Indian cities are expanding rapidly with their population growth and economic developments impose a significant impact on the generation rate of Municipal Solid Waste (MSW). It is imperative to segregate MSW, which leads towards the increase in the production of Organic Fraction of Municipal Solid Waste (OFMSW) in most cities of developing nations. OFMSW is the most favourable substrate for the anaerobic digestion process to meet the goal of waste-to-energy in recent times. The present study aims to improve the anaerobic digestion process of OFMSW using co-substrate.

In developing nations like India, sewage is treated with Up-flow Anaerobic Sludge Blanket technology (UASB) where effluent needs to meet disposal standards. The treated effluent of UASB is conventionally treated with the Activated Sludge Process (ASP). In such plants, bio-flocculated sludge generated from the Secondary Settling Tank (SST) needs special attention and its quantity is relatively less for the separate digestion requirement. Bio-flocculated sludge is rich in microbial biomass and is chosen for its potential to enhance methane production during the anaerobic co-digestion process. The use of bio-flocculated sludge aligns with the waste valorization principle where the bio-product of sewage treatment can be used as a potential co-substrate for the anaerobic co-digestion process.

Anaerobic co-digestion is the potential treatment for OFMSW as OFMSW needs liquification for a higher degradability rate and sludge being rich in microbial biomass enhances methane production during the anaerobic co-digestion process. In a year, most Indian states have favourable meteorological conditions where temperature remains 20°C to 40°C (about 9 to 10 months of a year). This integrated solution addresses the challenges associated with wastewater treatment and leverages resource synergies to promote energy generation and environmentally conscious waste management practices.

The composition 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 for lab-scale experimental work. OFMSW and bio-flocculated sludge mixed with different ratios of 50:50, 75:25, 90:10, 100:0 &0:100 (by %wet mass). The mixing ratio of OFMSW and bio-flocculated sludge is optimized using batch anaerobic co-digestion lab-scale experimental work under mesophilic conditions. Anaerobic co-digestion shows a quick phase of acclimatization and raises methane production. The maximum specific methane gas yield of anaerobic co-digestion is 369.28±55.51 $L/kgVS_{added}$ compared to 167.78±16.45 $L/kgVS_{added}$ in batch experimental mono-digestion of OFMSW. Lab-scale experimental data validate the anaerobic co-digestion process of OFMSW and bio-flocculated sludge using kinetic modelling. The most popular kinetic models, the Modified Gompertz model and the Logistic Function model for methane production demonstrate the acceptance of anaerobic co-digestion batch experimental methane yield with R^2 0.99 for a mixing ratio of 75:25 with a high methane production rate and higher hydrolysis rate constant.

An optimized mixing ratio of 75:25 (%wet mass) of OFMSW and bio-flocculated sludge is used to perform a 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. The OLR is systematically varied within the range of 2,3,4,5,6 and subsequently 8 & 12 gm VS/L/d. The operation of the anaerobic mesophilic reactor consistently demonstrated fluctuation in biogas yield, pH, VFA/Alkalinity ratio and % Volatile Solids (VS) removal even at the same OLR. This variation is attributed to changes in the characteristics and composition of the substrate utilized for the anaerobic co-digestion process. Throughout the semi-continuous flow anaerobic reactor, with the fluctuating %Total Solids (TS) range and varying loading rate, the reactor performs well with a range of OLR 2 to 3 gm VS/L/d range. The Optimum OLR for the anaerobic co-digestion process of OFMSW and bio-flocculated sludge is 3 gm VS/L/d due to a higher biogas yield of an average of 37.20 L/gm $VS_{consumed}$ with lower VFA/Alkalinity ratio of 0.19±0.06, pH 6.9±0.5, %VS removal efficiency of 73.9± 1.9 during the operation of the reactor. A new hybrid kinetic model that combines the first-order kinetic model and logistic function model is developed and applied to experimental data which predicts a more accurate cumulative biogas yield with R^2 0.99 compared to other kinetic models. The Modified Stover-Kincannon model, Grau's Second-Order model and the First-Order kinetic model are applied for substrate removal efficiency prediction. U_{max} – the maximum removal rate constant and K_B - the saturation constant is achieved at 31.74 (gm/L*d) and 86.02 (gm/L*d) using the Modified Stover-Kincannon model. Grau's Second-Order kinetic constants a and b are 0.58 and 3.1 respectively. The First-Order kinetic model rate removal constant k_r is 0.12. The finding of the study demonstrates the value of kinetic models as a tool for improving the control of the anaerobic co-digestion process.

The development of the best prediction model depends upon the choice of appropriate modelling technique for the anaerobic co-digestion process. The substrate quality analysis parameter (%TS), the operational parameters (pH, VFA/Alkalinity ratio) and process control parameters (Organic Loading Rate, Hydraulic Retention Time) are considered as input variables; $\%VS_{removal}$ and methane yield are considered as output variables for the development of prediction model using Artificial Neural Network (ANN) modelling technique. The ANN model architecture has been optimized for accurate prediction of output variable $\%VS_{removal}$ and methane yield with architecture 5-19-2 and 5-17-2, respectively. Feed Forward Neural Network using Bayesian Regularization (trainbr) training algorithm shows high coefficients of determination (R^2) of 0.98 and 0.95 for $\%VS_{removal}$ and methane yield, respectively. The results demonstrate the effectiveness of ANN-based modelling in capturing complex relationships with the methane yield process, facilitating accurate prediction of crucial output parameters. Two sophisticated modelling approaches Artificial Neural Network-Particle Swarm Optimization (ANN-PSO) and Adaptive Neuro-Fuzzy Inference system (ANFIS) are used to predict methane yield in this anaerobic co-digestion study. The hybrid approach captures intricate and non-linear relationships among input variables and methane yield using the ANN-PSO model achieves an R^2 of 0.80. ANFIS further elevates the modelling precision by leveraging linguistic variables and membership functions to optimize prediction with R^2 0.90.

Metagenomic analysis using 16SrRNA genome sequencing shows the abundance of Firmicute and Bacilli at the phylum level, Clostridia and Bacilli at the class level, Lachnospiraceae and Lactobacillaceae at the family level and Anaerostignum, Lactobacillus and Clostridium sensu stricto are found at the genus level. Lachnospiraceae and methanogens or acetogens have the potential, can directly convert lignocellulose to methane gas and other value-added biochemicals. The Anaerostignum genus found in abundance is of the same order level as Lachnospirales of the Lahnospiraceas family and from the Firmicutes phylum.

This study contributes to advancing waste-to-energy practices as a solution for integrated solid-liquid waste management is offering valuable insights for the potential use of bio-flocculated sludge from SST (post-UASB) as co-substrate for anaerobic co-digestion of OFMSW for the effective management of OFMSW. The lab-scale process employed in 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 prediction model developed with ANN with curve fitting application provides more accurate modelling compared to traditional kinetic modelling for Volatile Solids removal using a modified Stover-Kincannon model. Further data integration will fortify the accuracy and applicability of the proposed prediction models using ANN. The presence of the Lachnospiraceae family and

Anaerostignum genus in abundance shows the potential of OFMSW and bio-flocculated sludge from SST (post-UASB) as a substrate to improve the anaerobic co-digestion process.

Keywords: Organic Fraction of Municipal Solid Waste, Bio-flocculated sludge, Anaerobic co-digestion, Kinetic modelling, Stover-Kincannon model, modified Gompertz model, Artificial Neural Network