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Solid state anaerobic digestion of water poor feedstock for methane yield: An overview of process characteristics and challenges

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Abstract

Solid state anaerobic digestion (SSAD) of water poor feedstock may be a promising technology for energy recovery. Feedstocks having high solid concentration like lignocellulosic biomass, crop residues, forestry waste and organic fraction of municipal waste may be the appropriate feedstock for its biochemical conversion into energy carries like biomethane through SSAD. Compared to liquid state anaerobic digestion (LSAD), SSAD can handle higher organic loading rates (OLR), requires a less water and smaller reactor volume, may have lower energy demand for heating or stirring and higher volumetric methane productivity. Besides these, pathogen inactivation may also be achieved in SSAD of biodegradable waste. Around 60% of recently built AD systems have adopted SSAD technology. However, the process stability of an SSAD system may have several constraints like limited mass transfer, process inhibitors and selection of digester type and should be addressed prior to the implementation of SSAD technology. In this article, a comprehensive overview of the key aspects influencing the performance of SSAD is discussed along with the need for mathematical modelling approaches. Further to this, reactor configuration for SSAD and digestate management requirement and practice for solid state condition are reviewed for a better insight of SSAD technology

Keywords: Solid state anaerobic digestion; Clean energy; Mathematical modelling; Digestate management; Biogas; Biomass

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1. Introduction

Anaerobic digestion (AD) has a dual-purpose route for waste management which are formation of renewable energy and biofertilizer. The main product of AD is methane (50-70% of biogas), a renewable fuel, with CO_2 (30-50% of biogas) as a significant by-product and NH_3, H_2S and siloxane as few notable impurities [1]. Methane gas produced in AD may be used as a renewable energy carrier to acquire certificates for emission reduction as per Kyoto Protocol [2, 3]. Anaerobic digesters can be classified into two different categories (Table 1). The first one is liquid state anaerobic digestion (LSAD), with TS content <15%, while the second one is solid state anaerobic digestion (SSAD), where the TS content is >15%. The main advantages of SSAD over LSAD are that (1) it can handle higher organic loading rates (OLR), (2) it requires a smaller reactor volume for equal volumetric biogas production and (3) lower energy demand for heating or stirring is required [4 – 7]. However, the slower mass transfer in SSAD makes the retention time longer, up to three times, compared to LSAD [8,9]. In this review, a critical overview of the SSAD process is provided and the key factors affecting the process stability of SSAD are discussed. Specifically, emphasis on the effect of temperature, inoculation efficiency, inhibition in SSAD reactors, pre-treatment and co-digestion along with microbial community analysis were reviewed. Further to this, mathematical modelling approaches needed to describe and predict SSAD performance are presented along reactor types and design.

Table 1: Features of anaerobic digestion in solid and liquid state [4 – 7].

Parameters	Liquid state anaerobic digestion (TS < 15%)	Solid state anaerobic digestion (TS > 15%)

Primary substrate	Sewage sludge, Liquid manure, diluted food waste	Organic fraction of municipal waste, lignocellulose, crop residues
Loading rate	1–5 kg VS/m^3	5–12 kg VS/m^3
Pretreatment	May enhance the overall process	May reduce recalcitrance for better process stability
Mode of operation	Single, double and multi-stage	Single, double and multi-stage
Abrasion of reactor	Sand and grit present in feedstock may cause abrasion and sedimentation in the system. Also clogging of the nozzle may happen, and operation problems may occur	Less or no abrasion
Effluent	Large volume of effluent, not very easy to handle. Techniques needed to treat the effluent	Handling of effluent is comparatively easy.
Operation	Operational problems may occur as mixing is required. Short-circuiting may happen	Moving parts are limited, which ensures that less operational problems occur

2. Feedstock selection

The process stability of the SSAD system mostly depends on the physical and chemical composition of the substrate. Highly recalcitrant substrates may hinder the digestion process while substrates having high cellulose content may be beneficial for the methanogenesis process (Table 2). Climatic conditions and seasonal variations alter the composition of organic fraction of municipal solid waste (OFMSW), which may have some effects on the SSAD process [10]. Bolzonella et al. [11] reported that the biogas yield is majorly affected by the physical and chemical properties of OFMSW. Michele et al. [12] performed SSAD of OFMSW by recirculation of the digestate with the mixing ratio of 1:1.18–1:0.9 (waste to digestate) on w/w basis for a total of 21 days. 50% of theoretical methane were observed during SSAD of OFMSW and liquid effluent mix. However, the methane production dropped to 26% in the case of LSAD of same mix. [12].

High concentrations of organic solubles are present in food waste (FW), which can easily be converted into simple molecules through AD process. However, high concentrations of organic soluble may result in the formation of excess volatile fatty acids (VFAs), which may further hinder the AD process [13 - 14]. Expired dog food was co-digested with wood chips and sludge by Lu et al. [15] to control VFA inhibition in the SSAD process. It was reported that at 35ºC, the pH value decreased from 6.7 to 4.2 but at 55ºC, only a drop of 0.9 was observed in the pH of the system [15]. Brown at al. [16] adopted Feedstock to inoculum (F/I) ratio of 1, 2 and 3 with FW percentages of 0, 10 and 20, respectively, based on VS. Increased methane yields and volumetric productivities were observed when the percentage of food waste was increased to 10% and 20% of the substrate at F/I ratios of 2 and 1, respectively. In another experiment performed by Wang et al., the effect of different mixes of FW and distiller's grain in SSAD was evaluated [17]. The adopted ratio of distiller's grain and FW was10/1, 8/1, 6/1, 4/1, 1/0, and 0/1, respectively, on TS basis. It was concluded that co-digestion of distiller's grain and FW showed good synergistic effects on the propionate/acetate ratio and the VFA/alkalinity ratio. Co-digestion of soybean processing waste along with hay was investigated for biogas production by employing SSAD technique [18]. The ratio of 75:25 (VS basis) of soybean processing waste and hay, at F/I ratio of 3, resulted in 256 L/kg VS of methane yield. This yield was 148% and 50% higher than that of mono-digestion of soybean processing waste and hay, respectively.

Lignocellulosic material is a highly recalcitrant material to be digested anaerobically. Primarily, agricultural waste, crop residues and forestry wastes are considered as lignocellulosic material. Holocellulose (Cellulose + hemicellulose) present in lignocellulose waste is easily degradable component while lignin is known for being recalcitrant to anaerobic degradation [19-20].

Xu et al. [21] inoculated corn stover in mesophilic reactor for SSAD by using LSAD digestate of sewage sludge, FW and dairy waste at three different F/I ratios (2, 4 and 6). Maximum methane yield (238.5 L/kg VS) was observed in the case of dairy waste inoculation which was 19% higher to that of reactor inoculated with FW digestate. In another study, SSAD of corn stover was compared to various lignocellulosic biomass by Liew et al. [22]. Corn stover showed maximum methane production (81.2 L/kg VS) and it was 22, 50, and 98% more to that of wheat straw, leaves and yard waste respectively at F/I ratio of 2. In another study, volumetric methane yield was compared for tropical biomass waste in SSAD and LSAD system respectively by Ge et al. [23]. It was reported that volumetric methane yield was 5-fold higher in SSAD system to that in LSAD system.

Cui et al. [24] compared the raw wheat straw and spent wheat straw from horse stall in SSAD system for biogas production. The adopted TS was 20% for the experiment and inoculum was collected from the L – AD reactor and F/I ratio employed was 2, 4 and 6. As per results, at F/I ratio 2 and 4, daily maximum methane yield was observed to be peaked at 8 and 3days before in the case of spent straw respectively. Similarly, composting rice straw was studied for biogas production in SSAD reactor [25]. The team studied the interactive effect of temperature, solid concentration and carbon to nitrogen(C/N) ratio on the digestion process. It was reported that maximum gas production was attained at 35.6 ºC, 20% TS (initial) and a C/N ratio of 29.6. These studies showed that composting helped to reduce the recalcitrance of biomass.

Energy crops are also an attractive biomass for SSAD. Sheets et al. [26] investigated the effect of TS (20 and 30%) on biogas production using switchgrass as substrate under mesophilic and thermophilic conditions. As per reported experiment, mesophilic SSAD showed maximum methane production (102 and 145 L CH_4/ kg of VS added at solid concentration 20 and 30% respectively) than that of thermophilic SSAD (88 and 113 L CH_4/kg VS added). Yang et al., [27] also reported that 20-23% of TS showed maximum biogas in the case of giant reed.

Table 2: Solid state anaerobic digestion and methane yield in previously reported study

Substrate	Reactor Condition	Methane yield /productivity	Unit	References
Food waste	Single-phase batch	2.51	$m^3/m^3/d$	[28]
OFMSW	Single-phase batch reactor	1.324	L/L.d	[29]
Food and paper waste	Single-phase CSTR	0.25	m^3/g COD added	[30]
Sewage sludge	Single phase CSTR	190	L/kg VS	[31]
Food, fruit and vegetable and green waste	Single-phase with digestate recirculation	121 – 327	L/kg VS	[32]
Food and livestock waste	Single-phase CSTR	0.26	m^3/g COD added	[30]
Blue mussel and reed	Two-phase	0.33	m^3/kg VS	[33]

Rice straw and piggery waste	Single-phase batch with leachate recirculation	12 – 231	L/kg VS	[34]

3. Key factors affecting process stability of SSAD

3.1. Solid concentration

Solid concentration can alter the mass transfer phenomenon, reduce the requirement of larger reactor volume and its construction cost. A high solid concentration in the reactor may also introduce disturbance between microbes and substrate synergy in terms of basic anaerobic reaction and lower the biogas production [35].

Forster-Carneiro et al., showed that volumetric methane yield reduced by 60% when solid concentration increased to 30% [10]. Dry mesophilic methanogenesis was observed by Hyaric et al. [36] by employing MSW digestate and it was concluded that specific methanogenic activity and solid concentration were linearly related. Anaerobic mesophilic digestion of MSW was performed by Fernandez et al. [37] at two different solid concentration (20 and 30%). Higher level of removal of dissolved organic carbon and VFAs was achieved at 20% TS. Also, a decrease in the VS reduction by 17% was observed when solid concentration was increased to 30% [37]. Abbassi-Guendouz et al. [38] also reported a decline in methane yield as TS was increased up to 30%. Palm mill oil industry waste was studied for optimized methane yield under three different solid concentration (16, 25 and 35%) and at 16% solids concentration, organic wastes had higher methane yield than at 25 and 35%. Also, total solid removal was also better in the reactor with 16% solid concentration [39].

These results showed that high solid concentration altered the methanogenic activity. However, evidences have been lacking in terms of mechanism behind this phenomenon. Most of the researchers attributed this phenomenon to dysfunction of mass transfer [37-38]. For example, Bollon et al. [40] concluded that diffusion coefficient of solutes in the medium was decreased by 3.7 times when solid concentration was increased to 25% [40].

3.2. Inoculation

To start-up the biochemical reactions under anaerobic condition inside the digester, inoculation is major key factor. Inoculation not only provides microorganisms for enzymatic activity but also sometimes nullify the micronutrient imbalance [24, 41]. Effluent from L – AD sources, rumen fluid, sewage sludge and manure may be employed as inoculum for SSAD reactors. As per research performed by Xu et al., digestate from L – AD proved to be more efficient in initiating SSAD process as compared to lake sediments, sewage sludge, manure and rumen fluid [19]. Forster-Carneiro et al. noted a remarkable shift in the lag phase (20–30 days to 2–5 days) when the inoculum was switched from fresh manure to L – AD effluent [10]. L – AD effluent as inoculum for SSAD was also compared with SSAD effluent as inoculum by Suksong et al. [42]. It was reported that L – AD effluent as inoculum showed 2-fold increment in methane yield as compared to SSAD effluent as inoculum [42].

Instead of employing methanogenic microbes, Wieß et al. [43] employed hydrolytic microbes to improve methane yield from lignocellulosic biomass. It was reported that xylanase activity was increased by 162% by supplementing hemicellulolytic microbes to the AD process. An increase of 53% in methane yield was also recorded. Ma et al. [44] discovered that the optimal ratio of employing hydrolytic microorganism to methane generating microbes in AD was 24. If this ratio is < 24 then hydrolysis becomes the rate-limiting step while at >24, methanogenesis is rate-limiting phase in the anaerobic process. Hydrolytic microbes may alleviate the methane yield in SSAD as discovered by Xu et al. [21] after employing dairy manure as inoculum source for digestion of corn stover. Dairy manure inoculation enhanced the methane yield by 30 and 100% to that of food waste and sewage sludge digester effluent as inoculum for corn stover respectively. Gu et al. [45] compared the digestate from dairy manure as inoculum source for different feedstocks and reported that reactors inoculated with digested dairy manures achieved higher biomethanation and lignocellulose degradation.

Inoculation volume is another factor for higher methanogenic activity as they provide more methanogens. Optimized sizing of inoculum may start-up the SSAD process and may reduce the lag phase [9]. Inoculation volume simply refers to the feedstock to inoculum ratio in the digester. The most commonly used terms across the globe are feedstock to inoculum (F/I), substrate to inoculum (S/I) and feedstock to microbes (F/M) ratio. A higher inoculation volume may ensure the process stability, and, in this context, lots of research has been performed. Inoculation volume in the range of 2 – 3 on VS basis have been recommended for robust SSAD process stability in mesophilic region [18, 22, 44]. In thermophilic region, recommended inoculation volume ranges between 4 – 6 as per experiment performed on corn stover [46-47]. High solid concentration in SSAD reactor makes difficult to mix the substrate and inoculums in a better manner for the SSAD process stability. In this regard, mixing of inoculum with the substrate is required prior to the loading in the SSAD reactor. In large or pilot scale SSAD bioreactor may fail to provide proper interaction between microbes and feedstock due to improper mixing. In this regard, two different scenarios were created by Zhu et al. [18] for analysing the effect of premixing and partial mixing on SSAD process stability and net methane yield. In first scenario, the inoculum mixed completely with substrate and in second scenario, half of the inoculum was mixed with substrate and after this, another 50% of inoculum poured on the top. Results showed that methane yield was same in both the digester whereas the start-up time was less in premixed SSAD reactor. In another study performed by Zhu et al. [48] three premixing conditions were employed to digest corn stover anaerobically in SSAD reactor. Comparison of completely mixed scenario was performed with partially mixed in one and two layers. It was reported that by adopting inoculation volume between 4 – 6, two-layer mixing strategy of inoculum yielded highest methane.

Due to limited moisture content, mass transfer is slow in SSAD reactors [35]. To overcome this inevitable situation, recirculation of leachate is sometimes adopted in SSAD bioreactors [49]. There are school of opinion which endorse the concept of leachate recirculation for AD [50-51] while some research group did not get desired result by leachate recirculation in AD process [18, 52]. Accumulation of ammonia and VFAs may occur while recirculating leachate multiple times which may hinder the microbial activity and so the leachate should be diluted with fresh water for better applicability in the digestion process [52].

3.3. Temperature

Temperature is one of the most challenging factors for the SSAD process. Thermophilic and mesophilic conditions have been widely applied for the digestion. AD at mesophilic temperature zone is comparatively stable to that of thermophilic temperature zone but kickstarting the digestion process is quite easy in thermophilic zone as it accelerates the hydrolysis [9, 54]. Zeshan et al. [53] used pilot-scale thermophilic reactor for inspecting the effect of ammonia – N accumulation in SSAD process of FW, fruit and vegetable waste, yard waste and paper waste. It was reported that the net energy gain was 50 – 75% higher in the thermophilic temperature zone. Although thermophilic SSAD enhances the methane and biogas yield most of the time (Figure 1), it requires high energy input as compared to mesophilic condition. Sheets et al. [26] observed that besides having higher production rate of methane lower net energy gain was achieved in thermophilic condition while digesting switchgrass anaerobically. Also, thermophilic condition in SSAD enhances the hydrolysis of the substrate by activating hydrolytic microorganism in the reactor. This acceleration of the hydrolysis in the SSAD reactor may cause the rapid increase and accumulation of VFAs in the reactor [41]. This may hamper or inhibit the methanogenesis process of the bioreactor. In this regard, solid concentration, inoculation volume and optimized carbon to nitrogen ratio of substrate (s) will have a noteworthy role in the digestion process [54].

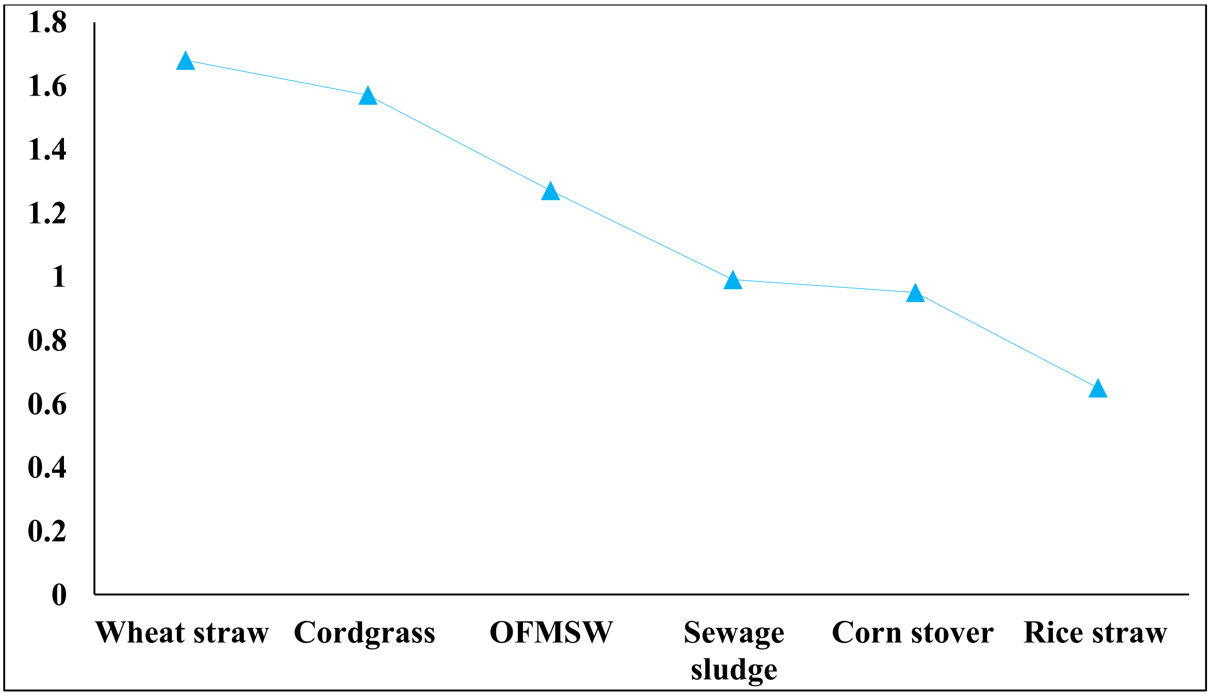


Figure 1: Ratio of methane yield of various substrate at both thermophilic and mesophilic temperatures [55 – 60].

TAD – Thermophilic anaerobic digestion; MAD – Mesophilic anaerobic digestion

Transition of temperature (mesophilic temperature range to thermophilic one) in SSAD process may affect the stability of reactor and digestion time of lignocellulosic biomass. Shi et al. [55] reported that degradation rate of cellulose and hemicellulose was high in thermophilic condition to that in mesophilic condition in first 12 days. A total of 6 – 41% of cellulose and 2 – 34% of hemicellulose degradation was recorded during the thermophilic SSAD. This result was ascribed to the bigger population of cellulolytic and xylanolytic microorganisms (10 – 50 times) in the SSAD bioreactor. OFMSW was investigated for thermophilic and mesophilic condition in SSAD reactor by Fernández-Rodríguez et al. [56]. While operating the bioreactor at the thermophilic condition, 27 – 60% higher specific growth rate of microbes was observed to that for mesophilic region. Research group concluded that the rate of degradation of organic matter may be achieved in shorter time if thermophilic temperature employed for the SSAD (40 days in mesophilic condition versus 20 days in thermophilic condition).

3.4. Inhibition

Feedstocks and other parameters in the bioreactor have the inherent capacity to alter the ongoing process and make it unstable for long run. The improper interaction between these factors sometimes results in inhibition for the methane generation. This may also hamper the process stability of the ongoing AD plant. Solid concentration, if not properly optimized, may end up resulting in VFA accumulation [61]. Excess VFA affects the methanogens. Three types of methanogenic activity are known. First one utilizes hydrogen and carbon dioxide and converts them into methane. Second pathway comprises the conversion of acetate formed in the acidogenesis and acetogenesis step into methane. And third, many methanogens can use methyl components for methane production. Wang et al. [62] contemplated that in SSAD; acetoclastic pathway shifted towards mixotrophic and hydrogenotrophic pathway when TS increased from 5 to 20%. The problem with accumulation of VFAs is the general inhibiting effect of undissociated VFA to which the methanogens are most susceptible and the decreased pH which inhibits the methanogens further. One of the main factors discovered for higher VFA accumulation in the anaerobic reactors is higher organic loading rate The threshold limit of VFA in SSAD was reported as 16.5-18 g/L during anaerobic codigestion of FW and pig manure [63]. However, for process stability, alternative feedstocks maybe adopted. Zhang et al., employed FW and packaging waste to cease VFA accumulation in the reactor[64]. It was discovered that selection of heterogeneous waste may allow higher loading of substrate in the digestion unit.

Khanal suggested that alkalinity and VFAs ratio may help to determine the stability of the digester[65]. When VFA/ alkalinity is < 0.4, reactor is safe and stable. While if VFA/alkalinity is > 0.8, reactor is prone to fail. However, if the system failure occurred because of excess ammonia nitrogen, concept of VFA to alkalinity ratio may not be helpful. Duan et al., reported a lower percentage of methane even at the VFA/alkalinity ratio of 0.2 [31]. Results acquired by Zeshan et al., also agrees with the fact that dependence on the VFA/alkalinity ratio to know reactor condition could be deceptive in the long operation of AD plant [53]. Therefore, a clear understanding of ammonia inhibition is required to predict the process stability.

Substrate rich in protein (OFMSW, FW) are primary source of free ammonia (NH_3) and ammonium ion (NH_4^+) in the digestion reactor. The operating temperature and pH of the SSAD system is the trigger point of ionic form (NH_3) and non – ionic (NH_4^+) form of ammonia in the reactor as depicted by equation 1 and 2 [66].

$$pK_a = 0.09018 \left(\frac{2729.92}{T + 273.15}\right) \quad (1)$$

$$FAN = \frac{TAN}{1 + 10^{(pK_a - pH)}} \quad (2)$$

where, pK_a - Dissociation constant of ammonium ions, T - Temperature, °C; FAN - Free ammonia nitrogen; TAN - Total ammonia nitrogen.

Around 60 – 80% of nitrogen available in the substrate is converted into ammonia or ammonium ion through ammonification process [67]. At lower concentration, ammonia (FAN) helps in microbial growth but higher concentration of it may act as an inhibitor and cause proton imbalance and/or make a cell wall potassium deficient [9]. Threshold value of non – ionic form of ammonia is suggested to be between 300 – 800 mg/L [31, 67]. Concentration of ammonia in the reactor is also altered by OLR and C/N ratio. In a study performed by Zeshan et al., accumulation of ammonia nitrogen (3200 mg/L) was observed at C/N ratio of 27 [32]. Also, as per report, at lower ratio of C/N, minimal inhibition was observed due to ammonia nitrogen.

Digesting citrus fruits waste, citrus fruit peelings or processed fruit waste in SSAD system for renewable fuel is an attractive alternative for waste management. However, D – limonene, an aqueous and colorless secondary plant metabolite comprising a cyclic terpene have been reported as an inhibitor in methanogenesis process [68]. D – limonene, a compound present in citrus fruit waste, may damage the microbial cell membrane. Solvent extraction and steam distillation may help to remove D – limonene but these processes will make the SSAD an energy-intense one (Martín et al., 2013). The pretreatment of hemicellulose rich complex substrates produce inhibitory furanic compounds such as furfurals and 5-hydroxyl methyl furfural which have adverse effect on AD process. Digestion process would be stable at < 1 mg/L furan but 2 mg/L furan and 3 mg/L 5 – hydroxyl methyl furfural hinder the methane production rate [69 – 70].

Feedstock like brewery spent grain have *p*-cresol as degradation product which hamper the SSAD process. However, use of granular biomass in two-stage SSAD has helped to overcome the negative effect of *p*-cresol [71].

4. Methods to improve SSAD performance

Lignin, if present in the substrate opted for SSAD, would act as a barrier to the digestion process in the reactor because of its recalcitrance nature. Pretreatment is a widespread practice to reduce the sturdy nature of substrate and increase the production of biogas [72-73]. Decrystallization of cellulose, increased surface area, hemicellulose removal and disintegration of lignin are the subset of pretreatment process. Apart from these, pretreatment of feedstocks prior to SSAD may improve the start-up phase of reactor with less VFAs accumulation [74].

Decrystallization of cellulose helps to make it more porous and accessible to the microbes [75]. Acid pretreatment of substrate before employing for digestion may help to decrystallize cellulose. Inorganic acids (H_2SO_4, HCl, HNO_3 and H_3PO_4) may decrystallize the cellulose but they are harsh on plant cell wall. To overcome this problem pertaining to inorganic acids, ionic liquids have been discovered which reacts with the hydroxyl group and break the hydrogen bond for the dissolution of cellulose, if employed for the pretreatment process [76], [77]. Ionic liquids also strengthen the pretreatment process by recovery option of both, the decrystallized cellulose (by anti-solvents like methanol, ethanol and acetone) and the ionic liquid itself which is nearly 100% recoverable [75]. One of the most frequently used ionic liquids for pretreatment of lignin rich substrate is N-methylmorpholine-N-oxide monohydrate (NMMO). A total 47 % increase in methane yield was recorded by employing NMMO as pretreatment aide for straw by Akhand et al., [78]. Surface area of the substrate provides interface to microbes for enzymatic/microbial activity. Increased surface area could provide more contact area for microorganisms and could alleviate the reaction process which further may enhance the biogas yield. Napier grass was examined in different sieve sizes (6, 10 and 20 mm) for methane production by Surendra and Samir [79]. It was discovered that grass which passed through 6 mm sieve showed higher methane yield as compared to grass passed through 10 and 20 mm sieve. Hemicellulose removal from lignocellulosic substrate may open the gate for enhanced surface area of cellulose. Steam explosion, liquid hot water pretreatment and dilute acid are prominent pretreatment technique for hemicellulose amputation [80]. Lignin deconstruction may be achieved by alkaline pretreatment, wet oxidation and/or biological pretreatment. The linkage between lignin and carbohydrate may be distorted by using hydroxides such as NaOH, $Ca(OH)_2$ and KOH (Kumar et al., 2018)

Zhao et al., pretreated yard trimmings by white rot fungi (*Ceriporiopsis subvermispora*) in SSAD process [72]. They investigated scenarios with three different solid concentrations (55, 40 and 25%). Results showed that *Ceriporiopsis subvermispora* was able to alter 7.4% of cellulose at 40% solid concentration. Also, digester with 40% solid concentration achieved highest methane yield (44.6 L/kg VS) among three which was 154% higher than raw yard trimmings. However, treating albizia chips with same strain of *Ceriporiopsis subvermispora* showed a 370% enhancement in methane yield [81] which was higher as compared to treating grass trimmings. Feedstock with higher lignin content such as spruce (29%) could be pretreated with alkali for enhanced methane production. In a study performed by Mohsenzadeh et al., spruce was pretreated with four different reagent combinations (NaOH/urea, NaOH/thiourea, NaOH/urea/thiourea, and NaOH/polyethylene glycol) at four different temperature (-15, 0, 22 and 80 °C)[82]. Up to 23% reduction in lignin and 57 % glucose yield was observed using alkaline pretreatment conditions (NaOH/thiourea, -15 °C). Zhu et al., inspected alkali pretreatment at different concentration to enhance biogas generation from corn stover[83]. The research group adopted 1, 2.5, 5 and 7.5% w/w concentration of NaOH. Result showed that by increasing loading of NaOH from 1 to 7.5%, lignin degradation enhanced from 9.1 to 46.2%. A biogas yield of 372.4 L/kg VS was achieved when the NaOH concentration was 5%. However, no significant increase was observed because of alkaline pretreatment. On the other hand, NaOH pretreatment resulted in increased methane yield when the substrate was poplar waste and reduction in lignin after pretreatment was observed to be 19.2% [84]. Combination of different pretreatment conditions for lignocellulosic biomass have also employed for improved biodegradability. Mustafa et al., pretreated rice straw with the combination of physical and biological pretreatment techniques for SSAD [85]. Rice straw was incubated with *Pleurotus ostreatus* for 10, 20 and 30 days. 30.4 % of lignin removed in the combination of physical and biological pretreatment. It was also reported that methane yield was 165 % higher as compared to untreated rice straw for SSAD process.

For a healthy anaerobic digester, a balanced C/N ratio, proper distribution of macro &micronutrient spectrum (Fe, Se, Co, Ni, Zn, W and Mo) and a diverse microorganism community are imperative. Co–digesting substrate with heterogeneous nature would placate such needs. In recent years, researchers have advocated anaerobic co-digestion for better process stability and higher methane yield around the globe [25, 86-88]. Co-digesting substrates for methanogenesis have tremendous benefit including optimized C/N ratio (if e.g. lignocellulosic biomass and slaughterhouse waste blended), a well-adjusted buffering ability in the reactor (blending carbohydrate rich substrate with others to manipulate TAN and FAN). Also, digester with enhanced rheology, no or less need of external micronutrient supplementation, healthy microbial dynamics (diversifying substrate endorsing microbial growth) and less or no inhibition are other aids [63, 89]. Digestion process is likely to be severely affected if the blending ratio of various substrates are not optimized prior to the start of batch or continuous reactor [90].

Agro – industrial waste such as spent mushroom from mushroom processing unit was examined for co – digestion with lignocellulosic waste [47] in solid state batch reactor. With the solid concentration of 20% and feedstock to inoculum ratio of 2, 3 and 4, substrates were mixed in 1:1 ratio (spent mushroom waste with wheat straw and yard trimmings respectively) on VS basis. The first combination of spent mushroom waste and wheat straw showed 269 L/kg VS of cumulative methane yield which was 23 times higher to that of mono – digestion of spent mushroom waste. Also, the second combination of spent mushroom waste and yard trimmings showed 16 times higher methane yield as compared to mono – digestion of mushroom waste. In a study, corn stover co – digested with chicken manure in 1:0, 3:1, 1:1, 1:3 ratio on VS basis and solid concentration of 20% after pretreating corn stover with NaOH [88]. While pretreatment of corn stover showed no effect on methane increment, co – digestion ratio of 3:1 showed maximum methane production (177.6 mL/g VS). Food and cardboard waste are also great substrate for anaerobic co – digestion in SSAD process. Anaerobic co-digestion may establish the synergy in the biodigesters which may elevate the methane production. However, it is required to consider the hydrolysis rate of the feedstock intended for co-digestion. Blending nitrogenous feedstock such as animal manure, pig urine with carbonaceous feedstock such as LCB may enhance ethe anaerobic bioconversion. Li et al. [91] co-digested corn stover with tomato residues and dairy manure for enhanced methane production. The maximum methane yield observed was 415 L/kg VS at 13% tomato residues. However, excess of the tomato residues caused VFA accumulation in the SSAD system. Similar results were reported by Wang et al. [92] in which cucumber residues codigested with corn stover helped to elevate the methane yield. though higher concentration of cucumber residues inhibited the process

5. Modelling approaches for SSAD

In SSAD, low reaction rate is one of the main drawbacks in comparison to L – AD. No or limited agitation and slow release of soluble substrates from feedstocks are believed to be responsible for having slow reaction rate in the SSAD [9]. Microbe – substrate interaction phenomenon, mass transfer mechanism, kinetics of the reaction and inhibition have been targeted by various mathematical models [93]. Researchers have employed statistical, theoretical and empirical approaches for assessing the behaviour of SSAD reactor and associated process parameters.

5.1 Statistical modelling approaches

Statistical models are those who employ experimental results for calibration, validation and prediction. One of the benefits of using statistical tools or model is minimum application of physiochemical or biochemical knowledge for its development. Simple linear regression (SLR), multiple linear regression (MLR) and artificial neural network (ANN) are profound techniques in statistical modelling approach for SSAD. If the digestion process is meticulously designed, SLR may be applied to know the correlation between two variables. VS removal of lignin rich feedstock in enzyme driven AD was correlated with biomethanation by Liew et al. [22] and Brown et al. [4]. These two parameters showed great correlation with coefficient of square (R^2) value of 0.86 and 0.99 respectively.

Effect of solid concentration, inoculation and size of substrate was studied applying MLR quadratic model (Eq. 3) developed by Motte et al., for lignocellulosic biomass[94]. For experimental value, wheat straw was used as substrate at solid concentration ranging from 15 to 25%. F/I ratio was between 28 and 47 (based on VS) and size of substrate particles was selected as 0.1 to 1.4 mm.

$$y = a_0 + \sum_{i=1}^{k} a_m x_i + \sum_{i=1}^{k} a_{mm} x_i^2 + \sum_{i=1}^{k} a_{mn} x_i x_j \qquad (3)$$

Where, y = response variable (Methane, VFA, pH); $x_i x_j$ = explanatory variables (solid concentration, inoculation, substrate size); a_0, a_m, a_{mm}, a_{mn} = model coefficients

Motte et al., ran the experiment for 270 days and concluded that correlation of particle size with solid concentration and inoculation showed considerable level of significance ($p<0.5$) [94]. Also, the research group discovered that F/I ratio showed greater effect in starting phase of AD. A variety of explanatory variables such as solid concentration, inoculation, C/N ratio, feedstock characteristics, alkalinity were regressed against response variable (methane) using MLR by Xu et al. [95]. Lignin percentage and feedstock to inoculum ratio was revealed to be significant for response variable in 30 day span of methanogenesis. Comparison of MLR with ANN was also performed by Xu et al., for prediction of the methane production using aforementioned parameters [95]. The research group exposed that standard error was low while applying ANN for the prediction. One of the benefits using ANN over MLR is its ability to predict performance of the system using complicated non-linear data [96].

5.2. Logistic/general kinetic modelling approaches

Logistical modelling approach targets only specific key factors which may have effects on over all process of SSAD like microbial concentration. Pommier et al., pitched some assumptions that only microbial consortia are responsible for methane production, whose population is governed by hydrolysis and feedstock concentration [97]. Based on these assumptions, an equation (Eq. 4) was developed for kinetics of biogas in SSAD batch reactors. Pommier et al., stated that only thoseportions of feedstock which are saturated with water, are accessible to microbes for methanogenic activity. Also amount of water (ω) was correlated by the authors using eq. 5 and 6.

$$\frac{dB}{dt} = \mu_{max} B \left(1 - \frac{(X_0^{max} - X)}{X_0}\right) \qquad (4)$$

$$\mu_{max} = \tau \, \mu_{max}^{R} \qquad (5)$$

$X_0 = \tau X_0^{max}$ (6)

Where,B = biomass growth;μ_{max} = maximum specific growth rate (d^{-1}) ; X = concentration of feedstock ($g_{COD}/g_{initial\ TS}$) ; X_0^{max} = initial value of X ; X_0 = amount of feedstock accessible to microbes ($g_{COD}/g_{initial\ TS}$); μ_{max}^{R} = optimal maximum specific growth rate (d^{-1}); ω_R= water holding capacity;$\tau = \frac{\omega - \omega_{min}}{\omega_R - \omega_{min}}$ $if\ \omega_{min} < \omega < \omega_R$; $\tau = 1\ if\ \omega > \omega_R$; $\tau = 0\ if\ \omega_{min} > \omega$; ω_R= water holding capacity; ω_{min}= minimum water required for starting biological activity

This modelling effort open the door for moisture and solid concentration optimization for better methanogenesis. Result showed that coefficient of microbial growth gets affected at bove 194% of water content ($g_{water}/g_{dry\ substrate}$).

General kinetic model was applied for the study of solid concentration and its effect on overall methane production by Fernandez et al., [37]. The base of the developed model was reaction rate law (Eq. 7)

$$B + X \overset{k}{\rightarrow} \Gamma B \quad (\Gamma > 1)(7)$$

Where,k = rate constant of process; X = dissolved organic carbon in feedstock (g/L); B = The concentration of microbes in dissolved organic carbon (g/L); Γ = stoichiometric constant

By above stated equation, a general kinetic equation was derived (Eq. 8) which prepared base for the equation for methane production by correlating feedstock consumption rate with methane generation rate (Eq. 9)

$$-\frac{dX}{dt} = \mu_{max}\frac{(h - X)(X - X_{NB})}{X_0 - X_{NB}} \qquad (8)$$

$$G = Y_{\frac{G}{X}}\left(\frac{\exp(\emptyset t) - 1}{\frac{1}{(h - X_0))} + \frac{\exp(\emptyset t)}{(X_0 - X_{NB})}}\right) and\ \emptyset = \mu_{max}\frac{h - X_{NB}}{X_0 - X_{NB}} \qquad (9)$$

Where,

X_0= initial solid feedstock concentration (g / L); X_{NB} = concentration of non – biodegradables (g / L); h = achievable maximum microbial cell mass (g dissolved organic carbon / L); G =

total methane generated (L $_{CH4}$/L) and $Y_{\frac{G}{X}}$ = methane yield per unit feedstock spent (L$_{CH4}$ / g dissolved organic carbon consumed)

Fernandez et al., applied these models to the experimental values obtained in SSAD of OFMSW at solid concentration of 20 and 30%, respectively. Results showed that maximum specific growth rate was achieved at 20% (0.265 d^{-1}) solid concentration as compared to that at 30% (0.147/d). These results agreed to the concept tossed by Pommier et al., (2007) that solid concentration alters microbial growth in SSAD process [37].

5.3. Theoretical modelling approaches

Theoretical modelling approaches attempt to establish sound mathematical base for the phases of AD. This approach tries to encompass the dynamics of each entity like feedstock (both soluble and insoluble), microorganism and biomethane of AD in mathematical simulation. In attempts to develop a mathematical model for SSAD, Kalyuzhnyi et al., assumed that SSAD system is heterogeneous and consist of homogeneous 'waste' (feedstock) and 'seed' (inoculum) particles within the system [98]. The seed particles in the model concept are supposed to have a lower biodegradability but great ability for methanogenesis and vice versa for waste particles. The authors postulated that 'waste' particle provides VFAs to the 'seed' particle by hydrolysis and acidogenic activity inside the SSAD system (Figure 2). Also, authors assume that there was no leachate generation in the reactor and consequently no exchange of microorganisms. The rate of diffusion of VFAs was calculated by Eq. (10)

$$r_d = 2D_e \frac{(S_s - S_w)}{L_s^2 + L_w^2} \qquad (10)$$

Where, r_d = diffusion rate of solute (g/L/s); D_e = effective diffusion coefficient of solute in medium (cm^2/s); L_s, L_w= diameters of 'seed' and 'waste' particles (cm), respectively ; S_s, S_w = solute concentration in seed and waste particle (g/L), respectively. In the above stated model, authors assumed that diameters of 'seed' and 'waste' particles were 0.5 cm and solute diffusion rate in 'seed' and 'waste' particle were 2 × 10^{-6} cm^2/s. Results showed that solute transportation rate and biodegradability of feedstock mostly influence the reactor performance.

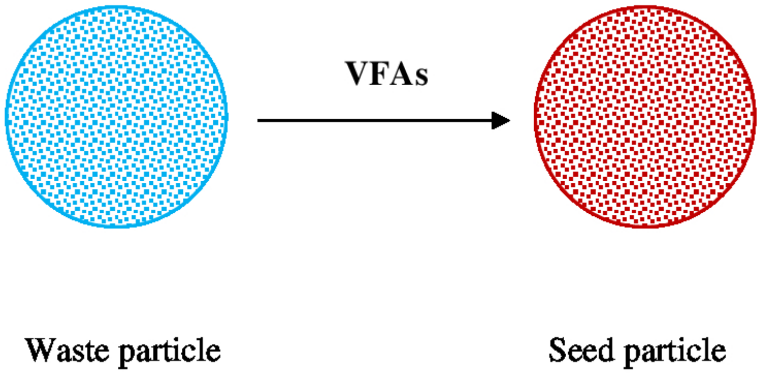


Figure 2: Waste and seed particle model [98]

Unlike considering the 'seed' particle homogeneous, Martin [99] suggested that 'seed' particles were a 'reaction front' having multiple layers and outside of this front, there is a solid feedstock layer which is getting acidified and its hydrolysis continuously depleted due to pH drop (Figure 3). The thin acetogenic zone broke down VFAs into acetate after getting introduced with acidified waste. The methanogenic zone behind buffer zone converts acetate into methane and finally feedstock stabilized after digestion. The diffusion of solutes between the layers are supposed to be following Fick's law. The assumption made for calculating methane were even distribution of seed in feedstock, diameter of seed particles assumed to be zero initially, reaction front has a well-defined thickness, propagates at constant rate and reaction rate within the SSAD system depends on reaction front volume [99-100].

Martin [99] proposed radius 'r' (cm) for the reaction front at time 't' and each reaction front has an equidistant of 2R (cm) in a cubic grid arrangement. The SSAD process according to reaction front model will have two phases namely acceleration phase and deceleration phase. As the digestion process starts, radius of reaction front 'r' will increase. After it exceeds the '2R' distance and starts to overlap other 6 reaction fronts in cubic arrangement, SSAD process will start decelerating. The area of each reaction front ‘A’ and radius ‘r’ is related as per eq. 11.

$A = 4\pi r^2 - 6\pi(r^2 - R^2)$ (11)

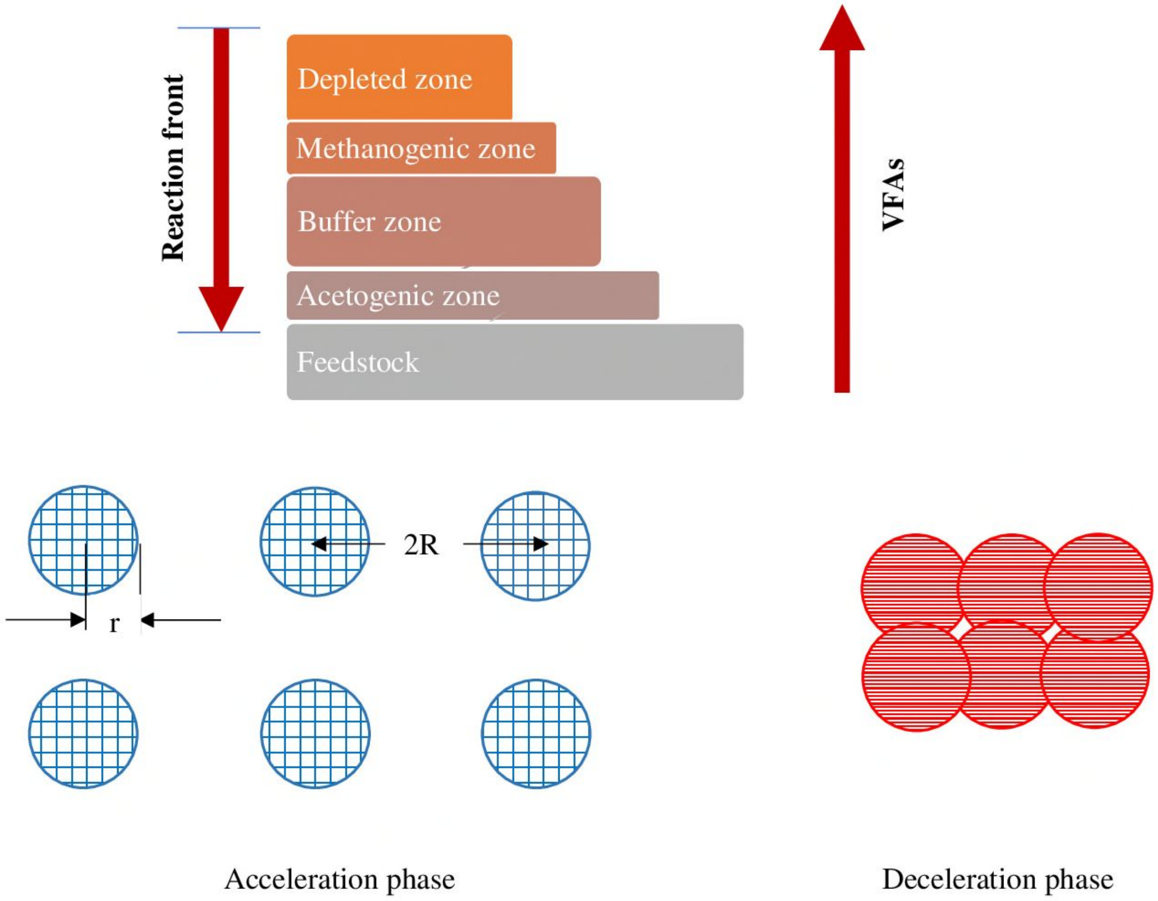


Figure 3: Reaction front model [99]

As per model interpretation, the kinetics of SSAD system would depend on the distribution of each seed particles. Moreover, mixing pattern of seed particles with waste particle would provide sufficient number of methanogenic zone and buffer zone to reduce acidification. In the direction of theoretical modelling approaches for SSAD, Vavilin et al. [101] and Eberl [102] have developed one dimensional distributed model and spatial temporal model respectively. Vavilin et al. [101] combined acidogenesis and acetogenesis as a single step in which a stoichiometric coefficient χ has been introduced to correlate acetate production rate with hydrolysis products concentration directly (Eq. 12 – 16).

The assumption behind this approach adopted was faster conversion of hydrolysis output to acetate. Apart from this, concentration of microbes and acetate was supposed to be the result of feedstock consumption, leachate flow and diffusion. Rate of methane generation was modelled as the function of microorganism growth rate and solid concentration.

$$\frac{\partial X}{\partial t} = -\,k_h X f(s),\;\; f(s) = \frac{1}{1+\left(\frac{I}{K_f}\right)^{m_f}} \tag{12}$$

$$\frac{\partial S}{\partial t} = D_S \frac{\partial^2 S}{\partial Z^2} - q\frac{\partial S}{\partial Z} + \chi k_h X f(S) - \rho_{max}\frac{SB}{K_s + S}\, g(S),\quad g(s) = \frac{1}{1+\left(\frac{I}{K_g}\right)^{m_g}} \tag{13}$$

$$\frac{\partial B}{\partial t} = D_B \frac{\partial^2 B}{\partial Z^2} - q\alpha\frac{\partial B}{\partial Z} + \, Y_{\frac{B}{X}}\,\rho_{max}\frac{SB}{K_s + S}\, g(S) - \, k_d B \tag{14}$$

$$\frac{\partial G}{\partial t} = \gamma\left(1 - \, Y_{\frac{B}{S}}\right)\rho_{max}\frac{SB}{K_s + S}\, g(S) \tag{15}$$

$$\frac{\partial N}{\partial t} = D_N \frac{\partial^2 N}{\partial Z^2} - q\frac{\partial N}{\partial Z} \tag{16}$$

Where,

$X, B, G, N =$ Concentrations of feedstock, microorganism, methane and sodium (g/L); k_h = first order hydrolysis rate constant (d^{-1}); S = concentration of the soluble feedstock in the SSAD system (here acetate); $f(S), g\ (S)$ = inhibition functions of acetate to hydrolysis and microbial growth ; $I = S - (60/23)N$ = stabilizing concentration of non – ionized VFA (g/L); K_f, K_g = inhibition constant Z = represents the vertical coordinate of the SSAD reactor (cm) where $0 \leq Z \leq L$ and L effective length of working volume of reactor; $D_S D_B =$ diffusion coefficients of the soluble substrate and microbes (cm^2/d); q = volumetric liquid flow rate per unit surface area; $\chi =$ stoichiometric coefficient;K_S = half saturation constant of acetate (g/L); α = fraction of microbe's cell mass shifted by liquid flow; $Y_{\frac{B}{S}}$ = methanogenic microbe growth yield coefficient w.r.t. acetate consumed (g/g); ρ_{max} = maximum acetate consumption rate (d^{-1}); k_d = microbial cell mass decay coefficient; γ = mass fraction of CH_4 in biogas.

Based on model results, Vavilin [100] concluded that both the rate of hydrolysis and acidogenesis should be matched with methanogenesis rate for maximum balanced performance of SSAD reactor. The model of Eberl followed aforementioned approach of one dimensional distributed model with reaction front model, incorporated inhibition occurred due to VFAs and mass transfer resulted from leachate flow and diffusion in the SSAD reactor (Eq. 17 – 20) [101-102].

$$X_t = D_X \Delta X - a_i\, q \nabla X - b_i f(s) X \qquad (17)$$

$$S_t = D_S \Delta S - q \nabla S + k_2 X f(s) - b_3 g(s) B \qquad (18)$$

$$B_t = D_B \Delta B - a_2\, q \nabla B + b_4\, g(S) B - b_5 B \qquad (19)$$

$$G_t = D_G \Delta G - q \nabla G + b_6 g(s) B \qquad (20)$$

Where,

$X, S, B, G =$ concentration of feedstock (solid), feedstock (soluble), microorganism and biomethane (g/L); t = time in days, $f(S), g\ (S)$ = inhibition functions of acetate to hydrolysis and microbial growth; q = velocity of leachate flow in convective mode (L/m^2/d); a_i , b_i= model parameters such that $a_i > 0, b_i > 0$. D_X, D_S, D_B, D_G = diffusion coefficients for substrate (solid), substrate (soluble), microorganism and biomethane. In this model, relation between methanogenesis and inoculation along with feedstock could be simulated in spatial distribution fashion. It was supposed that for native feedstock to get stabilized, propagation of reaction front has importance.

Lignocellulosic substrate has been modelled for biomethanation in SSAD system regarding solid concentration by Xu et al. [103].

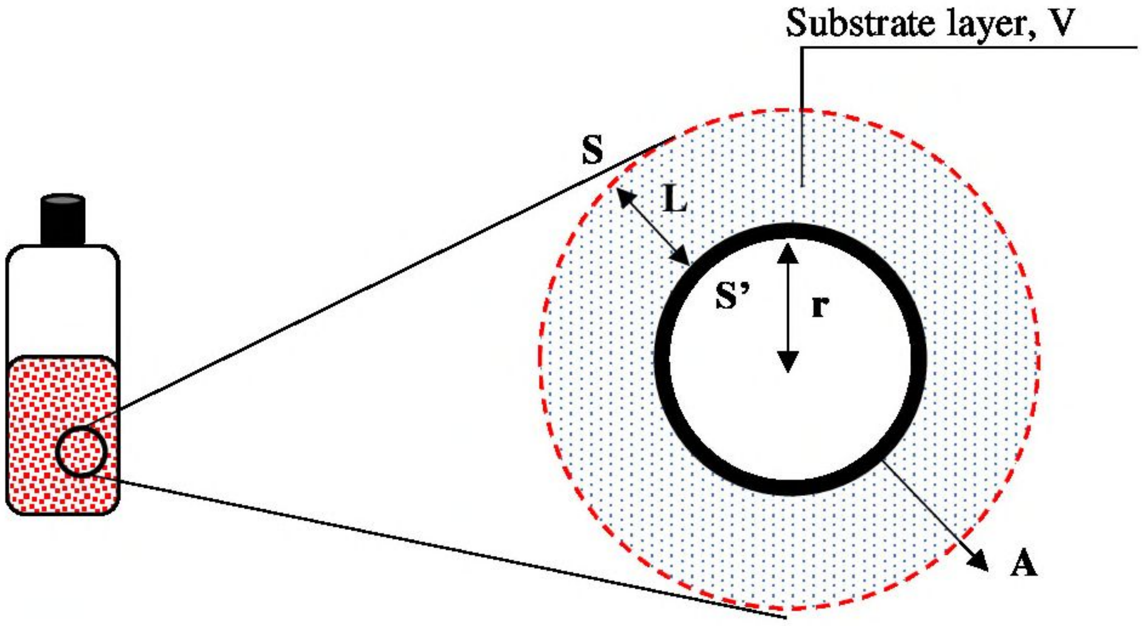


Figure 4: Mass diffusion modelling [103]

In this modelling approach (Figure 4), effect of solid concentration was also validated by the research group. A term 'microflora' for inoculation into feedstock was stated which thrive enzymes into the vicinity of feedstock for conversion of cellulose and hemicellulose into sugars (Eq. 21). Results showed that a threshold of 20% solid concentration does exist in SSAD at 37°C and after 20%, biomethanation gets affected because of inhibited hydrolysis in the system.

$$R_d = \frac{D_e A}{LV} (S - S') \qquad (21)$$

Where, R_d = rate of sugar diffusion (g/L/D); D_e = diffusion coefficient (cm^2/d); A = microflora surface area (cm^2); L = enzymatic hydrolysis zone length (μm); V = volume of feedstock layer (L); S = concentration of sugar (g/L); S' = concentration of sugar (inside microflora, g/L)

All the modelling approaches have some basic structure of manifestation and their interpretation. Table 3 summarizes the aspects of all modelling approaches.

Table 3: Summary of SSAD modelling approaches

Modelling approach	**Modelling Structure**	**Model calibration, validation and application**	**Model Output**	**Model interpretation**
Statistical	Research and experimental data utilization for prediction for model development	Validated using experimental set of data. Applied for SSAD of wheat straw with solid concentration ranging from 15 to 25%	Feedstock concentration, Biogas	Feedstock concentration and its characteristic affects the SSAD process
Logistic/general kinetic	Correlate the predominating set of parameters with solid concentration and its retention time	Validated using experimental data from SSAD of OFMSW and paper and cardboard	Feedstock concentration, biogas and microbial concentration	Microbial growth rate related to feedstock concentration along with its accessibility
Theoretical	Establishment of theoretical relation between methanogenesis and acetogenesis	Data collected from literatures for constants and some assumptions made	Feedstock concentration, biogas and microbial concentration,	Mixing, dispersion of inoculum in feedstock and leachate

	in special distribution		pH maximum methane production	recirculation affects biomethanation

6. Digesters for SSAD

For proper utilization of substrates as a source of renewable fuel, anaerobic reactors have been designed depending upon the properties of substrate and prevailing conditions. Primary aspects of a digester for SSAD are orientation like vertical or horizontal, loading rate and retention time [31 - 32]. Solid digestion system is capable to handle higher organic loadings (~ 15 kg VS/m^3/d) as compared to LSAD (5 kg VS/m^3/day) system for same methane yield and consumed VS during the process [104, 31].

Based on orientation, SSAD system may be categorized into vertical, horizontal and inclined one (Figure 5). Every bioreactor type has its pros and cons. Constructing a horizontal SSAD is comparatively expensive compared to a vertical one as fixtures are needed in the horizontal bioreactor. However, design of horizontal bioreactor ensures an optimal substrate utilization as solid residence time (SRT) is more as compared to vertical bioreactor. In Europe, 65 % of OFMSW is treated in mesophilic digester vertical/horizontal/inclined [105].

By mode of operation, SSAD systems subcategorized into batch, continuous and semi – continuous. Solid concentration in the batch system is around 35%. However, the conversion rate of feedstock in batch system is high and handling of batch system is easy. In continuous system, feedstock keeps entering at steady state which maintains the steadiness in the reactor and provide optimal use of the reactor volume. The problem associated with continuous systems is the mixing of partially digested substrate in the effluent. Dry anaerobic codigestion (DRANCO), Valorga, Kompogas, German rectangular fermenters (garage type), DiCOM,and SUBBOR (super blue box recycling), are typical examples of solid state anaerobic reactors whether employed at lab or full scale [63, 106-107].

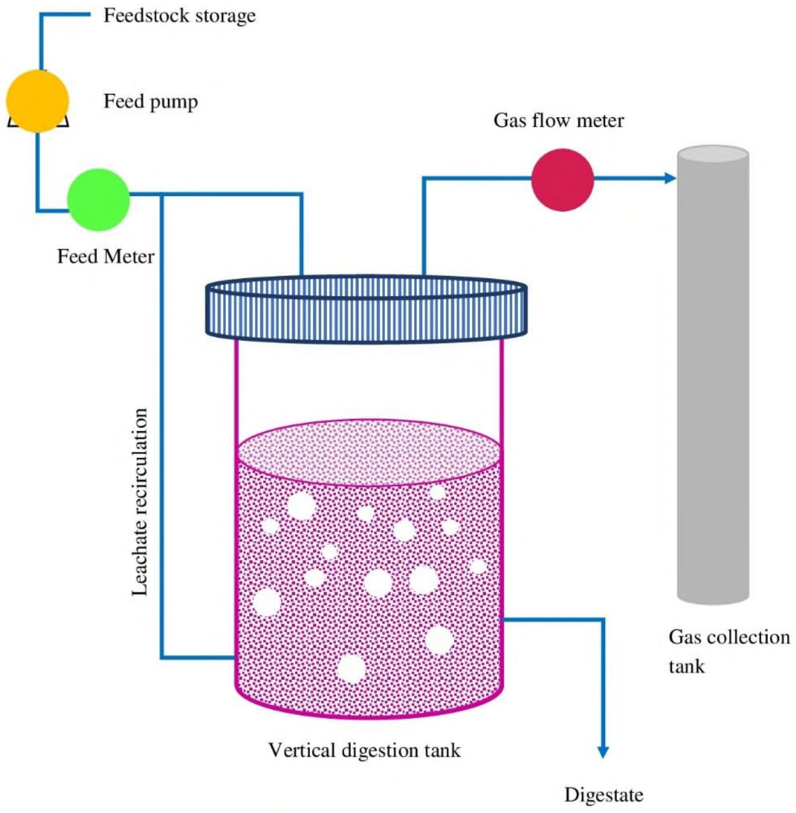
Dranco model is a vertical system. The base of Dranco model is silo shaped and there is no internal mixing unit for the inflow. However, the feedstocks were mixed properly before getting introduced into the digester. In this mixing, effluent from the digester gets mixed with fresh feedstock in the ratio of 1:6 [100, 108]. This ratio of mixing already digested material limits the entry of fresh feedstock and increase the digestion process and affects the process stability. Belgium base firm "Organic waste system" initiated the marketing of Dranco model. There are several working model of Dranco installed in European countries like in Brecht (Belgium) which processes whooping 12,000 t/a. Another one is in Kaiserslautern (Germany) processing 20000 tonne of municipal waste per annum.

Valorga model is also a vertical bioreactor which was developed in France. It includes a vertical wall extended up to certain height in the system which divides the reactor into two zones. The primary objective of the wall is to enhance the contact area for substrate and microbes. All the inlet and outlet valves are fixed to the base of the system. To handle high viscous flow, high pressure nozzle also appointed at the base of the reactor. Only drawback associated to this model is intensive energy use to circulate the feedstock in the system [46]. Operating solid concentration of Valorga model is 25 – 35 %. Installed bioprocessing plants consist of Valorga model in France are, Grenoble, treating 16,000 tonne of waste per annum, Amiens, processing 85,000 tone of organic waste on annual basis. Tilburg city of The Netherlands also have Valorga model which process 52,000 tonnes waste per annum.

Kompogas model originated in Switzerland in late 80's by Schmid situated in Glattbrugg as a modified version of horizontal plug flow model. Kompogas has an internal mixer for feedstock. This model works well at solid concentration of 25 – 28%. Already digested substrate sometimes mixed with fresh feedstock to maintain microbial integrity. Leachate recirculation system is employed in the German rectangular model. This model works at 40% solid concentration. This model resembles to landfill system where leachate is recirculated [109].

Unlike Kompogas model, the German rectangular do not have mixing mechanism which may reduce the proper interaction between feedstocks and microbes. Also, to refill this model, entire system has to be deflated which hinder the continuous methanogenesis.

Another model is SUBBOR which utilizes steam explosion pretreatment [110]. Steam explosion (55 – 63 bar pressure) makes paste of the feedstock which improves the microbial interaction but making it economically constrained. Another two-phase digester is bipercolate system in which aerobic pretreatment is incorporated. This model is capable to treat 15 kg of VS/ m^3 day and works on the concept that biofilm attached to the feedstock increase the resistance of methanogenic microbes to ammonia [111]. Figure 2 shows the vertical and horizontal SSAD reactor configuration.



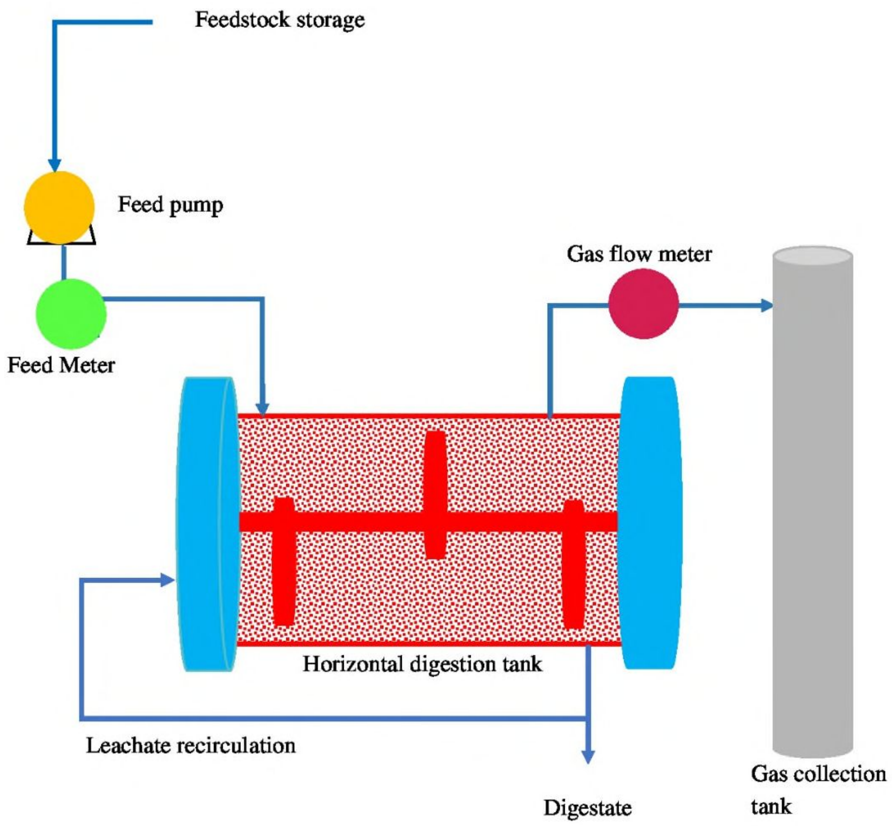


Figure 5: Schematic of SSAD reactor (Vertical and horizontal)

7. Digestate management

Digestate is usually rich in nutrients primarily consisting of nitrogen, phosphorus and potassium and therefore can be used as soil amendment after proper treatment [112]. Nutrient for plants available in soil may be alleviated immediately by adding digestate to it [113]. Tambone et al. [114] suggested that in developing countries, biogas digestate is of utter importance for maintaining nutrient in the soil for crop production. However, solid concentration and moisture in the biogas digester determines the nature and quantity of nutrients in the digestate [115]. In an experiment performed by Bernet et al. [116] free water and bound water content was examined.

Operating condition of digester and characteristics of substrates was reported to be responsible for total moisture in the digestate. A total water content of 3.3 to 4.6 g/g of dry mater was detected. It shows that design of the SSAD system and the operating condition for the digestate management is of sheer importance for further applications. In a reported study, Wang et al., also advocates that operating condition (here temperature) of SSAD will help to make the digestate pathogen free. Wang et al., (2017) took digestate from a SSAD plant running on distiller's grain waste and provided aerobic treatment for value added products. It was reported that after 65 days of aerobic digestion germination index of SSAD digestate has been improved to 110% from 60% which increases its suitability as fertilizer and soil conditioner [117].

Removal of moisture is necessary for further application of digestate as soil conditioner (Figure 6). Dewatering and drying of digestate, aerobic treatment and characterization of digestate are the steps involved in making digestate ready to use [63]. Dewatering and drying of digestate means to remove moisture from the digestate. Mechanical technique for dewatering is well known and practiced often. Simple drying by spreading digestate on land also practiced and have less economic burden to that of employing mechanical devices like press filters, screw pumping and vacuum evaporation. However, environmental impact of this traditional technique like odour nuisance and greenhouse gas emission makes it less feasible. Also, shelter is required in rainy season for land drying of digestate to avoid contact with rain water.

Zhang et al., concluded that co – digesting may enhance the overall performance of SSAD biodigester but the quality of digestate gets affected in terms of nutrient quality which is based on feedstock selection[64]. DiCOM in Australia and DRANCO in Belgium employed aerobic composting and on – site air inflow duct respectively to treat SSAD digestate to meet national standards of compost [118-119]. Characterization of digestate from SSAD process is required to optimize the after use of it. Parameters like temperature, C/N ratio, amount of nutrient like nitrogen, phosphorus and potassium (generally known as NPK value), heavy metal quantity and seed germination index provide direction for its optimum use. Characterization of SSAD digestate before and after treatment would be required to understand the potential effects of digestate treatment. In an experiment performed by Vaneeckhaute et al., dewatering of biogas digestate resulted in loss of nutrients [115]. As per results, total nitrogen and total phosphorus was 3.6 and 0.9 g/kg in solid part after dewatering process as compared to 4.7 and 0.27 g/kg in liquid part. The research group concluded that avoiding dewatering of digestate would help to retain its nutrient value.

Application of digestate in a water logged agricultural area could result in leachate generation as biogas digestate may get in contact with water table and contaminate watercourses [120]. Apart from this, digestate from a SSAD reactor would be high in terms of solid concentration and would provide more contact area to nutrient to be adsorbed. The more the concentration of nutrient, the more mobile the nutrient to the applied land [121-122]. SSAD of lignocellulosic material would enhance the adsorption of nutrient as because of solid concentration in the digester and fibres present in the lignocellulosic biomass may play the role of adsorbent for nutrients [123].

A number of studies were performed on lab scale. For commercialization of SSAD technology based in lignocellulosic biomass, pilot and full-scale experimentation is needed in near future. Special focus on mass transfer and microbial community dynamics may enhance the technological aspect of a commercial scale SSAD system. This will also ensure the techno-economic feasibility of commercial scale SSADS systems.

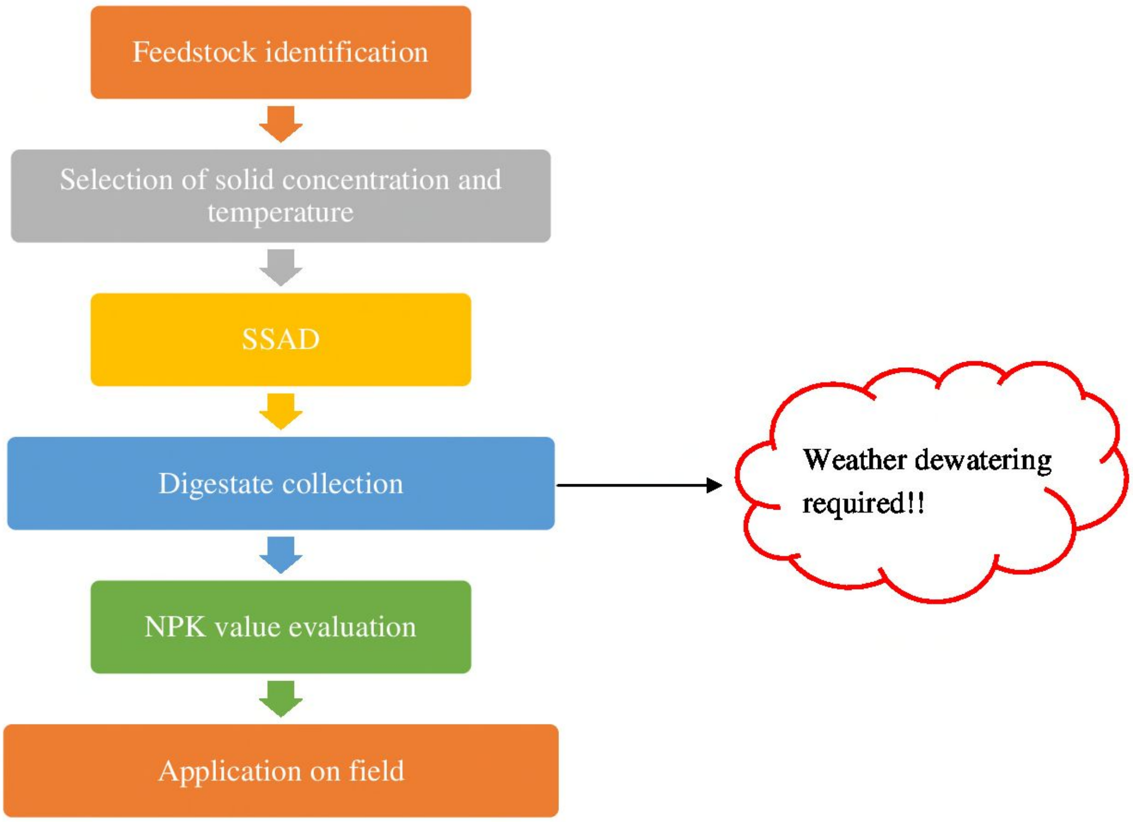


Figure 6: SSAD digestate management process flow

Conclusions

The challenges of a SSAD reactor is effective mass transfer, recalcitrant nature of lignocellulosic biomass, acid accumulation in the reactor and proper inoculation of input feedstock. However, SSAD can offer cost effective solution for organic waste and energy management in water stressed areas. Also, it may help to provide organic fertilizer for field application. Other strategies such as pretreatment, codigestion and temperature selection may enhance the process stability and reactor performance. Commercial application of SSAD such as Kompogas, Dranco and Valorga proved the effectiveness of this approach for waste management. However, further study and modelling approaches for coordination in waste transportation, storage and handling as well as utilization of biomass may help to improve the effectiveness of SSAD.

Abberviation

AD	Anaerobic Digestion
ANN	Artificial neural network
C/N	Carbon to nitrogen
DGGE	Denaturing gradient gel electrophoresis
DRANCO	Dry anaerobic codigestion
F/I	Feedstock to inoculum
F/M	Feedstock to microbes
FAN	Free ammonia nitrogen
FW	Food waste
HRT	Hydraulic retention time
LSAD	Liquid state anaerobic digestion
MAD	Mesophilic anaerobic digestion
MLR	Multiple linear regression
MPN	Most probable number
MSW	Municipal solid waste

NMMO	N-methyl morpholine-N-oxide monohydrate
OFMSW	Organic fraction of municipal solid waste
	Organic loading rate
OLR	
ORP	Oxidation reduction potential
S/I	Substrate to inoculum
SLR	Simple linear regression
SRT	Solid retention time
SSAD	Solid state anaerobic digestion
SUBBOR	Super blue box recycling
TAD	Thermophilic anaerobic digestion
TAN	Total ammonia nitrogen
TS	Total solids
VFA	Volatile fatty acids
VS	Volatile solids

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Authors' contributions

KP, VV and NK: Literature survey and manuscript draft; VK: Figures and editing; YBF and FC: data collection and tables; DS and NP: editing and revision of the manuscript. VV: Final revision and submission. All authors read and approved the final manuscript.

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Competing interests

The authors declare no competing interest.

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