TOWARDS SUSTAINABLE WASTE MANAGEMENT: REUSE AND ENERGY RECOVERY POTENTIALS FROM WASTE WATER SLUDGES AND AGRO-WASTES

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ABSTRACT

A growing concern has emerged during the recent years for innovative, environmentally sound and economically viable opportunities for sustainable agricultural waste management. In sustainable waste management systems, there is a reduced reliance on non-renewable energy sources and a substitution of renewable sources by using agro-wastes (crops residuals, etc.). In recent years, the co-digestion of energy crops and agro-industrial wastes with wastewater sludge has become a promising technology that is increasingly being used to improve the biogas yield. This study aims to investigate the biogas production potential of wastewater sludges co-digested with agricultural biomass (energy crops including cloverleaf, wheat, grass, barley and manure and crops' residuals as being nutshell, potato peel, olive bagasse and maize silage) through mesophilic anaerobic digestion. The study showed that the applied co-digestion process appeared to be more effective than single sludge digestion in terms of biogas production and organics removal. The highest biogas and methane yields were obtained by wastewater sludges co-digested with cloverleaf as 834 $m^3/gVS_{degraded}$ and 400 $m^3CH_4/gVS_{degraded}$, respectively. The maximum biogas yield from single sludge digestion was only 240 $m^3/gVS_{degraded}$.

Keywords: Agro-wastes; anaerobic co-digestion, biogas production, energy crop, methane yield, wastewater sludges.

1. INTRODUCTION

Recent investigations on sustainable/renewable energy have been focused on the new alternative energy sources especially the "bio-wastes" [1]. The production of biogas, gaseous fuels produced from different types of biomass, has recently become one of the key strategic issues in Turkey like all around the World and consequently, the energy deficiency of Turkey has resulted in the development of new technologies for the efficient use of biogas. In the literature, the majority of the studies on biogas production investigated sources like municipal organic waste, livestock manure, animal wastes and several industrial wastewaters [2-4]. Latest progress in biogas production has been made in cultivating energy crops and crops residual for the biogas production in using reactor systems for the anaerobic digestion. Therefore, several types of feedstock with their abundant availabilities in Turkey can be used as the suitable materials for the anaerobic digestion due to its high biomass yield and biogas production capacity.

The anaerobic digestion of feedstock "alone" is, however, may not be always efficient since the required nutrients in the some feedstock like maize silage are not at adequate level for the bacterial growth. In these cases, co-digestion is one of the solutions applied to increase the digestion efficiency and the biogas production capacity. In most case, the addition of wastewater sludge to agricultural products would improve the efficiency of anaerobic digestion by achieving optimum C/N ratio. In addition to the improved biogas generation, co-digestion process generates an alternative solution for the disposal problem of waste materials like sewage sludge, which is generated in excessive amounts all over the World.

Turkey, having a large agricultural potential, produces around 65-Mtons of agricultural waste annually from fruit and vegetable processing. On the other hand, treatment and disposal of gradually increasing wastewater sludges (WAS) is another important global problem. Based on the surveys filled out by wastewater treatment plant operators, total daily sludge production in Turkey was around 332 ktons (on dry basis) in 2013 and expected to reach 911 ktons on dry basis by the year 2040 [6].

There are many sludge disposal techniques currently applied such as incineration, landfilling, composting, etc.; but the sludge disposal with these conventional methods is difficult and expensive, often requiring over 50% of the operating budget for the treatment plant [7]. Among all, energy recovery from WAS appears to be one of the most favorable way of sludge reuse/disposal.

In terms of energy efficiency, anaerobic digestion (AD) is one of the most preferred sludge stabilization methods in Turkey. AD is a microbially mediated biochemical degradation of complex organic material into simple organics and dissolved nutrients. This process has several advantages such as producing renewable energy, accommodating relatively high rates of organic loading and preventing transmission of diseases while stabilizing waste organic matter. There is substantial amount of scientific work on cultivating energy crops and crops residual for biogas production in reactor systems through the AD process [8-15].

The aim of this study was to assess the viability of the anaerobic “co-digestion” of WAS with several agricultural products, energy crops (cloverleaf, wheat, grass, barley and manure) and agro-wastes, crops’ residuals (nutshell, potato peel, olive bagasse and maize silage), in order to investigate the maximum biogas production potential.

2. MATERIALS AND METHODS

2.1. Substrates

In the study, WAS samples were obtained from the return activated sludge stream of an advanced wastewater treatment plant located in Istanbul Metropolitan Area. The inoculum sludge (I) used for seeding the batch reactors was obtained from a full-scale anaerobic digester of one of the biggest yeast factories in Turkey operated at mesophilic conditions. The characteristics of the sludge samples are given in Table 1. The conducted analyses for the mixtures of substrates and sludge were performed according to the Standard Methods for the Examination of Water and Wastewaters [16].

Table 1. Characteristics of the sludge samples used in the research

Parameter	**Unit**	**Inoculum**	**Wastewater Sludge**
TS	mg/L	38331	20992
VS	mg/L	25360	12385
MLSS	mg/L	37250	15480
MLVSS	mg/L	24000	9570
COD	mg/L	38470	16750
sCOD	mg/L	5154	927
TKN	mg/L	870	980
NH^{4+}	mg/L	294.00	51.75
TP	mg/L	430	410
PO_4^{-3}	mg/L	1310	1260
SO_4^{-2}	mg/L	110	5
Capillary Suction Time (CST)	sn	>1000	51.3
Alkalinity (as $CaCO_3$)	mg/L	5302.5	1155
pH	-	7.3	6.72
Conductivity	mS/cm	20.10	3.02
Salinity	‰	14.0	1.8
Total Coliform	kob/100mL	$2.0*10^6$	$2.0x10^6$
Fecal Coliform	kob/100mL	$2.2*10^5$	$1.6x10^5$
Fecal Streptococ	kob/100mL	$3.2*10^4$	$4.4x10^4$

The selected agricultural biomass products (energy crops) were cloverleaf, wheat, grass, barley and manure and the agro-wastes (energy crops' residuals) were nutshell, potato peel, olive bagasse and maize silage. Parkin and Owen reported that the agricultural products which are known for their insufficient nutrient content were not effective substrates in anaerobic mono-digestion [17]. In methane production, the optimal carbon to nitrogen ratio (C/N) is accepted to be 20 to 30. For that reason, the addition of WAS having C/N ratio of about 6-16 to these products improves the efficiency of anaerobic digestion to a great extent by achieving the desired C/N ratio [18].

2.2. System Configuration and Reactor Loadings

The substrates were anaerobically digested for 40 days in 2500 mL reactors each having 1600 mL active working volumes. The digestion was performed at mesophilic conditions (37 °C).

The degree of waste stabilization and the fate of waste constituents were evaluated throughout the study with regular monitoring of gas samples collected from the reactors. All reactors were equipped with a V shape gas collection port at the top. One of the openings was connected to a MiliGascounter® (Ritter MGC-1) by silicone tubing to measure the amount of biogas produced and the other opening was used to take samples for gas composition. The gas composition (CH_4 and CO_2) analysis was performed by using HP 6850 Gas Chromatograph (Carboxen 1010 plot column 30 m x 0.53 mm) equipped with a thermal conductivity detector.

In the study, anaerobic digestion process was performed in 22 identical reactors operated in parallel. The inoculum contents of the reactors were 33% of the total mixture by weight. In all of the reactors, the initial total solid (TS) contents were adjusted to 6.5% on weight basis. The content of the reactors were given in Table 2.

Table 2. The content of the reactors

Reactors	**Content**
R1	I
R2	I + Wastewater Sludge
R3	I + Wastewater Sludge + Cloverleaf
R4	I + Wastewater Sludge + Wheat
R5	I + Wastewater Sludge + Nutshell
R6	I + Wastewater Sludge + Potato Peel
R7	I + Wastewater Sludge + Olive Bagasse
R8	I + Wastewater Sludge + Maize Silage
R9	I + Wastewater Sludge + Grass
R10	I + Wastewater Sludge + Barley Silage
R11	I + Wastewater Sludge + Manure

3. RESULTS AND DISCUSSIONS

The anaerobic digester performance was known to be influenced by pH and alkalinity values. The pH values in the reactors ranged between 7 and 7.6 while the alkalinity concentrations were in the range of 2300 - 7500 mg $CaCO_3$/L, indicating a potentially well-balanced anaerobic digestion process.

The effects of the anaerobic co-digestion of the wastewater sludges with the agricultural biomass products on the anaerobic biodegradability were evaluated in terms of the organic removal efficiency and the biogas production. The initial and final total solid (TS) and volatile solid (VS) contents of the reactors are presented at Figures 1 and 2, respectively.

As it can be seen from Figure 1, TS removal efficiencies of the reactors were in the range of 51-79%. The highest TS removal of 79% was achieved at reactor R9 including the mixture of WAS and grass, while the lowest removal efficiency of 51% was obtained in reactor R2 including only WAS. The results showed that addition of agricultural biomass into the reactors as co-substrate increased the TS removal efficiencies by 22 to 55% compared to mono sludge digestion.

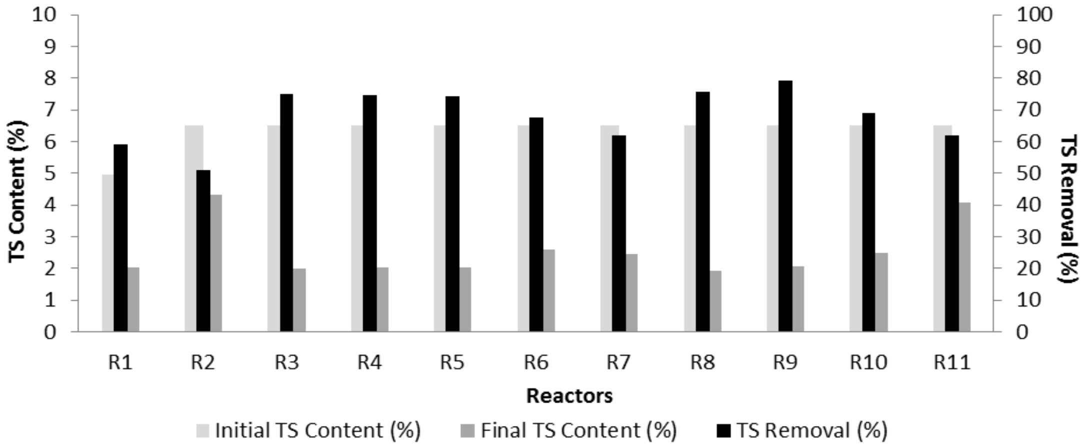

Figure 1. TS content and removal of the reactors

It is revealed from Figure 2 that the addition of agricultural biomass to WAS as co-substrates increased VS removal efficiencies in all of the reactors by 25-60% which consequently resulted in higher biogas productions. VS removal efficiencies of the reactors were in the range of 54-87% (Figure 2). The highest VS removal efficiency of 87% was achieved in reactor R3 having a mixture of wastewater sludge and cloverleaf, while the lowest removal efficiency of 54% was obtained in reactor R2 containing only wastewater sludge. The values reported by other researchers on the VS reductions were found quite comparable with the findings of this study. Parkin and Owen, as an example, obtained a 20 to 50% of VS reduction in WAS digestion [17].

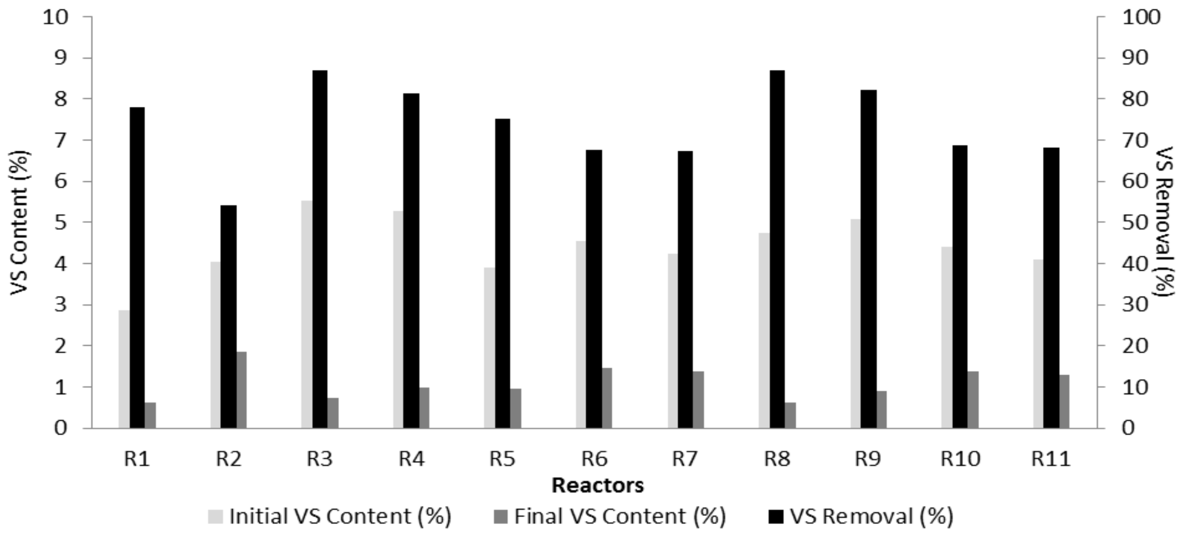

Figure 2. VS content and removal of the reactors

The percent soluble chemical oxygen demand (sCOD) removals in the reactors were in the range between 54-91%. The results followed a similar trend with the VS removal efficiencies. The highest sCOD removal efficiency of

91.05% was obtained in reactor R3 having a mixture of wastewater sludge and cloverleaf. The lowest removal efficiency of 54% was obtained in reactor R2 accommodating just wastewater sludge samples.

Table 3 presents the microbiology results of the study. These results showed that the applied anaerobic co-digestion process was very effective in the removal of the pathogens. The final fecal coliform and fecal streptococ concentrations in the reactors were found to be quite negligible while the total coliform concentrations remained at accepted levels [19].

Table 3. Microbiology results of the reactors

Reactors	Total Coliform "Initial" [kob/100mL]	Total Coliform "Final" [kob/100mL]	Fecal Coliform "Initial" [kob/100mL]	Fecal Coliform "Final" [kob/100mL]	Fecal Streptococ "Initial" [kob/100mL]	Fecal Streptococ "Final" [kob/100mL]
R1	$2.0x10^6$	$1.1\ x10^2$	$2.2x10^5$	≤1	$3.2x10^4$	42
R2	$2.0x10^6$	$1.5\ x10^2$	$1.6x10^5$	≤1	$4.4x10^4$	14
R3	$2.5x10^6$	$4.1\ x10^2$	$3.8x10^5$	1.4	$1.4x10^4$	≤1
R4	$4.2x10^6$	$3.0\ x10^2$	$1.7x10^5$	2.5	$4.6x10^4$	12
R5	$1.8x10^6$	$5.0\ x10^2$	$1.2x10^5$	1.0	$2.0x10^4$	10
R6	$3.1x10^6$	$1.5\ x10^2$	$2.2x10^5$	≤1	$2.0x10^4$	≤1
R7	$2.0x10^6$	≤ 1	$1.5x10^5$	2.3	$5.4x10^4$	≤1
R8	$2.5x10^6$	$4.0\ x10^2$	$4.0x10^5$	78	$2.3x10^4$	12
R9	$5.0x10^6$	$2.0x10^2$	$1.8x10^5$	51	$8.0x10^4$	7
R10	$1.7x10^6$	≤ 1	$1.1x10^5$	≤1	$1.7x10^4$	≤1
R11	$2.5x10^6$	$2.2\ x10^2$	$1.8x10^5$	≤1	$3.3x10^4$	≤1

In the chromatographic Volatile Fatty Acid (VFA) analysis, acetic, propionic, butyric, caproic and valeric acids, with the first two being the predominant components, were detected in the reactors. At the end of the anaerobic digestion process, in all of the reactors, VFAs were degraded completely by methanogens to produce CH_4 and CO_2.

The initial and final NH^{4+}-N concentrations in the reactors were measured to investigate the potential inhibitory effects of ammonium on methanogens and found to be in the range of 20-55 mg/L., which were at safe levels in terms of ammonia inhibition reported in the literature. The results on VFA and methane productions also showed that there was no methanogenic activity inhibition sourcing from free ammonia nitrogen.

Methane contents of the reactors also indicated the stability and performance of the anaerobic digesters. In this study, the highest methane content of 59 and 58% was obtained in reactors R3 and R8 containing the mixtures of wastewater sludge with cloverleaves and grass; respectively, while the lowest methane content of 39% was obtained in reactor R5 having nutshells. The nutshells used in the study were impossible to grind into powder form with the available grinder in the laboratory. The course grinding that limits the solubility of organics in the nutshells might be the reason of low CH_4 content in the biogas obtained from R5. The cumulative biogas and methane productions in the reactors were recorded daily for a 40-day period and the results are presented in Figure 3.

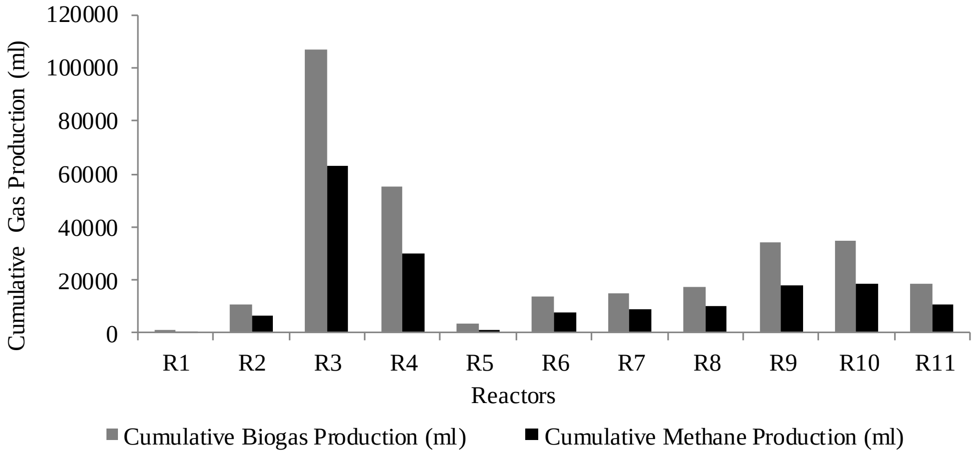

Figure 3. The cumulative biogas and methane productions of the reactors

Maximum cumulative biogas productions among the reactors were measured to be 107,058 mL and 55,500 mL for the reactors R3 containing cloverleaf and R4 having wheat, respectively. The biogas volume for the reactor R2 with the wastewater sludge alone was only 10,844 mL after 40th day of digestion. It means that, in reactor R3, the cumulative biogas production was almost ten times and the methane yield was twice higher than that in reactor R2 containing WAS alone.

The ultimate biogas and methane yields of the batch mesophilic anaerobic digesters operated in the study are presented at Figure 4. It is clear that the addition of agricultural biomass to WAS as co-substrates increased biogas and methane yields (with the exception of reactor R5 including nutshells). Mixing of nutrient and carbon-rich wastes in the co-digestion process helped reach more desirable carbon to nitrogen ratio (C/N).

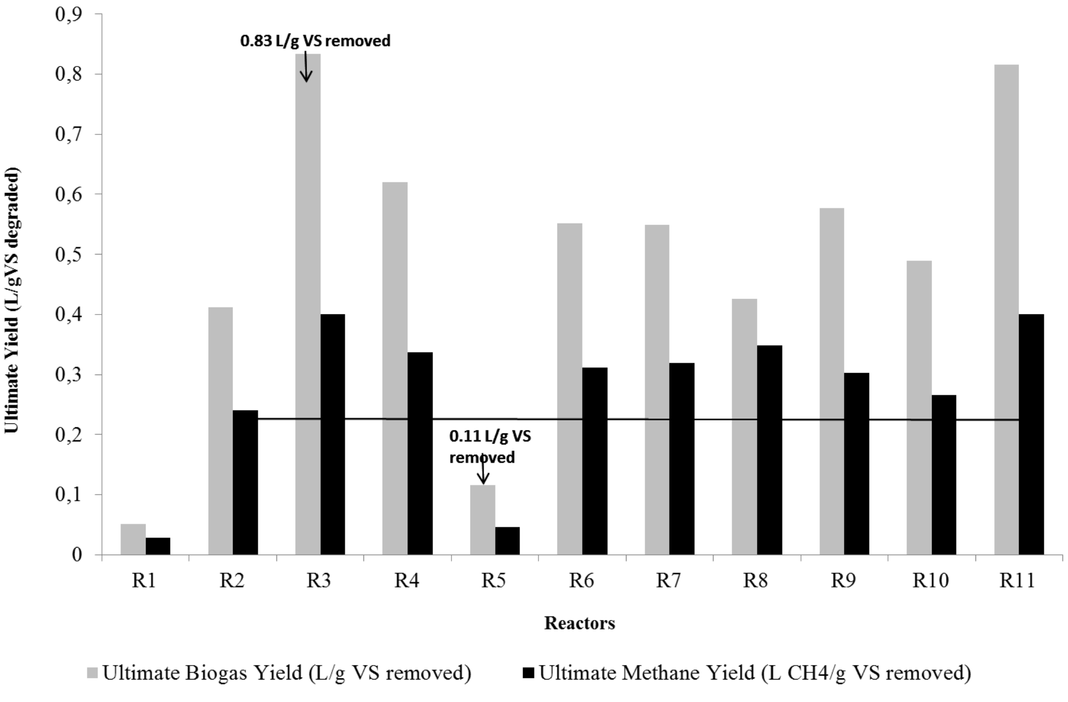

Figure 4. Ultimate Biogas and Methane Yields at the Reactors (L/g VS removed)

Taken overall, the results in Figure 4 suggest that, based purely on the cumulative gas production and biogas and methane yields, cloverleaf is the most successful substrate for the co-digestion with WAS. From this figure it is also shown that biogas and methane yields obtained from agricultural waste materials were compatible with those obtained from energy crops except cloverleaf. The addition of agricultural biomass, regardless of being energy crop or waste, as co-substrate promoted anaerobic digestion and biogas/methane production efficiency. Results showed that the presence of only nutshell in WAS digestion provided a reduced yield (46 $m^3/gVS_{degraded}$), compared with the control value of 240 $m^3/gVS_{degraded}$ from single sludge digestion. The problems in grinding the nutshells to powder form (with limited solubility of organics) is believed to be the main reason of these lower yields. Whereas the highest biogas yield was 833 $m^3/g\ VS_{removed}$ when the sludge was co-digested with cloverleaf.

4. CONCLUSIONS

In this study, the biogas production potential of several agricultural biomass (cloverleaf, wheat, nutshell, potato, olive bagasse, maize silage, grass, barley and manure) co-digested with WAS generated from the wastewater treatment plants was investigated through the anaerobic digestion process. The effects of the applied co-digestion process on the anaerobic biodegradability were evaluated in terms of the biogas production and the organic removal efficiency.

The results showed that the anaerobic co-digestion of wastewater sludges and agricultural biomass, regardless of being agricultural crops or waste, was a viable and more convenient option for the improvement of the biogas production than sludge mono digestion. When the agricultural products and the wastes are compared based on their energy production potentials, the energy production from the waste materials are found to be enough efficient and quite compatible with the potential energy obtained from agricultural crops itself. Instead of fossil fuels, the use of widely available renewable resources like biomass to adopt and sustain clean energy strategies is come up as a promising solution.

The applied co-digestion in the study increased the methane yields in the reactors by 11 to 67% due to the improved balance of nutrients. In addition to the improved biogas generation; co-digestion process generates an alternative solution for the disposal problem of wastewater sludge.

The most efficient biodegradation and the highest biogas and methane yields were obtained from reactor R3 having a mixture of wastewater and cloverleaf to be 0.83 $L/gVS_{removed}$ and 0.40 $CH_4L/gVS_{removed}$, respectively. The cumulative biogas production was almost ten times higher for this reactor R3 than mono- sludge digestion reactor R2.

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