Mass-Energy balance for the Anaerobic Digestion of the Ultrasonicated Sludge

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Abstract

Mass-energy balance is performed to estimate greenhouse gas (GHG) emisssions during sludge management mainly ultrasonication pre-treatment, anaerobic digestion (AD) of the ultrasonicated wastewater sludge, dewatering, transportation and land application of the sludge digestate. The mass and energy balance was also conducted for the non-treated sludge. It was found that the energy release was positive, the energy ratio (energy output/energy input) was greater than one and GHG emissions are reduced at high solids concentration and low ultrasound energy input during sludge ultrasonication. Increased sludge temperature during sonication will reduce the energy input, increases the net energy and energy ratio and reduces GHG emissions. Mass-energy balance for the proposed process indicated that at high solids concentration (44 g TS/L) and low ultrasound energy input (641 kJ/kg TS) is favourable.

Keywords: Anaerobic digestion, ultrasonication, greenhouse gas emissions, specific energy input, net energy, energy ratio

1. Introduction

Global warming and climate change has made it essential to quantify greenhouse gas emissions (GHGs) from each and every source and to implement necessary actions for reducing these emissions. Sludge generated during the wastewater treatment processes convert to CO_2, CH_4 and N_2O (three principal GHGs) during treatment, disposal and/or reuse. GHGs production during sludge treatment and end use processes can constitute up to 40% of the total GHG emissions associated with wastewater treatment [1-3]. Sludge generated during the wastewater treatment is disposed on land as fertilizer, landfilled or incinerated, which are the sources of GHGs [2]. The factors such as environmental problems, increasing stringent sludge disposal regulations, economical sludge disposal and increasing public awareness of the different sludge disposal options are forcing the wastewater treatment plants operators to re-evaluate their sludge management strategies. In recent years, researchers have focused their attention on pre-treatment of sludge to enhance biodegradability of sludge. When considering the pre-treatment technologies, ultrasonication, thermal and Fenton pretreatment technologies have emerged as promising treatment technologies to enhance biodegradability of sludge [3-6] . Pre-treatment of sludge followed by anaerobic digestion (AD) has been considered as one of the beneficial options for stabilising the sludge [4-6]. Among the various available pre-treatment techniques, ultrasonication of sludge is an emerging and promising mechanical disruption technique for sludge disintegration due to several inherent merits like efficient sludge disintegration, improvement in biodegradability, improved solids quality, increased biogas production [4-10].

Based on the increased biogas production, the various researchers [4-10] have concluded that ultrasonication pre-treatment enhances the energy recovery during the AD of the pre-treated sludge. However many issues remain unanswered:

(i). Is enhanced production of biogas due to sludge pre-treatment (ultrasonication) of sludge (secondary) provides positive energy balance?

(ii) How much solids could be reduced during anaerobic digestion for final residual sludge disposal and what was their impact on energy balance and GHG emissions?

(iii) How much temperature increased during sludge ultasonication pre-treatment and what were consequences on overall energy balance?

(iv) What are the conditions of pre-treatment of each technology that could favour a positive energy balance?

(v) What are the consequences of sludge pre-treatment followed by anaerobic digestion of pre-treated sludge on downstream processing of residual sludge or the digestate (dewatering, transportation and digestate application to land)?

(vi) Will the overall energy balance be favorable?

Moreover, during ultrasonication, the solids concentration affects the ultrasonication efficiency as well as the energy input during AD; therefore, it is essential to compute the energy balance for ultrasonication and AD process in relation to sludge solids concentration. Moreover, analysis of data with respect to mass-energy and GHG emissions as criteria to evaluate sludge management including all process steps is not available. These process steps include: (i) sludge pre-treatment process (ultrasonication), (ii) anaerobic digestion, (iii) sludge dewatering, (iv) sludge transportation to land and (v) land application of sludge. Therefore, this study is intended to compute the mass-energy balance and GHG emissions for the sludge management with ultrasonication pre-treatment.

2. Procedure for evaluating mass-energy balance of ultrasonication of sludge, anaerobic digestion and land application of digested sludge

The overall pathway (or system boundary/process steps) considered for evaluating the mass-energy balance and corresponding GHGs estimation is defined in Figure 1. Mainly five steps are considered for evaluating the mass-energy balance. Step 1 ultrasonication of sludge, step 2 anaerobic digestion, and step-3, 4 and 5 are digestate dewatering, transportation and land application, respectively. The mass-energy balance is computed using Microsoft Excel 2003 with the adopted and design values as presented in Table 1.

2.1 Ultrasonication of sludge

Ultrasonication of sludge (first step) enhances sludge biodegradability [5-8, 10-13] by solubilising the suspended solids. During AD, biodegradable carbon is converted to biomass, CO_2 and CH_4. The optimum ultrasonication parameters (ultrasonication time and ultrasonication density) to achieve maximum biodegradability of the secondary sludge were determined by Pham et al. [14]. During ultrasonication, sludge temperature is increased, and it will impact on the cavitation and on the energy requirement for AD process. The specific energy (SE) input for sludge ultrasonication can be calculated by Eq. (1). Specific energy input at different sonication time and sonication intensity evaluated by Pham et al. [14] is considered for evaluating the mass-energy balance (Table 1).

$$SE = \frac{\mathrm{P\ t}}{\mathrm{V\ TS}} \tag{1}$$

where SE is the specific energy input in kJ/kg TS, P is the power input (kW), t is the ultrasonication time (sec), V is the volume of sludge (m^3), and TS is the total solids concentration (kg/m^3).

Calculation of temperature increase during ultrasonication of the sludge

As mentioned above the increase in temperature of the sludge during ultrasonication may have a significant effect on increase in the sludge biodegradability. The cavitation threshold increases with increase in bulk temperature up to 60 ^{o}C, further increase in temperature reduces the cavitation impact. With increase in temperature, the liquid (solution) reaches its boiling point and produces large number of cavitation bubbles concurrently, which acts as barrier to ultrasound wave's transmission and nullify the effect of ultrasound energy [5, 15]. On the other hand, an increase in the sludge temperature during ultrasonication [16-18] will reduce the energy requirements for heating the sludge to 35 ^{o}C (temperature required for anaerobic digestion process). This will impact the net energy gain of the combined process (ultrasonication followed by AD) as the energy required would otherwise be produced by fossil-fired power plants (significant GHG contributors).

From the total energy input during ultrasonication, a part of the energy is transformed into thermal energy (heat energy), which eventually increases the sludge temperature. The total energy input in to the system during ultrasonication is distributed as given below.

$$E_s = E_\alpha + E_C + E_{ab} + E_{ts} \tag{2}$$

E_s - total energy input into the sludge during ultrasonication

E_α - energy dissipated into the sludge sample (responsible for sludge temperature rise)

E_C - energy required for the cavitation

E_{ab} - energy absorbed by the sludge (for disintegration)

E_{ts} - energy transmitted through the sludge (to overcome the attenuation effect)

The total energy required during different fractions of sonication has not been evaluated; therefore, extensive research is needed to understand the energy efficiency of different functions in the ultrasonication system. Due to cavitation threshold the temperature increase during ultrasonication should be maintained below 60 ^{o}C. The temperature of the raw sludge generally varies between 10 -15 ^{o}C, whereas anaerobic digester is operated at a designed temperature (either mesophilic 35 ^{o}C - 40 ^{o}C or thermophilic 55 ^{o}C - 60 ^{o}C). Therefore, the temperature of the sludge needs to be raised to a desired level. Thus, the rise in temperature of the sludge during ultrasonication can substantially reduce the amount of energy required to increase the sludge temperature. Theoretical relation between the sludge temperature increase (Δt) and power required (p) is represented by Equation 3 [19].

$$\Delta T = T_f - T_i = \frac{p\,t}{C_p\,M} \tag{3}$$

where T_f is the final temperature of the sludge, T_i is the initial temperature of the sludge, p is the power diverted for temperature increase of the sludge (W), C_p is the specific heat of the sludge (4.2 kJ /kg ^{o}C) and “M” is the mass of the sludge used (kg) and t is the ultrasonication duration.

Various researchers [16-18] have observed an increase in sludge temperature during ultrasonication, but until date no correlation has been established between ultrasonication power input and sludge temperature rise. There are also contradictory results on the temperature increase during sludge ultrasonication. Many researchers reported an increase in sludge temperature [10, 16, 20-23] whereas the others observed a negligible temperature increase during sludge ultrasonication [17, 24, 25].

We attempted to evaluate the percent power diverted towards heating the sludge (or temperature increase) using Equation 3. In order to calculate the fraction of power utilized to increase the temperature of the sludge during ultrasonication, the data of power input and the corresponding temperature increase (ΔT) of the sludge from Chu et al. [16] and Feng et al. [17] were adopted. Calculations revealed that the percentage of power utilized to increase the temperature of the sludge was only up to 0.12 % of the total power input (723 W for 50 sec ultrasonication time). From the above results it is clear that the calculated fraction of power utilized to increase the sludge temperature was the lowest. At higher total solids content (4% w/v), volume of the sludge and the attenuation effect reduces the effect on the fraction of the power diverted for temperature increase during ultrasonication. In conclusion, there is a large variation of temperature increase due to ultrasonication as reported by various researchers and depends on many factors such as energy input per unit volume, solids concentration, sonication duration and horn height. Therefore it is difficult to compare the results reported by various researchers.

Due to this uncertainty, we performed the energy balance by assuming two cases, Case-1 that there is no temperature increase in the sludge after ultrasonciation and Case-2 an increase by 10 ^{o}C in sludge temperature after ultrasonication.

2.2 Anaerobic digestion of ultrasonicated sludge

The aerobic biodegradability of the ultrasonicated sludge at different solids concentration (Table 1) was evaluated in our previous work by Pham et al. [14] and the data were adopted for evaluating the mass-energy balance during AD of the sludge. Considering biodegradability data of Pham et al. [14], the methane produced in the AD was evaluated according to Equation 4. Moreover, it was found by various researchers that during anaerobic digestion the amount of volatile solids reduced were 10% higher than the total solids degraded [26-28]. Therefore, in order to obtain the amount of volatile solids biodegraded during the AD process, the amount of 10% was added to the total solids biodegraded. The values of volatile solids degraded based on the calculation at different solids concentration and at different specific energy input during sonication are shown in Table 2. Based on the results of Pham et al. [14], anaerobic digestion time (solids retention time) was assumed as 20 days. The volume of methane calculated (according to Equation 4) based on the volatile solids degraded at different solids concentration and different specific energy input is presented in Table 2. During the sludge digestion mainly CO_2 and CH_4 gases are produced. N_2O is mainly produced during nitrification and de-nitrification process. Therefore, production of N_2O during the AD of the sludge was not considered. Carbon dioxide emission from biological pathway is considered as biogenic CO_2 emissions. Therefore, this is not taken into account in national protocols due to the fact that they are considered (by convention) as “carbon neutral” (global warming potential equal to zero) [28]. The CO_2 generated during methane combustion for energy recovery was considered as potential

GHG. The design inputs required to perform the energy balance for anaerobic digestion of ultrasonicated sludge and control sludge are given in Table 1.

Methane produced (m^3/day) = $VS_{reduction}$ (kg /m^3) x 0.5 (m^3 CH_4/ kg $VS_{destroyed}$) x V (volume of sludge, m^3 /day) (4)

2.3 Dewatering, transportation and Land application of digested sludge

It is assumed that digestate is dewatered (Step 3) using centrifuge to increase solids concentration. The supernatant of centrifuged sludge (wastewater) is sent back to the wastewater treatment unit by gravity. The energy required for dewatering the digestate using centrifuge is given in Table 1. Transportation of dewatered solids (step 4) or the quantity of diesel required for the vehicles to transport the solids from wastewater treatment plant (WWTP) to the land application site was considered. The distance between WWTP to land application site to transport the dewatered solids was assumed 50 km [29]. The diesel consumption rate of the waste collection vehicle is 3.5 L per 100 km and GHG emission values are equivalent to 2730 g CO_2/L of diesel, 0.12 g CH_4/L of diesel, and 0.08 g N_2O/L of diesel [29]. The energy required for spreading the dewatered solids on to the land (step 5) is presented in Table 1. The CO_2, CH_4, and N_2O emissions from the land applied digestate are estimated using the factors as reported in Table 1. The GHG emissions in various process steps (the energy consumed during ultrasonication pre-treatment, anaerobic digestion, dewatering of the digested sludge, transportation, and land application) were evaluated using national emission intensity coefficient 0.53 kg CO_2/kWh (developed by Environment Canada study based on the Resources for the Future (RFF) model).

3. Results and discussion

3.1 Mass balance for ultrasonication of sludge, anaerobic digestion, dewatering, transportation and land application of digestate

The results of the mass balance for different solids concentration and different specific energy input are summarised in Table 2. An increase in specific energy input during sludge ultrasonication increased the volatile solids degradation (or reduction) compared to the control, irrespective of the solids concentration. For example, at 23 g TS/L, for control the volatile solids reduction is 37.4% and for SE 1226 kJ/kg TS the volatile solid reduction is 41.3% and for SE 10370 it is 66%. The increased degradation of volatile solids was due to increased solubilisation of sludge organic matter with increased SE input [14].

From the mass balance (Table 2) it is clear that the digestate obtained for dewatering, transportation and land application for the ultrasonicated sludge (at different specific energy input) is lower than the corresponding control. The minimum weight of the sludge (or digestate) generated to dewater, to transport, and for land application was found 23.8 tonnes (Table 2) at specific energy input of 10370 kJ/kg TS.

3.2 Comparison of Case 1 and Case 2 on the energy required for heating the sludge at different solids concentration

The impact of Case 1 and Case 2 on the energy required for heating the sludge to reach 35 ^{o}C (required for the anaerobic digestion) is shown in Figure 2. The energy required for heating the sludge to AD temperature (35 ^{o}C) is lower with increase in temperature of the sludge after sonication (Fig 2), i.e., for Case 1, at 23 g TS/L the energy required for heating the sludge is 884 kWh/t of dry solids, and for Case 2 the energy required is 761 kWh/t of dry solids. At higher solids concentration (44 g TS/L), comparatively lower amount of energy was required to heat the sludge to 35 ^{o}C. This was attributed to the heating the less volume of sludge at high solids concentration. For example, at 23 g TS/L, 1739 m^{3}/day of sludge is required to heat, whereas at 44 g TS/L, only 909 m^{3}/day is required to heat.

3.3 Effect of solids concentration on Energy and GHG emissions

3.3.1 Effect of solids concentration on net energy

The total energy input (for sonication, anaerobic digestion, dewatering, transportation and land application), energy recovered and the net energy recovered corresponding to the different specific energy input during sonication for 23, 33 and 44 g TS/L was presented in Figure 3a, 3b and 3c, respectively. With increase in the total energy input, the energy recovered was increased compared to the control (without sonicaton) irrespective of the solids concentration. For example, at 23 g TS/L for control the energy recovered is 993 kWh/t of dry solids and for SE 1226 kJ/kg TS the energy recovered is 1570 kWh/t of dry solids and for SE 13070 kJ/kg TS the recovered is 2508 kWh/t of dry solids. The recovered energy increased due to high volatile solids degradation with corresponding increase in methane generation. But for small increase in the total energy input, there was no increase in the energy recovery, i.e. for specific energy input of 3457 and 3678 kJ/kg TS, the energy recovered remained constant (Fig 3a). This was due to the fact that the volatile solids reductions remained constant (Table 2).

The net energy (energy recovered-total energy input) at different specific energy input during sludge sonication for different solids concentration revealed that at low solids concentration the net energy was negative. This is due to the fact that at low solids concentration (the volume of the sludge is high) the energy required to heat the sludge is very high (Fig 2) as compared to the energy recovered. At low solids concentrations (23 g TS/L) with increase in specific energy input during sonication the energy balance was increasingly negative (Fig 3a). However, considering the 10 ^{o}C increase in the temperature of the ultrasonicated sludge showed, higher net energy was observed at all solids concentration. At higher solids concentration and lower specific energy input during sonication, the net energy is positive (Fig 3c). For example, at 44 g TS/L, the net energy for the control was -131.4 kWh/t TS, and at specific energy input of 641 kJ/kg TS the net energy was 459.5 kWh/t TS with no increase in temperature of the sonicated sludge. At increase in 10 ^{o}C during sonication, the net energy increased to 724.69 kWh/t TS. However, at higher specific energy input (5420 kJ/kg TS) the net energy became negative (-925.8 kWh/t TS).

At 33 g TS/L the net energy was negative for the control i.e. net energy was -309.44 kWh/t TS of control and -496.49 kWh/t TS at specific energy input of 3135 kJ/kg TS for 0 ^{o}C increase in the temperature of the sonicated sludge. But considering 10 ^{o}C increase of the sonciated sludge, the net energy was comparatively higher but still negative (-142.95 kWh/t TS). The data for specific energy input are available only at high energy input and at this high specific energy input the net energy is negative. Therefore, further experiments are required at lower specific energy input and at 33 g TS/L to evaluate the domain of positive net energy with respect to input energy for sonication. Moreover, an increase in the energy input increases the solids solubilisation but beyond a certain energy input (optimum) there is no impact on sludge solubilisation. Therefore, at high solids concentration with low specific energy input during sonication the net energy balance is positive (Fig 3c).

3.3.2 Effect of solids concentration of energy ratio

The energy ratio (energy output/energy input) at different specific energy input for different solids concentration was presented in Figures 4a, 4b and 4c. The energy ratio for the sonicated sludge was greater than the control at all solids concentration but increasing the specific energy input the energy ratio became less than the control. For example, with specific energy input of 10370 kJ/kg TS and at solids concentration of 23 g TS/L, the energy ratio was 0.55 (ultrasonicated), whereas the energy ratio for the control was 0.58. Similarly, at 44 g TS/L, the energy ratio was more than one up to specific energy input of 1923 kJ/kg TS during sonication (Figure 4c). Moreover, increase in temperature of the sludge after ultrasonication increased the energy ratio irrespective of solids concentration and the energy input. For example, at specific energy input of 641 kJ/kg TS and 44 g/L TS, the energy ratio was 1.37 (Case 1) and 1.74 (Case 2) (Fig 4c). At higher sonication specific energy input the energy ratio was less than one, irrespective of solids concentration (Figure 4a, 4b, and 4c). As mentioned above at solids concentration 33 g TS/L, low specific energy input data need to be generated. Therefore, the low specific energy input during sonication and high solids concentration should be preferable to have a net energy balance positive or energy ratio greater than one.

3.3.3 Effect of solids concentration on GHGs

The total GHG emissions at different specific energy input during sonication and for different solids concentration are presented in Figure 5a, 5b and 5c. Increase in the specific energy input increased the energy demand but did not generate corresponding high amount of methane, which substantially enhanced the total GHG emissions irrespective of specific energy input during sonication and the sludge solids concentration (Figure 5). Comparing the effect of temperature (Case 1 and Case 2) on the GHGs, it is clear that considering the increase in temperature of sludge after sonication (Case 2) will reduce the GHGs (Figure 5). For example, at a specific energy input of 1226 kJ/kg TS and sludge solids concentration of 23 g/L TS, the GHGs are reduced by 37.7% for Case 2, compared to Case 1. Similarly at high solids concentration (44g TS/L) for specific energy input of 641 kJ/kg TS the GHG emissions were reduced by 34 % (Case 2). Moreover, it is also evident that at low specific energy input and high solids concentration GHGs are reduced compared to the control (Figure 5).

Based on maximum sludge biodegradability during ultrasonication, Pham and co-workers [14] concluded that 23 g TS/L with 10362 kJ/kg TS energy input during ultrasonication was the optimum condition. The methane generated (11804 m^3, Table 2) under these conditions (as computed in this work) was also maximum. However, this study has established that considering the mass-energy balance of ultrasonicated as well as non-sonicated sludge followed by anaerobic digestion (considering the biodegradability or volatile solids degraded) and downstream steps (sludge dewatering, transportation and land application of the digestate) at solids concentration of 44 g TS/L and at lower specific sonication energy input (641 kJ/kg TS) there is a positive energy balance with energy ratio greater than one and reduced GHG emissions. Therefore conclusion merely based on biodegradation and increase in methane generation may be misleading with respect the energy recovery and the energy ratio as well as GHGs emissions.

5. Conclusion

We can conclude that there is no correlation between ultrasonication power input and sludge temperature rise. The theoretical calculation performed in this work revealed that the percentage power utilized to increase the temperature of the sludge during sludge ultrasonication was the lowest. Mass-energy balance of ultrasonication, anaerobic digestion, dewatering, transportation, and land application of sludge concluded that at high solids concentration (44 g TS/L) and low ultrasound energy input (641 kJ/kg TS) is favourable. The net energy and energy ratio of the ultrasonicated sludge was greater than the control at all solids concentrations (23, 33 and 44 g TS/L). Considering the temperature increase by 10 ^{o}C during ultrasonication increased the net energy and energy ratio. Greenhouse gas emissions are reduced at high solids concentration (44 g TS/L) and low ultrasound energy input 641 kJ/kg TS). Greenhouse gas emissions are also reduced by considering the temperature increase in the sludge after ultrasonication.

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Table 1. Operating parameters considering in evaluating mass-energy balance and GHGs

Parameter	**Value**	**Unit**	**Reference**
Mass of sludge to be treated	40000	Kg dry TS /day	Assumed
Total solids concentration	23, 33, 44	g TS/L	
Specific energy input at 23 g TS/L (i) 20 min sonication time 0.27 W/ cm^2 (ii) 40 min sonication time 0.75 W/ cm^2 (iii) 60 min sonication time 0.27 W/ cm^2 (iv) 60 min sonication time 0.75 W/ cm^2	 1226 3457 3678 10370	kJ/kg TS	[14]

Specific energy input for 33 g TS/L (v) 40 min sonication time 0.52 W/ cm^2	3235	kJ/kg TS	[14]
Specific energy input for 44 g TS/L (vi) 20 min sonication time 0.27 W/ cm^2 (vii) 20 min sonication time 0.75 W/ cm^2 (viii) 60 min sonication time 0.27 W/ cm^2 60 min sonication time 0.75 W/ cm^2	641 1807 1923 5421	kJ/kg TS	[14]
Temperature of Control sludge Sonciated sludge	10 20	^oC	Assumed
Anaerobic digestion temperature	35	^oC	[30]
Density of sludge	1000	Kg/m^3	[30]
Heat loss during anaerobic digestion	150.84	kJ/day m^3 of reactor volume	[30]
Mixing and pumps power requirement Control Sonicated sludge	10 6.5	W/ m^3 reactor volume	[9, 31]
Methane production rate for control Methane production rate for sonicated sludge	0.499 0.73	m^3 $CH_{4/}$ kg $VS_{destroyed}$	[9, 32]
Heating value of methane	31.79	MJ/m^3 CH_4	[30]
Volumetric mass of methane	0.714	kg CH_4/m^3	[30]
Energy required for land application	351.68	kWh/tonne of dry solids	[33]
Land application of sludge CH_4 emissions CO_2 emissions N_2O emissions	3.18 17.2 0.03	kg CH_4/tonne of dry solids kg CO_2/tonne of dry solids Mg of CO_2 equivalent /tonne of dry solids	[1, 26, 33, 34]

Table 2. Mass balance of control and sonicated sludge at different solids concentration

Description	**23 g TS/L**					**33 g TS/L**		**44 g TS/L**				
	Specific energy input (kJ/kg TS)					**Specific energy input (kJ/kg TS)**		**Specific energy input (kJ/kg TS)**				
	0	**1226**	**3457**	**3678**	**10370**	**0**	**3235**	**0**	**641**	**1807**	**1923**	**5421**
Mass of dry solids (kg) entering AD	40000					40000		40000				
%Volatile solids degradation at HRT 20 days	37.4	41.3	42.6	42.6	66	37.90	44.63	36.2	44.8	43.2	42.5	43.4
Volume of methane Produced (m^3)	4673	7387	7619	7619	11804	4736	7982	4523	8013	7726	7601	7762
Weight of Volatile degraded during AD (kg)	9163	10118	10437	10437	16170	9286	10934	8869	10976	10584	10413	10633
Digestate dry solids remaining after centrifugation, which will be transported and land applied	30837	29882	29563	29563	23830	30714	29066	31131	29024	29416	29587	29367

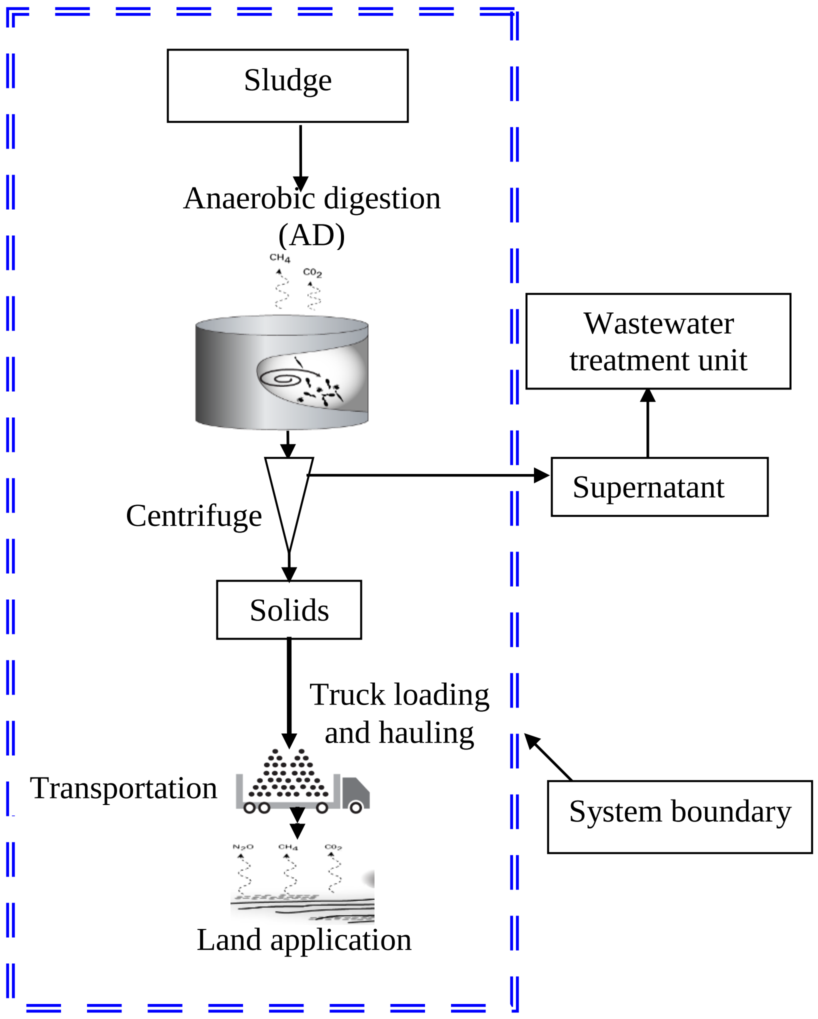

Figure 1. Pathway (or system boundary) considered for evaluting mass-energy balance and GHGs

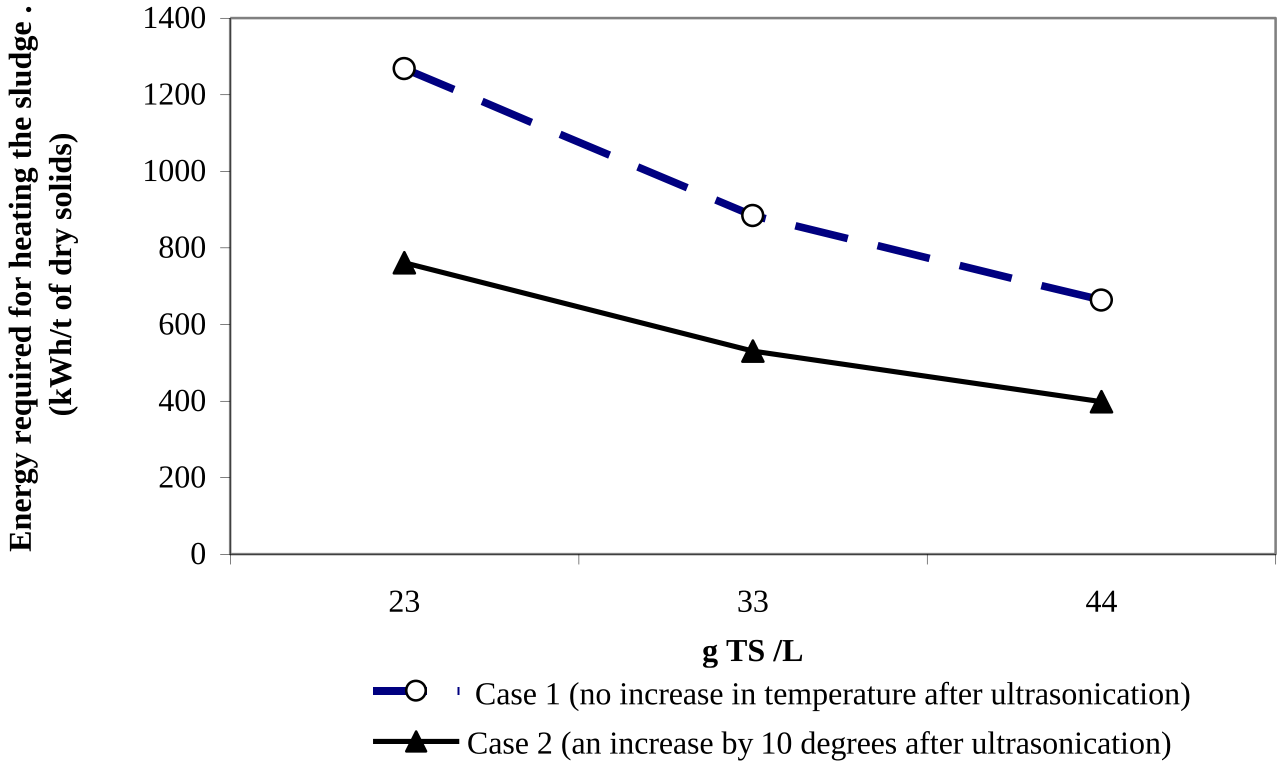

Figure 2. Effect of rise in sludge temperature during ultrasonication on the energy requirement for heating the sludge to 35 °C required for anaerobic digestion

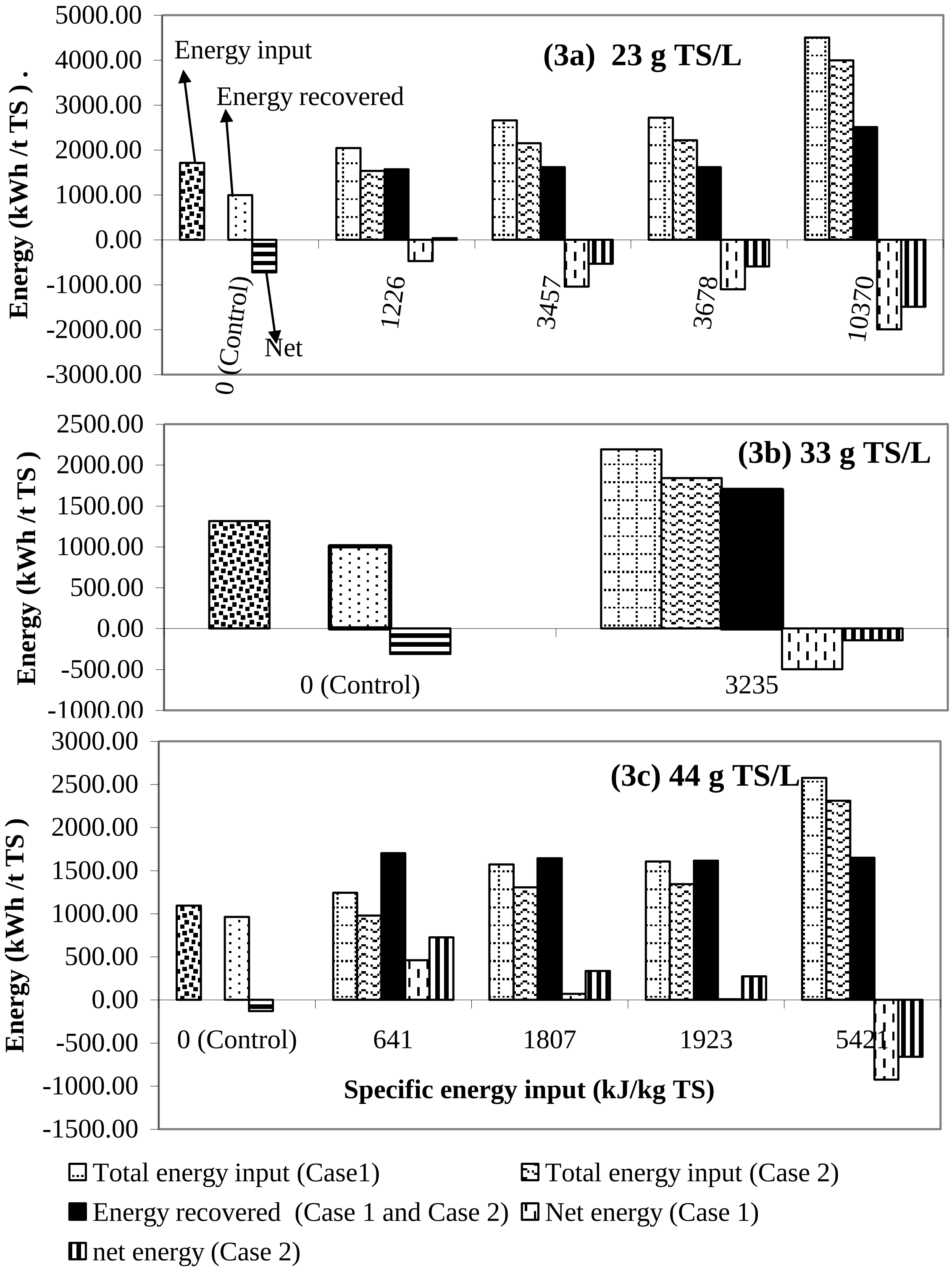

Figure 3. Effect of increase in temperature during ultrasonication on the total energy input and energy recovered and net energy at different solids concentration and specific energy input during ultrasonication.

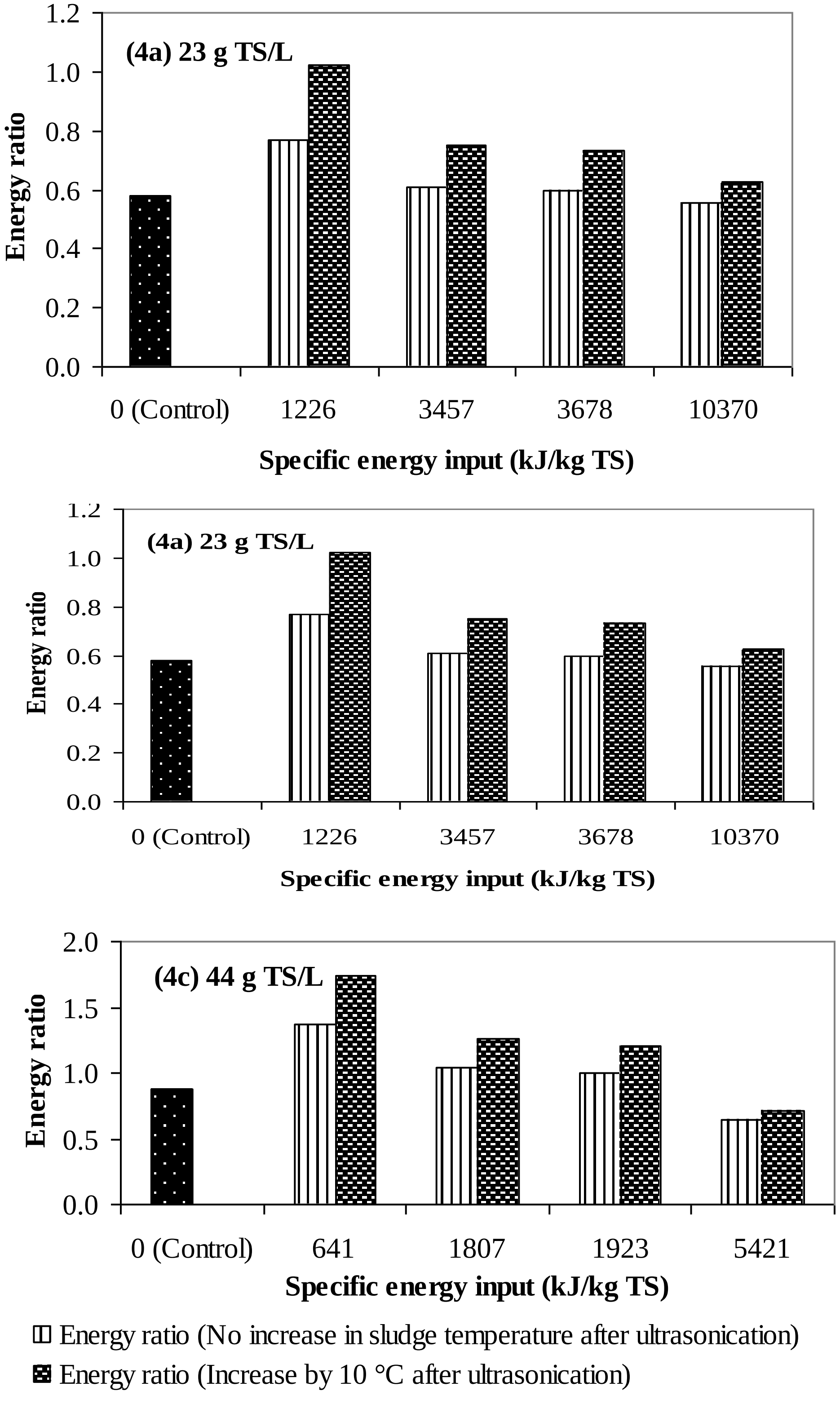

Figure 4. Effect of rise in temperature during ultrasonication on the energy ratio at different solids concentration and at different specific energy input during ultrasonication

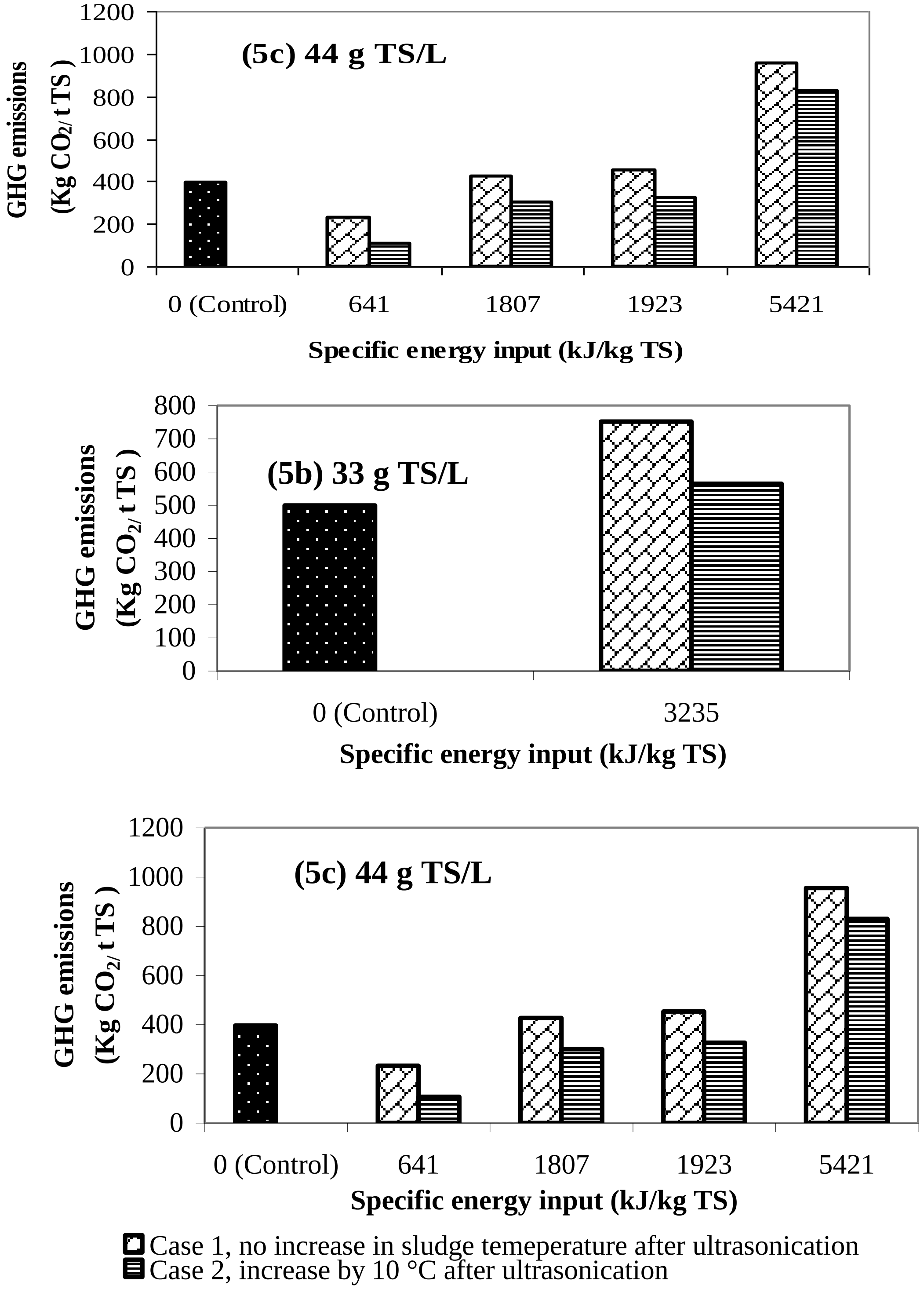

Figure 5. Effect of rise in temperature during ultrasonication on the GHG emissions at different solids concentration and at different specific energy input during ultrasonication