

Chapter II - LITERATURE REVIEW

2.1 History and classification of anaerobic digester

Modern society generates large amounts of waste that represents a tremendous threat to the environment and human/animal health. The method for controlling pollution is based on maximum safety, minimum environmental impact on the valorization of waste and final recycling of the end product. Today's waste management policies focus on reducing the stream of waste going to landfills and recycling the organic matter and plant nutrients provided back to the soil. Anaerobic digestion is one of the ways to achieve the goal. AD process reduces energy consumption and may help to produce energy.

The first time that combustible gases may be produced by decomposing organic waste was discovered by Jan Baptita Van Helmont in the 17th century, according to the history of the anaerobic digestion process. India's first digestion factory was constructed in 1859, while England began using anaerobic digestion in 1895 to recover gas from waste management. 1965–1957: L. John Fry constructed an anaerobic facility in South Africa in 1960 after building a digester out of a 50-gallon oil drum. Cornell University constructed the first plugflow digester in 1978. Anaerobic digestion was carried out using cow dung in an Indian digester known as the Gobar digester, according to Institute J.J. Patel's design. Unlike the Indian digester, the Sunken Tank-Floating Gas Dome-Type digester built in Taiwan was entirely subterranean. Anaerobic digestion remains popular in Europe where some facilities have been in operation for over 20 years, with Denmark leading the way in terms of experience. The existing different types of digesters are shown in Figure 3 as per mixing device and number of stages.

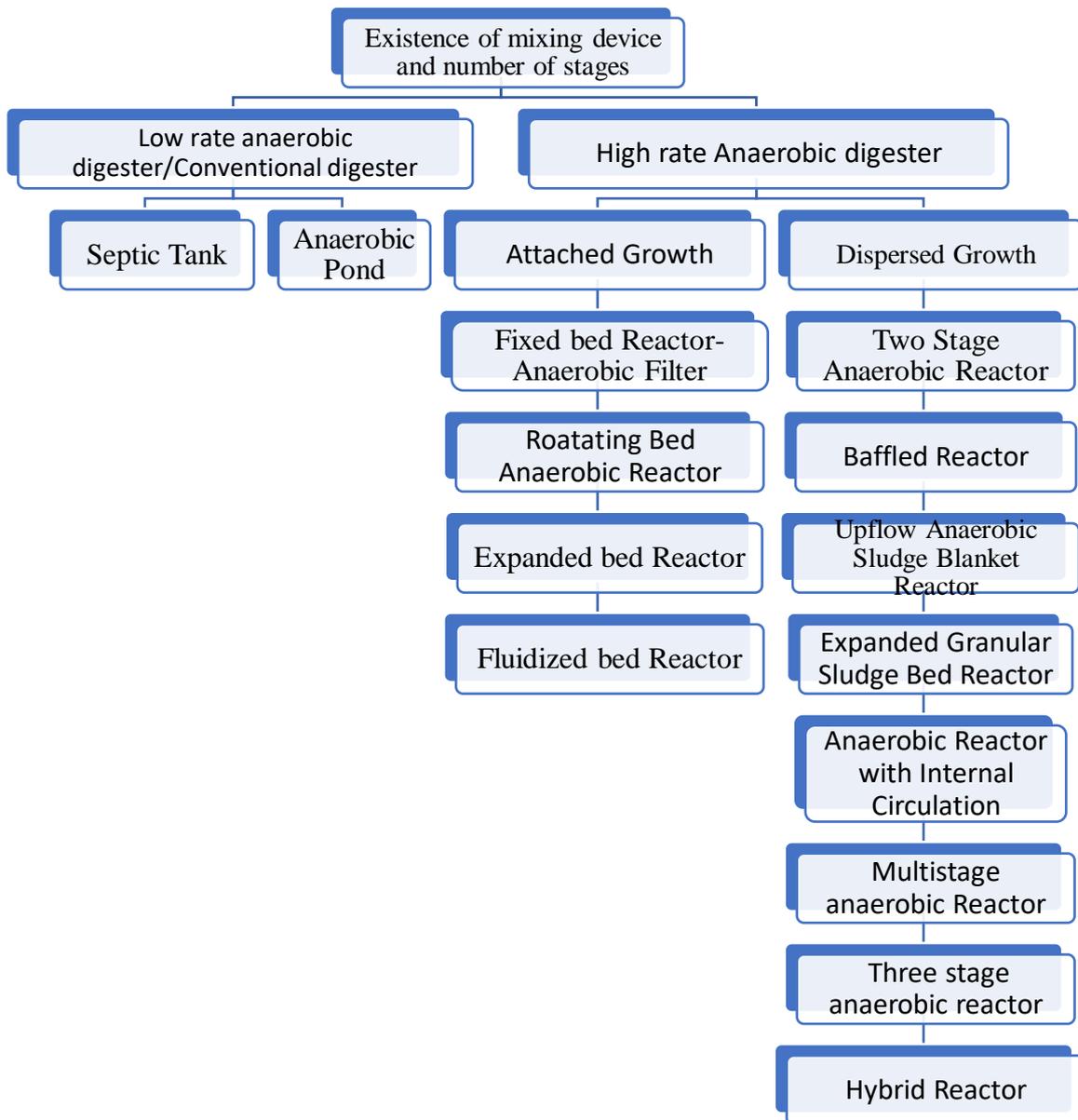


Figure 1: Types of anaerobic reactors

2.2 Use of different substrates and application for anaerobic co-digestion process

Sharma & Jain, 2019b studied that high population growth, industrialization urbanization and economic development resulted in increased consumption of natural resources and waste generation, ecological degradation and pollution. This increases the demand for new waste management practices and disposal methods in the environment. The existing situation of Municipal Solid Waste generation, composition and management problems associated with it, in Indian cities are statistically described where solid waste production was 450vm/capita/day in 2015. 82% of waste was collected and 18% was litter. 28% of collected waste was treated and 72% was openly dumped. Waste collection in smaller cities was below 50%. It was observed that poor public involvement and lack of responsibility for MSW management are major issues. MSWM service can be improved by Solid waste sorted at the source which increases recycling and reduces disposal requirements, recycling provides new employment, and waste to energy generation. NSWAI has developed a sustainable model to solve solid waste management problems where sustainability can be achieved with stakeholders (Municipalities, NGOs, Private sectors, financial institutions etc.); Waste Streams (Generation & Segregation Collection - Transfer and Transport-Treatment and Disposal-Waste Reduction, Reuse, Recycling, Recovery); Factors (Technical, Environmental, Financial, Industrial, Socio-cultural, Legal/Political/Policy).

Shahab & Anjum, 2022 study the factors affecting Municipal Solid Waste generation in Indian cities. They studied different factors and according to that, they predicted the main factor that will affect the MSW generation rate by 2050 is rapid urbanisation. It was estimated that by 2031 Indian population will produce 107.01 million tons of waste per year and by 2041 it will be 160.96 million tons per year which is approx. fivefold growth which also leads to a landfill disposal area of about 1400 square km land by 2051. India has 53 metropolitan cities which provide housing for more than 45% of the urban population. Waste generation is directly proportional to population growth. The waste generation rate (kg/capita/day) is projected 0.56 for the lower-income group, 0.79 for the lower middle-income group, 0.99 upper middle-income group and 1.87 for the upper-income group by 2050. This clearly shows urbanization is the main factor for increasing the waste generation rate. Real-time monitoring of bins, collection vehicles and illegal dumping issues are addressed in this study. Illegal dumping issues can be resolved with a multipath convolutional neural network (mp-CNN) to detect localised and street dumping. The model was trained with a weakly supervised learning

approach according to image class. In the testing phase model performance evaluation matrices shows 97.82% precision, 98.86% of recall, 98.34 F1 score, 98.33% accuracy and 98.63% of AUROC for binary classification. Overlapping mask generated by the model with region waste in the actual image, the score was 3.884 out of 5. mp-CNN performs remarkably good detection, classification and localization of waste.

Villamil et al., 2018 studied OFMSW anaerobically co-digested with a liquid fraction from hydrothermal carbonization (LFHTC) of dewatered secondary sludge with an 85% moisture content, collected from a full-scale membrane bioreactor processing Industrial wastewater from a cosmetics factory. OFMSW was grinded and particle size was kept less than 0.02m. The ratio of OFMSW to LFHTC was kept at 50:50, 25:75 and 0:100 where higher VFA accumulation reduce the biogas generation. The ratio of 75:25 of OFMSW: LFHTC generated 179 ± 3 ml CH_4 /gm added which was found lower than mono digestion of OFMSW in this study. The experimental data was validated with the Modified Gompertz model; the methane gas production increased by 29.3% ($11.96 \text{mlCH}_4/\text{COD}$) compared to the mono digestion of OFMSW. So Optimized mixing ratio obtained with 25% LFHTC helps in the valorization of co-substrate to enhance biogas production with an anaerobic co-digestion process.

Kumari et al., 2018 experimented anaerobic co-digestion process with a UASB reactor with different co-substrates where Sewage Sludge (SS) from a sewage treatment plant and Cow Manure (CM) from a dairy farm were the primary substrates. Four co-substrates were added with a 1:2 mixing ratio with Kitchen Waste + Sewage Sludge (KW+SS), Yard Waste+ Sewage Sludge (YW+SS), Food Waste + Cow Manure (FW + CM) and Dairy Wastewater + Cow Manure (DWW+CM). All reactors were operated under mesophilic conditions for 20 days where pH was observed 5 to 7.5 and VFA was 3500 to 500 mg/L. After the completion of the cycle of 20 days COD removal efficiency was observed at 76 to 86%. The biogas production rate was found 4.5L/day. EDAX analysis shows the presence of C & O in large amounts. The highest peak observed with FTIR shows the presence of C & O. Anaerobic co-digestion is the most efficient and stable process for biogas yield with some challenges.

Sosnowski et al., 2003 studied the methane fermentation of sewage sludge and OFMSW under thermophilic and mesophilic conditions. The experiment was carried out in five different types of reactor conditions. Experiment (1) Primary sludge and excess activated sludge (1:1) fed in the bioreactor working under batch mesophilic condition, (2) 75% sewage sludge and 25% OFMSW co-digested under batch thermophilic condition, (3) Quasi-continuous two-stage

anaerobic reactor fed with OFMSW where acidogenic digestion under thermophilic condition and methane fermentation under mesophilic condition, (4) Primary sludge and thickened activated sludge under ratio of 1:1 from WWTP, (5) two-stage anaerobic digestion for 75% sewage sludge and 25% OFMSW. From the experiment, it is observed that biogas production increases at an increase in the amount of OFMSW. At higher OLR specific biogas production is much less compared to lower OLR ranges between 0.4-0.6 dm³/gm VS_{added}. It is also observed that biological efficiency for methane production is 49.3% in the batch study while 82% and 62.7% in the quasi-continuous experiment. Two-stage quasi-continuous reactors work more efficiently due to the separation of the acidogenesis and methanogenesis phases of the anaerobic reactor.

Smith & Almquist, 2014 observe that the study of anaerobic co-digestion of Food Waste (FW) with horse Manure using a Lab-scale two-phase mesophilic reactor will provide valuable insights. The composition of FW was sweet corn, cucumber, red pepper, celery, lettuce, broccoli, cabbage, melon, cauliflower etc. and Horse Manure was obtained from Miami University's Equestrian Centre. The different mixing ratio of FW and horse manure was used in the phase 1 reactor 100% food waste, 90% food waste, 75% food waste, 50% food waste and 0% food waste. The first phase of the reactor was operated with a Total Solids concentration was 6%. The second phase of the reactor was inoculated with a 3% Total Solids concentration of cow manure two weeks before operation. The second phase reactor was operated as the methanogenesis phase. 5ml of filtrate from the phase I reactor was transferred to the corresponding anaerobic reactor and the first feed of 2nd phase reactor was considered as the initial of the reactor performance. The observation in the phase I reactor shows that the initial pH goes down to 4 due to the acidogenesis phase and then remains stable. Initial methanol and ethanol present 50mg/L and acetic acid and other fatty acid concentration was 500mg/L. While pH of only horse manure stays 6 and above throughout the study period where alcohol or fatty acids could not be found. pH in phase 2 remains stable with 7 and above. OLR of phase I was increased by increasing FW as substrate. Methane yield from the phase II reactor was statistically similar within a 95% confidence interval. Phase 2 reactor generated more than 80% of the theoretical maximum methane yield.

Zhang, Loh, et al., 2017 the novel three-stage anaerobic reactor was developed having three separate stages high solid hydrolysis stage, acidogenesis and methanogenesis. Food waste was anaerobically digested in three-stage reactors and simulated with one-stage reactor and two-stage reactors. FW with 20%TS operated using seed sludge under one stage reactor till the

hydrolysis process that wastes at 10%TS operated under a two-stage anaerobic reactor for acidogenesis phase and after that, all three reactors operated at semi-continuous flow with different OLR 1.6, 2.4, 4.0, 5.2,8 and 10 VS/L. Three stages anaerobic digester shows a high biogas yield of 0.307 ± 0.006 L CH₄/VS with 50-67% methane content and 83-84% VS_{reduction} while single-stage and two-stage anaerobic reactor shows 0.199 ± 0.015 and 0.249 ± 0.008 biogas yield, respectively. ThThree-stage anaerobic reactor shows around 24-54% increment of methane yield. A stage anaerobic reactor is a compact reactor design that efficiently operates at higher OLR.

Girault et al., 2012 investigate the optimum ratio of greasy sludge with WAS in batch and CSTR experiments. When sewage sludge from WWTP is anaerobically digested, it helps to reduce the volume of sludge and stabilize after recovering energy. WAS is less biodegradable and BMP is also less compared to a mixture of primary sludge and secondary sludge. Low methane potential and high operating and construction costs make anaerobic treatment technology for WAS less efficient. Greasy sludge is generated from the wastewater process of the meat industry. Greasy sludge mixed with WAS in 20% to 30% of feed COD, creates inhibition in batch experimental work while in the CSTR experiment inhibition occurs with 60% and above feed COD mixing of greasy sludge. With the CSTR experiment greasy sludge above 60%-90% of feed mixing with WAS, methane yield decreased by 75%. It concludes that the batch process can predict methane yield in CSTR only when biodegradation is without inhibition.

Björn et al., 2017b studied the feasibility of OFMSW for anaerobic co-digestion with primary and waste-activated sludge (PWASS). Two semi-continuous flow anaerobic reactors were used with inoculum from the anaerobic digester for experimental work. Co-digestion of OFMSW and PWASS at a ratio of 3:1 on a VS basis and at OLR 5gmVS/L shows the potential to increase four times biogas production from 1.0 ± 0.1 to 3.8 ± 0.3 L. This shows that these substrates for anaerobic co-digestion seemed to favour methanogenic community composition and help to degrade intermediate products like acetate, propionate and oleate.

Dai et al., 2019 studied the effectiveness of particle size on biogas production. Rice straw from the field was taken to the laboratory and only the stem was used and nodes were removed. The particle size reduced from 20mm to 1mm, 0.15mm and 0.075mm and biogas yield was observed with an anaerobic co-digestion process. The digestion mechanism clarified microbial community and rice straw properties. Particle size reduction of rice straw improved methane yield from 107 ml/gm VS to 197 ml/gm VS. The comminution pretreatment improved the basic

morphology, dissolution ability and bio-liquefaction which helps in the shifts of the bacteria community and decreases bacterial diversity.

Zhang et al., 2017 from a large-scale anaerobic digester and sludge dewatering machine, inoculum and substrate were collected. Food waste was the co-substrate collected from canteen waste and homogenised by grinding. FW, WAS and inoculum were added in a ratio of 1:1:0.6 in the anaerobic reactor and co-pretreatment was provided with different periods. This co-pretreated waste was added to the anaerobic reactor of FW and WAS. Methane yield from anaerobic co-digestion of co-pretreated FW and WAS was 24.6% higher than without pretreated anaerobic digester. The optimum pretreatment time was achieved 24 h and 10.1% in solids reduction was achieved in anaerobic digester. It also described that in comparison to mono digestion of FW, co-digestion of FW and WAS resulted in higher treatment performance. Co-pretreated substrate improves methane yield and the synergistic effect of pH enhances WAS particle solubilization. Pyrosequencing analysis indicated a reduction in the abundance of filamentous bacteria of genus *Levilinea* in the co-digestion process which improve the anaerobic digestion process to achieve higher methane yield. *Methanobacterium*, *Methanosarcina* and *Methanosaeta* were observed in archaeal taxonomy at genus level with 20.8%, 46.5% and 32.2% respectively.

Ahmadi-Pirlou et al., 2017 OFMSW and WAS from dewatering pool anaerobically co-digested can result in low methane yield with High Solids (15%-20%) compared to low solids (5%-10%) content and with 5% TS maximum biomethane yield of 337 N mL/g VS achieved. This study shows substrate quality also impacts biomethane yield, especially total solid concentration.

Van Eerten-Jansen et al., 2013 study about the conversion of CO₂ into methane from methane production biocathode electrochemically and microbiologically. A flat plate electrochemical cell of volume 1.24L is used with an anode and cathode made up of graphite (290cm² surface area) having a volume of 0.62L using a cation exchange membrane. Sample from biocathode is used to characterize and composition of the microbial community. 16S rRNA gene sequence was carried out for the archaeal and bacterial community. It contains three phylotypes of archaea of which two are related to *Methanobacterium palustre* and six phylotypes of bacteria *Methanobacterium aarhusense*. This shows that not only methanogenic archaea but also methanogenic bacteria may support methane production through hydrogen production as an intermediate.

Ghosh et al., 2020 study metabolic pathways for MSW and sewage sludge. Organic fraction of MSW segregated and co-digested with sewage sludge. It is observed that methane yield increases with different co-digestion ratios compared to mono digestion of OFMSW. Metagenomic analysis was carried out and bacteria, archaea and fungi were analysed. Microbial diversity of sludge was found prominent which helps to improve the anaerobic digestion process. It is observed that *Methanosacring* sp. increased with time in abundance and was able to tolerate high acetate concentration. The knowledge of specific microbial consortia helps to maximize the methane yield during the anaerobic digestion process.

2.3 Kinetic modelling and prediction modelling for anaerobic co-digestion process

Mougari et al., 2021 collected data from several published work-related mono-anaerobic digestion and anaerobic co-digestion of different organic waste. The prediction model was developed for cumulative biogas yield (CBY) and cumulative methane yield (CMY) using a multilayer perceptron algorithm (MLP) and modified Gompertz Model (MG). An Artificial Neural Network based model was developed in MATLAB and optimization was done through a genetic algorithm (GA). Volatile Solid to Total Solid ratio (% VS/TS), carbon content (%C), carbon-to-nitrogen ratio (%C/N), and digestion time (%DT) were input parameters to develop an ANN-based prediction model. Two ANN models were developed where ANN1 was for cumulative biogas yield and ANN2 was for cumulative methane yield. GA-ANN1 model achieves an accuracy of 0.0045 RMSE and R 0.9996 with 2 hidden layers, 15 neurons in 1st hidden layer and 28 neurons in the second hidden layer with the application of activation function log-sigmoid for the first hidden layer and tan-sigmoid for 2nd hidden layer and training function trainlm. GA-ANN2 model had accuracy with 0.0046 RMSE with R 0.9998 where 1st hidden layer had 30 neurons and 2nd hidden layer had 22 neurons and applied log sigmoid activation function on both layers and trainlm was the training function. For CBY using MG coupled with GA 1.5280 RMSE and R² 0.95 and for CMY 0.6175 RMSE and 0.96 R² was achieved. Moreover, GA-MG should be developed for each substrate mixture for prediction and that is a time-consuming process. The study shows the robustness of the ANN base prediction model for CBY and CMY over kinetic modelling and it can be an effective tool for the scale-up of anaerobic digestion units and techno-economic studies.

Rego et al., 2019 study on the performance of biodigester to enhance biogas production. The swine manure (SM) collected from the swine breeding unit and rice husk was collected, dried and cut into 0.5-1mm length. The mixture of swine sewage and rice husk was provided OLR

between 1 to 1.5 gmVS/L/d where rice husk was used to provide more carbon source and added in a proportion of 2% wt. To predict the volume of biogas Artificial Neural Network (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) were used as predictive tools using MATLAB2018b. The model was developed using four operational conditions- reactor type, temperature, pH and FOS/TAC as input parameters and biogas volume as output parameters. The experiment data were divided into 67% training dataset and 33% testing dataset. ANN model was developed with trainlm and trainer training algorithm, logs and tansig activation function and Levenberg-Marquadt was the optimization function. ANFIS model was developed with Sugeno fuzzy inference where fuzzy rules are related to input variables and defuzzification method with Membership function Gaussian curve (gaussmf) based on subtractive clustering (SC) and using hybrid training algorithm data were tested with linear function in the output. This study shows ANN with R^2 0.78 and ANFIS with R^2 0.81 having the capacity to predict biogas volume at its best configuration where ANFIS shows better performance than ANN.

Nor Faekah et al., 2020 studied partially packed up-flow anaerobic fixed film (UAF) reactor under the bench scale method. A mixture of digested sludge from a rubber development company was used for the UAF reactor. The reactor was operated on different HRTs. The experimental data were used to develop a kinetic model to determine bio-kinetic co-efficient. Using the Monod model the bio-kinetic growth yield co-efficient (Y) was 0.027 gVSS/gm COD and endogenous co-efficient (K_d) was observed 0.1705/d. Half saturation constant (K_s) and maximum substrate utilization rate K is 84.1 mg/L and 0.371/d while the maximum specific growth rate (μ_{max}) was 0.011/d. Using the Stover-Kincannon model the kinetic constant U_{max} and K_b found 6.57 g/L/d and 6.31 g/L/d respectively. In the Second order, Grau's model substrate removal rate was 105/d observed. All models are fit with good correlation R^2 80 to 99%. Partially packed with PVC support media UAF reactor had good agreement with Stover-Kincannon and Grau's second-order models.

Yetilmezsoy et al., 2013 developed the prediction model of biogas generation from the anaerobic digestion of molasses wastewater in a mesophilic UASB reactor. OLR, influent pH, effluent pH, operating temperature, influent alkalinity, effluent alkalinity, effluent COD, and VFA are considered input parameters and Biogas and methane production are effluent parameters for the development of the ANN model. The data are also compared with non-linear

regression analysis with the multiple regression software package DataFit V8.1.69. ANN model developed with tangent sigmoid transfer function at hidden layer and purelin transfer function at the output layer. Neural Network Back Propagation and Principal component Analysis with scaled conjugate gradient algorithm optimize 9 and 12 neurons at hidden layer with MSE 0.0623 and 0.0648, respectively. Compared to the conventional multiple regression-based techniques, ANN predict more accurate biogas and methane production with R^2 0.935. It proves that ANN-based modelling is more accurate for complex and dynamic systems like anaerobic digestion.

Roberts et al., 2023 studied comparative analysis of five kinetic models for banana peel and orange peel waste. Logistic, Gompertz, First-order, Richard and Transfert models are used for the comparative study with experimental methane yield. All models showed an accuracy of predicting methane potential of over 95% on both the substrates that were focused on. The time taken to reach maximum methane yield as compared to the experimental data was the Gompertz model with a cumulative deviation of 76.6%. The model, that was the least accurate, was the Transfert model which had a cumulative deviation of 274.7%

Ahmadi et al., 2019 study provides valuable insights into the performance and multi-kinetic modelling of a membrane bioreactor treating actual oil refinery wastewater. A grey box model of evolutionary polynomial regression (EPR) and white-box models (first order, Grau second order, and modified Stover-Kincannon) were used to evaluate the experimental outputs. COD removal is observed with the EPR model and white box model for MBR treating oil refinery wastewater. Maximum COD reduction of 97% is achievable at the mixed liquor suspended solids (MLSS) of 8.5 g/l and hydraulic retention time of 24 h. The optimum operating conditions according to EPR model HRT 21hr, MLSS 8.2g/L were recommended. The modified Stover-Kincannon model and Grau's Second-order kinetic model show an approach for COD reduction in MBR with R^2 0.98 and 0.92, respectively.

2.4 Outcome from the literature study

- Municipal Solid Waste Management is a growing issue now a days. The use of MSW for the growth of the economy is a valuable and sustainable practice for the environment.

- Anaerobic digestion is the proven treatment technology for the treatment of OFMSW. However, due to its varied composition and characteristics, the common practice of OFMSW treatment cannot be applied at every location.
- When two different substrates are co-digested, it improves its performance for the anaerobic co-digestion process. Different co-substrates help improve anaerobic digestion and can be applied only according to their availability in particular areas.
- Pretreatment is an important aspect of improving the anaerobic digestion process. Various pretreatment technologies are available to apply according to substrate quality.
- Appropriate selection of anaerobic reactor design plays an important role in the anaerobic co-digestion process.
- Optimization of process parameters for anaerobic co-digestion only depends upon substrate characteristics, environmental conditions, and process control parameters. Due to this limitation, an anaerobic digestion study is required for different areas.
- Kinetic modelling helps to identify substrate removal efficiency and prediction of biogas generation with the particular substrate under the anaerobic digestion process.
- ANN-based modelling is an advanced technique that includes all aspects of the anaerobic digestion process including substrate quality, process parameters, and operation parameters to predict the performance of the anaerobic digestion process. This improves the accuracy of modelling, reduces the time for analysis and helps to manage on-field conditions during the operations of digesters.

