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# Anaerobic Co-digestion as a Smart Approach for Enhanced Biogas Production and Simultaneous Treatment of Different Wastes

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## 1.1 Introduction

The world has witnessed tremendous growth over the past hundred years fueled by richness of earth's natural resources, but now we stare at the bleak prospects of exhaustion due to overutilization. With future economies balanced precariously on cost of fuel, with increasing demand for energy, ever-increasing annual fuel consumption, limited natural resources, volatility and disruption in fossil energy supplies, need of clean technologies has certainly driven us toward a pragmatic approach for optimized and proper use of natural resource for a sustainable ecosystem. Insightful planning and innovative methods are essential to enhance energy production in order to meet surge in future energy demands. Another scourge of the modern society is waste management; especially in the developing economies punctuated by improvement in individual purchase parity, it has led to tripling of waste generation per person just over the last one decade. An attempt is made in this chapter to link these two possible issues of fuel generation and waste management through a biotechnological intervention. The era of biotechnology as a futuristic technology strives to tap the service of the potential saprophytic microbes, which not only hastens the recycling of dead organic matter but can provide the fuel for running the future economy.

### 1.1.1 Biodegradation – Nature's Art of Recycling

The elemental components of our periodic table have finely blended the earth into molecules of infinite diversity. The organic forms of molecules are the basis of life existence in which the principal elements carbon, hydrogen, nitrogen, and oxygen have a subtle role in the formation of living system. The photosynthetic forms of life are one of the biggest producers of the organic matter, and it comes with an inherent clause of undergoing natural degradation over a period of time. This biodegradation is a very important invention of the nature, for, without recycling, a continuous existence of new life over millions of years would have been impossible. Microorganisms

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play a pivotal role in this process of biodegradation, without it recycling would have been unimaginably slower.

### 1.1.2 Anaerobic Digestion (AD)

Naturally existing anaerobic ecosystems such as paddy fields, swamps, lakes, ponds, intestine of ruminants, and ocean sediments rich in dead organic matter have paved way for microbes especially the archaeal obligate anaerobes-methanogens, mutual togetherness with other prokaryotic anaerobe leading to the production of methane. Though it can be attributed as a natural process, it leads to release of methane, a potential greenhouse gas capable of global warming far many times higher than carbon dioxide ($CO_2$). Anaerobic digestion (AD) as a technology refers to a provision of a closed condition for efficient digestion of the organic waste and to collect the by-product, methane.

The benefits of AD are immense for both the economy and ecosystem:

- Firstly, the digestion takes place in a closed environment, thereby preventing air pollution from obnoxious gases or disease-spreading germs.
- There is no issue of leachate escaping into water bodies and thus prevents open water body pollution.
- No underground seepage and pollution of groundwater.
- Faster degradation of organic matter compared with composting (aerobic).
- The AD process can be easily monitored circumventing the problems, for example, seasonal variation in temperatures.
- A microbial consortium can be developed, and it would aid in continuous and efficient digestion of waste.
- Biogas production with a range of fuel applications.
- Downstream processing is not required as biogas collects in the head space and is siphoned off for clarification and usage.
- Further effluent treatment would not be necessary as the slurry can be used as organic manure.
- Pathogens are inactivated, thus rendering the digestate harmless and safe.

The drawbacks are few, but critical enough to be highlighted:

- Limited access to high-quality feedstock that is free of contamination
- Non-perennial aspects of feedstock
- Transportation costs
- Long-term sustainable biomethanation
- Unexpected digester failures
- Maintenance of high fuel quality
- Issues of multistakeholders (in case of co-digestion)

The first four issues are related to feedstocks and its management, while the last three issues are related to lack of good microbial inoculum. Thus in this chapter, these two aspects of feedstock and real-time monitoring of operational parameters are dealt in detail.

Technical issues could be overcome by reliable public–private partnership, government initiatives, financial supports followed by technological advancement.

### 1.1.3 Sustainable Biomethanation

Sewage water treatment plants mandatorily follow AD for sludge treatment, and the ensuing methane-based gas is used for running wastewater treatment plants (WWTPs), though this is in principle, but the scenario is that many WWTPs struggle to maintain sustainable digesters, which are progressively jeopardized by frequent reactor failures. Biogas plants were ideally found to be an alternate source for renewable energy and were operated widely in rural areas of India; however, over the last few decades, it has taken a back seat, partially attributed to:

- digester operational instability,
- nonhomogeneous substrate,
- lack of good microbial inoculum,
- promotion and easier availability of LPG,
- deeper reach of electricity to remote rural areas,
- dip in active promotion of AD and their significance, especially in rural areas.

Renewed interest in AD stems from the problems of rapid urbanization and urgent need of waste management. Running successful biogas digesters depends mainly on two important factors: nature of substrate and the quality of inoculum. Real-time monitoring emphasizes on the following factors:

- balanced micro- and macronutrients,
- efficient microbial inoculum,
- digester design optimization,
- optimized organic loading rate (OLR),
- efficient monitoring of critical parameters (pH fluctuations, temperature range, total solids (TSs) utilization rate, volatile solids (VSs) accumulation and dispersal rates, microbial profiling: that is, eubacterial versus archaeal load ratio),
- continuous evaluation of digester performance [rate of biogas production, methane percentage, reduction in total solids, reduction in chemical oxygen demand (COD)],
- Reducing inhibitor concentrations.

## 1.2 Anaerobic Co-digestion (AcD)

Biogas technology is a perfect example to emphasize on zero waste concept, conversion of waste into fuel, and even the final digested remnant slurry's immense value as organic manure, which is potentially free of pathogens. Mono-digestion refers to the classical way for biogas production from a single type of feedstock while a co-digestion refers to mixing of two different feedstocks in a digester for biogas production. Co-digestion was initially planned to balance a carbon-to-nitrogen

(C/N ratio) content of the feedstocks, as few feedstocks are either rich in carbon (agricultural) or found to be rich in nitrogen (animal waste). High C/N ratio of feedstock will ultimately lead to reduction in microbial load due to overall nitrogen deficiency while lower C/N can result in ammonia poisoning that could particularly affect methanogens leading to lower biogas production. Excess of carbohydrates in feedstocks needs shorter retention time (RT) in digesters attributed by its quick oxidation, while excess protein content leads to lesser biogas production ascribed to accumulation of toxic levels of ammonia; on the other hand, excess lipids though results in higher biogas production but RT nearly doubles [1] further characterized by high concentrations of volatile fatty acids (VFAs) and low pH, thus leading to a consensus that excess of any nutrient cannot be beneficial for biogas production [2]. The anaerobic co-digestion (AcD) thus offers an opportunity to modify the composition of the waste to our need that suits our microbial consortium very well, and in this regard, C/N ratio can be altered to the optimum range. WWTPs around the world have increasingly opted for co-digestion to increase biogas output, and a WWTP in Mesa, USA, has successfully evaluated co-digestion of commercial solid food waste with sewage sludge in pilot-scale anaerobic digesters [3]. Lipid-rich restaurant waste has been co-digested with sewage sludge [4].

### 1.2.1 Zero Waste to Zero Carbon Emission Technology

The biogas as renewable energy can contribute in a big way to meet an overzealous future goal of zero emission economy by supplying fuel to major contributors of greenhouse gas emissions such as transportation and heavy industries (power plants, steel and cement industry, to name a few). Presently the biogas, which is rich in methane, burns clean and helps in the cutdown of carbon emissions at a domestic level. It is evident now as many countries have taken initiatives in setting goals for tapping the renewal energy resources, the Australian water industry is said to have generated 187 GW/year of electricity from biogas via WWTPs and an additional 5.5 GW/year through AcD [5]. Channeling of organic wastes from land fill, restaurants, other urban wastes toward existing and time-tested WWTPs is advocated by many countries and has envisioned zero carbon emission by the year 2040. Figure 1.1 summarizes the scope of AD.

### 1.2.2 Alternative Feedstocks

Feedstock refers to the particular form of organic waste available for AD but if left unattended can lead to environmental pollution. United State Environmental Protection Agency (USEPA) has assigned each feedstock a unique RIN (renewable identification number) that helps to rate how much of greenhouse gas it can emit in comparison to fossil fuel [3]. Cattle dung has been traditionally preferred as the typical substrate for AD; however, in terms of substrate quality it represents the semi-digested material excreted by ruminants. However, the advantage of cattle dung as a substrate is that it has inherent microbes catered from intestines of ruminants specialized in AD and biogas production. Any substrate for AD is

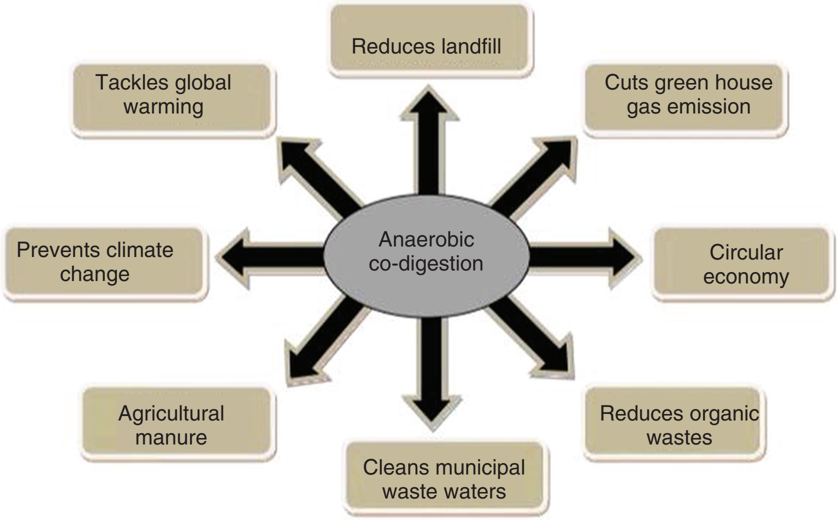

**Figure 1.1** Applications of anaerobic co-digestion.

basically referred to as organic wastes generated at its source; it can be available in many forms and its characteristic depends on the source. It can be available from a single crop agricultural waste to a blended form as municipal solid waste (MSW/urban waste) categorized in terms of complexity in defining the exact composition of waste. Emphasis has been laid on alternative feedstock such as:

- agricultural residues (energy crops),
- commercial food waste (canteen/mess/restaurant),
- retail wastes/fruits and vegetable wastes (peels, press cake),
- animal waste (ranch waste/poultry waste/livestocks processing wastes),
- effluent treatment in industries (dairy wastes, bioprocess industry, sugar industry),
- garbage waste (MSW),
- sewage sludge (WWTP), etc.

It is still contradictory to classify based on source/origin because some untreated waste such as food waste may ultimately end up in land fill or may be diverted to WWTP. The wastes are characterized based on principal nutrient content for microbes, namely carbohydrates, proteins, and fats. Animal wastes are protein-rich, while agricultural wastes are carbon-rich with cellulose, hemicelluloses, lignin, etc. Dairy-industry-generated wastes are fats and protein-rich. Thus each type of feedstock is unique in composition and based on that requires different approach for digestion. Feedstock composition should be assessed for certain inhibitors of methanogenesis, such as nitrates, sulfates as they could support growth of denitrifiers and sulfate reducers at the expense of methanogens [6, 7]; this tends to have a drastic effect on hydrogen foraging methanogen population leading to suboptimum biogas production. Though the organic waste is abundant in nature, its availability at a particular location could vary on a daily basis. Moreover, substrate heterogeneity, seasonal variation, and feasibility of transportation of waste from source are also to be coordinated. The idea of setting up the AD at the source of waste generation is a viable option; still the supplies could be erratic or inconsistent. The opportunity to go for co-digestion not only helps in circumventing the problem of nonavailability of single substrate but also helps in managing different wastes generated at source efficiently.

### 1.2.3 Microbiological Aspects

The emphasis of the role of microbes is well documented in every successful biogas digester. There is a systematic and sequential breakdown of complex organic waste into methane carried out by four metabolically distinct bacterial groups:

- hydrolyzing bacteria: complex carbohydrates, fats, and proteins converted to simple sugars, long-chain fatty acids (LCFAs) and amino acids;
- acidogens: lead to the accumulation of VFAs, alcohols, and carbonic acids;
- acetogens: further degradation results in acetic acid, hydrogen, carbon dioxide with trace amount of ammonia, $H_2S$, etc.; and
- methanogens: scavenge on $H_2$ and C1 and C2 carbon compounds for energy leading to production of methane.

Each of the aforementioned groups plays a pivotal role in AD and inactivation of any one group could possibly lead to accumulation of intermediate compounds impacting the outcome of the digester performance, while methanogen biomass ratio is miniscule in comparison to other groups [8]; still their influence is immense and found to be critical for sustainable biomethanation [9].

### 1.2.4 Strategies for Inoculum Development

It is highly impossible to define the exact microbial composition of any anaerobic digester, culturing techniques in coordination with molecular diagnostics can aid in identification, but never have we deduced the true potential population of AD. Inoculum for any biogas digester is usually sourced from ruminant fluid, municipal WWTPs, landfill leachate, or sludge collected from any preexisting active biogas digester. It is primarily important to relate inoculum with its role in biogas digesters, for example, an inoculum collected from WWTP may have few cellulolytic bacteria and thus may not lead to a sustainable biomethanation of agricultural wastes. Ruminant intestines harbor a natural population of methanogens, hydrolytic and other fermentative anaerobes, which cater to efficient biogas production and general success only for cattle-dung-based digesters; the same success is difficult to reproduce when inoculum from cattle-dung-based digester is added to digest poultry waste or dairy-waste-based digesters. Microbial population may vary even between sample inoculum and digester, for example, fresh cattle dung is rich in hydrogenotrophs (93–80%) [10] compared with acetoclastic methanogens (6–20%) [10] (Reasons being nonavailability of acetates, which are being reabsorbed by ruminant intestines along with other VFAs leading to the formation of animal fat) [10] while active digesters exhibit higher load of acetoclastic methanogens in comparison to hydrogenotrophs.

Even within digesters the microbial population may change, which can be attributed to the complex metabolic processes leading to accumulation of various intermediates that continuously influence the dynamics of microbial population. Hence, there is need for inoculum development, which involves acclimatizing a set of microbes to the digester environment; this could be done by pooling in a set of potential dominant anaerobes isolated from successfully running digesters to form a working consortium. Such microbial consortium had proven to give higher yield of biogas and better degradation of biological waste [11].

Consortium development is mostly targeted on methanogens as they are found to be the sole reason for biogas digester failure. The consortium has to be tested under lab-scale digesters for their efficiency before implementing in larger-scale biogas digesters. Care should be taken while developing consortium to select potential strains capable of withstanding digester environment fluctuations in pH and temperature, resistance to inhibitors, nutritionally diverse, and can syntrophically coexist. Potential strains of methanogens have been mostly identified to be hydrogenotrophic methanogens, acetoclastic and methylotrophic methanogens. The most abundant species among hydrogenotrophic methanogens are *Methanobacterium*, an hydrogen foraging methanogen that is known to dominate rumen intestinal environment while its role in a typical biogas digester is overshadowed by acetate utilizing methanogens (*Methanosaeta*, *Methanosarcina*, and *Methanospirillum*) that represent nearly 75% of the methane produced in digesters, still hydrogenotrophs are crucial for interspecies hydrogen transfer between syntrophic bacteria that could help diminish the concentrations of fatty acids in digesters [1], especially propionic acid as its presence can upset digester performance.

As mentioned earlier, there are four groups of bacteria in a synergetic action in digesters, each group of bacteria have their own physiological requirements and show varying degree of growth efficiency and wide range of sensitivity to environmental parameters. Acidogenic bacteria are among the fastest-growing organisms, generally leading to quick accumulation of acid end products. While acetogenic bacteria and methanogens are slow-growing organisms, to further complicate the matter, the methanogens are found to be very sensitive to changes in environmental parameters, which is detrimental for sustained biomethanation. Hence, inoculum is a critical parameter for determining the efficiency of anaerobic digesters. There is still diverse population of microbes that could not be cultivated and assessed from AD, and hence, any potential microbial consortium that is developed in laboratory should be considered as an supplementary feed and cannot by itself regarded as sole group of organisms that could digest waste in a digester [12].

### 1.2.5 Real-Time Monitoring of AcD

Real-time monitoring is essential for sustainable biogas production, will help us to continuously evaluate the digester performance, and help us to take immediate

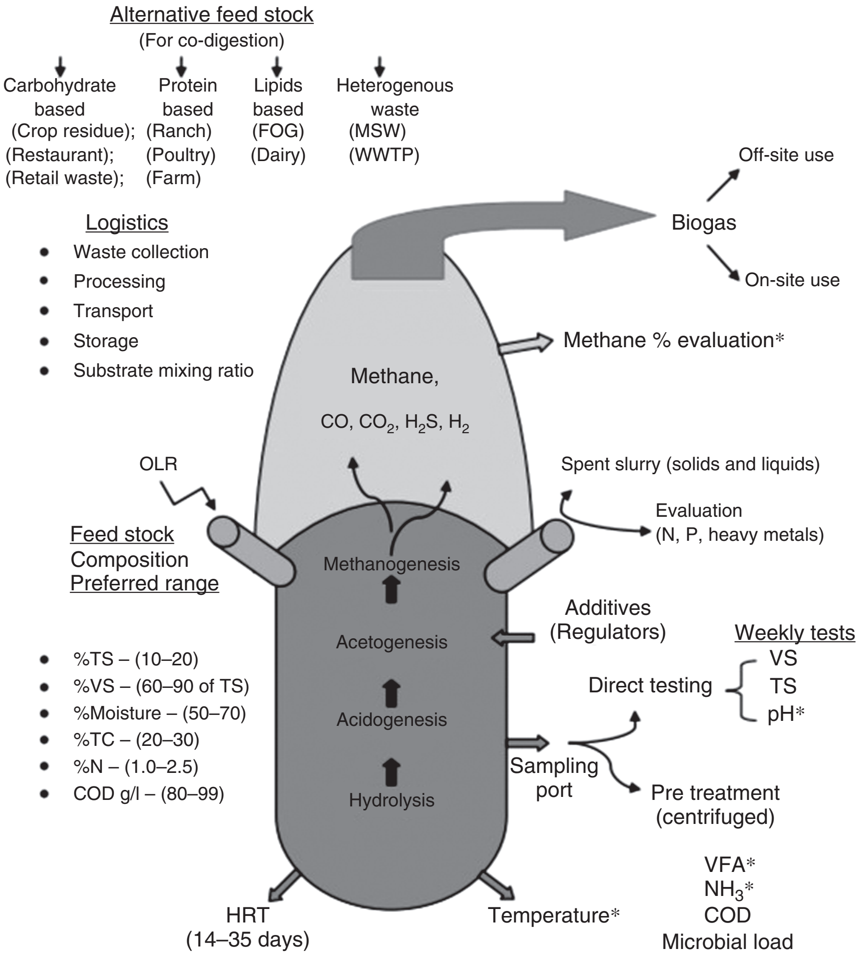

**Figure 1.2** Real-time monitoring of anaerobic digesters. * Daily tests. FOG – fat, oil, and grease; P – phosphorus.

remedial action to circumvent the problem and prevent digester failures (Figure 1.2). Direct monitoring of microbial growth is not always a feasible option, as it requires an equipped anaerobic laboratory for studies, further the problems are compounded by slower growth rate of methanogens as it takes days to evaluate the exact microbial content of the digester. Molecular techniques such as fluorescence *in situ* hybridization (FISH), 16S rRNA, real-time polymerase chain reaction (RT-PCR), and denaturing gradient gel electrophoresis (DGGE) aid in assessment of microbial load feasible mostly for laboratory studies and applicable to large-scale biogas digesters.

### 1.2.5.1 The pH Fluctuations

There are other ways of monitoring bioreactor performance; these parameters are simple and can efficiently diagnose the current status of the working reactors. pH is one such factor that can be readily checked at regular intervals; neutral pH is preferred for sustainable biomethanation; and any variation in pH can drastically cut down methane production. Fluctuations in pH are one of the biggest problems associated with AD and mostly shift toward lower pH, which is directly attributed to accumulation of VFAs. Sometimes pH may shift toward alkalinity contributed by accumulation of ammonia. This pH problem is due to microbial metabolism, especially by higher growth activity of acid-producing bacteria, compounded by the absence of buffering agents. Simultaneous degradation of proteins can lead to formation of ammonia that could help in balancing of pH in a digester averting shift toward acidic range. As mentioned earlier, too much of protein degradation in digesters can lead to excessive ammonia shifting pH toward 8.0 that shuts down microbial activity. The pH fluctuations should be seriously dealt with and a delay could permanently alter the microbial population of the digesters and sometimes cause irreversible damage to digester performance. Either way the methanogens are said to very sensitive to pH change and the problem can be overcome by neutralizing the pH with an alkali or a weak acid, but could turn to costlier affair to invest on alkali treatment, which is not generally recommended. A robust and an efficient microbial population of VFA converters are essential, while few digesters have adopted for dual digesters/two-stage digestion for circumventing the pH problem.

#### 1.2.5.2 Carbon–Nitrogen Content

It is essential to know the total carbon (TC) and nitrogen (N) content of the feedstock while the optimum C/N ratio for AD should preferably be in a range of 20–30. And increase in the value signifies the problem of nitrogen shortage leading to lesser load of microbes and process of AD getting delayed while lower ratio could imply higher microbial growth but the biogas could abruptly stop due to problems associated with by-products of protein degradation significantly changing the digester balance toward inactivity. The AcD thus plays a crucial role as we can finely balance the carbon–nitrogen ratio for optimum biogas production.

Anaerobic digesters can work in a wide range of temperature; however, it been noted that temperatures below 20 °C can affect the efficiency of digesters by considerably slowing down the process; still in natural habitats, methanogenesis is found to happen significantly at low temperatures and over a period of time has contributed to global warming [13].

#### 1.2.5.3 Temperature

Eightfold reductions in COD can be observed with mesophilic and thermophilic digestion at hydraulic retention time (HRT) of 35 days, while digesters at lower temperature are stable for a longer period of time more than 45 days [12]. Digesters around the globe are mostly operated in mesophilic conditions with recommended temperatures of around 35 °C, while faster digestion is generally reported at thermophilic temperatures of 55 °C but that comes with an inherent need of heat exchangers for temperature maintenance that can either shoot up or drastically fall reflecting microbial metabolism. Here biogas can be self-employed for heating the digesters, and thus it could be self-sustained process without much investment. It has been noted that the microbial population dynamics vary greatly between mesophilic and thermophilic digesters, for example, at 55 °C, hydrogenotrophs are found to dominate and if properly supplemented by syntrophic acetate-oxidizing bacteria [14] could even lead to sustainable biogas production in complete absence of acetoclastic methanogens.

#### 1.2.5.4 Volatile Fatty Acids

Efficient monitoring of digesters can also be carried out by constant evaluation of VFA content of the digesters. Though VFA accumulation above 2000 mg/l leads to digester failures, still it should be kept in mind that the same VFA gets finally converted to methane, in fact carbon atom of VFA is the principal source for methane production. The answer lies in the nature of VFA that accumulates in the digesters; most preferred form of VFA is acetic acid as it is the essential substrate for methanogens.

Fatty acid oxidizing bacteria breakdown LCFA to acetic acid, and these bacteria are inherently resistant to the toxic effects of accumulated LCFA. It has been noted that microbial load of fatty acid oxidizing bacteria fluctuates within the digesters directly influencing LCFA conversion rate, and their total absence in digesters leads to digester failures. Fatty acids oxidizing bacteria have been identified to be either producer of hydrogen (obligate hydrogen-producing acetogens [OHPAs]) or hydrogen consumer (homoacetogens) but certainly lead to the formation of acetic acid. Not all VFA contributes to methane, certain volatile acids have a deleterious effect on the overall process especially propionic acid, and its accumulation decreases the pH to an extent of inhibiting the growth of methanogens, leading to fall in biogas production.

#### 1.2.5.5 Ammonia

High protein content-based feedstocks on AD can trigger an alkaline shock with accumulation of ammonia or ammonium ions, at about pH 8.0 the drastic reduction in microbial activity can be noted and with pH reaching 8.5 can completely deactivate methanogens thereby completely stopping methane production. The problem can be circumvented by balancing C/N ratio of the feedstock; immediate actions would be to reduce loading rate and further diluting the digester content. This corrective action can quickly adjust the pH to optimum range, it is imperative that the microbial consortia play a significant role in AcD.

Both ammonia and VFA thus play a crucial role and are intricately related to pH fluctuations; a VFA/ammonia ratio of 0.1 is preferred for a balanced sustainable digesters and increase to 0.5 indicates that the digesters could fail and further rise can completely stop biogas production.

#### 1.2.5.6 Organic Loading Rate

Continuously operated digesters require balanced input of feedstock, (feedstocks/organic) loading rate (OLR) refers to the rate at which the feedstocks are fed into the digesters. OLR depends on the waste composition and is directly correlated to microbial growth rate, substrate conversion rate and evaluated by the rate of methane production. Excess OLR can dilute the microbial load, reduce digestion, foaming, and lesser yield of methane. OLR is further related to HRT, which implies the time taken by the digester for maximum gasification of the feedstocks. Shorter RT is preferable to avoid accumulation of fatty acids and toxins but way less than shorter RT can lead to microbial washout. Minimum one day RT is enough for stable buildup of fermentation bacteria especially for protein and nonfiber carbohydrates-based feedstocks; cellulose and hemicelluloses may require two to three days to establish the process, while fat-based feedstock may require longer RT of five days.

Complete gasification of waste can be achieved in a digester by increasing RT to 35 days (in case of batch digestion); the process is influenced by temperature: higher the temperature, shorter the RT, and RT of more than 35 days is required for psychrophilic temperature. Longer RT leads to improvement in quality of biogas in terms of methane concentration, shorter RT may generally exhibit 70% methane content while the percentage of methane tends to increase with longer RT. Total solid (TS) of more than 30% is not preferred for AcD as it leads to the problem of mixing concentrated pockets of temperature and pH burst in a continuously operated digesters depends on feedstock composition. The volatile solid (VS), which is a part of TS, is generally preferred in a range of 60–90% for efficient biogas production and for optimum microbial growth.

Pretreatment of feedstock is essential to minimize the natural flora on the surface of substrate as it will hinder the role of potential consortium developed for the purpose that is already active inside the digesters.

## 1.3 Digester Designs

The earliest digesters were simple in design with a digestion chamber, an inlet for feedstocks, and two outlets, one for spent slurry and one for biogas. The appropriate modeling of anaerobic digesters is imperative for biogas production. Digesters are designed with the view of maintaining strict anaerobic conditions and for collection and retrieval of biogas. The digesters can be operated in batch or continuous phase. Anaerobic biogas digester such as the one used in WWTP is distinct as it is continuously fed with heterogeneous liquid wastes, microbes agglomerate to form the granules (sludge) that set in to form a layer/blanket with a constant upflow hydraulic regime [15]. WWTPs around the world have opted for upflow anaerobic sludge blanket (UASB) digester for anaerobic treatment, which has been found to be cost-effective and emphasizes the role of microbial granules (solid phase) that knit into a group of specialized agglomerated bacterial biofilm [16].

Expanded granular sludge beds (EGSBs) are a modified version and next-generation biogas digesters with enhanced flow rate of liquid waste that could result in mixing of sludge particles establishing contact with nutrient for the purpose of breakdown. Further efforts have been taken to make thin, lighter-weight biofilm of uniform thickness (granular sludge) for better fluidization and at lower energy expenses in the form of inverse fluidized bed reactors (IFBR), which would reduce HRT at a higher OLR that was initially carried out for distillery effluent [17].

Digesters with constant mixing can take up higher OLR, and it has been reported that OLR increased up to 300 kg COD/$m^3$/d using super high rate anaerobic bioreactor (SAB) that works on a principle of spiraling baffle running through the middle of the digester body [15].

Mixing helps in uniform distribution of feedstocks during AcD and provides access of metabolic intermediates, microbial interaction; prevents stratification and release of trapped methane that has been observed with completely stirred/mixed tank reactors (CSTRs) [4]. Mixing of digester content can occur naturally to some extent by rise of methane bubbles, which is by itself not sufficient for optimum biogas production, hence auxiliary mixing is essential. It has been reported that intermittent mixing leads to better biogas production in comparison to continuous mixing [4].

As we know that four groups of microbes are responsible for biogas production, an attempt has been made to build two-stage digesters basically dividing microbial role of hydrolysis/acidogenesis and acetogenesis/methanogenesis [18]. The first-stage hydrogenic reactor (HR) and the second-stage methanogenic reactor (MR) are linked but operated at different pH [19] and only recommended for digesting sugar-rich feedstocks [20]

## 1.4 Digestate/Spent Slurry

The effectiveness of AcD can be evaluated based on the quality of the digestate/spent slurry of the digester. The composition of the digestate will naturally differ from initial feedstock, there should have been a drastic reduction in total solids content and COD. With richness in nitrogen and potassium and low on carbon content, the digestate can be an excellent source for organic manure for crop production, could support by minimizing usage of chemical fertilizers, and bedding can prevent soil erosion and help to retain soil fertility [21]. There have been few concerns on long-term impact on usage of manure as fertilizer:

- chances of altering preexisting and natural soil microflora,
- impact of excessive nitrogen emissions from manure applied farm lands,
- presence of recalcitrant compounds, and
- slow degrading remnant organic matter contributed by manure.

There has been considerable research over the aforesaid drawback, and we have conclusive results with reports stating minimal or of minor relevance with no major impaction on overall soil fertility [22]. Manure can be packed and stored over of period of few months without much loss in nitrogen content and has been evaluated for storage during different seasons for their efficacy [23]. The grade of the manure would vary and generally rely on the nature of feedstocks digested, for example, AD of agricultural feedstocks may yield manure with less nitrogen content while livestocks waste or dairy waste manure may be nitrogen-rich, especially liquid compost; accordingly soil management plan is essential to determine the quality and quantity of manure and its influence on appropriate soil type before any large-scale application of manure over farm land [24].

## 1.5 Conclusion

Circular economy is mooted to loop in the excess energy dissipated from human activities, which gets dispersed into environment in the form of greenhouse gases leading to global warming. International Renewable Energy Agency (IRENA) has called for a global energy transition toward complete de-carbonization of energy sector by the year 2040. Water treatment boards around the world have partnered with various environmental technological companies and have initiated zero waste movement, an ambitious plan to divert organic waste from landfills and incinerators to AcD. Steps have been taken to reduce carbon foot print by investing in infrastructural upgradation of AcD especially for treatment of commercial food waste with existing wastewater anaerobic sludge treatment plants. AcD has been identified as a key technology to attain net zero. Many countries have even linked bio-methane produced from AcD to the national grid for gas transmission. Few nations have reported more than 100% growth in popularity of AD and have set up hundreds of digester plants and are operating them successfully.

Steps are being taken by the scientific community to address the issue of natural methane emission into atmosphere from organics-rich land environment, water bodies and ocean sediments, substantial livestocks population, and man-made landfills. Methane mitigation efforts are taken on all frontiers to cut the flow of methane into the atmosphere that is presently contributing to global warming. One such technology is being reviewed for methane mitigation from cattle by supplementing feed with anti-methanogen IgY antibodies [25], while AcD is way forward envisaged for zero waste. Few logistics issues pertaining to feedstock and its transportation have already been highlighted earlier in this chapter, and this has to be addressed in future. In this regard, it can be noted that WWTPs are the best examples for case study to see through the reason for its success and it can be chiefly attributed to continuous supply of wastewater, sewage treatment plant (STP) generating uninterrupted solid sludge (feed stocks), digesters designed for retaining microbial granules, thus reducing energy and cost for transportation. And yet again linking other feedstock (like food waste) with WWTP leading to AcD has further enhanced the scope of the key technology for visualizing a world of net zero waste.

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