ATIPC – 2020 Special Issue

J. Indian Chem. Soc.,
Vol. 97, No. 12b, December 2020, pp. 2840-2846

Co-digestion of organic fraction of municipal solid waste (OFMSW) and industrial organic solid waste

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Manuscript received online 11 December 2020, accepted 31 December 2020

Co-digestion is a technique increasingly used for the concomitant treatment of various liquid and solid organic wastes. In anaerobic co-digestion, organic solid wastes from industries like food, paper and pulp, slaughterhouse etc. are mixed with the organic fraction of municipal solid waste (OFMSW) to facilitate high rate of stabilization. The objective of mixing various substrates in this process is to control C:N ratio by adjusting the proportion of biodegradable substrates. The present paper explored the scope of co-digestion of OFMSW with various industrial wastes. It has been found that there is high potential and benefits of co-digestion towards smooth stabilization of industrial solid wastes. Many studies in this area have resulted in more balanced and nutrient-assorted substrate that improves the production of biogas for the composite OFMSW-industrial waste mix.

Keywords: Industrial organic solid waste, OFMSW, anaerobic stabilization, co-digestion, C/N ratio.

Introduction

Organic waste is a natural refuse type that comes from plants or animals. It comes in many forms – food waste, biodegradable plastics, paper waste, green waste, human waste, manure, sewage, and slaughterhouse waste. Earlier, the organic waste was disposed through landfill all over the world. At present, landfilling is no longer the advisable solid waste management method which causes serious long-term adverse effects to environment. Because of the oxygen deficit, organic waste undergoes the process of anaerobic decomposition until it buried in a landfill. It releases methane, which is considered to be a greenhouse gas. Hence, capturing methane from anaerobic digestion and its' utilization is extremely needful in stabilizing OFMSW.

Retaining certain elements of urban organic waste, as well as numerous other materials, the organic fraction of industrial waste spans a broad spectrum. Paper mill sludge, meat processing waste, brewery waste, and textile mill fibers are a couple of examples of industrial organic waste. Waste managers constantly experiment with various "recipes" for stabilization of industrial organic waste. Because certain processed industrial wastewaters and sludge contain high levels of organic content, they could be used as soil fertilizers and amendments as well. However, anaerobic digestion (AD) is a new technology, which supports the increase of the renewable energy in form of biogas[1].

The AD of organic waste has valuable benefits like reducing the volume at landfills, faster degradation process, reducing greenhouse gases and along with production of biogas which is clean energy[2].

The AD process is found to be difficult in controlling due to some drawbacks. In this regard, co-digestion is an interesting option that may boost the biogas production and process efficiency requiring for adding at least two waste components for anaerobic digestion[1,3]. The objective of this review is to explore the impact and flexibility of AD in stabilizing two different organic wastes with recent results, viz. OFMSW and industrial organic solid waste simultaneously with additional benefits contributing to the renewable energy sector. The goal is also set to find out the potential advantages over the conventionally practiced management techniques, for stabilization of all the above-mentioned organic wastes.

Industrial organic solid wastes

The industrial organic wastes considered in this study are solid organic residue from food, slaughterhouse, paper and pulp industry etc.

Many wastewater treatment plants (WWTPs) adopting AD for sludge treatment face the issue of low organic loading and biogas (methane) yields[4]. Thus, a sustainable approach for combating this problem is co-digestion of industrial organic waste i.e. industrial sewage sludge from WWTPs with OFMSW to increase biogas production. Several studies resulted the efficient co-digestion of sewage sludge and OFMSW[5,6]. In particular, the adding of sewage sludge with OFMSW improves the C:N ratio of mixes and stimulates biogas production through AD under mesophilic digestion[7].

The food production produces a significant amount of waste, including solid and liquid, during processing and consumption. The food processing sector in India includes fruits and veggies, meat, bakery items, milk products, soy protein, protein rich foods, etc.[8]. Carbohydrates, proteins and lipids are mainly present in food waste. The composition varies depending on food waste type. The food waste containing primarily of rice and vegetables is ample in carbohydrates and the food waste containing primarily of meat and eggs is rich in protein and lipids. This food waste is typically incinerated or discarded in an open field, which can result in serious environmental and health problems. The food waste's carbon footprint is predicted to lead the emissions of GHG by releasing approximately 3.3 billion tons of CO_2 each year into the atmosphere[9]. Therefore, for the treatment of food waste, better techniques should be utilized.

Due to their high energy yield, slaughterhouse wastes are potentially valuable substrates for the AD process[10]. Slaughterhouse waste is a good substrate to anaerobic digestion, allowing for a chemical oxygen demand (COD) of more than 90% removal. In slaughterhouse waste, lipids represent a major fraction of the organic charge. Triglycerides and long-chain fatty acids are mainly composed of (LCFAs). LCFA and glycerol may be hydrolyzed by triglycerides. LCFA accumulation may inhibit anaerobic digestion, since there are two major groups responsible for the degradation of LCFAs - acetogens and methanogens[1]. Co-digestion of mixtures is used in studies that have been held out to develop the C:N ratio and lower the nitrogen concentration, which may cause issues with inhibition in certain cases. The need to a co-substrate with a lesser nitrogen and lipid volume boosts biogas efficiency. Increased yields can be achieved by co-digesting waste mixtures with others that have lower nitrogen and lipid content[1].

Solid organic waste is created in pulp and paper industry from the wastewater treatment sludge, both primary and secondary system[11]. The disposal of solid organic waste (particularly if it is wet) is costly, while thermal combustion is costly and energy-intensive[12]. AD is the suitable option for treating the secondary wastewater sludge, especially when anaerobic pulp and paper mill sludge is co-digested with OFMSW in order to overcome nutrient deficiency. As a wide variety and amount of industrial organic waste is generated, there is a great deal of potential for biogas to generate renewable energy.

Nonetheless, there are some disadvantages associated with substrate properties in the anaerobic digestion of singular substrate (mono-digestion). For example, sewage sludge may contain low organic loads, there may be a significantly higher accumulation of heavy metals and the slaughterhouse waste includes risks related to high nitrogen (N) and/or long chain fatty acid (LCFA), both of which are potential inhibitors for methanogenic activity[13]. Also, high solid content, slowly biodegradable elements, large particle size and the heterogeneity of the waste, make it difficult to control anaerobic processes[14]. In general, OFMSW is associated with a higher C:N ratio, a deficit of macro- and micro-nutrients (N and trace metals) and the lignocellulose present that can results in limitation of digestion efficiency[1]. By adding a co-substrate to anaerobic co-digestion as it's called recently, most of this problem can be solved. Anaerobic co-digestion arose at the end of the 1970s, allowing a wider variety of agricultural waste to be stabilized. Higher macro- and micro-nutrient availability and balance (besides better microbial growth), dilution of inhibitory substances, humidity control, and improved mixture buffering capacity are provided by anaerobic co-digestion of two or more substances. An optimistic synergistic effect with anaerobic co-digestion is the improvement of the biodegradable portion and the increase of the microbial community. As a result, process stability has improved and biogas production has enhanced[15].

Factors affecting the co-digestion

A few parameters rely on the optimal efficiency of anaerobic co-digestion. These are temperature, pH, particle size, C/N ratio, organic loading rate (OLR) and hydraulic retention time (HRT) etc.[16].

Role of various factors:

Temperature:

The standard practice is to maintain the mesophilic (approx. 35°C) and thermophilic (approx. 55°C) conditions. Particularly in comparison to thermophilic process, since a large groups of microorganism choose mesophilic temperature, the mesophilic phase needs to be stable[17]. Also, ammonia in high concentrations make the thermophilic stage unstable. Although the rate of gas production increases with rising temperatures, it reduces the content of methane[18]. At 32–35°C[19], a much more reliable and consistent methane production is gained. Thus, for microbial growth and biogas generation, the temperature is a crucial influencing parameter.

pH:

In the anaerobic digestion system, the pH influences the solubilization of organic matter, as it is an important control parameter. The enzymatic reactions of microorganisms are dependent on pH[20]. The digester's pH significantly influences fermentation to generation of biogas because various microorganisms have various pH requirements in biogas production but a majority of they choose pH levels that are neutral. Most literatures have stated that it is preferable to maintain a pH between 6.8 and 7.2 for higher methane yield. Hydrolyzing and acidogenic microorganisms choose the range for pH is 5.5–6.5. However, the effective pH for the methanogen microorganism is close to 7.0[21]. The variation in pH range is primarily for two-stage reactors in order to ensure optimal performance in acidogenic and methanogenic phase[22]. The development of VFAs in the early phases of digestion decreases the pH of the digestion tank and restricts microorganisms' methanogenic activity[16].

Particle size:

Particle size influences co-digestion process in the production of biogas. Greater particles can effect clogging and makes the process of digestion tougher. The specific surface area is enhanced by smaller particle size, which helps microorganism to operate in the hydrolysis stage more quickly. To minimize this issue, one feasible alternative is the application of two-phase digestion systems. The study[23] improved the methane rate of production about 10–29% by making the size of wasted food in the range of 2.5–8 mm. Other study[24] found outstanding performance throughout the co-digestion of sewage sludge (SS) and OFMSW. However, there was no major shift in methane production through decreasing the amount of the OFMSW from 20 to 8 mm.

C/N ratio:

The C:N ratio of organic compounds has an influence on the rest co-digestion method. Enough resources of microorganisms are provided by substrates with an optimal. C:N ratio to increase biogas output. Lesser C:N ratios lead to increased ammonia concentrations, which inhibits development of microorganism. Whenever the C:N ratio throughout the fermentation process is greater than the ideal value, a huge proportion of VFAs is formed. Maintaining adequate C:N ratio is crucial in the co-digestion procedure of biogas production. The optimum C:N ratios of different substrates produced by various anaerobic digestion processes are likely to differ. Anaerobic digestion is highly stable whenever the C:N ratio is between 20 and 30. In order to balance the C:N proportion in digesters, co-substrates are added during the process of co-digestion[25]. A C:N ratio is suggested to unify a particular range, containing current carbon from a readily degradable portion while excluding carbon that really isn't presently degradable by microorganisms[26].

Organic loading rate (OLR):

A quantity of dry organic solids packed into a digestive system per unit time and per unit volume, may be considered to be the organic loading rate. For optimum microbial activity, OLR is a key parameter. Lower OLR leads to anaerobic digestion technology being inefficient and vice versa[27]. Higher OLR increases various microbial species, requires very little heating energy and decreases the size and cost of the necessary digesters[28]. However, if the OLR is raised beyond particular range, it will increase VFA and ethanol accumulation and inefficient heat transfer. If it exceeds the pump's carrying capacity, greater OLR can destroy the circulating pump[29]. Various optimal OLRs occurred from different AD processes on organic waste. The study[30] mentioned that an OLR of 1.24 g VS L^{-1} d^{-1} was optimal for methane production and organic removal at mesophilic. condition (37°C) with a two-stage continuous stirred tank reactor.

Hydraulic retention time (HRT):

Metabolic activity of microorganisms is inhibited by uncontrolled HRT. Microorganisms will die as a result of nutrient shortages during lengthy HRTs. In case of industrial application, a shorter HRT is required to minimize digester volume and capital costs and to maximize the production of biogas and net electrical energy[7]. The HRT can be reduced by adding water to the substrate. Unless the HRT is smaller than microbes' generation times, nevertheless, the microbes will be washed away, resulting in the AD system failure[31]. A Study[32] resulted the amount of VFAs and alkalinity improved as HRT was raised and vice versa. It was also observed that the optimal HRT may differ for various co-digestion processes depending on the desirable temperature limit and microbial characteristics. Author[31] reported that at a HRT of 16 days, that largest proportion of methane production is 0.90 L/L_R d.

Performance of pre-treatment:

Pre-treatment steps are appropriate for enhancing the co-digestion of a mixture of two or more substrates[33]. The objective of such pre-treatment approaches is to raise the solubilisation of complex matrixes in speeding up the hydrolysis process, that is slightly slower and perhaps most restrictive procedure for complex substrates[2]. Microorganisms are unable to easily degrade cellulose, hemicellulose, and lignin[34] because of their complex structures. Pre-treatment is needed to turn such materials into biodegradable compounds that microorganisms will easily consume[35]. Pre-treatment is often used to increase the COD while also releasing intracellular nutrients from the substrate and improve the production of methane[20]. The total solids (TS) was dosed into mixture of sewage sludge and OFMSW, prior to ultrasound pre-treatment a 24% increase in biogas production was observed[36]. The pre-treated mixture of cow manure and slaughterhouse waste (SHW) resulted an 11% rise in the specific methane potential (SMP) when either 1000 or 6000 kJ kg^{-1} TS were applied to the mixture[37]. Steam explosion has showed good results in improving the SMP of distinct lingo-cellulosic wastes among all thermal pre-treatment choices.

The steam explosion includes high temperatures (between 150 and 250°C) for few seconds followed by a rapid drop in pressure for several minutes[38]. Steam exploded Salix is heated upto 10 min at 210°C and co-digested at different C/N ratios with cow manure and noted a 50% improved performance in biogas production due to the Salix pre-treatment[39]. They are allowed to increase the SMP upto 20% while applying at 130°C and 160°C, for 10 min, using a marine seaweed[38]. It is clearly said that a steam explosion is a viable pre-treatment to improve the production of biogas of such waste and meanwhile a moderate energy consumption is claimed[40].

High-temperature, non-explosive pre-treatment (150–220°C) has frequently been associated with reduced methane potential due to formation of anaerobic digestion refractory compounds. Results were obtained from a study[1] in which mono-digestion or co-digestion with OFMSW of pre-treated SHW (for 20 min at 133°C, 43 bar) was tried. On the other hand, the author[41], who pre-treated a mixture of SS and OFMSW at 170°C for 60 min, have not identified any effect on biogas production, but improved stability, dewaterability and kinetics. Low-temperature pre-treatment (60–90°C) results have been positive, although usually greater contact times are needed. The author[37], who hygienized a mixture of CM and SHW (70°C, 60 min), mentioned a 20% and 8% rise in SMP in batch and continuous experiments compared to the untreated sample.

Application of co-digestion of industrial organic solid wastes

Numerous researches have been published in which OFMSW was co-digested together with organic waste types such as sewage sludge, food waste, slaughterhouse and meat processing industrial waste, etc.[1,5,6,42]. There are also lab and full-scale studies on active sewage sludge co-digestion with OFMSW[5,6]. It has been found that the adding of sewage sludge to OFMSW boosts biogas efficiency by improving the C:N ratio of the mixtures via mesophilic anaerobic digestion[7]. However, for satisfactory operational improvement, optimization of a material mix proportion is needed. Biogas output and TVS reductions at their highest levels was obtained in wet anaerobic digestion with an OFMSW-sewage sludge mix ratio of 80:20 on a TS basis (and 25:75 on volume basis)[43]. The appropriate C:N ratio in OFMSW and SS co-digestion is intended to control a good nutrient equilibrium for bacterial growth, ensuring smooth and enhanced methane production. Process instability is normally caused by nutrient deficiency and weak substrate extraction and production when the C: N ratio exceeds 30. However, the digestion process can also be adversely affected by C:N ratios below 6, but this will be because of inadequate carbon content and high ammonia levels inhibiting anaerobes[15]. The key advantages of co-digestion of such wastes are enhanced methane production and enhanced degradation levels of treated substances and biogas (Table 1).

The addition of Food Waste (FW) most likely enhances the production of biogas due to its higher lipid and therefore carbon content. Compared to carbohydrates or proteins, lipids may generate almost double the amount of biogas[44]. However, anaerobic digestion of this waste is frequently hindered because of inhibition effect of intermediate compounds (LCFAs) and operational issues like sedimentation clogging and scum forming[45]. This kind of waste can be stabilized in a better way by the use of anaerobic co-digestion through formation of fermentative hydrogen as well. An impact of thermophilic co-digestion of FW and OFMSW[42] at 1.9 d HRT and 66 kg TVS/m^3 d OLR resulted in 2.5 m^3 $H_2/m^3{}_{reactor}$.d, 0.038 m^3 H_2/kg TVS_{added} and 44% H_2 production. To inhibit the spread of H_2 users, such as methanogens, the reduced retention time and low pH seemed to be acceptable[52].

Because OFMSW has comparatively low nitrogen and lipid levels, co-digestion of SHW will raise the C/N ratio. The H_2 yield and TVS extraction during the first reactor was 71.3 L/kg TVS removed and 47.9%, collectively, in a two-phase co-digestion analysis with a 10:1 (dry weight basis) OFMSW and SHW ratio under mesophilic conditions. The amount of biogas output in the second reactor was 0.989 L/d with a total TVS removal of 69.7%[55]. SHW has also been assessed as a feedstock digester[1]. Fermentation in a semi-continuous pilot plant functioning at mesophilic temperature and HRT from 52 to 50 days was conducted in the analysis. Results indicated that the implementation of OFMSW to the co-digestion process enhanced the removal of fat and VS (approximately 4.6% and 35%) and double biogas output on a regular basis The study also showed that only if the biomass was slowly acclimatized to higher fat and LCFA levels the reactor performance would have improved with stable methane production. This was done by steadily reducing HRT around 50 to 25 days.

In the past, anaerobic digestion was considered for pulp and paper mill sludge. Previous research has shown that nitrogen deficiency is a primary problem in anaerobic digestion of pulp and paper mill sludge. In order to improve the nutrient status of co-digestion, a nutrient-rich waste content

Table 1. Results of co-digestion of OFMSW with some industrial organic solid wastes

Substrate type and mixing ratio	Reactor type	Operational conditions	Biogas/Methane yield	TVS removal (%)	Ref.
OFMSW:SS 54:46 (TVS basis)	CSTR	Mesophilic, 1.9 kg TVS/m^3.d, 22 d HRT	0.395 m^3 CH_4/kg TVS_{added}	70	24
OFMSW:SS 5:1 (TS basis)	Dry batch	55°C, C:N 31, 20% TS	0.051 m^3 H_2/kg $TVS_{removed}$ and 36% H_2 conc.		47
OFMSW:WAS 75:25 (volume basis)	Batch	35°C, 4.2% TS	0.376 m^3 CH_4/kg TVS_{added} and 140% better yield than control	61	48
OFMSW:SS 20:80 (TVS basis)	CSTR	37°C, 1.0 kg VSS/m^3.d OLR	0.60 m^3 biogas/kg VSS and 1.54 times greater CH_4 yield		50
OFMSW:Fruit and vegetable waste 1:3 (VS basis)	Batch	35°C,18.9% VS, C:N 34.7	0.397 m^3 CH_4/kg TVS and 141% rise in CH_4 yield than OFMSW only	54.6	51
OFMSW:FW 80:20. (TS basis)	SSTR	55°C, 20% TS, 1.9.d HRT, 66 kg TVS/m^3.d OLR	38 mL H_2/g TVS_{added} and 2.5 L $H_2/L_{reactor}$.d and 44% H_2 fraction in biogas		42
OFMSW:FW	CSTR	35°C, OLR 3 g VS $g^{-1}.d^{-1}$	0.49 m^3 CH_4 kg^{-1} VS_{added}	74.9	54
OFMSW-SHW 10:1 (dry. wt. basis)	CSTR	34°C, 3.d HRT	71.3 L H_2/kg $TVS_{removed}$ and 27.5% H_2 in biogas	47.9	55
			34°C, 15 d HRT	69.7	
OFMSW-SHW 80:20 (weight basis)	CSTR	38°C, 21 d HRT, 4 kg TVS/m^3 OLR	35% increase in biogas yield		56

is preferred, which should be a low cost alternative for the AD of the same. With a view to successfully eliminate the nitrogen deficiency issue, a research[54] utilized co-digestion in sludge from the pulp mill and monosodium glutamate waste liquor.

A study co-digestion of manure with silage from grass and sludge from pulp and paper mills was carried out in another study[57]. For 20 days, under mesophilic conditions, anaerobic digestion was conducted in batch reactors. The season for grass silage and manure collection has proven to be an important variable impacting methane production. Spring grass silage provided a maximum of 250 mL/VS_{added} and 150 mL/VS_{added} for spring manure, while autumn grass silage provided a maximum of 140 mL/VS_{added} and 45 mL/ VS_{added} for autumn manure. The sludge of the pulp mill utilized both primary and secondary sludge and generated at most 50 mL/VS_{added} of methane, regardless of the season from co-digestion. In some situations, even slowly degradable substrates, like paper and pulp mill sludge, could be used without reducing methane production. The results of co-digestion of OFMSW with some industrial organic solid wastes are presented in Table 1.

Conclusion

Co-digestion of OFMSW and Industrial Organic Solid Waste (SS, SHW, FW, Pulp and Paper mill Sludge) can make a large difference in output of biogas and the degradation of treated substances, improving the stability of the process when preparing the mixture of substrates with appropriate proportions of various organic substances. The positive impact of co-digestion is mainly due to the dilution of potential toxic substances, improved biodegradable fraction load, enhanced nutritional balance and macro- and micro-nutrient contents. However, it is needful to provide necessary digester feed moisture content and fermentation buffering capacity. Apart from that, it is also required to adjust the feedstock C:N ratio to the optimum range for maximum production of methane. To overcome other unforeseen troubles in the digester, pre-treatment is still needed and it showed the best results in improving the specific methane production. Various studies have reported that for both industrial-scale and laboratory-scale, this technology is a cost-effective tool for biogas production.

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