PROCESS OPTIMIZATION FOR THE CO-DIGESTION OF ORGANIC FRACTION OF MUNICIPAL SOLID WASTE AND BIO FLOCCULATED SLUDGE GENERATED IN ACTIVATED SLUDGE PROCESS OF SEWAGE TREATMENT USING ANAEROBIC PROCESS

A THESIS

Submitted by

KINJAL CHINTAN SHROFF

(FOTE/994)

For the award of the Degree

of

DOCTOR OF PHILOSOPHY

In

Civil (Environmental) Engineering

Under the supervision of

Dr Nirav G. Shah

(Assistant Professor)

सत्यं शिवं सुन्दरम्

Department of Civil Engineering

Faculty of Technology and Engineering

The Maharaja Sayajirao University of Baroda, Vadodara 390 001

October 2024

TABLE OF CONTENTS OF THESIS

TABLE OF CONTENTS OF EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

INTRODUCTION

Indian cities are expanding rapidly with their population growth and economic developments significantly impact the generation rate of Municipal Solid Waste (MSW). The rate of production of MSW in India is 160038.9 TPD out of which 50% is treated, 18.4% is disposed-off in landfills and 31% is unaccounted which contributes to the release of greenhouse gases (Annual Report on Solid Waste Management (2020-21)). At the same time, the segregation of MSW has gained momentum which led towards more production of Organic Fraction of Municipal Solid Waste (OFMSW). Biodegradable organic matter which is a significant portion of MSW also known as the Organic Fraction of Municipal Solid Waste (OFMSW). If this biodegradable organic matter is disposed-off in a landfill without treatment, it will naturally decay and produce greenhouse gases. It is feasible to segregate the OFMSW and process it using composting, vermicomposting, incineration and anaerobic digestion. OFMSW is the most favourable substrate to meet the goal of waste-to-energy conversion through anaerobic digestion.

The increasing population generates more sewage. There are 1093 sewage treatment plants in operational condition in India which can treat approximately 20235 MLD of sewage (CPCB annual report, 2021). Sewage treated with UASB-based treatment technology is the most advantageous due to its low operational and maintenance costs. However, sewage treated with UASB is required post-treatment using ASP to meet inland surface water disposal standards specific to Indian conditions. After the UASB process, when the sewage is treated with the ASP, it results in the production of bio-flocculated sludge which requires proper attention for its treatment and disposal. The bio-flocculated sludge generated from SST has low porosity, is low in quantity is rich in microbial nutrients and needs special attention for disposal.

Anaerobic digestion has emerged as a highly preferred process due to its cost-effectiveness for growing nations like India with low investment and potential for revenue generation. Anaerobic digestion of OFMSW has issues such as large particle size, high solids, slow biodegradation, lignin-rich waste and the heterogeneous nature of the waste makes the process challenging. India is a diverse country with significant differences in geographical regions and living standards in these areas, resulting in different patterns of garbage generation. Substrate availability, composition, characteristics, geographical condition, climatic condition, economic condition, treatment processes, waste management approach etc. are the key factors for the anaerobic digestion process. The study of the substrate and its efficiency for a particular area is a significant factor in the success of any anaerobic process.

Need of the study:

Anaerobic digestion of OFMSW needs liquefication for a higher degradability rate. The sludge formed in the SST (post-UASB) is less in quantity, has poor porosity is difficult to dewater, is low in solid content and therefore difficult to dispose-off in conventional sludge drying systems. This sludge must go through some process to reduce volume, improve its characteristics, and reduce health problems and hindrances to meet disposal standards and acceptance. The bio-flocculated sludge produced in the SST has an abundance of microorganisms that can enhance the anaerobic digestion process. Hence, bio-flocculated sludge can become the potential co-substrate and enhance methane generation. The prime use of bio-flocculated sludge from SST (post-UASB) for the anaerobic co-digestion process still needs to be focused based on various parameters and availability in Indian conditions to enhance the anaerobic digestion process of OFMSW. The favourable meteorological conditions (20℃ to 40̊ C for more than 9 months of a year) in the majority of states of India help in the anaerobic co-digestion process. The estimated quantity of OFMSW generation and bio-flocculated sludge generation rate is 600kg/d and 104kg/d respectively, for 1 lakh of the population

The report published by the Ministry of Housing and Urban Affairs under the flagship of the Swachh Bharat Mission adopting circular economy mission states that bio-methanation of wet solid waste is significantly more profitable than composting. It also highlighted the concern about municipal sewage sludge management as it is being utilized unscientifically and without regulatory standards in India.

The study of anaerobic co-digestion of OFMSW and bio-flocculated sludge from SST (post-UASB) is required to check the synergistic effect that can arise by using solid-liquid waste to enhance the methanation process (Figure 1). This study underscores the potential of integrated waste management practices for sustainable and economical solutions

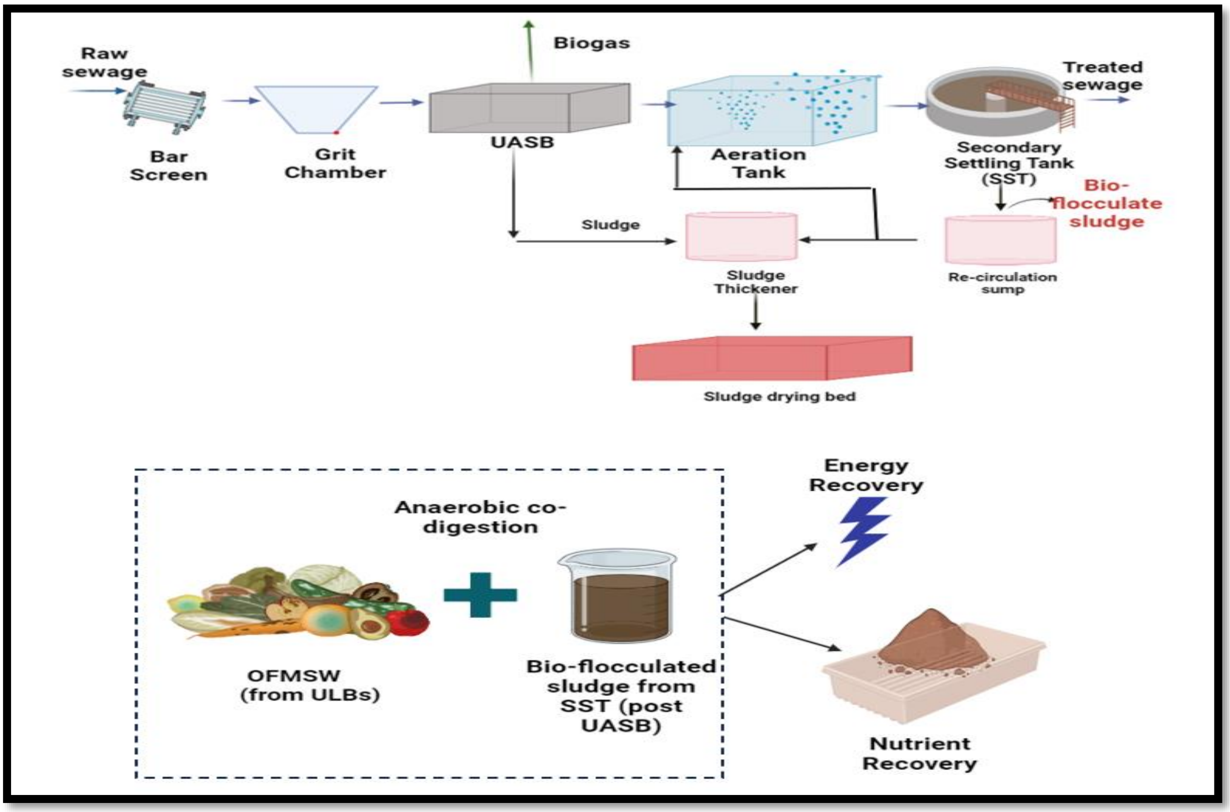

Figure 1: Substrate for anaerobic co-digestion process

Objectives of the present study

- To check the feasibility of an anaerobic process for the co-digestion of OFMSW & Bio flocculated sludge generated in ASP (Post UASB) of conventional sewage treatment in Indian conditions.
- To identify optimum conditions for various parameters to achieve satisfactory degradation and gas production for the co-digestion process.
- To scale up an analytical model for running a treatment scheme as suggested.

BRIEF RESEARCH METHODOLOGY

MSW comprises a maximum bio-degradable waste of 42-53% including fruits & vegetable waste & food waste. The cities of India according to population size can generate an average of 41-52% of biodegradable waste. The wet mass of OFMSW is finalized with 60-70% vegetable and fruit waste, 20-30% food waste, 0.5 to 1 % paper waste and 2-5% yard waste considered for lab-scale experimental work.

Sludge generated from the SST (post-UASB) process is rich in microbial activity so it is called bio-flocculated sludge. In the present study bio-flocculated sludge generated from SST is collected from 43MLD UASB-based sewage treatment plants with aeration treatment (ASP treatment) post-UASB.

Pre-treatment of OFMSW is required to improve the anaerobic co-digestion process. The simplest and economically viable pre-treatment method applied for the present study is cutting and grinding. The OFMSW is grinded to a size of 2 mm ~ 5 mm. Grinding enabled the increase in surface area available for microbes (Figure 2).

Figure 2: Pre-treatment of OFMSW and substrate preparation

An anaerobic reactor of 10 L volume is made of an acrylic sheet. The substrate is fed on a wet mass basis in each batch reactor. A mixer with paddles is used for complete mixing (intermediate mixing) of the substrate at low speed using a 12V DC motor. To maintain the mesophilic condition (30-35°C) inside the reactor, the water jacketing system is provided with a heating rod. This system effectively controls the inside temperature of an anaerobic reactor and provides optimal temperature conditions for the anaerobic digestion process. The biogas produced during the batch study is quantified using water displacement. The biogas is routed through the solution of NaOH which can absorb CO_2 from the biogas (Figure 3). The reactor is operated for batch study and semi-continuous flow study.

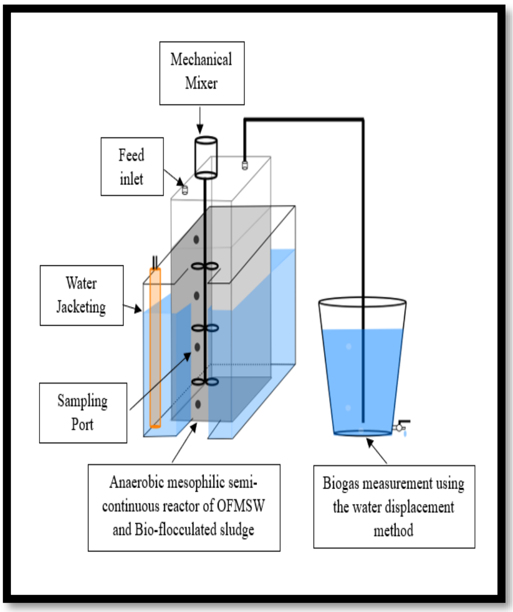

Figure 3: Schematic diagram and the lab-scale experimental setup

To determine the initial and final characteristics of the feedstock, the samples are prepared for analysis according to the procedures prescribed in APHA, Standard Methods for Examination of Water and Wastewater, 2017. pH, Total Solids and Volatile Solids are measured regularly (2540-G). For the measurement of COD, a closed-reflux titration method is used (5220-C). Total Kjeldahl nitrogen and Total Phosphate are measured with the Macro Kjeldahl method and Stannous Chloride method (4500 N_{org}-B, 4500P-D) respectively. The volatile Fatty Acids to Alkalinity ratio is measured with Kapp's method.

OFMSW and bio-flocculated sludge mixed with different mixing ratios of 50:50, 75:25, 90:10, 100:0 &0:100 (by %mass.). The mixing ratios of OFMSW: bio-flocculated sludge optimized using batch anaerobic co-digestion lab-scale experimental work (Figure 4). Anaerobic co-digestion exhibits a quick phase of acclimatization and raises methane production.

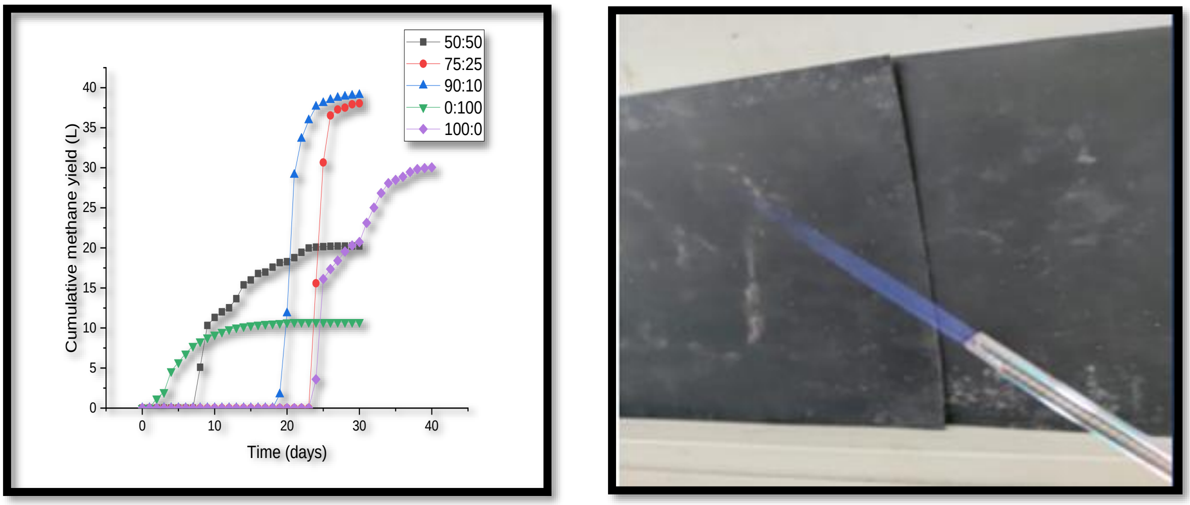

Figure 4: Methane gas yield during the lab-scale batch experimental study

An optimized mixing ratio of 75:25 (%wet mass) of OFMSW and bio-flocculated sludge is used to perform lab scale experimental study using a semi-continuous flow anaerobic reactor. The reactor is operated with varied Organic Loading Rates (OLRs) with slight variations in composition and characteristics of OFMSW to reflect actual field conditions.

Kinetic studies can be used to forecast digester performance, digester design, and substrate biodegradability. The first-order kinetic model, Modified Gompertz model and Logistic Function model are used to model experimental methane production for all co-digestion mixing ratios. With IBM SPSS 2021, the model's kinetic constants for P_m, R_m, and λ are calculated using the least squares fitting method (non-linear regression methodology).

Kinetic models help to quantify how fast organic matter is degraded in the anaerobic digester which helps to select the most suitable feedstock and anaerobic digester performance. A kinetic model is a mathematical representation of the relationship between COD concentration and HRT for the estimation of degradation rates. The rate at which COD or VS is removed directly impacts the rate of biogas production and kinetic models help to estimate and optimize the rate of biogas production by correlating with the substrate removal rate. The Modified Stover-Kincannon model, Grau's Second-Order Model and First-order Kinetic models are utilised to predict substrate removal efficiency.

The human brain is a complicated structure with a densely linked network of basic processing units, or neurons. The simplified representation of the organic nervous system is called an Artificial Neural Network or Neural Network. An artificial neural network (ANN) is a computer learning system that uses mathematical relationships between input-output variables to discover the link between a set of defined input data and output data with a wide range of operational conditions. An input layer, a hidden layer, and an output layer are the three layers are there in ANN. Input variable (%TS, OLR gmVS/L/d, pH, HRT, VFA/Alkalinity ratio) and output variable (%$VS_{removal}$ and Methane yield (L/kg$VS_{removed}$)) are included from the experimental data to develop the prediction model (Figure 5). ANN study is carried out with MATLAB 2021a to implement the Feed Forward training algorithm with the curve fitting application (fitnet). Levenberg-Marquardt, Bayesian Regulation, and Scale Conjugated Gradient are the three training algorithms employed in this work along with the tan sigmoid transfer functions.

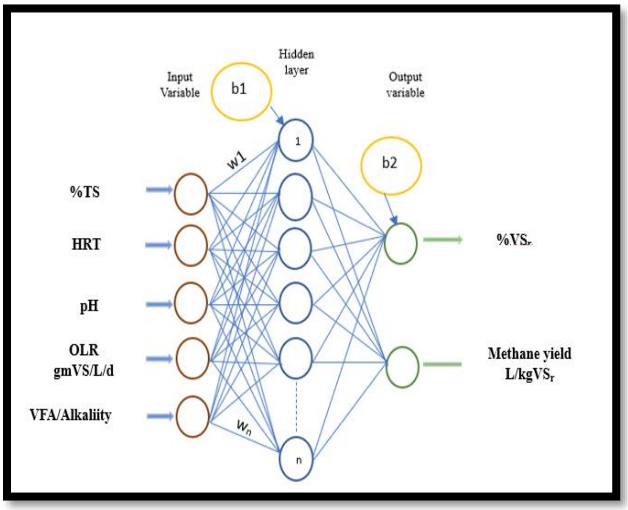

Figure 5: Architecture of ANN

ANN models are typically utilized to determine the association between input and output variables. The connection weight method is the most acceptable method for knowing the importance of the input variable. Artificial Neural Networks coupled with Particle Swarm Optimization (ANN-PSO) have emerged as powerful predictive modelling techniques for the anaerobic co-digestion process. ANFIS combines fuzzy logic and neural network approaches to create a hybrid intelligent model with the advantages of both methods.

The sample retrieved from the methanogenesis phase is used to analyse microbial presence in an anaerobic co-digestion process. The sample is analysed under a Scanning Electron Microscope (SEM) (Figure 6).

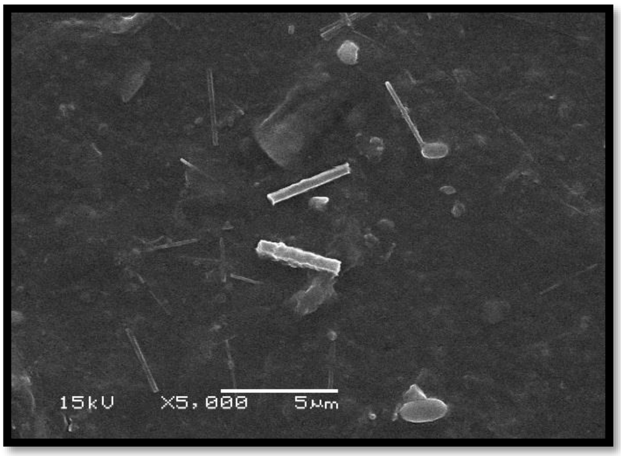

Figure 6: SEM image of methanogens

Metagenomic analysis is carried out to identify the dominant bacteria responsible for making the anaerobic co-digestion of OFMSW and bio-flocculated sludge efficient. The Analysis is carried out with genome sequencing using 16SrRNA methodology. The sample is collected during the acclimatization phase of the reactor for analysis. The fermentation or acidogenesis phase is also a very important phase of the anaerobic digestion process where the presence of microbes leads to the success of the anaerobic co-digestion process (Figure 7).

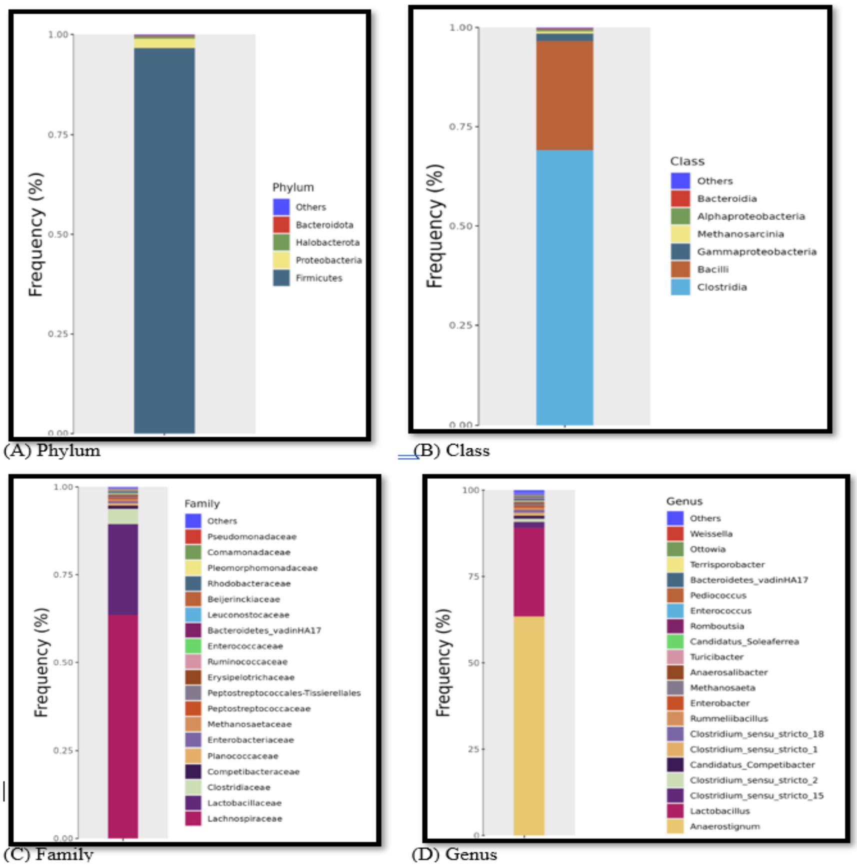

Figure 7: Abundance of bacterial community at (A) Phylum level (B) Class level (C) Family level (D) Genus level

KEY FINDINGS

- Bio-flocculated sludge generated from SST (post–UASB) is the potential co-substrate for OFMSW for anaerobic co-digestion due to its characteristics of high pH 7.9±0.2, high %moisture content 94.76±0.6, low %TS 5.24 ± 1.18, COD 52.22 ± 4.03 mg/gm and having potential to generate specific biogas yield 419.44±11.59 L/kg VS_{added} under optimum conditions.
- 75% (wet mass) of OFMSW, when co-digested with 25% (wet mass) of bio-flocculated sludge from SST, can achieve a specific methane yield of 256.44±12.98 L/kg VS_{added} which is quite higher than mono-digestion of OFMSW.
- Modified Gompertz model validates the experimental methane yield in batch experimental study for mixing ratio of 75:25 of OFMSW and bio-flocculated sludge with goodness to fit R^2 0.99 with the prediction of maximum methane production rate 137.49 L/kg VS_{added}*d and hydrolysis rate constant (k) 0.664.
- The lab-scale semi-continuous flow anaerobic reactor operated with an optimized (75:25) mixing ratio of OFMSW and bio-flocculated sludge with varied organic loading rate. The reactor performed well with an OLR range of 2 to 3 gm VS/L/d with high biogas yield and %VS removal efficiency.
- Kinetic constants obtained for semi-continuous flow anaerobic reactor with Stover Kin-cannon model (maximum removal rate constant U_{max} = 31.74, Saturation rate constant K_B = 86.02), Grau's Second-Order kinetic constants (a = 0.578, b = 3.1) contribute for prediction of substrate removal efficiency.
- Prediction model developed using Feed Forward Neural Network (FFNN) fitting application (fitnet) simulate experimental data of $\%VS_{removal}$ and methane yield with goodness to fit R^2 more than 0.96 for anaerobic co-digestion process operated under semi-continuous flow while prediction model using ANN-PSO with R^2 of 0.80 and ANFIS with gauss2 membership function with R^2 of 0.90 shows versatility of different modelling approach in accurate prediction of methane yield.
- Metagenomic sequencing analysis 16SrRNA shows the presence of Lachnospiracea, Lactobacillacea and Clostridiaceae are the dominant families with Anaerostignum, Lactobacillus and Clostridium Sensu Stricto genus found with high levels of abundance. They are dominant for the fermentation process of the anaerobic co-digestion process.

CONCLUSION

This study contributes to the potential use of bio-flocculated sludge from SST (post-UASB) as a co-substrate for anaerobic co-digestion of OFMSW for the effective management of OFMSW. This study including substrate composition and characteristics has the advantage of its simplicity and economic affordability for replicating its use in large-scale plants in developing nations. The developed prediction model can be used to predict methane yield and $\%VS_{removal}$ efficiency with varied substrate characteristics for large-scale plant operation. The metagenomic analysis shows the potential of OFMSW and bio-flocculated sludge from SST (post-UASB) as a substrate to improve the anaerobic co-digestion process. Anaerobic co-digestion of OFMSW and bio-flocculated sludge from SST is a key to solving solid-liquid waste management problems with in-house substrate availability within the ULBs with minimal pretreatment to achieve waste-to-energy goals.

RECOMMENDATIONS

- Pilot-scale anaerobic digester using OFMSW and bio-flocculated sludge should be operated.
- Field-operated data can improve the accuracy of an Artificial Neural Network-based prediction model for methane yield.
- Life Cycle Assessment to evaluate environmental impact assessment and circular economy of the anaerobic co-digestion process of OFMSW and bio-flocculated sludge .
- Microbial insight using metagenomic analysis of each phase of the anaerobic co-digestion process of OFMSW and bio-flocculated sludge (post-UASB)

PUBLICATIONS

1. Shroff, K. C., & Shah, N. G. (2023). The Performance Evaluation and Process Optimization of Anaerobic Co-digestion of OFMSW with Bio-flocculated Sludge from Secondary Settling Tank: A Key to Integrated Solid–Liquid Waste Management. *Waste and Biomass Valorization*. https://doi.org/10.1007/s12649-023-02176-7

2. Shroff, K., & Shah, N. (2024). Prediction Modelling to Enhance Anaerobic Co-digestion Process of OFMSW and Bio-flocculated Sludge Using ANN. *Pollution*, *10*(1), 481-494. doi: 10.22059/poll.2023.365129.2065

3. A research paper entitled "Comparative study of kinetic modelling for anaerobic co-digestion process for substrate removal efficiency" is under publication for the journal Environmental Science and Pollution Research under Special Issue: INCEEE-2023

CONFERENCES

1. Kinjal Shroff, Nirav Shah, entitled **"Development of prediction model for the performance of anaerobic co-digestion of OFMSW and Bio-flocculated sludge using Artificial Neural Network"** presented on fourth international conference on Advanced Engineering Optimization Through Intelligent Techniques (AEOTIT) held by Department of Mechanical Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, India during 28-30 September, 2023.
2. Kinjal Shroff, Nirav Shah, entitled **"Comparative study of kinetic modelling for anaerobic co-digestion process for substrate removal efficiency"** presented at a third international conference on New Frontiers in Chemical, Energy and Environmental Engineering (INCEE-2023) conducted by Department of Chemical Engineering, National Institute of Technology, Warangal, Telangana, India during 24-25 November, 2023.

BIBLIOGRAPHY

Ahmadi, M., Zoroufchi Benis, K., Faraji, M., Shakerkhatibi, M., & Aliashrafi, A. (2019a). Process performance and multi-kinetic modelling of a membrane bioreactor treating actual oil refinery wastewater. *Journal of Water Process Engineering*, *28*, 115–122. https://doi.org/10.1016/j.jwpe.2019.01.010

Ahmadi, M., Zoroufchi Benis, K., Faraji, M., Shakerkhatibi, M., & Aliashrafi, A. (2019b). Process performance and multi-kinetic modelling of a membrane bioreactor treating actual oil refinery wastewater. *Journal of Water Process Engineering*, *28*, 115–122. https://doi.org/10.1016/j.jwpe.2019.01.010

Ahmadi-Pirlou, M., Ebrahimi-Nik, M., Khojastehpour, M., & Ebrahimi, S. H. (2017). Mesophilic co-digestion of municipal solid waste and sewage sludge: Effect of mixing ratio, total solids, and alkaline pretreatment. *International Biodeterioration and Biodegradation*, *125*, 97–104. https://doi.org/10.1016/j.ibiod.2017.09.004

Ahmed, B., Tyagi, V. K., Priyanka, Khan, A. A., & Kazmi, A. A. (2022). Optimization of process parameters for enhanced biogas yield from anaerobic co-digestion of OFMSW and bio-solids. *Biomass Conversion and Biorefinery*, *12*(3), 607–618. https://doi.org/10.1007/s13399-020-00919-3

Aichinger, P., Wadhawan, T., Kuprian, M., Higgins, M., Ebner, C., Fimml, C., Murthy, S., & Wett, B. (2015). Synergistic co-digestion of solid-organic-waste and municipal sewage sludge: 1 plus 1 equals more than 2 in terms of biogas production and solids reduction. *Water Research*, *87*, 416–423. https://doi.org/10.1016/j.watres.2015.07.033

Alam, M. N. (2016). *Codes in MATLAB for Training Artificial Neural Network using Particle Swarm Optimization Cochlear Implant View project Application of operation research on solving electrical engineering problems View project Codes in MATLAB for Training Artificial Neural Network using Particle Swarm Optimization*. https://doi.org/10.13140/RG.2.1.2579.3524

Ambaye, T. G., Rene, E. R., Dupont, C., Wongrod, S., & van Hullebusch, E. D. (2020). Anaerobic Digestion of Fruit Waste Mixed With Sewage Sludge Digestate Biochar: Influence on Biomethane Production. *Frontiers in Energy Research*, *8*. https://doi.org/10.3389/fenrg.2020.00031

Anderson, G. K., & Yang, G. (n.d.). *Determination of bicarbonate and total volatile acid concentration in anaerobic digesters using a simple titration*.

Andualem, M., Seyoum, L., & Karoli, N. N. (2017). Kinetic analysis of anaerobic sequencing batch reactor for the treatment of tannery wastewater. *African Journal of Environmental Science and Technology*, *11*(6), 339–348. https://doi.org/10.5897/ajest2017.2305

Antonio, R., Universidad, V., México, L. S., Garro, B. A., Sossa, H., & Vázquez, R. A. (2011). Back-Propagation vs Particle Swarm Optimization Algorithm: Which algorithm is better to adjust the Synaptic Weights of a Feed-Forward ANN? In *Article in International Journal of Artificial Intelligence*. www.ceser.in/ijai.html

Appels, L., Baeyens, J., Degrève, J., & Dewil, R. (2008). Principles and potential of the anaerobic digestion of waste-activated sludge. In *Progress in Energy and Combustion Science* (Vol. 34, Issue 6, pp. 755–781). https://doi.org/10.1016/j.pecs.2008.06.002

Arelli, V., Mamindlapelli, N. K., Begum, S., Juntupally, S., & Anupoju, G. R. (2021). Solid state anaerobic digestion of food waste and sewage sludge: Impact of mixing ratios and temperature on microbial diversity, reactor stability and methane yield. *Science of the Total Environment*, *793*. https://doi.org/10.1016/j.scitotenv.2021.148586

Ariunbaatar, J., Panico, A., Esposito, G., Pirozzi, F., & Lens, P. N. L. (2014). Pretreatment methods to enhance anaerobic digestion of organic solid waste. In *Applied Energy* (Vol. 123, pp. 143–156). Elsevier Ltd. https://doi.org/10.1016/j.apenergy.2014.02.035

Astals, S., Batstone, D. J., Mata-Alvarez, J., & Jensen, P. D. (2014). Identification of synergistic impacts during anaerobic co-digestion of organic wastes. *Bioresource Technology*, *169*, 421–427. https://doi.org/10.1016/j.biortech.2014.07.024

Banerjee, P., Hazra, A., Ghosh, P., Ganguly, A., Murmu, N. C., & Chatterjee, P. K. (2019). Solid Waste Management in India: A Brief Review. In *Waste Management and Resource Efficiency* (pp. 1027–1049). Springer Singapore. https://doi.org/10.1007/978-981-10-7290-1_86

Bareither R, Bargh N, Oakeshott R, Watts K, Pollard D. Automated disposable small scale reactor for high throughput bioprocess development: a proof of concept study. Biotechnol Bioeng. 2013 Dec;110(12):3126-38. doi: 10.1002/bit.24978. Epub 2013 Jul 1. PMID: 23775295.

Biogas Production by Co-Digestion of Municipal Sewage and Municipal Solid Waste 202 BIOGAS PRODUCTION BY CO-DIGESTION OF MUNICIPAL SEWAGE AND MUNICIPAL SOLID WASTE 1 VASUMATHI A M, 2 MATHURAM A. (n.d.). www.intechopen.com

Björn, A., Shakeri Yekta, S., Ziels, R. M., Gustafsson, K., Svensson, B. H., & Karlsson, A. (2017a). Feasibility of OFMSW co-digestion with sewage sludge for increasing biogas production at wastewater treatment plants. *Euro-Mediterranean Journal for Environmental Integration*, *2*(1). https://doi.org/10.1007/s41207-017-0031-z

Björn, A., Shakeri Yekta, S., Ziels, R. M., Gustafsson, K., Svensson, B. H., & Karlsson, A. (2017b). Feasibility of OFMSW co-digestion with sewage sludge for increasing biogas production at wastewater treatment plants. *Euro-Mediterranean Journal for Environmental Integration*, *2*(1). https://doi.org/10.1007/s41207-017-0031-z

Bolzonella, D., Battistoni, P., Susini, C., & Cecchi, F. (2006). Anaerobic co-digestion of waste activated sludge and OFMSW: The experiences of Viareggio and Treviso plants (Italy). *Water Science and Technology*, *53*(8), 203–211. https://doi.org/10.2166/wst.2006.251

Borowski, S. (2015). Co-digestion of the hydromechanically separated organic fraction of municipal solid waste with sewage sludge. *Journal of Environmental Management*, *147*, 87–94. https://doi.org/10.1016/j.jenvman.2014.09.013

Bouallagui, H., Touhami, Y., Ben Cheikh, R., & Hamdi, M. (2005). Bioreactor performance in anaerobic digestion of fruit and vegetable wastes. In *Process Biochemistry* (Vol. 40, Issues 3–4, pp. 989–995). https://doi.org/10.1016/j.procbio.2004.03.007

Cabbai, V., Ballico, M., Aneggi, E., & Goi, D. (2013). BMP tests of source selected OFMSW to evaluate anaerobic codigestion with sewage sludge. *Waste Management*, *33*(7), 1626–1632. https://doi.org/10.1016/j.wasman.2013.03.020

Cardinali-Rezende J, Debarry RB, Colturato LF, Carneiro EV, Chartone-Souza E, Nascimento AM. Molecular identification and dynamics of microbial communities in reactor treating organic household waste. Appl Microbiol Biotechnol. 2009 Sep;84(4):777-89. doi: 10.1007/s00253-009-2071-z. Epub 2009 Jun 24. PMID: 19551378.

Cecchi, F., Bolzonella, D., Pavan, P., Macé, S., & Mata-Alvarez, J. (2011). Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste for Methane Production: Research and Industrial Application. In *Comprehensive Biotechnology, Second Edition* (Vol. 6, pp. 463–472). Elsevier Inc. https://doi.org/10.1016/B978-0-08-088504-9.00332-9

Charles, W., Walker, L., & Cord-Ruwisch, R. (2009). Effect of pre-aeration and inoculum on the start-up of batch thermophilic anaerobic digestion of municipal solid waste. *Bioresource Technology*, *100*(8), 2329–2335. https://doi.org/10.1016/j.biortech.2008.11.051

Chiu, S. L. H., & Lo, I. M. C. (2016). Reviewing the anaerobic digestion and co-digestion process of food waste from the perspectives on biogas production performance and environmental impacts. *Environmental Science and Pollution Research*, *23*(24), 24435–24450. https://doi.org/10.1007/s11356-016-7159-2

Dai, X., Duan, N., Dong, B., & Dai, L. (2013a). High-solids anaerobic co-digestion of sewage sludge and food waste in comparison with mono digestions: Stability and performance. *Waste Management*, *33*(2), 308–316. https://doi.org/10.1016/j.wasman.2012.10.018

Dai, X., Duan, N., Dong, B., & Dai, L. (2013b). High-solids anaerobic co-digestion of sewage sludge and food waste in comparison with mono digestions: Stability and performance. *Waste Management*, *33*(2), 308–316. https://doi.org/10.1016/j.wasman.2012.10.018

Dai, X., Hua, Y., Dai, L., & Cai, C. (2019). Particle size reduction of rice straw enhances methane production under anaerobic digestion. *Bioresource Technology*, *293*. https://doi.org/10.1016/j.biortech.2019.122043

Dasgupta, A., & Chandel, M. K. (2020). Enhancement of biogas production from organic fraction of municipal solid waste using acid pretreatment. *SN Applied Sciences*, *2*(8). https://doi.org/10.1007/s42452-020-03213-z

Deepanraj, B., Sivasubramanian, V., & Jayaraj, S. (2017a). Effect of substrate pretreatment on biogas production through anaerobic digestion of food waste. *International Journal of Hydrogen Energy*, *42*(42), 26522–26528. https://doi.org/10.1016/j.ijhydene.2017.06.178

Deepanraj, B., Sivasubramanian, V., & Jayaraj, S. (2017b). Effect of substrate pretreatment on biogas production through anaerobic digestion of food waste. *International Journal of Hydrogen Energy*, *42*(42), 26522–26528. https://doi.org/10.1016/j.ijhydene.2017.06.178

Dong, L., Zhenhong, Y., & Yongming, S. (2010). Semi-dry mesophilic anaerobic digestion of water sorted organic fraction of municipal solid waste (WS-OFMSW). *Bioresource Technology*, *101*(8), 2722–2728. https://doi.org/10.1016/j.biortech.2009.12.007

Elsayed, M., Diab, A., & Soliman, M. (2021). Methane production from anaerobic co-digestion of sludge with fruit and vegetable wastes: effect of mixing ratio and inoculum type. *Biomass Conversion and Biorefinery*, *11*(3), 989–998. https://doi.org/10.1007/s13399-020-00785-z

Esposito, G., Frunzo, L., Panico, A., & Pirozzi, F. (2011). Modelling the effect of the OLR and OFMSW particle size on the performances of an anaerobic co-digestion reactor. *Process Biochemistry*, *46*(2), 557–565. https://doi.org/10.1016/j.procbio.2010.10.010

Ghosh, P., Kumar, M., Kapoor, R., Kumar, S. S., Singh, L., Vijay, V., Vijay, V. K., Kumar, V., & Thakur, I. S. (2020). Enhanced biogas production from municipal solid waste via co-digestion with sewage sludge and metabolic pathway analysis. *Bioresource Technology*, *296*. https://doi.org/10.1016/j.biortech.2019.122275

Girault, R., Bridoux, G., Nauleau, F., Poullain, C., Buffet, J., Peu, P., Sadowski, A. G., & Béline, F. (2012). Anaerobic co-digestion of waste activated sludge and greasy sludge from flotation process: Batch versus CSTR experiments to investigate optimal design. *Bioresource Technology*, *105*, 1–8. https://doi.org/10.1016/j.biortech.2011.11.024

Guo, J., Peng, Y., Ni, B. J., Han, X., Fan, L., & Yuan, Z. (2015). Dissecting microbial community structure and methane-producing pathways of a full-scale anaerobic reactor digesting activated sludge from wastewater treatment by metagenomic sequencing. *Microbial Cell Factories*, *14*(1). https://doi.org/10.1186/s12934-015-0218-4

Hartmann, H., & Ahring, B. K. (2005). Anaerobic digestion of the organic fraction of municipal solid waste: Influence of co-digestion with manure. *Water Research*, *39*(8), 1543–1552. https://doi.org/10.1016/j.watres.2005.02.001

Hegde, S., & Trabold, T. A. (2019). Anaerobic digestion of food waste with unconventional co-substrates for stable biogas production at high organic loading rates. *Sustainability (Switzerland)*, *11*(14). https://doi.org/10.3390/su11143875

Iacovidou, E., Ohandja, D. G., & Voulvoulis, N. (2012). Food waste co-digestion with sewage sludge - Realising its potential in the UK. *Journal of Environmental Management*, *112*, 267–274. https://doi.org/10.1016/j.jenvman.2012.07.029

Jayanama, K., Phuphuakrat, A., Pongchaikul, P., Prombutara, P., Nimitphong, H., Reutrakul, S., & Sungkanuparph, S. (2022). Association between gut microbiota and prediabetes in people living with HIV. *Current Research in Microbial Sciences*, *3*. https://doi.org/10.1016/j.crmicr.2022.100143

Jijai, S., Siripatana, C., O-Thong, S., & Ismail, N. (2016). Kinetic models for prediction of COD effluent from upflow anaerobic sludge blanket (UASB) reactor for cannery seafood wastewater treatment. *Jurnal Teknologi*, *78*(5–6), 93–99. https://doi.org/10.11113/jt.v78.8644

Katiyar, R. B., Suresh, S., & Sharma, A. K. (n.d.). ICGSEE-2013[14 th-16 th March 2013] International Conference on Global Scenario in Environment and Energy Characterisation Of Municipal Solid Waste Generated By The City Of Bhopal, India. In *International Journal of ChemTech Research CODEN* (Vol. 5, Issue 2).

Kesharwani, N., & Bajpai, S. (2020). Batch anaerobic co-digestion of food waste and sludge: a multi criteria decision modelling (MCDM) approach. *SN Applied Sciences*, *2*(8). https://doi.org/10.1007/s42452-020-03265-1

Keucken, A., Habagil, M., Batstone, D., Jeppsson, U., & Arnell, M. (2018). Anaerobic co-digestion of sludge and organic food waste-performance, inhibition, and impact on the microbial community. *Energies*, *11*(9). https://doi.org/10.3390/en11092325

Khajuria, A., Yamamoto, Y., & Morioka, T. (2010). Estimation of municipal solid waste generation and landfill area in Asian developing countries. In *Journal of Environmental Biology*.

Khanto, A., & Banjerdkij, P. (2016). Biogas production from batch anaerobic co-digestion of night soil with food waste. *EnvironmentAsia*, *9*(1), 77–83. https://doi.org/10.14456/ea.1473.9

Kim, W., & Whitman, W. B. (2014). Methanogens. In *Encyclopedia of Food Microbiology: Second Edition* (pp. 602–606). Elsevier Inc. https://doi.org/10.1016/B978-0-12-384730-0.00204-4

Koch, K. (2015). Calculating the degree of degradation of the volatile solids in continuously operated bioreactors. *Biomass and Bioenergy*, *74*, 79–83. https://doi.org/10.1016/j.biombioe.2015.01.009

Kumar, A., & Samadder, S. R. (2017). An empirical model for prediction of household solid waste generation rate – A case study of Dhanbad, India. *Waste Management*, *68*, 3–15. https://doi.org/10.1016/j.wasman.2017.07.034

Kumar, S., Sau, S., Pal, D., Tudu, B., Mandal, K. K., & Chakraborty, N. (2013). Parametric performance evaluation of different types of particle swarm optimization techniques applied in distributed generation system. *Advances in Intelligent Systems and Computing*, *199 AISC*, 349–356. https://doi.org/10.1007/978-3-642-35314-7_40

Kumari, K., Suresh, S., Arisutha, S., & Sudhakar, K. (2018). Anaerobic co-digestion of different wastes in a UASB reactor. *Waste Management*, *77*, 545–554. https://doi.org/10.1016/j.wasman.2018.05.007

Li, Y., Park, S. Y., & Zhu, J. (2011). Solid-state anaerobic digestion for methane production from organic waste. In *Renewable and Sustainable Energy Reviews* (Vol. 15, Issue 1, pp. 821–826). Elsevier Ltd. https://doi.org/10.1016/j.rser.2010.07.042

Liao, X., Li, H., Cheng, Y., Chen, N., Li, C., & Yang, Y. (2014). Process performance of high-solids batch anaerobic digestion of sewage sludge. *Environmental Technology (United Kingdom)*, *35*(21), 2652–2659. https://doi.org/10.1080/09593330.2014.916756

Lim, J. W. (2011). *Anaerobic Co-digestion of Brown Water and Food Waste for Energy Recovery. Daniel Thevenot. 11th edition of the World Wide Workshop for Young Environmental Scientists (WWW-YES-2011)-Urban Waters: resource or risks?* (Issue 14). WWW-YES-2011. https://hal.archives-ouvertes.fr/hal-00607958

Liotta, F., D'Antonio, G., Esposito, G., Fabbricino, M., Frunzo, L., Van Hullebusch, E. D., Lens, P. N., & Pirozzi, F. (2014). Effect of moisture on disintegration kinetics during anaerobic digestion of complex organic substrates. *Waste Management and Research*, *32*(1), 40–48. https://doi.org/10.1177/0734242X13513827

Meng, X., Zhang, Y., Sui, Q., Zhang, J., Wang, R., Yu, D., Wang, Y., & Wei, Y. (2018). Biochemical conversion and microbial community in response to ternary ph buffer system during anaerobic digestion of swine manure. *Energies*, *11*(11). https://doi.org/10.3390/en11112991

Minghua, Z., Xiumin, F., Rovetta, A., Qichang, H., Vicentini, F., Bingkai, L., Giusti, A., & Yi, L. (2009). Municipal solid waste management in Pudong New Area, China. *Waste Management*, *29*(3), 1227–1233. https://doi.org/10.1016/j.wasman.2008.07.016

Mohsen, A., Park, J., Chen, YA. *et al.* Impact of quality trimming on the efficiency of reads joining and diversity analysis of Illumina paired-end reads in the context of QIIME1 and QIIME2 microbiome analysis frameworks. *BMC Bioinformatics* 20, 581 (2019)

Mota, V. T., Santos, F. S., Araújo, T. A., & Amaral, M. C. S. (2015). Evaluation of titration methods for volatile fatty acids measurement: Effect of the bicarbonate interference and feasibility for the monitoring of anaerobic reactors. *Water Practice and Technology*, *10*(3), 486–495. https://doi.org/10.2166/wpt.2015.056

Mougari, N. E., Largeau, J. F., Himrane, N., Hachemi, M., & Tazerout, M. (2021). Application of artificial neural network and kinetic modeling for the prediction of biogas and methane production in anaerobic digestion of several organic wastes. *International Journal of Green Energy*, *18*(15), 1584–1596. https://doi.org/10.1080/15435075.2021.1914630

Nguyen, T. H., Nguyen, M. K., Le, T. H. O., Bui, T. T., Nguyen, T. H., Nguyen, T. Q., & Ngo, A. Van. (2021). Kinetics of Organic Biodegradation and Biogas Production in the Pilot-Scale Moving Bed Biofilm Reactor (MBBR) for Piggery Wastewater Treatment. *Journal of Analytical Methods in Chemistry*, *2021*. https://doi.org/10.1155/2021/6641796

Nkeiruka Nweke, C., & Nwabanne, J. T. (2021). Anaerobic Digestion of Yam Peel for Biogas Production: A Kinetic Study. In *Journal of Engineering and Applied Sciences* (Vol. 18, Issue 1).

Nor Faekah, I., Fatihah, S., & Mohamed, Z. S. (2020). Kinetic evaluation of a partially packed upflow anaerobic fixed film reactor treating low-strength synthetic rubber wastewater. *Heliyon*, *6*(3). https://doi.org/10.1016/j.heliyon.2020.e03594

OLDEN, J. (2004). An accurate comparison of methods for quantifying variable importance in artificial neural networks using simulated data. *Ecological Modelling*. https://doi.org/10.1016/s0304-3800(04)00156-5

Olden, J. D., & Jackson, D. A. (2002). Illuminating the "'black box'": a randomization approach for understanding variable contributions in artificial neural networks. In *Ecological Modelling* (Vol. 154). www.elsevier.com/locate/ecolmodel

Pal, M. S., & Bhatia, M. (2022). Current status, topographical constraints, and implementation strategy of municipal solid waste in India: a review. *Arabian Journal of Geosciences*, *15*(12). https://doi.org/10.1007/s12517-022-10414-w

Ponsá, S., Gea, T., & Sánchez, A. (2011). Anaerobic co-digestion of the organic fraction of municipal solid waste with several pure organic co-substrates. *Biosystems Engineering*, *108*(4), 352–360. https://doi.org/10.1016/j.biosystemseng.2011.01.007

Prabhu, M. S., & Mutnuri, S. (2016). Anaerobic co-digestion of sewage sludge and food waste. *Waste Management and Research*, *34*(4), 307–315. https://doi.org/10.1177/0734242X16628976

Rabii, A., Koupaie, E. H., Aldin, S., Dahman, Y., & Elbeshbishy, E. (2021). Methods of pretreatment and their impacts on anaerobic codigestion of multifeedstocks: A review. In *Water Environment Research* (Vol. 93, Issue 12, pp. 2834–2852). John Wiley and Sons Inc. https://doi.org/10.1002/wer.1636

Ramachandran, A., Rustum, R., & Adeloye, A. J. (2019). Review of anaerobic digestion modeling and optimization using nature-inspired techniques. In *Processes* (Vol. 7, Issue 12). MDPI AG. https://doi.org/10.3390/PR7120953

Rao, M. S., & Singh, S. P. (2004). Bioenergy conversion studies of organic fraction of MSW: Kinetic studies and gas yield-organic loading relationships for process optimisation. *Bioresource Technology*, *95*(2), 173–185. https://doi.org/10.1016/j.biortech.2004.02.013

Rego, A. S. C., Leite, S. A. F., Leite, B. S., Grillo, A. V., & Santos, B. F. (2019). Artificial neural network modelling for biogas production in biodigesters. *Chemical Engineering Transactions*, *74*, 25–30. https://doi.org/10.3303/CET1974005

Roberts, S., Mathaka, N., Zeleke, M. A., & Nwaigwe, K. N. (2023). Comparative Analysis of Five Kinetic Models for Prediction of Methane Yield. *Journal of The Institution of Engineers (India): Series A*, *104*(2), 335–342. https://doi.org/10.1007/s40030-023-00715-y

Sada, S. O., & Ikpeseni, S. C. (2021). Evaluation of ANN and ANFIS modeling ability in the prediction of AISI 1050 steel machining performance. *Heliyon*, *7*(2). https://doi.org/10.1016/j.heliyon.2021.e06136

Saini, S., Rao, P., & Patil, Y. (2012). City Based Analysis of MSW to Energy Generation in India, Calculation of State-Wise Potential and Tariff Comparison with EU. *Procedia - Social and Behavioral Sciences*, *37*, 407–416. https://doi.org/10.1016/j.sbspro.2012.03.306

Sato, N., Okubo, T., Onodera, T., Ohashi, A., & Harada, H. (2006). Prospects for a self-sustainable sewage treatment system: A case study on full-scale UASB system in India's Yamuna River Basin. *Journal of Environmental Management*, *80*(3), 198–207. https://doi.org/10.1016/j.jenvman.2005.08.025

Shah, F. A., Mahmood, Q., Rashid, N., Pervez, A., Raja, I. A., & Shah, M. M. (2015). Co-digestion, pretreatment and digester design for enhanced methanogenesis. In *Renewable and Sustainable Energy Reviews* (Vol. 42, pp. 627–642). Elsevier Ltd. https://doi.org/10.1016/j.rser.2014.10.053

Shahab, S., & Anjum, M. (2022). Solid Waste Management Scenario in India and Illegal Dump Detection Using Deep Learning: An AI Approach towards the Sustainable Waste Management. *Sustainability (Switzerland)*, *14*(23). https://doi.org/10.3390/su142315896

Shahzad, H. M. A., Khan, S. J., & Habib, Z. (2022). Performance evaluation and substrate removal kinetics in a thermophilic anaerobic moving bed biofilm reactor for starch degradation. *Water Practice and Technology*, *17*(1), 157–166. https://doi.org/10.2166/wpt.2021.111

Sharholy, M., Ahmad, K., Vaishya, R. C., & Gupta, R. D. (2007). Municipal solid waste characteristics and management in Allahabad, India. *Waste Management*, *27*(4), 490–496. https://doi.org/10.1016/j.wasman.2006.03.001

Sharma, K. D., & Jain, S. (2019a). Overview of Municipal Solid Waste Generation, Composition, and Management in India. *Journal of Environmental Engineering*, *145*(3). https://doi.org/10.1061/(asce)ee.1943-7870.0001490

Sharma, K. D., & Jain, S. (2019b). Overview of Municipal Solid Waste Generation, Composition, and Management in India. *Journal of Environmental Engineering*, *145*(3). https://doi.org/10.1061/(asce)ee.1943-7870.0001490

Singhal, A., Gupta, A. K., Dubey, B., & Ghangrekar, M. M. (2022). Seasonal characterization of municipal solid waste for selecting feasible waste treatment technology for Guwahati city, India. *Journal of the Air and Waste Management Association*, *72*(2), 147–160. https://doi.org/10.1080/10962247.2021.1980450

Smith, D. B., & Almquist, C. B. (2014). The anaerobic co-digestion of fruit and vegetable waste and horse manure mixtures in a bench-scale, two-phase anaerobic digestion system. *Environmental Technology (United Kingdom)*, *35*(7), 859–867. https://doi.org/10.1080/09593330.2013.854398

Sosnowski, P., Wieczorek, A., & Ledakowicz, S. (2003). Anaerobic co-digestion of sewage sludge and organic fraction of municipal solid wastes. In *Advances in Environmental Research* (Vol. 7).

Syaichurrozi, I., Sumardiono, S., & Authors, corresponding. (2013). Biogas production from bioethanol waste: the effect of pH and urea addition to biogas production rate. *Budiyono et al. 1 Waste Technology*, *1*(1), 1–5. https://doi.org/10.1277/wastech.1.1.2013.1-5

Tchobanoglous, George., Burton, F. L. (Franklin L., Stensel, H. David., & Metcalf & Eddy. (2003). *Wastewater engineering : treatment and reuse*. McGraw-Hill.

Thitame, S. N., Pondhe, G. M., & Meshram, D. C. (2010). Characterisation and composition of Municipal Solid Waste (MSW) generated in Sangamner City, District Ahmednagar, Maharashtra, India. *Environmental Monitoring and Assessment*, *170*(1–4), 1–5. https://doi.org/10.1007/s10661-009-1209-x

Tyagi, V. K., Fdez-Güelfo, L. A., Zhou, Y., Álvarez-Gallego, C. J., Garcia, L. I. R., & Ng, W. J. (2018). Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges. In *Renewable and Sustainable Energy Reviews* (Vol. 93, pp. 380–399). Elsevier Ltd. https://doi.org/10.1016/j.rser.2018.05.051

Van Eerten-Jansen, M. C. A. A., Veldhoen, A. B., Plugge, C. M., Stams, A. J. M., Buisman, C. J. N., & Ter Heijne, A. (2013). Microbial community analysis of a methane-producing biocathode in a bioelectrochemical system. *Archaea*, *2013*. https://doi.org/10.1155/2013/481784

Vashi, N. V., Shah, N. C., & Desai, K. R. (2019). Performance of UASB Post Treatment Technologies for Sewage Treatment in Surat City. *Oriental Journal Of Chemistry*, *35*(4), 1352–1359. https://doi.org/10.13005/ojc/350415

Villamil, J. A., Mohedano, A. F., Rodríguez, J. J., Borja, R., & De la Rubia, M. A. (2018). Anaerobic Co-digestion of the Organic Fraction of Municipal Solid Waste and the Liquid Fraction From the Hydrothermal Carbonization of Industrial Sewage Sludge Under Thermophilic Conditions. *Frontiers in Sustainable Food Systems*, *2*. https://doi.org/10.3389/fsufs.2018.00017

Vinodbhai Mewada, M., Mewada, M., Albert, S., & Padhiar, A. (2020). Municipal Solid Waste Management System in Vadodara City: Current Scenario. *IOSR Journal of Environmental Science*, *14*(2), 45–50. https://doi.org/10.9790/2402-1402024550

Yetilmezsoy, K., Turkdogan, F. I., Temizel, I., & Gunay, A. (2013). Development of ann-based models to predict biogas and methane productions in anaerobic treatment of molasses wastewater. *International Journal of Green Energy*, *10*(9), 885–907. https://doi.org/10.1080/15435075.2012.727116

Zaplana, T., Miele, S., & Tolonen, A. C. (2023). Lachnospiraceae are emerging industrial biocatalysts and biotherapeutics. In *Frontiers in Bioengineering and Biotechnology* (Vol. 11). Frontiers Media SA. https://doi.org/10.3389/fbioe.2023.1324396

Zhang, J., Li, W., Lee, J., Loh, K. C., Dai, Y., & Tong, Y. W. (2017). Enhancement of biogas production in anaerobic co-digestion of food waste and waste activated sludge by biological co-pretreatment. *Energy*, *137*, 479–486. https://doi.org/10.1016/j.energy.2017.02.163

Zhang, J., Loh, K. C., Lee, J., Wang, C. H., Dai, Y., & Wah Tong, Y. (2017). Three-stage anaerobic co-digestion of food waste and horse manure. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-01408-w

Zupančič, G. D., Uranjek-Ževart, N., & Roš, M. (2008). Full-scale anaerobic co-digestion of organic waste and municipal sludge. *Biomass and Bioenergy*, *32*(2), 162–167. https://doi.org/10.1016/j.biombioe.2007.07.006

Zwietering, M. H., Jongenburger, I., Rombouts, F. M., Van ' K., & Riet, T. (1990). Modeling of the Bacterial Growth Curve. In *APPLIED AND ENVIRONMENTAL MICROBIOLOGY*.