Enhancement of food waste digestion in the hybrid anaerobic solid-liquid system

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ABSTRACT

The hybrid anaerobic solid-liquid (HASL) system is a modified two-phase anaerobic digester for food waste treatment. To enhance the performance of anaerobic digestion in the HASL system, thermal pre-treatment (heating at 150°C for 1 h) and freezing/thawing (freezing for 24 h at − 20°C and then thawing for 12 h at 25°C) were proposed for food waste pre-treatment before the anaerobic digestion. Both processes were able to alter the characteristics and structure of food waste favoring substance solubilization, and hence production of methane. However, there was no net energy gain when the energy required by the pre-treatment processes was taken into account.

Key words | anaerobic digestion, energy balance, food waste, freezing and thawing pre-treatment, thermal pre-treatment

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INTRODUCTION

Food waste is a significant portion of municipal solid wastes (MSW). In Singapore, the food waste produced from food-processing companies, restaurants, food courts, markets, and households comprises 20% (w/w) of MSW; currently almost all the food waste is incinerated together with the treatment of the MSW. Anaerobic digestion, a microbial anaerobic conversion of organic matter into methane, carbon dioxide, inorganic nutrients and humus-like matter, appears to be the most promising method for food waste treatment. It reduces the volume of food waste, generates fuel biogas containing 55 to 75% (v/v) of methane, and produces organic residue that can be used as a soil conditioner or fertilizer. Compared to incineration, anaerobic digestion may also reduce the cost of food waste treatment. Working on a pilot-scale two-phase anaerobic system with a treatment capability of 5 tonnes per day in Korea (Anyang, South Korea), Lee *et al.* (1999) demonstrated that the operating cost of the plant was 60 US dollars per tonne of food waste; in contrast, about 90 US dollars was required while incinerating 1 tonne of food waste.

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A two-phase anaerobic digestion system has been considered to be more effective for the treatment of solid food wastes than a single-stage digestion process (Verrier *et al.* 1987; Raynal *et al.* 1998; Mata-Alvarez *et al.* 2000; Pavan *et al.* 2000; Han & Shin 2002). The principle of the two-phase anaerobic process is the separation of liquefaction/acidification (fermentation) and acetogenesis/methanogenesis phases (Pohland & Ghosh 1971). For the treatment of solid food waste, the aim of liquefaction/acidification is hydrolysis and acidogenic fermentation to obtain a liquid fraction with dissolved organics, which are degraded further in the acetogenesis/methanogenesis phase. Hydrolysis and liquefaction of organic waste is often a rate-limiting step in the anaerobic process (Shin *et al.* 2001).

To increase solubilization, thermal pre-treatment of food waste can be used (Kim *et al.* 2005). Solubilization of organic matter can be increased also due to cell disruption (Mata-Alvarez *et al.* 2000). In addition, freezing of organic matter at low temperature leads to intracellular ice crystals formation causing damage of cell membranes and to cell disruption (Thomashow 1998). The aim of the present research was to study the two-phase anaerobic system for the treatment of food waste, and to evaluate the effect of thermal pre-treatment and freezing/thawing pre-treatment methods on food waste fermentation in terms of system performance and operating cost.

MATERIALS AND METHODS

Food waste was collected from a canteen in the university. Waste was shredded into particles with an average size of 6.0 mm by a Robot-Coupe Shredder (CL50 Ultra, Hobart, France). The composition of food waste used in the experiments was as follows (% of wet weight): vegetable roots, 50; orange peels, 20; rice, 15; and noodles, 15. The contents of total solids (TS) were 16.3 and 18.6%; the contents of volatile solids (VS) were 88.0 and 92.9% of TS in the mixed fresh waste in experiment with thermal pre-treated and frozen/thawed food waste, respectively. Anaerobic microbial sludge, used as inoculum for the acidogenic reactor, was collected from an anaerobic digester in a local wastewater treatment plant. Microbial anaerobic granules acclimated with high-concentration volatile fatty acids (VFA)-rich wastewater were inoculated into the methanogenic reactor.

Two identical sets of two-phase systems were used for the treatment of food waste in the present study, each consisting of an acidogenic column reactor and a modified upflow anaerobic sludge blanket methanogenic reactor with recirculation of effluent from the methanogenic reactor into both the acidogenic and methanogenic reactors (Figure 1). Such a two-phase system is known as the Hybrid Anaerobic Solid Liquid (HASL) system developed by Wang *et al.* (2005). The effluent from the methanogenic reactor in the HASL system was divided into two streams: 20% effluent was recycled into the acidogenic reactor to reduce the volume of the effluent to be discharged from the anaerobic system and to avoid water to be added for hydrolysis of food waste to the acidogenic reactor, while 80% effluent was used for the dilution of effluent from the acidogenic reactor to maintain optimal pH for methanogenesis in the methanogenic reactor.

Two separate batch experiments were conducted with thermal pre-treated food waste (E1) and frozen/thawed food waste (E2). Each batch was accompanied by its separate control (C1 or C2) simultaneously. All the tests were operated in a batch pattern at 35 ± 1°C for 12 days as described previously (Stabnikova *et al.* 2005). After inoculating with 1 litre anaerobic sludge, the acidogenic reactors were fed with 1 litre distilled water and 800 g fresh or pre-treated food waste. Food waste used in E1 was diluted in 1 litre distilled water and then heated at 150°C for 1 h, whereas the food waste used in E2 was frozen for 24 h at − 20°C and then thawed for 12 h at 25°C.

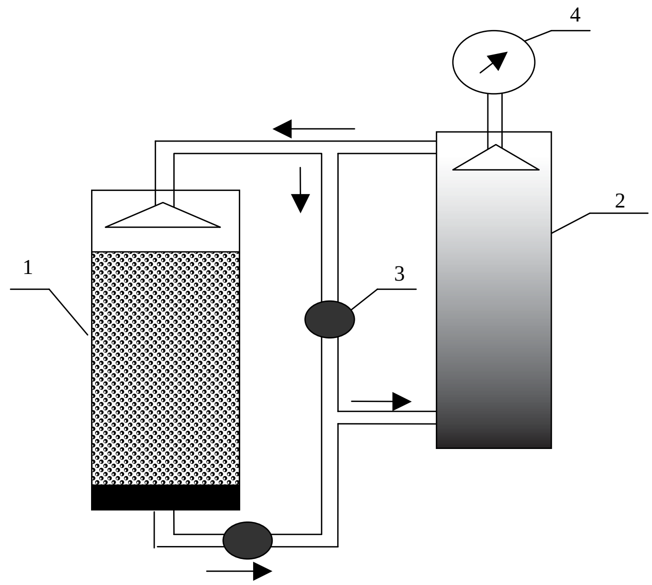

Figure 1 | Schematic diagram of the HASL system: 1, acidogenic reactor, Ra;2, methanogenic reactor, Rm; 3, peristaltic pump; 4, wet gas meter.

The micro-structure of fresh and pre-treated food waste was observed by a scanning electron microscope (SEM) (Stereoscan 420, Leica Cambridge Instruments). The leachate from the acidogenic reactors and the effluent from the methanogenic reactors were collected daily for analyses. The pH value was measured using a pH meter (Corning 145, Halstead, Essex, England). TS, VS, and chemical oxygen demand (COD) were determined according to standard methods (*Standard Methods* 1998). For the determination of VFA, samples were filtrated through Whatman 0.2 μm nitrocellulose membrane filters and then analyzed using a HPLC (Perkin Elmer, Series 200, Norwalk, CT, USA). The HPLC was equipped with 220 mm × 4.6 mm polypore H column and UV 210 nm detector. The mobile phase was 0.005 N H_2SO_4 with a flow rate of 0.15 ml/min. Gas production was monitored using a wet gas meter

(Ritter TG 05, Bochum, Germany), while gas composition was analyzed using a Hewlett Packard GC HP5890A (Hach, Avondale, PA, USA). The GC was equipped with a thermal conductivity detector and a stainless-steel column packed with Hayesep Q (80/100 mesh). The operating temperatures of the injector, detector and column were set at 100°C, 200°C and 50°C, respectively. Helium was used as a carrier gas at a flow rate of 40 ml/min. All analyses were carried out in triplicates.

RESULTS AND DISCUSSION

Thermal pre-treatment was able to improve the structure of food waste, i.e. increased porosity and decreased bulk density, thickness and volume of the material. After heating at 150°C for 1 hour, cavities appeared, and the structure of vegetable roots became loose (Figure 2a, b). Thermal pre-treatment significantly enhanced the content of soluble organic materials in the food waste as the initial soluble COD concentrations were 3.5 g/l and 7.6 g/l in C1 and E1, respectively.

The highest soluble COD and VFA concentrations in the leachate from the acidogenic reactor treating fresh food waste, observed on the 4th day of the process, were 17.6 g/l and 12.5 g/l (Figure 3a), respectively. Meanwhile, the soluble COD and VFA concentrations in the leachate from the acidogenic reactor with thermal pre-treated food waste peaked on the 2nd and 3rd day of the process, at 24.2 g/l and 19.8 g/l, respectively. During the first six days, in comparison with anaerobic treatment of fresh food waste, thermal pre-treatment of food waste increased the total soluble COD production by 13% and total VFA production by 20% in the acidogenic reactor, and also increased the total methane production by 42% in the methanogenic reactor. Use of thermally pre-treated food waste diminished the time to produce the same quantity of methane by 48% in comparison with anaerobic digestion of fresh food waste (Figure 4). This improvement was thought to be due to speed up of organic matter hydrolysis.

The hydrolysis and fermentation processes in the acidogenic reactor of the two-phase anaerobic system, operated in batch mode, were facilitated when food waste was frozen for 24 hours at −20°C and then thawed for 12 hours at 25°C in comparison with fresh food waste. As shown in SEM images (Figure 2c, d), the structure of food waste material after freezing/thawing became looser, which

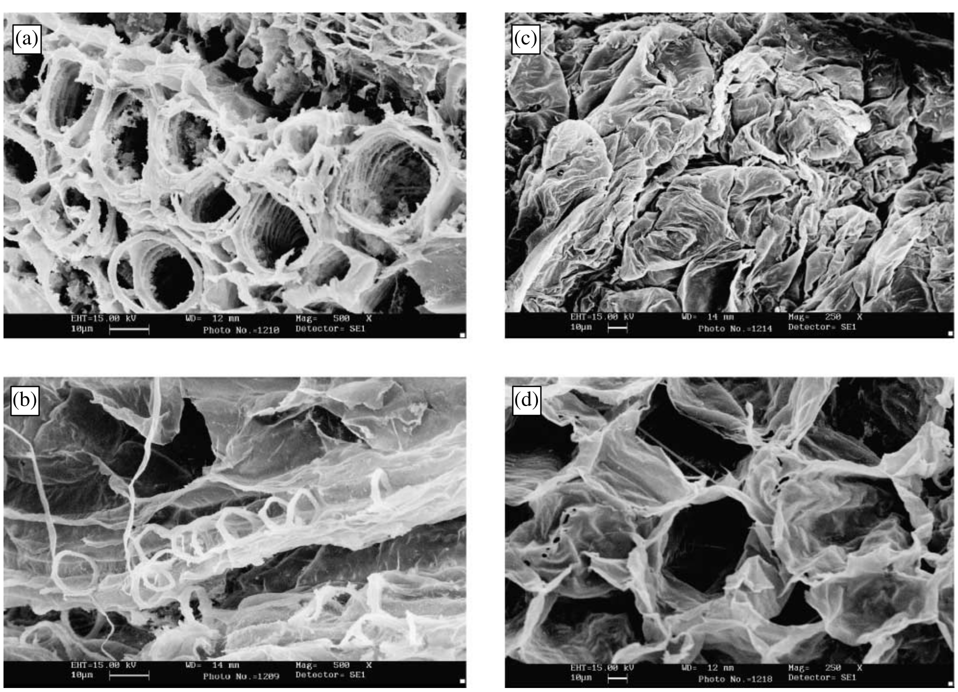

Figure 2 | SEM images of fresh (a) and thermally pre-treated (b) vegetable waste; of fresh (c) and frozen/thawed (d) vegetable waste.

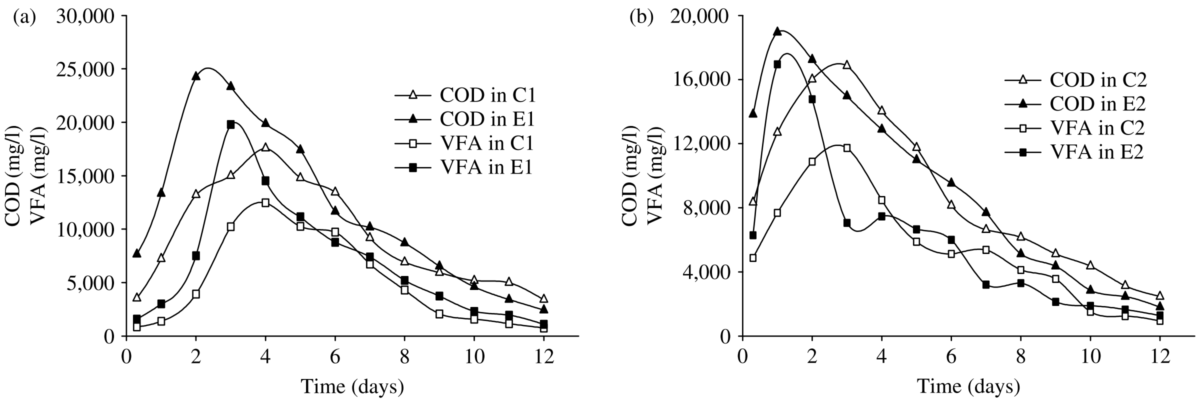

Figure 3 | Changes in concentration of COD and VFA in control (C) and experiments (E) for thermally treated waste (a) and frozen/thawed waste (b).

caused the increase in dissolved organics concentration. The initial soluble COD concentration was 13.8 g/l in the acidogenic reactor in E2, and increased 1.7 times compared to the control test (C2).

The highest soluble COD and VFA concentrations in the leachate from the acidogenic reactor treating fresh food waste, observed on the 3rd day of the process, were 16.9 g/l and 11.7 g/l (Figure 3b), respectively. In contrast, the soluble COD and VFA concentrations in the leachate from the acidogenic reactor treating frozen/thawed food waste peaked with the respective maxima of 18.9 g/l and 17.0 g/l on the 1st day. During the first six days, in comparison with C2, freezing and thawing resulted in an increase in the total soluble COD production (39%) and total VFA production (37%) in E2. As a consequence, 29% increase of methane production was attained in the methanogenic reactor. The same volume of methane produced in 12 days in the control digestion with fresh food waste was produced in 7 days in the experiment with frozen/thawed food waste (Figure 4). This pre-treatment reduced the operational time by 42%. A similar improvement was achieved with thermal pre-treatment of food waste at 150°C for 1 hour in E1, which also reduced time needed to produce the same quantity of methane by 48% in comparison with C1. This improvement was thought to be due to speed up of organic matter hydrolysis.

Obviously, thermal pre-treatment and freezing/thawing pre-treatment both enhanced the energy recovery from food waste in terms of methane production. However, external energy was required to implement those pre-treatment processes. An energy balance between the energy required by the pre-treatments and increased energy output was made. If the energy losses from heating and refrigerating processes are not considered, theoretical energy requirement for heating 800 g food waste (TS of 18.6% w/w TS) and 1000 ml water from 25°C to 150°C was $Q = c_{solid} m_{solid} \Delta t + c_{water} m_{water} \Delta t = 0.89$ J/g°C × 148.72 g × (150–25) °C +4.18 J/g°C × (651.28 + 1000)g × (150–25)°C = 879.33 kJ. Assuming there was no phase change for food waste during freezing, only water was in the form of ice at below 0°C. The theoretical energy for freezing was $Q = c_{solid} m_{solid} \Delta t + c_{water} m_{water} \Delta t + c_{ice} m_{ice} \Delta t + Lf_{water} m_{water} = 0.89$ J/g°C × 148.72g × (25 + 20)°C + 4.18 J/g°C × 651.28g × (25 − 0)°C + 2.06 J/g°C × 651.28 g × (0 + 20)°C + 334.4 J/g × 651.28 g = 318.64 kJ, where the specific heat capacity of water, $c_{water} = 4.18$ J/g°C, the specific heat capacity of ice, $c_{ice} = 2.06$ J/g°C, the specific heat capacity of organic matter, $c_{solid} = 0.89$ J/g°C, and the latent heat of fusion $Lf_{water} = 334.4$ J/g water. The energy of methane released by the digestion of 800 g of food waste was estimated to be 1273 kJ. The increased energy

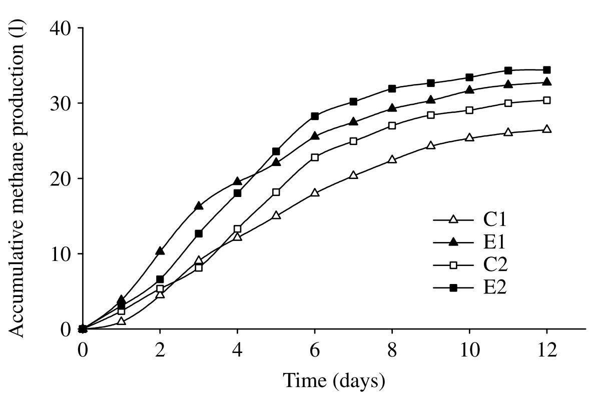

Figure 4 | Accumulative methane productions in control (C) and experiments (E) for thermally treated waste (1) and frozen/thawed waste (2).

was 385 kJ and 302 kJ, respectively, as the food waste was subject to the thermal pre-treatment or freezing/thawing procedure. It seems to indicate that there is no net energy generation, while employing pre-treatment procedures compared to the control tests. In addition, it should be realized that the actual energy required by those pre-treatments could be much greater than the calculated theoretical value since thermodynamic efficiency was not considered. For example, the thermodynamic efficiency of the refrigeration cycle, which is proportional to the temperature difference, i.e. the energy required to cool a sample from 25°C to −20°C is much greater than $C_p \times (25 - (-20))$ as assumed. However, optimization of pre-treatment procedures, such as reducing reaction time might result in an enhanced energy recovery. In fact, an external energy input of 522.5 kJ which was required to heat 1,000 mL from 25°C to 150°C was likely to be saved if only food waste was heated while following the thermal pre-treatment procedure.

CONCLUSIONS

Thermal pre-treatment of food waste at 150°C for 1 hour as well as freezing of food waste for 24 hours at −20°C and then thawing for 12 hours at 25°C facilitated the hydrolytic and fermentation processes in the acidogenic reactor and ensured faster supply of nutrients in the methanogenic reactor. Use of thermal pre-treated food or frozen/thawed food waste reduced operational time of batch digestion by 48% and 42% respectively in comparison with the anaerobic digestion of fresh food waste. Thermal and freezing/thawing pre-treatment enhanced the production of methane, but there is no net energy output as the energy required by pre-treatment procedures is considered.

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