Anaerobic Co-Digestion of Sewage Sludge and Waste – A Review with a Focus on the Mixing Ratios, Pre-Treatment, and Challenges

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Abstract - *Anaerobic digestion is a viable commercial option for a variety of wastes. However, there are several limitations to the anaerobic digestion of single substrates due to substrate properties. Anaerobic co-digestion of two or more substrates is a viable option for overcoming the mono-digestion drawbacks and increasing the economic viability of a plant. At the moment, anaerobic co-digestion can be considered the most significant topic within anaerobic digestion research, as half of the publications have been published in the last two years. The aim of this paper is to present a review of the anaerobic co-digestion food waste and sewage sludge with a focus on the major factors affecting the co-digestion, mixing ratios, mixing strategies, various pretreatment strategies, and main challenges within the last years. In anaerobic co-digestion (AcoD), higher biodegradability and variability of FW are critical challenges. To minimize the challenges of Food Wastes for increasing methane production, optimization for each substrate combination and adequate pre-treatment are critical. As a result, AcoD has the potential to be commercially viable and contribute to the economy, particularly in developing countries.*

Key Words: Anaerobic co-digestion, Anaerobic digestion, Food Waste, Sewage Sludge…

1.INTRODUCTION

In oxygen-depleted conditions, Anaerobic digestion (AD) is a naturally occurring biological process of microbial degradation. Organic matter is broken down into simpler chemical components like methane, carbon dioxide, hydrogen sulphide, and manure throughout the AD process. Hydrolysis, acidogenesis, acetogenesis, and methanogens are the main four processes of anaerobic metabolism [1], [2].

Plant and animal wastes, cow manure, waste paper, grass clippings, leftover food in municipal solid waste, home, and industrial wastewater, and other biodegradable organic materials can all be handled with AD technology [3], [4]. Originally, the AD process was intended for sewage sludge and animal manure [5]. Sewage sludge and manure, on the other hand, do not have a strong potential for AD. As a result, to improve the efficiency of the process, the digesters can be fed with two or more types of feedstocks in a co-digestion process [6].

Sludge contains high concentrations of nitrogen and trace elements but is low in bio-degradable organic matter [7], [8]. Food Waste (FW) is a problematic organic waste that comes in large quantities. The volatile solids in FW are abundant, and they can be easily converted to methane via an anaerobic method. However, it usually has a low amount of nutrients [9]. AcoD is an approach where two or more substrates with complementary characteristics are mixed for combined treatment.

Co-digestion of food waste accelerates the rate of methane production and a higher methane yield [10]. It can use the nutrients and bacterial diversities in different wastes to enhance the digestion process [11]. It seems to have a synergistic impact, overcoming nutritional imbalances and improving biodegradation. When compared to the AD of a single waste, this impact leads to a larger methane production, which increases the organic content inside the reactor, improves digestate stabilization, and dilutes potential inhibitory and/or hazardous chemicals such as ammonia, Na^+, and so on [12]–[14].

The energy contained in wastewater and sludge is predicted to be ten times greater than the energy required for treatment [15]. AD of SS has been recognized as the most appropriate technique for renewable energy recovery and the creation of nutrient-rich fertilizer in a sustainable manner in recent decades [16].

Traditional AD or AcoD of sewage sludge is often carried out at low solid concentrations, which means that water makes up the majority of the digester's content. High-solids anaerobic digestion (HSAD) uses a higher-solids feedstock than low-solids anaerobic digestion (LSAD), and the total solids (TS) percentage of the digestate is higher than 10–15 percent [17]. Smaller digesters, lower energy usage for heating feedstock and digesters, and higher volumetric biogas generation are some of the benefits of HSAD [18].

2. BIOCHEMISTRY OF ANAEROBIC DIGESTION

AD is a set of complex biological processes that occur mostly in the absence of oxygen and involve bacteria hydrolyzing polymeric organic carbon molecules before converting them to biogas and biofertilizer. The methane and carbon dioxide percentages are about 50-65 % and 40-50 % respectively from the biogas, and trace amounts of other gases such as hydrogen sulphide, nitrous oxide, and others. The AD process involves four important biochemical steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [19]–[23].

The four key stages of anaerobic digestion involve hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

- **Hydrolysis**: Extracellular enzymes that convert carbohydrates, lipids, and proteins into sugars, long-chain fatty acids (LCFAs), and amino acids are secreted by hydrolytic bacteria.
- **Acidogenesis**: breakdown of the remaining components by acidogenic bacteria. Here, volatile fatty acids (VFAs) are created, along with ammonia, carbon dioxide, and hydrogen sulfide, besides other byproducts.
- **Acetogenesis**: Acetogens digest the simple molecules produced during the acidogenesis phase to produce mostly acetic acid, as well as carbon dioxide and hydrogen.
- **Methanogenesis**: Methanogens transform the intermediate products from the previous stages into methane, carbon dioxide, and water.

3. FACTORS AFFECTING ANAEROBIC CO-DIGESTION

Biomass is made up of a variety of biological and inorganic components. Chemical composition, operational parameters (temperature, pH, retention duration, Carbon to Nitrogen (C/N) ratio, loading rate, etc.), biodegradability, and substrate characterization are all important factors in optimizing the AcoD process of biogas generation technology.

3.1 Temperature

The temperature has a big impact on microbial communities, interfering in the process stability, microbial growth, the rate of substrate utilization, and production of biogas [24]. In anaerobic digesters, four temperature schemes can be employed to produce biogas [25]–[27]: (1) psychrophilic temperatures range (10–20°C) with optimum at 25 °C; (2) mesophilic temperatures range (20–45°C) with optimum at 35 °C; (3) thermophilic temperatures range (50–65°C) with optimum at 55 °C; and (4) extremely thermophilic temperatures range between 65 and 70 °C.

The biological and chemical reactions occur more slowly under psychotropic conditions [28], while underneath thermophilic conditions, the metabolic rate of microorganisms increases. Hence, thermophilic temperatures are commonly utilized in large-scale biodigesters [25], [26]. Also, thermophilic temperatures guarantee that pathogens be destroyed at a faster rate [29]. However, using high temperatures needs higher energy costs, increased process control to ensure a uniform and stable temperature inside the biodigester [25].

3.2 pH

The perfect pH range for AD is very limited, usually ranging between 6.8 and 7.2 [30], Depending on the substrate utilized in the process as well as the digesting technique used [31]. The growth rate of methanogenic bacteria is decreased in conditions with pH below 6.6, while a very alkaline pH (around 8) may lead to the disintegration of microbial granules and subsequent failure of the process. Furthermore, in most cases involving high alkalinity, the biodegradation process produces bicarbonate alkalinity, which neutralizes the acidity created by the biodegradation process [32]. Therefore, an ideal pH for the methanogenic phase is usually around 7 [30].

3.3 Retention Time

Hydraulic retention time (HRT) is the required time it takes for the organic matter to completely break down or the time in which the organic material stays in the biodigester. HRT is affected by the process temperature and the type of substrate to be digested [26]. Usually, the HRT for mesophilic schemes varies from 10 to 40 days, while for thermophilic schemes the time is shorter, 14 days [26].

3.4 C/N Ratio

The carbon-to-nitrogen ratio (C/N) is the proportion of carbon to nitrogen in organic matter. This ratio is critical in the AD process since the type, availability, and complexity of the substrate all influence the AD rate [24], [26]. In the anaerobic degradation process, nitrogen molecules from organic waste are transformed into ammonia. Nitrogen, in the form of ammonia, helps to keep the pH of the medium steady during the process [24].

A high C/N ratio indicates that the material is rich in carbon, while a low C/N ratio indicates that high protein content is available [25]. If the C/N ratio is high, the methanogenesis microorganisms quickly consume the nitrogen, resulting in lower gas production, while an accumulation of ammonia occurs if the ratio is low. The activity of methanogenic bacteria is negatively affected When the medium is alkaline (pH > 8.5) [26]. For AD of organic waste, the C/N ratio should be between 20 and 25 according to [25]. The maximum biogas production achieved using a C/N ratio of 31 [33], while another study stated an optimum C/N ratio of 28 for the production of biogas [34].

3.5 Moisture Content in Feedstock

The anaerobic digestion and production of methane can be influenced by the amount of moisture content in the feedstock. Fujishima reported that the produced methane yield was reduced from 330 to 280 mL/g-VSS when the moisture content reduced from 97 to 89% on the AD [35]. This indicates that an optimum level of moisture content is essential for the anaerobic digestion process.

4. ANAEROBIC CO-DIGESTION OF FOOD WASTE AND SEWAGE SLUDGE

4.1 Mixing Strategies

When operating at a high organic loading rate and a short hydraulic retention time, AD mixing becomes critical. Inadequate mixing appears to cause significant sedimentation, foaming, scumming, and frothing materials to float on the digester's top liquid surface, obstructing the release of biogas from the AD liquid [36]. On the other hand, Excessive mixing intensity causes the juxtapositioning and syntrophic bacterial interactions of interspecies hydrogen transfer between closely attached flocs of acetogenic and methanogenic granules to break down, lowering the hydrogen partial pressure and negatively affecting AD [37], [38].

The impeller or propeller, or agitator-based mechanical mixing, slurry recirculated hydraulic mixing, and biogas recirculated pneumatic mixing are the three types of AD mixing modes used. Numerous researchers have studied varying results about the effect of the mixing method on biogas yield. The digestibility of HSAD has been enhanced by using periodic mixing followed by waiting as intermittent cycles and attributed an optimum condition for bacteria to release the biogas [38]. It is stated that the role of mixing evolves more significantly with an increase in high-rate TS concentration in the feed slurry because the biogas produced in the mixed digester is approximately 15% more than the biogas produced from the unmixed digester [39].

4.2 Benefits of Food Waste as A Co-Substrate

Co-digestion of FW and SS has been widely used in recent years, with numerous researchers highlighting the benefits of enhanced methane (CH_4) generation and dilution of hazardous chemicals [40]–[43].

Due to population increase and growing living standards, the generation rate of MSW is gradually increasing by 2–3 percent every year among the various waste sources [44]–[46]. The FW, which represents raw/cooked food items after/before meal preparation in households, as well as from the manufacturing/production and foodservice sectors, is a key component of MSW that varies from 20 to 50 percent in different nations [47].

In general, FW has a higher C/N ratio (11.1–36.4), but SS has a lower C/N ratio (6–9) and by mixing it can be enhanced to a range of 6–15[48]. The methane production from the addition of FW to SS digesters enhances the C/N ratio and kinetic reaction, making AcoD operations both economically and practically possible [10], [49]–[52]. The optimum C/N ratio for digester performance is around 20–30, and C/N ratios higher than 30 upset the digester due to nutritional deficiency, which affects microbial activities and results in a decreased substrate removal rate. However, if the C/N ratio is less than 6, it has a harmful impact on the process, resulting in low carbon levels and high ammonia levels, inhibiting the growth of hydrogenotrophic methanogens. [10], [48], [53], [54].

4.3 Effect of FW to SS Mixing Ratios

Methane production was found to be improved significantly by increasing the fraction of FW in SS, making clear the importance of the co-digestion approach. However, there is a limitation to which adding FW to SS can lead to an improvement in methane production. If the FW is added to SS below or above the optimum mixing ratio which differs from one system to another, the digestion performance can be limited and therefore decrease CH_4 production, or cause a complete failure because of instability in the system [41], [55]–[57].

For higher methane production, different ratios of FW and SS were co-digested in prior research. A study found that when the FW and SS mixing ratio is 1:4, the highest CH_4 yield is 215 mLCH_4 g−1 VS, which is 85.3% more than the mono-digestion of FW alone [58]. The 1:1 mixing ratio (v/v) of OFMSW (particularly Food Waste) and Sewage Sludge also enhanced the production of methane by 47.2 percent (365 mLCH_4 g−1 VS), because of the enhanced C/N ratio [59]. Regardless of the substrate ratio, micronutrients supplementation, either directly or through leachate sources, was found to be useful for improved process efficiency. During mono- and co-digestion of FW, iron supplementation improves process stability and rate of methane production by 18–39%, according to several studies [60], [61].

According to a biomethane potential assay, FW combined with sludge in a 1:2 (VS) ratio produced the maximum biogas of 823 ml gVS^{-1} (21 days) with a 60% methane [62]. Marcelo et al., (2017) studied the co-digestion of FW and primary sludge (PS) under thermophilic (55 ^{0}C) and mesophilic (35 ^{0}C) conditions. The optimum FW:PS mixing ratio was 1:2 (VS) with an HRT of 21 days that obtained maximum specific methane of 270 and 205 ml CH_4/ gVS at thermophilic and mesophilic conditions respectively [63].

Mata-Alvarez et al. (1990) studied the mesophilic (35^0C) anaerobic co-digestion of a 50:50 mixture of OFMSW and SS that produced the maximum biogas of 0.36 m3 CH4 kg^{-1} VS^{-1} at the HRT of 14.5 days with an organic loading rate (OLR) of 2.80 kg VS m^{-3} d^{-1} [23]. According to the thermophilic (55^0C) anaerobic co-digestion performed by Del Borghi et al., (1999), OFMSW mixed with SS in a 50%:50% (VS) ratio produced the maximum biogas of .36 m3 kg-1 VS-1 (12 days) with a 64% methane [64].

When compared to SS mono-digestion, the SS:FW ratios of 0.50:0.50 showed significantly increased methane recovery, with the methane productivity increasing by 4.59 times and the rate of hydrolysis increasing by 3.88 times [65].

4.4 Pre-treatment Strategies to Improve the Anaerobic Co-Digestion

Anaerobic digestion needs a much longer duration for the stabilization of the organic because it is slower than aerobic biological digestion. The rate-limiting step of the AD is considered to be the hydrolysis step because the substrate surface adsorbs the hydrolytic enzymes and convert them into smaller molecules for additional degradation into VFA along with additional by-products [66], [67]. In order to improve hydrolysis, several pre-treatments have been studied to enhance the efficiency of digestion of waste by solubilizing decomposable organic substances and decrease the time required to the overall processing AD [68], [69].

Effective pre-treatment of both substrates is essential for improving methane recovery from AcoD of FW and SS. By influencing crucial process parameters like OLR and HRT, initial feed characteristics control the whole process and methane production. Hydrolysis is a critical phase in the treatment of highly organic wastes like FW, and its hydrolysis is highly dependent on FW properties such as chemical compositions and particle size. Numerous pre-treatment treatments have been documented to improve hydrolysis efficacy for increased biogas production, including biological, chemical, physical, thermal, and electrical methods [46], [70]–[77]. For FW treatment prior to AcoD, a variety of pre-treatment techniques were studied, and higher methane yields were produced [46], [76]– [80].

In recent years, several pre-treatments have been studied as thermal pre-treatment [78], thermo-chemical pre-treatment [81], ultrasonic pre-treatment [82], [83], and chemical pre-treatment [84]. Numerous studies utilized different pre-treatments to improve biogas production and solubilization by using either specific FW or sludge [58], [66], [85].

Furthermore, many studies have used single or combined pre-treatment like chemical, ultrasonic, or combined ultrasonic with thermal/chemical on waste activated sludge (WAS) and other wastes that are difficult to compare the efficacy of the pre-treatments [83], [84], [86], [87], and few studies reported multiple pre-treatments on WAS [58], [85]. Moreover, pre-treatment improved not only anaerobic digestion but also the generation of electricity in a microbial fuel cell [88] which studied the heat/alkali pre-treatments on different wastewater sludge. Also, Ma et al. [78] and Menon et al. [89] used different pre-treatments on food waste for AD. However, the mixed impact of different pre-treatments and co-digestion on WAS and FW has not been reported to the best of our knowledge, although several studies showed improved AD efficiency using various combinations of either FW with additional wastewater sludge and vice versa [90]–[92].

5. CHALLENGES OF FOOD WASTE CO-DIGESTION WITH SEWAGE SLUDGE

The anaerobic co-digestion is the integrated treatment of different wastes with various characteristics. Substrates have different potential energy and characteristics, and this depends on their availability and nature, so it is difficult and complicated to select the appropriate substrates for AcoD. AcoD improvement mechanisms have observed issues caused by the feedstock characteristics of the digester and the steps of hydrolysis [93], [94]. Separate rates of hydrolysis for each particulate component should be considered separately in the AcoD process as the rates of hydrolysis vary significantly.

The biogas production optimization was made possible by separating the characterization and phasing of the co-digested substrate hydrolysis [95], [96]. As a result, characterization of the various chemical compositions of substrates is useful in deciding which substrates to use for co-digestion and predicting the entire AcoD process for producing biogas using a mathematical model. The fundamental limitation of animal by-products is the nutritional imbalance, particularly the low carbon to nitrogen ratio, which reduces microbial activity. The Anaerobic digestion is stable at the optimum of the C/N ratio ranging between 20–30, which is sufficient to fulfill predictable energy requirements [97]–[99].

Therefore, while choosing substrates for AcoD, C/N is one main factor in increasing the AcoD performance in the production of biogas. The C/N ratio causes process instability, system failure, and biogas reduction when it becomes lower or higher than the optimum value. Large amounts of VFAs produced by the co-substrates with the high C/N ratio during the Acidogenesis process but those with low C/N ratio have high buffer capacity and during the Acidogenesis process, the ammonia increases. Also, the emissions of N_2O depend on the C/N ratio [100]. As the C/N ratio reduces, the emissions increase, and when the C/N increases the emissions decrease.

Because of the high variability of food waste, co-digestion of food waste with sludge may be limited. The composition of food waste added to sewage sludge affects digestion performance and changing it might induce instability in the anaerobic population and, as a result, in the digestion process [101], [102].

The light metal ions are very important in Anaerobic co-digestion performance. Its concentration plays an essential role in the smooth performance of the process because it can be the most potent cause of toxicity in AD. When a compound causes a negative change in the microbial population or breaks bacterial growth, it can be defined as toxic or inhibitory [14]. The light metal ions increased in the AD due to the increase of the food waste fraction, so it is very important to mix the food waste with the optimum mixture to protect the digestion and generate a high amount of biogas.

The challenges of choosing the food waste as a co-substrate with the sewage sludge are not stopped at this point but also the addition of FW to SS results in an initial accumulation in the concentration of VFAs because of the rapid acidification of soluble organic mixtures found in food waste [41], [58], [103].

6. CONCLUSIONS

AD and AcoD seem to be reliable and possible solutions and technologies for recovering and recycling both SS and FW. Because it is a renewable energy source with low emissions, it appears to be the ideal waste management alternative from an economic, social, and environmental standpoint. Although a more thorough knowledge of the process is required to ensure the appropriate development and stability of the microbial degradation. Adding the food waste to sewage sludge anaerobic digesters increases the nutrient content, weakens inhibitors, improves the alkalinity, decreases the formation of ammonia, and enhances the process stability.

Anaerobic digestion is a viable commercial option for a variety of wastes. However, there are several limitations to the anaerobic digestion of single substrates due to substrate properties. Anaerobic co-digestion of two or more substrates is a viable option for overcoming the mono-digestion drawbacks and increasing the economic viability of a plant. At the moment, anaerobic co-digestion can be considered the most significant topic within anaerobic digestion research, as half of the publications have been published in the last two years. The aim of this paper is to present a review of the anaerobic co-digestion with a focus on the mixing ratios, mixing strategies, and challenges within the last years. In AcoD, higher biodegradability and variability of FW are critical challenges. To minimize the challenges of Food Wastes for increasing methane production, optimization for each substrate combination and adequate pre-treatment are critical. As a result, AcoD has the potential to be commercially viable and contribute to the economy, particularly in developing countries.

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