High-Solid Anaerobic Digestion

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High-solid anaerobic digestion (HS-AD) and solid-state anaerobic digestion (SS-AD) are technologies presenting an outstanding capacity for treating organic wastes and requiring lower digester volumes.

solid-phase biogas enhancement conductive materials nanoparticles

1. Introduction

The valorization of biogas for the production of energy or to upgrade this gas to achieve a quality similar to that of natural gas is another integral component of digestion technology. Biogas conversion or upgrading also has a clear impact on the capital investment and operating costs of this technology. Energy production from biogas is usually performed by combined heat and power units (CHP), allowing the efficient use of on-site biogas [1]. The applications of fuel cells and micro-turbines are increasing, but the costs associated with these later technologies are still too high.

A large amount of water in wet digestion systems translates into lower methane productivity [2] since biogas yields are directly associated with the dry matter content of the feeding. Thus an increase in reactor productivity usually translates into increasing the solid content of the input material. Increasing the solid content in the digestion system exerts different effects on microbial performance; thus, the term “high-solid” is used to refer to an anaerobic process that are still considered wet digestion systems but which work with solid content values close to the higher limit of this solid range, and experience diffusion limitations [3][4]. High-solid anaerobic digestion seems to be a logical option for enhancing digestion performance, given that biogas production is directly associated with the mass of volatile solids fed into the digester. However, the strategy of working with a higher solid content implies a great variety of modifications in plant operation and the equipment needed, and the higher organic matter content significantly affects the performance of the anaerobic microflora.

The addition of water is necessary to set a specific solid content for the feeding, and it is usually recirculated to avoid excessive consumption of this resource. The liquid digestate may be treated for the recovery of nutrients through struvite precipitation [5][6] and solids can find applications as organic amendments in croplands. However, the amount of solid digestate produced is still high, and it may prove difficult to ensure a proper final disposal option all year round. Thus, alternatives are needed for increasing the conversion of the degradation process and the final valorization of the digestate to avoid generating an additional problem for farmers with no possibility of finding a solution for the final disposal of the digestate. Anaerobic reactors capable of treating highly concentrated substrates without experiencing significant inhibitory problems would aid in increasing plant feasibility, facilitating digestate handling operations, and final disposal.

2. Solid-State Anaerobic Digestion (SS-AD)

Solid-state fermentation is another way of operating digestion technology. TS values are higher than those used in HS-AD and seem more suitable for treating agricultural residues and food wastes, due to the lower water demand. Agricultural wastes have an intrinsic capacity to act as a structuring agent during fermentation because of their high content of lignocellulosic material. Many agricultural residues are untreated or underutilized, creating climate change problems associated with the emission of greenhouse gases (GHG) during the uncontrolled degradation of this type of waste [7]. Solid-state fermentation has been successfully studied for producing enzymes, biosurfactants, proteins, and biofuels [8][9] and a great variety of valuable products [10][11][12][13]. Anaerobic digestion has also been evaluated under this configuration and the co-digestion of different residues, such as manure, food wastes, and agricultural wastes, has also been studied under SS-AD conditions [14][15][16].

The separation of the digestion system into two stages, the first dedicated to the hydrolysis and acidogenesis of the feeding material and the second to the conversion into methane of the acidified liquor, is a way to overcome acidification problems and buffering accidental overloading. When applied to solid-phase systems, the first phase acts as a leachate bed reactor and the second one as a traditional CSTR or as an up-flow anaerobic sludge bed (UASB) system [17][18][19]. Liu and Liao [20] studied a two-stage process, with the first stage operating as a leachate bed reactor (LBR). These authors attained the conversion of the substrate in less than 6 days, with a 70.9% removal of VS from the leachate reactor. However, if the total mass of substrate loaded (10 kg) and the volume of the reactors are considered (70 L for the LBR and 35 L for the second methanogenic phase), the OLR applied would be equivalent to 1.5 g VS/Lr d—expressed in terms of the volume of the reactor—when the loading estimation is performed for a continuous system. Biogas production in the LBR displayed an evolution characterized by a peaking behavior immediately after the addition of the methanogenic leachate and a rapid decrease due to the excessive accumulation of VFAs. These authors also reported compaction to be a problem and hydrogen gas evolution was described during the initial recirculation stages, which indicates process imbalances.

The biogas yields obtained under solid-state conditions are lower than those from wet digestion systems. The increase in solid content causes a decrease in the biogas yield [21]. This fact was demonstrated by Li et al. [22] when evaluating the co-digestion of corn stover and chicken manure under different configurations, that is, wet, high-solid, and solid-state digestion. These authors tested mixtures of substrates, but in general, the wet digestion system (at 5.1–5.6%TS) achieved higher methane yields than any of the other experimental set-ups working at higher solid contents. The methane yield was reported to be 0.219 L/g VS added for the wet system, whereas this value decreased to 0.208 L CH_4/g VS in the system with a high-solid content (10.1–11.2%TS) and further decreased to 0.148 L CH_4/g VS when evaluating solid-state digestion (20.1–22.4%TS). In addition, the optimum mixture composition for obtaining the highest methane yield was different for solid-state digestion, with a proportion of 1:1 (VS basis, corn stover/chicken manure), whereas for the other two digestion systems, this proportion was found to be 3:1.

Kim et al. [23] studied the effect of moisture content in SS-AD using a bedding material composed of sawdust collected after 2–3 months of being used as cattle bedding. These authors evaluated this material as a substrate, which had a solid content between 17% and 30%. Although the values of methane yield reported were low for all cases tested, the system with a higher solid content presented a methane yield that was 29% lower than that at a TS content of 17%, thus corroborating the adverse effect associated with an extremely low water content. In solid-state fermentation, water activity (a_w) has a determinant influence on microbial activity, having a fundamental role in the mass transfer of water and solutes across microbial cells [24]. Therefore, there is clear evidence on the limits imposed regarding the levels of inhibitory components and the water content of the system, and their removal from the liquid phase is a necessity during SS-AD to avoid excessive toxic effects. The strategy proposed by Takashima and Yaguchi [25] of introducing an ammonia-stripping stage in HS-AD systems treating sewage sludge seems reasonable and leads to an expectation of success in digestion systems operating at even higher solid contents. Indeed, this is what Farrow et al. [26] intended when digesting poultry manure under a solid-phase configuration using struvite precipitation with pH controlled at around 7.0 during the ammonia removal stage to avoid adverse effects on the microbial biomass. This strategy allowed biogas to increase by about 30% under batch conditions and by nearly 235% when operating under semi-continuous conditions, reporting biogas yields of 0.420 ± 0.050 L/g VS added. However, the OLR was extremely low for an SS-AD system (OLR of 1.5 g VS/Lr d) and it should be added that they also experienced a decrease in the biogas yield with the increase in OLR.

3. The Effect of Adsorbents and Materials in Accelerating Anaerobic Degradation

The addition of adsorbents and carbon conductive materials to anaerobic reactors has been evaluated with success to decrease the impact of inhibitory compounds [27][28]. Adding this type of supplement to digestion allows for the enhancement of biogas productivity without greatly affecting the energy demands of the process [29]. The use of biochar derived from the thermal processing of lignocellulosic biomass in digestion systems has awakened interest among the scientific community, given its proven benefits regarding the mitigation of the negative effects of VFA and ammonia [30][31]. Other materials, such as zeolites, activated carbon and various adsorbents (kaolin, silica gel, polyvinyl alcohol, among others) have also provided benefits in biogas production [32][33][34][35] but the costs associated with these initiatives need to be carefully evaluated.

The mechanism of direct interspecies electron transfer (DIET) has been frequently proposed to explain the better performance of anaerobic digestion when carbon conductive materials are supplemented [36][37]. The enhancement is explained by the availability of a faster degradation route for the conversion of VFA [38][39][40], which is possible due to the prevalence of microbial species that become dominant due to the presence of materials that favor electron transport. Guo et al. [41] demonstrated the efficacy of adding GAC or magnetite on propionate degradation. These compounds favor the dominance of a syntrophic consortium by creating a DIET environment.

The addition of nanoparticles to digestion systems has recently demonstrated benefits in biogas production and the reduction of conversion times. The mechanism and effects of nanoparticles in anaerobic digestion have been reviewed by Abdelsalam et al. [42] and Faisal et al. [43]. Nanoparticles cause microbial activity stimulation based on the higher bio-availability of metal components essential for enzymatic reactions, thus enhancing cellular growth. Nanoparticles of iron oxide and zero-valent iron enhance interspecies hydrogen transfer and direct interspecies electron transfer, explaining the excellent results obtained when they are supplemented into digestion systems [44]. Other metals (Cu, Co, Ag, Ni) and metal oxides have also been studied as supplements in anaerobic digestion in the form of nanoparticles [45][46][47][48]. Nanomaterials, in general, may become a useful ally in promoting substrate degradation due to their unique characteristics such as their high surface area, high reactivity, and specificity, and their increased number of active sites [49]. There is a wide variety of reports available in the literature on the benefits associated with the addition of conductive materials and adsorbents.

Casals et al. [50] reported a threefold increase in methane production when supplementing iron nanoparticles (NPs). Abdelwahab et al. [51] studied the digestion of cattle manure and obtained a biogas yield of 0.953 L/g VS when evaluating a concentration of 15 mg/L of (Fe) NPs against a value of 0.589 L/g VS obtained from the control experiments. Not only was the biogas yield enhanced, but the presence of these particles also favored a lower production of H 2S, which is of great relevance regarding subsequent biogas up-grading operations. Similarly, Farghali et al. [52] studied the addition of iron oxide (Fe 2O 3) and titanium dioxide (TiO 2) nanoparticles, reporting a twofold increase in biogas yields and a decrease in H 2S production. The addition of magnetite NPs was studied by Ali et al. [53] and Zhong et al. [54], with the latter indicating that the presence of these particles was probably responsible for accelerating the transfer of electrons from acid oxidizers to syntrophic methanogenesis, stimulating acid oxidizers to degrade acetate into H 2/CO 2, and finally to facilitate methane production. These reports open a new line of research completely disrupting the current efficiency of digestion plants, improving performance, and offering a completely radical change in the valorization of biogas. However, other factors—more than just economic criteria and bioenergy production—must also be evaluated when considering organic waste treatment. Sociocultural ideas, environmental impacts associated with this technology, and local knowledge may appear as important constraints [55], necessitating careful assessment to avoid causing a negative perception in local communities.

4. Temperature and Digestion Performance

Temperature is a crucial parameter for increasing the degradation rate. Psychrophilic conditions refer to systems working at temperatures lower than 20 °C, mesophilic conditions range between 20 °C and 45 °C, and thermophilic conditions have temperatures higher than 45 °C [56]. Any increase in temperature will translate into a greater biogas production rate, and therefore it is reasonable to assume that ideal operation should be based on optimum temperature conditions. However, this is not always possible since capital investment and operating costs are also parameters that greatly influence plant profitability. Thus, operation at low temperatures has been studied to determine the decrease produced in process performance and evaluate ranges of feasible operation [57]. The absence of a heating system to reduce operating costs also leads to variable performance due to daily temperature variations, which may cause process instabilities [58], and extremely low activities in the winter season.

SS-AD has been tested at temperatures below 34 °C. Since the main advantage of this technology is its simplicity, the installation of a heating system would add unnecessary operating costs. Avoiding these additional costs is vital if this technology is extensively applied in developing countries and/or tropical countries where excessive low ambient temperatures are not experienced. Ghosh [59] evaluated the fermentation of solid wastes around 25 °C, obtaining a yield of 0.26 L CH 4/g VS added, thus proving the suitability of this process even at this temperature. Operating at lower temperatures to establish optimum conditions for low-cost digestion systems is needed.

Psychrophilic digestion has been studied by different authors, reporting lower biogas yields [60][61] and solid accumulation [62], but successful experiences have also been described, with gas yields similar to those obtained at higher temperatures, indicating that the process was not significantly affected by the increase in the OLR, as would be expected [63][64]. These reports are important as many small-scale digesters operate under this regimen. When the performance of these systems is analyzed, better yields are obtained than those expected from control laboratory conditions. This is probably explained by the well-established consortium attained after an extended operation time in industrial operating reactors [65]. Zhao et al. [66] studied digestion performance at 4 °C, indicating that the maximum treatment capacity was set at 4.33 g VS/Lr d of OLR. Therefore, low-temperature operating digestion systems may become a low-cost solution for the operation of decentralized reactors with a treatment capacity equivalent to that of more complex mesophilic and thermophilic reactors.

However, it is undeniable that increasing the temperature of the process affects reaction rates; therefore, to speed up biological degradation, the temperature should be increased. Moving from a mesophilic to a thermophilic regimen has been implemented to improve the treatment capacity of the reactor and thus productivity. Thermophilic conditions allow higher degradation rates, thus achieving a greater capacity for treating organics and attaining higher pathogen destruction [67]. A temperature rise from mesophilic to thermophilic conditions reduces the required volume of the digester and significantly decreases capital investment costs [68]. This feature translates into a significant increase in the treatment capacity of the plant for reactors that are already operating at lower temperatures but also result in a higher energy demand. The feed needs to be heated up to the desired thermophilic conditions, requiring a greater amount of energy, and this demand is accentuated in the winter season. Thermal losses are also higher due to the greater temperature gradient associated with the process and the ambient temperature, making insulation crucial to avoid excessive energy losses.

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