtainable in anaerobic digestion, supporting the idea that the latter may be a preferable technology for converting potato waste to fuel [8].

There is a lack of information on methane yield from various organic substrates including potato and on the influence of different operating parameters such as TS and ISR. The ISR shows the effect of substrate concentration during anaerobic digestion as well as the effect of inoculum concentration on anaerobic degradability and methane productivity [10]. One aim of this study was to characterise the anaerobic biodegradability potential of potato waste and its methane potential (measured as methane yield) using different concentrations of potato of TS and ISR. Furthermore, the effect of ISR on methane yield and productivity was evaluated. This research can also be applied to solid potato waste like peeling wastes and potato chunks culled from food processing lines.

The amount of one type of organic waste generated at a particular site at a certain time may not be sufficient to make anaerobic digestion cost-effective all year round. Co-digestion then becomes an interesting alternative as it is a well-established concept [11–13] and it has many advantages [14]. Co-digestion as a process has been examined for a wide range of waste combinations [15,16]. However, much of the information in the literature involves co-digestion of cattle manure with other agro-waste where the manure provides nitrogen for the system [11,17–19]. Most industrial co-digestion plants treat the organic fraction of municipal solid waste plus sewage [14]. However, no scientific reports were found on co-digestion of potato waste and sugar beet leaves. The beet leaves provide additional nitrogen to the system. This paper describes some initial studies on the anaerobic co-digestion of potato waste with sugar beet leaves. Batch experiments were undertaken with different proportions of potato and sugar beet leaf pulp in order to determine optimum mixtures for successful co-digestion.

2. Materials and methods

2.1. Substrates and inoculum

The potato waste and beet leaves were homogenised using a kitchen blender (Moulinex Masterchef 350, France). Anaerobically digested sewage sludge from a wastewater treatment plant in Eslöv, Sweden was used as inoculum in the batches. The culture was thoroughly mixed and filtered through a screen with a pore size of 1 mm before use. The characteristics of the potato waste pulp, sugar beet leaf pulp and inoculum are listed in Table 1.

2.2. Anaerobic digestion of potato waste—experimental design

All the experiments were conducted in duplicate in 0.5 l Erlenmeyer flasks incubated at 37 °C in a shaking water bath (GFL 1086; Gesellshaft fur Labortechnik GmbH, Burgwedel, Germany) at a frequency of 70 rpm. The active volume of the reactors was 0.3 l. Anaerobic conditions were established by flushing the flasks with a nitrogen:carbon dioxide mixture (80:20%) for 3 min, and the flasks were sealed immediately with butyl rubber stoppers. An outlet in the stopper was used for collecting biogas in gas-tight aluminium foil bags. Controls containing only inoculum were used to measure the background methane production from the inoculum and this was subtracted from the total gas production.

Table 1
Characteristics of the potato waste, sugar beet leaves and inoculum from sewage treatment used in the experiments

Characteristic	Potato	Sugar beet	Inoculum
pH	5.7	6.8	7.5
Total solids (%)	19	11	1.6
Volatile solids (% of TS)	95	84	57
Total phosphates (g/l)	1.3	0.3	1.5
Orthophosphates (g/l)	0.14	0.2	0.4
Total Kjeldahl nitrogen (% of TS)	1.5	3.3	0.1
Ammonium-nitrogen (g/l)	0.1	0.2	0.9
Organic carbon (% of TS)	53	46	
Carbon:nitrogen ratio (C:N)	35	14	

Table 2
Amounts of potato and inoculum, expressed as % of TS, used in the various batch digestion experiments (R1–R7). The inoculum-to-substrate ratio (ISR) is also given

Exp. No.	R1	R2	R3	R4	R5	R6	R7
Inoculum (% of TS)	90	80	70	60	50	30	20
Potato waste (% of TS)	10	20	30	40	50	70	80
Total Solids (%)	5	6	7	8	9	14	18
ISR	9.0	4.0	2.3	1.5	1.0	0.4	0.25

The different proportions of inoculum and potato waste investigated are presented in Table 2. Seven runs (R1–R7) containing potato pulp of 10–80% of TS were performed. The corresponding ISRs were 9.0, 4.0, 2.3, 1.5, 1.0, 0.4 and 0.25. The digestion mixtures had final TS concentrations ranging from 5% to 18% TS. Sodium hydrogen carbonate (4 g/l) was added to increase the initial buffering capacity of the reactors. The experiments were run for 50 days and terminated when no significant gas production was observed over a 2-week period.

2.3. *Co-digestion—experimental setup*

The co-digestion of mixed organic waste involves the mixing of the various substrates in varying proportions. If all other factors, such as physical parameters, are kept constant, the methane yield (l/g volatile solids (VS) added or removed) and the percentage VS degradation are functions only of the proportions used. In the batch experiments where potato waste comprised the feedstock, the highest methane yield was achieved at 40% of TS. In the co-digestion experiments, the proportions of potato and solids from sugar beet leaves were varied while maintaining the TS from potato and sugar beet at 40% of the total TS. The mixtures were obtained by decreasing the proportion of potato waste added from 40% to 0% of TS while increasing the proportion of sugar beat leaves from 0% to 40% of TS (Table 3). The TS concentration in all the reactors was approximately 8% TS. The initial C:N ratio in the co-digestion mixtures ranged from 35 to 14. In all tests, anaerobic

Table 3
Compositions of co-digestion feedstocks of potato waste and sugar beet leaves. The mixtures are based on % of TS. Each experiment was duplicated. The amount of inoculum was 60% of TS in all experiments

Exp. No.		Co1	Co2	Co3	Co4	Co5	Co6	Co7	Co8	Co9
Potato (% of TS)	1	39	31	28	25	19	17	13	7	0
	2	41	33	28	23	20	15	11	9	0
Beet leaves (% of TS)	1	0	8	12	15	21	24	29	32	41
	2	0	7	12	17	18	23	27	31	39
Initial C:N ratio	1	36	28	26	23	22	21	18	17	14
	2	34	27	24	23	21	18	16	16	14

sludge (described previously) was used as the inoculum for each mix contributing 60% of the TS.

2.4. Analytical methods

The biogas composition was determined using a gas chromatograph, (Varian 3350 Walnut Creek, CA, USA) fitted with a Haysep Q 80/100 mesh column, a molecular sieve column and a thermal conductivity detector. Helium gas was used as a carrier gas (12 ml/min). The column temperature was 70 °C and the injector and detector temperatures were 110 and 150 °C, respectively. The compounds detected were methane, carbon dioxide, nitrogen and oxygen. The volume of biogas collected in the gas-tight aluminium bags was measured using a wet-type precision gas meter (Schlumberger, Karlsruhe, Germany).

The TS, VS and total Kjeldahl nitrogen (TKN) levels were determined according to standard methods [20]. The concentrations of volatile fatty acids (VFAs) were determined using HPLC according to Björnsson et al. [21]. Dr. Lange cuvette tests and a *Lasa* 100 spectrophotometer (Dr. Bruno Lange GmbH, Germany) were used for the following analyses: total nitrogen LCK 338, total phosphates and orthophosphates PO_4 (PO_4-P) LCK 348. The amount of NH_4-nitrogen was measured on filtered samples (0.45 μl filter) using LCK 303.

3. Results

3.1. Anaerobic digestion of potato waste

The methane yield during anaerobic digestion of potato waste at different concentrations is shown in Fig. 1. The highest methane yield, 0.32 l CH_4/g $VS_{degraded}$, was obtained in the batch containing potato waste at 40% of TS and an ISR of 1.5. This was followed by 0.23 l CH_4/g $VS_{degraded}$, in the batch with potato waste comprising 50% of TS and an ISR of 1.0. The methane yield increased with increasing potato waste solids concentration from 10% to 40% of TS, and then

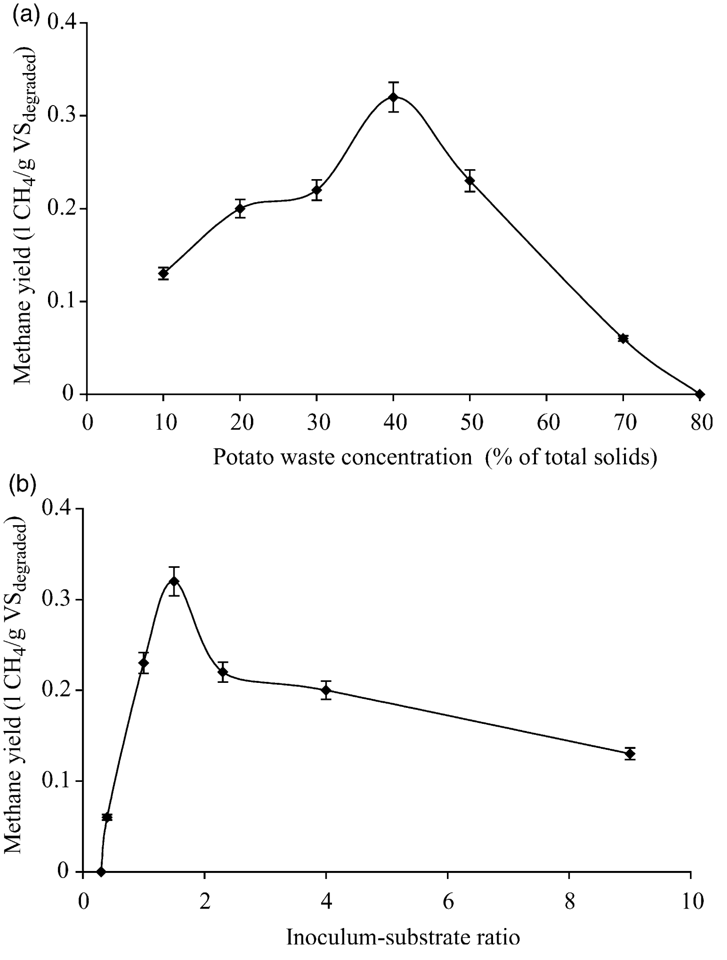

Fig. 1. Methane yields during batch anaerobic digestion of potato solids at different potato waste concentration (a) and inoculum–substrate ratios (b).

decreased with increasing potato solids concentration from 50% to 80%. The methane yield increased with increasing ISR from 0.25 up to 1.5 and decreased with higher ISRs up to 9.0.

The methane productivity (l CH_4/$l_{reactor\ volume}$/day) is illustrated in Fig. 2. There was a sharp decrease in the methane productivity after 2–4 days in runs R3, R2 and R1 compared with R5 and R4. The biogas composition in terms of methane content during batch digestion is shown in Fig. 3. In R7, the methanogenesis was initially inhibited for about 18 days followed by a slight increase to about 5% methane at day 22, and a final concentration of 12% CH_4 was reached. The methane composition in R6 slowly increased to about 50% CH_4 by the end of the experiment. In R1–R5, the methane content improved with increasing concentration of potato waste and

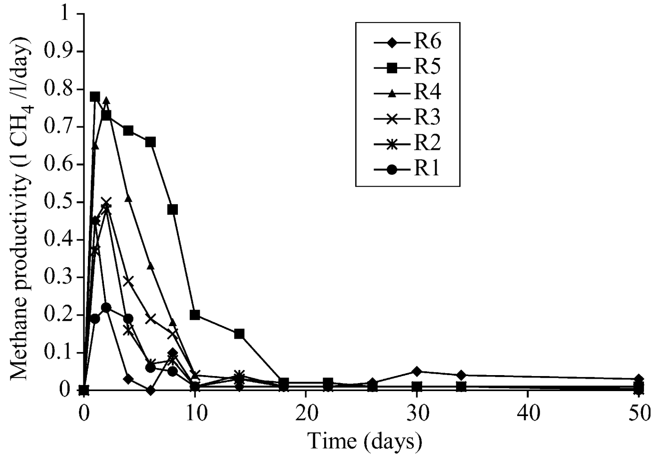

Fig. 2. Methane productivity (l CH_4/l/day) during anaerobic digestion of potato solids at different concentrations and ISR (see Table 2 for details).

decreasing ISR. The highest methane content of 84% was obtained in R4 after 10 days, followed by 83% in R5 after 10 days of incubation.

The properties of the digestate at the beginning and at the end of the experiments are given in Table 4. The pH of the contents in all the reactors initially ranged between 7.5 and 7.8. The final pH was between 7.9 and 8.0 in R1–R5. However, the final pH decreased to acidic levels (5.9 and 4.9) in R6 and R7, respectively. No VFAs were detected at the end of the experiments in R1–R5. Total VFAs accumulated to 17 and 27 g/l in runs R6 and R7. The initial partial

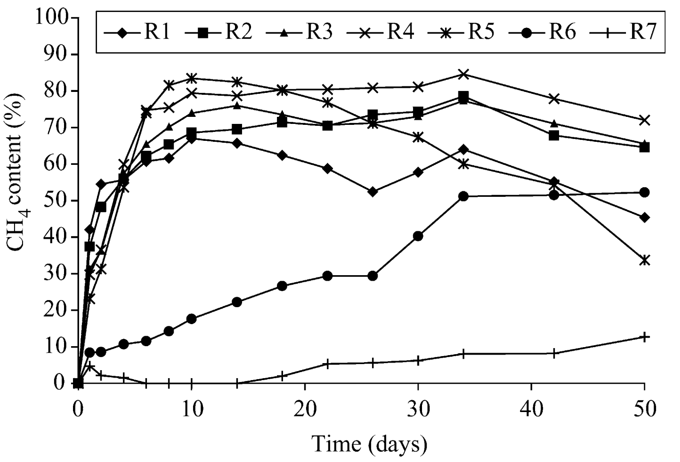

Fig. 3. Biogas composition in terms of methane content at different potato concentrations and ISRs (see Table 2 for details).

Table 4
Characteristics in terms of pH, partial alkalinity (PA) and ammonium nitrogen of the batch digestate at the beginning and end of anaerobic digestion of potato waste. Results are mean values of duplicate experiments

Exp. No.	Initial pH	Final pH	Initial PA (g/l)	Final PA (g/l)	Initial NH_4^+-N (g/l)	Final NH_4^+-N (g/l)
R1	7.7 ± 0.1	7.9 ± 0.1	7.3 ± 0.3	6.0 ± 0.2	0.80 ± 0.4	1.06 ± 0.2
R2	7.8 ± 0.2	7.9 ± 0.1	7.1 ± 0.3	6.1 ± 0.2	0.77 ± 0.3	1.08 ± 0.2
R3	7.8 ± 0.4	7.9 ± 0.1	6.5 ± 0.3	6.1 ± 0.1	0.74 ± 0.2	1.13 ± 0.1
R4	7.7 ± 0.2	7.9 ± 0.1	6.9 ± 0.4	6.3 ± 0.2	0.71 ± 0.3	1.19 ± 0.2
R5	7.7 ± 0.3	8.0 ± 0.1	6.2 ± 0.3	6.3 ± 0.2	0.64 ± 0.4	1.23 ± 0.2
R6	7.7 ± 0.3	5.9 ± 0.1	4.8 ± 0.3	8.0 ± 0.2	0.54 ± 0.3	1.14 ± 0.1
R7	7.5 ± 0.2	4.9 ± 0.1	4.3 ± 0.3	0.0	0.47 ± 0.4	0.87 ± 0.3

alkalinity (PA) decreased with increasing potato waste proportion and decreasing ISR. However, the final PA was rather constant at around 6 g/l in R1–R6. The final PA was zero in R7. The initial ammonium-nitrogen levels decreased from 0.8 to 0.5 g/l with increasing proportion of potato waste and decreasing ISR. The final ammonium-nitrogen concentration increased from the initial concentrations to around 1.0 g/l in R1–R6 and to 0.9 g/l in R7. The results showed that organically bound nitrogen was converted to ammonium in all the reactors.

3.2. *Co-digestion of potato and sugar beet leaf waste*

The cumulative methane production, and methane yield obtained with the different substrates digested alone and as mixtures during co-digestion are given in Table 5. The highest accumulated methane production was 1.63 l CH_4 for 24% potato, 16% beet and 60% inoculum TS (Co4) and the lowest methane production was 1.14 l CH_4 for 8% potato, 32% beet and 60% inoculum (Co8). All the co-digested mixtures performed better than the substrates digested separately in terms of methane yield. The methane yield ranged from 0.55 to 0.68 l CH_4/g $VS_{degraded}$ with

Table 5
Accumulated methane production and methane yield during co-digestion of potato and sugar beet leaf waste. Results are mean values of duplicate experiments

Exp. No.	Potato/beet (% of TS)	Accumulated methane (l)	Methane yield (l CH_4/g $VS_{degraded}$)
Co1	40:0	1.23 ± 0.02	0.42 ± 0.01
Co2	32:8	1.32 ± 0.01	0.61 ± 0.02
Co3	28:12	1.55 ± 0.03	0.67 ± 0.01
Co4	24:16	1.63 ± 0.04	0.68 ± 0.02
Co5	20:20	1.59 ± 0.02	0.67 ± 0.01
Co6	16:24	1.48 ± 0.04	0.64 ± 0.01
Co7	12:28	1.34 ± 0.03	0.57 ± 0.01
Co8	8:32	1.14 ± 0.02	0.55 ± 0.01
Co9	0:40	1.13 ± 0.02	0.52 ± 0.01

Table 6
Properties of digestion mixtures at the beginning and end of the co-digestion experiments

Exp. No.	Potato/beet (% of TS)	Initial pH	Final pH	Initial PA (g/l)	Final PA (g/l)	Initial NH_4^+-N (g/l)	Final NH_4^+-N (g/l)	Initial TVFAs (g/l)
Co1	40:0	8.2 ± 0.2	8.1 ± 0.1	8.6 ± 0.3	8.7 ± 0.2	0.6 ± 0.2	1.1 ± 0.1	0.6 ± 0.5
Co2	32:8	8.2 ± 0.1	8.2 ± 0.1	8.7 ± 0.2	8.7 ± 0.2	0.7 ± 0.2	1.1 ± 0.2	0.6 ± 0.4
Co3	28:12	8.2 ± 0.2	8.2 ± 0.1	8.7 ± 0.3	8.7 ± 0.1	0.7 ± 0.2	1.1 ± 0.1	0.6 ± 0.5
Co4	24:16	8.3 ± 0.1	8.1 ± 0.1	8.5 ± 0.3	8.6 ± 0.2	0.7 ± 0.3	1.0 ± 0.2	0.5 ± 0.1
Co5	20:20	8.3 ± 0.1	8.1 ± 0.1	8.7 ± 0.2	8.7 ± 0.2	0.7 ± 0.3	1.1 ± 0.1	0.9 ± 0.3
Co6	16:24	8.3 ± 0.1	8.2 ± 0.1	8.6 ± 0.3	8.7 ± 0.1	0.7 ± 0.2	1.1 ± 0.1	1.0 ± 0.2
Co7	12:28	8.3 ± 0.2	8.1 ± 0.1	8.6 ± 0.2	8.8 ± 0.1	0.7 ± 0.3	1.1 ± 0.1	1.1 ± 0.1
Co8	08:32	8.3 ± 0.1	8.1 ± 0.1	8.7 ± 0.1	8.8 ± 0.1	0.8 ± 0.2	1.2 ± 0.2	0.9 ± 0.1
Co9	0:40	8.2 ± 0.3	8.1 ± 0.1	8.6 ± 0.2	8.5 ± 0.1	0.7 ± 0.3	1.1 ± 0.3	1.2 ± 0.2
	Inoculum	8.3 ± 0.1	8.3 ± 0.1	8.6 ± 0.1	8.7 ± 0.1	0.5 ± 0.1	0.7 ± 0.1	0

the lowest in Co8 and the highest in Co4. Compared with the methane yield of 0.42 l CH_4/g $VS_{degraded}$ for the anaerobic digestion of potato waste alone (Co1), co-digestion of potato waste with sugar beet leaves enhanced methane yields by 31–62%. The gas composition reached a maximum of 84% CH_4 during co-digestion (data not shown).

The properties of the co-digestion mixtures at the beginning and end of the experiments are given in Table 6. None of the co-digestion batches was acidified. There was no difference between the initial and final pH and PA values after 60 days of digestion. The pH was around 8.0 and the PA was 8.7 g $CaCO_3$/l in all the combinations of potato waste and sugar beet leaves, and similar to that of the control. The ammonium-nitrogen increased from the initial value of 0.7 to 1.1 g/l in all the experiments. No VFAs were detected at the end of the digestion period in any of the co-digestion or control runs.

4. Discussion

4.1. Anaerobic digestion of potato waste

The two parameters investigated in this study were the concentration of potato waste expressed as percentage of TS in the reactors and the IRS ratio as these parameters have considerable effects on the cost, performance and reliability of the fermenters and the digestion process [22]. Methane yield is an important economic factor in anaerobic digestion. The highest methane yield of 0.32 l/g $VS_{degraded}$ during batch digestion of potato waste only is comparable to the methane yield of 0.43 l/g VS_{added} of potato waste reported by Stewart et al. [8] in continuous culture in a continuously stirred tank reactor at 33–37 °C and 20 days hydraulic retention time. Comparisons of methane yields reported in the literature cannot be precise because of possible differences in the feedstock and in the experimental conditions. Methane yields from potato would be expected to vary depending on whether potato solids, potato peel and rejects or potato-processing wastewater are used as feedstock, or if any storage or pretreatment differed. Acclimatisation of the inoculum to the feedstock is also important for optimum yields, as well as temperature and retention time. No studies performed on the anaerobic batch digestion of solid potato waste were found in the literature.

Rapid initial methane production was observed due to hydrolysis of the most soluble compounds of the potato waste and due to high volume of inoculum in R1–R5. The methane production rate decreased with time in all the experiments. After about 10 days, the methane production slowed down. This could be explained by the fact that the more easily degradable compounds were finished during the first 10 days and slow degradation of complex material taking place after that period. The biogas production patterns resembled each other and similar patterns have been reported for anaerobic batch degradation of solid poultry slaughterhouse waste [23], kitchen waste [22], and spent brewery grain [10].

Low methane yields indicated that methane production in R6 and R7 was inhibited. The observed inhibition of methanogenesis was supported by the low pH levels recorded in these reactors, which were below the range for methanogenic activity. There was also high concentration of VFA caused by rapid hydrolysis.

Ammonia may also be the cause of methanogenesis inhibition if the concentration exceeds a certain threshold level, which varies with the substrate and conditions [24–26]. The ammonia-nitrogen concentrations in this study were, however, below reported inhibitory threshold levels.

The highest methane yield from solid potato waste was obtained with a potato waste amount of 40% of TS. Regarding the start-up of an anaerobic batch system employing potato waste, the results showed that it was not necessary to start with an elevated inoculum volume or high substrate concentrations in order to obtain the highest methane yield. Whether one should use a high ISR or not depends on the final objective of the process: the production of methane or intermediate compounds such as VFAs. If methane production is more important, then a low ISR should be avoided as methanogenic inhibition could take place, as was observed in R6 and R7 (Fig. 3). For conventional anaerobic systems, these results would be especially important in avoiding such inhibition.

4.2. Co-digestion of potato and sugar beet leaf waste

The single wastes and mixtures of wastes were studied with regard to methane production in batch assays for a period of 60 days. Co-digestion of potato waste and sugar beet leaves improved the methane yield by 31–62% compared with that from batch digestion of potato waste alone and 6–31% compared with that from batch digestion of sugar beet leaves alone. The marked increase in the methane yield could be due to positive synergism established in the digestion liquor and the supply of additional nutrients by the co-substrates [14]. This is in agreement with an enhancement of about 60% in methane yield observed in studies on co-digestion of industrial confectionery waste with cow manure in a farm-scale biogas plant [12]. The increased methane yield could also be due to an improved C:N ratio in the co-digestion of the potato waste and sugar beet leaves. The C:N ratios of the co-digested potato waste and sugar beet leaves, which ranged between 16 and 28, are within the values required for stable anaerobic digestion of organic waste [27,28]. The well-balanced anaerobic digestion in the co-digestion was also evidenced by the absence of VFAs, neutral pH and good PA, observed at the end of the digestion period. Jenkins et al. [29] reported that the PA should be above 1.2 g $CaCO_3$/l for stable operation. The high ammonium-nitrogen concentrations contributed to the high buffering capacity.

5. Conclusions

The potato waste and sugar beet leaves were co-digested successfully resulting in improved methane yield and accumulated methane production compared with separate digestion of the substrates. Results from this study suggest that potato waste and sugar beet leaves are potential substrates for anaerobic digestion for the production of biogas and could provide additional benefits to farmers in southern Sweden. The general conclusion is that starch rich substrates may potentially be mixed with others rich in nitrogen content and then co-digested. More importantly, batch anaerobic digestion can be applied in developing countries where low and cheap technology is needed most.

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