

Flushed Hybrid Bioreactor Landfill: Innovation for enhancement of rate of biogas generation and reduction in stabilization time of the organic fraction of municipal solid waste in landfill

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Research Article

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3. Title: Flushed Hybrid Bioreactor Landfill: Innovation for enhancement of rate of biogas generation and reduction in stabilization time of the organic fraction of municipal solid waste in landfill.

Abstract

Anaerobic bioreactor landfill (ABLF) has the potential to overcome the environmental concerns associated with open landfilling used for municipal solid waste (MSW) disposal. It is essential to increase the degradation rate of the organic fraction of municipal solid waste (OFMSW) and to attain early stabilization of ABLF to minimize landfill space requirements and enhance economic viability through the optimization of operational and maintenance expenses. Researchers have attempted to reduce the hydrolysis phase and provide a favourable environment for anaerobic reactors. Experimentation on a flushed hybrid bioreactor was performed in reactors FHB1, FHB2 and FHB3 with combinations and variations in operational parameters with an aim to enhance the rate of landfill gas generation and reduce the stabilization time of OFMSW. Operational parameters considered were pretreatment of substrate, variation in frequency of aerations, and variation in leachate recirculation rate. Results revealed that the operational parameter used in FHB3 accelerated the gas generation rate of 420.59 L kg⁻¹ of volatile solids. The achieved gas generation rate is 17.16 % higher than ABLF; also 26.16 % reduction in stabilization time of OFMSW was achieved. Nonlinear regression of the cumulative biogas production demonstrated that Modified Gompertz growth and Modified Logistic equations fit the experimental results well.

Keywords: Organic fraction of municipal solid waste, Flushed hybrid bioreactor landfill, Biogas production rate, stabilization time, Gompertz growth equation. Modified Logistic equation

1. Introduction:

Open landfilling practised in developing nations has negative environmental impacts which may last for several decades [1,2]. Anaerobic bioreactor landfill is one of the options to open landfilling and is found to be effective in addressing environmental concerns associated with open landfilling, accelerating the waste stabilization process, enhancing the landfill gas production from the organic fraction of the municipal solid waste (OFMSW) and also for airspace recovery [3, 4]. The important phases in the life of the anaerobic bioreactor landfill are initial adjustment, hydrolysis, acidogenesis, acetogenesis, methanogenesis and the maturation phases [5, 6]. Hydrolysis is the rate-limiting step in anaerobic digestion [7]. Also, the maturation phase in the anaerobic landfill takes considerable time. Studies on strategies for the reduction of the hydrolysis phase have been done previously by adopting shredding of waste, aeration, addition of microbial culture in the aeration stage, and pH adjustment [8, 9,10]. Researchers have experimented with the anaerobic bioreactor technology for enhancement of the biogas generation [11,12,13], by leachate recirculation [14,15], addition of the anaerobic sludge [16], and addition of the gravel [8].

The reduction in the stabilization time of the OFMSW in the anaerobic bioreactor landfill is important as it will reduce the operation and maintenance cost, reduce the volume of the OFMSW and will make the landfill ready for resource recovery from the digestate and reusability of the land. Lignin in the feedstocks is found to be a recalcitrant compound to anaerobic digestion. The structural complexity and compositional heterogeneity of lignocellulosic feedstocks hinder their full degradation in anaerobic digestion and result in sub-optimal biomethane yields [17] and also increase the stabilization time of the landfill. However, the stabilization of these recalcitrant compounds is necessary.

Experimental results have shown that approximately 20-25% of the total time required for the stabilization of the OFMSW is devoted to the maturation phase, and only 10 % of the biogas is generated in this phase with very low methane content [8]. The maturation phase includes the stabilization of the anaerobically slow-degrading complex carbon compounds. These compounds degrade slowly in the anaerobic process, but can be tested to assess their degradation in the aerobic phase. Also, the potential for the formation of biogas in these compounds is less, considering the investment of time in this phase. As a result, the overall stabilization time for OFMSW increases, which also increases the operation and maintenance cost of the anaerobic bioreactor landfill. This study aims to enhance biogas generation and reduce the stabilization time of the OFMSW.

2. Methods

2.1 Flushed hybrid bioreactor

The concept of a flushed hybrid bioreactor focuses on converting the anaerobic degradation process to an aerobic degradation process before the start of the maturation phase for early stabilization of the OFMSW. The conversion to the aerobic process should happen keeping in view the satisfactory extraction of the biogas and appropriate reduction of the volatile content from the OFMSW.

For successful execution of the concept, the strategy executed for conversion of the process from anaerobic to aerobic was (a) the chemical oxygen demand (COD) of the leachate from the substrate should register the value lesser than 10 % of the peak COD value observed or (b) the biochemical oxygen demand (BOD) of the leachate from the substrate should register the value lesser than 5% of the peak BOD value or (c) total volatile solids (TVS) of the substrate should register the value lesser than 20% of the initial TVS value of the substrate. Fig. 1 demonstrates the methodology of the flushed hybrid bioreactor. These framed conditions ensured the appropriate reduction of the volatile matter in the substrate and also reduces the organic load for the aerobic process. The high organic load in the aerobic process will require a higher amount of energy for the supply of oxygen, making the process energy dependent.

2.2 Configuration of the experimental bioreactors

Four reactors were used to simulate the conditions for the stabilization process. All reactors were filled with the OFMSW. Reactor AB (Anaerobic Bioreactor) simulates a conventional anaerobic bioreactor with no enhancement techniques. Reactor FHB1 (Flushed Hybrid Bioreactor 1) simulates the flushed hybrid bioreactor concept with no enhancement techniques. Reactor FHB2 (Flushed Hybrid Bioreactor 2) and FHB3 (Flushed Hybrid Bioreactor 3) simulate the flushed hybrid bioreactor concept with different operating conditions.

The bioreactors were fabricated in acrylic material of 0.005 m thickness, having an internal diameter of 0.3 m and a height of 0.6 m. Each of the reactors had ports for leachate collection, leachate recirculation and gas collection. For proper drainage of leachate, a half-cut plastic ball with a 0.075 m diameter, 0.003m thick and 60 openings of 0.005 m diameter was kept over the leachate drainage collection port drilled at the center of the reactor base. The ball was covered with gravel of size 0.01-0.0125 m up to a 0.05 m thick layer. The substrate in the reactor was filled to a height of 0.45 m with alternate layers of OFMSW and soil. Each layer of OFMSW

was 0.12 m thick, and that of the soil layer was 0.01 m thick. The topsoil layer was 0.02 m thick. At the center of the reactor, a perforated pipe of 0.05 m diameter and height of 0.45 m was placed. The pipe had 235 holes drilled in it each of 0.005 m diameter.

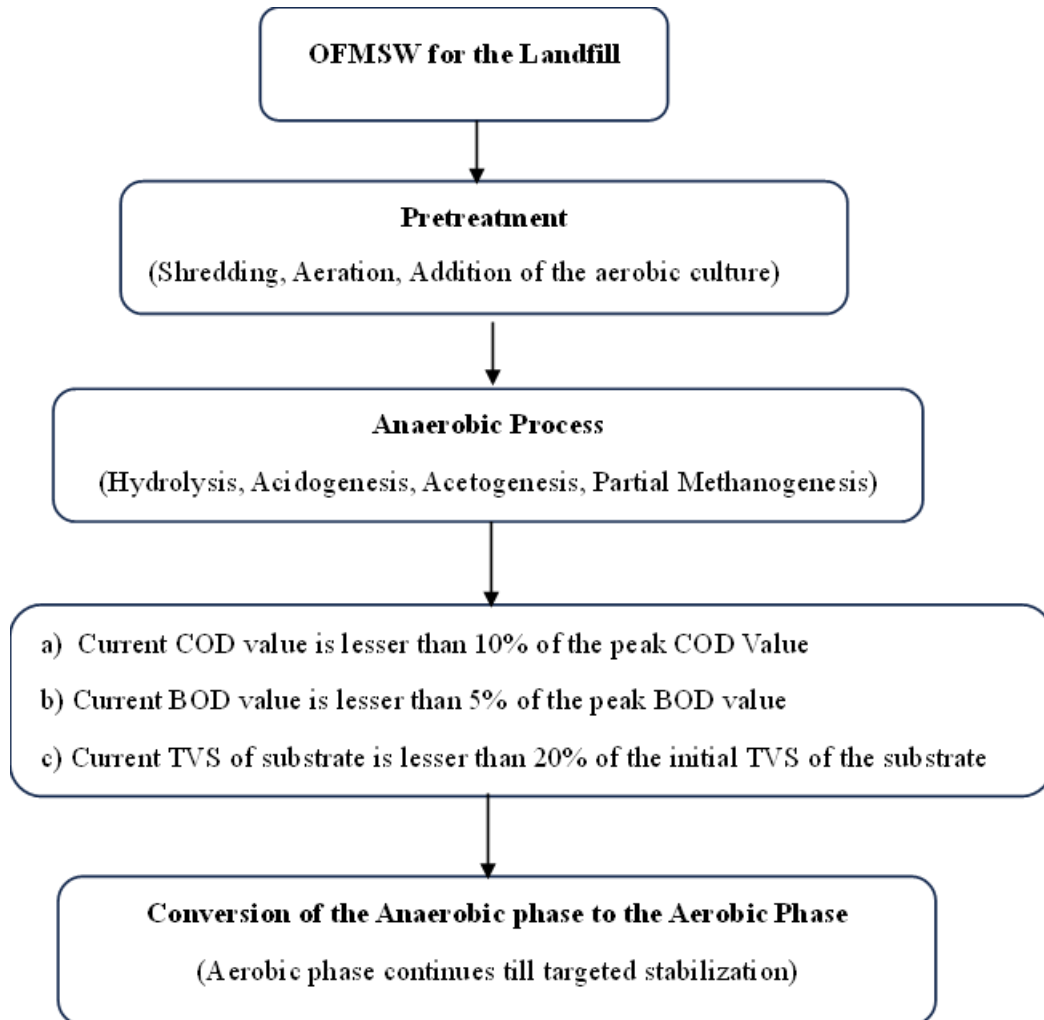


Fig. 1 Methodology for experimentation

Leachate was collected in the plastic container of volume 13 L kept at the bottom of the reactor. The leachate was manually recirculated in the reactor through the leachate collection port at the top of the reactor. The reactors were placed in the covered room under atmospheric conditions. Fig. 2 represents the reactor used in the experimentation.

2.3 Experimentation Process in the Bioreactors

The variation in the operating conditions in the reactors of the experimental set-up is tabulated in Table 1. The operating conditions selected are shredding of OFMSW, addition of the media, aeration in the hydrolysis stage,

addition of aerobic inoculum during the hydrolysis phase, leachate recirculation, adjustment of pH during the leachate, addition of anaerobically digested slurry, and aeration treatment in the post-methanogenic phase. The selection of the operation parameters was done considering the potential of their applicability in the field-scale application and their contribution to enhance the rate of degradation. The shredding of OFMSW was selected to increase the surface area of OFMSW for degradation [18], addition of the media was selected to increase the available surface area for microbial actions, aeration as a pretreatment [19] and addition of aerobic inoculum was selected to break the maximum complex chain compounds at a faster rate in the hydrolysis phase. Leachate recirculation with pH adjustment was selected for maintaining the moisture content and supply of drained nutrients to the substrate [20]. The addition of the anaerobically digested slurry through leachate recirculation was adopted to ensure the regular supply of anaerobes to the substrate. Aeration and addition of aerobic inoculum in the post-methanogenic phase were selected to increase the rate of degradation aerobically and to reduce the duration of the maturation phase. The intermittent rate of air supply and the phase-wise leachate recirculation rate were adopted in FHB3 to understand its effect on rate of degradation.

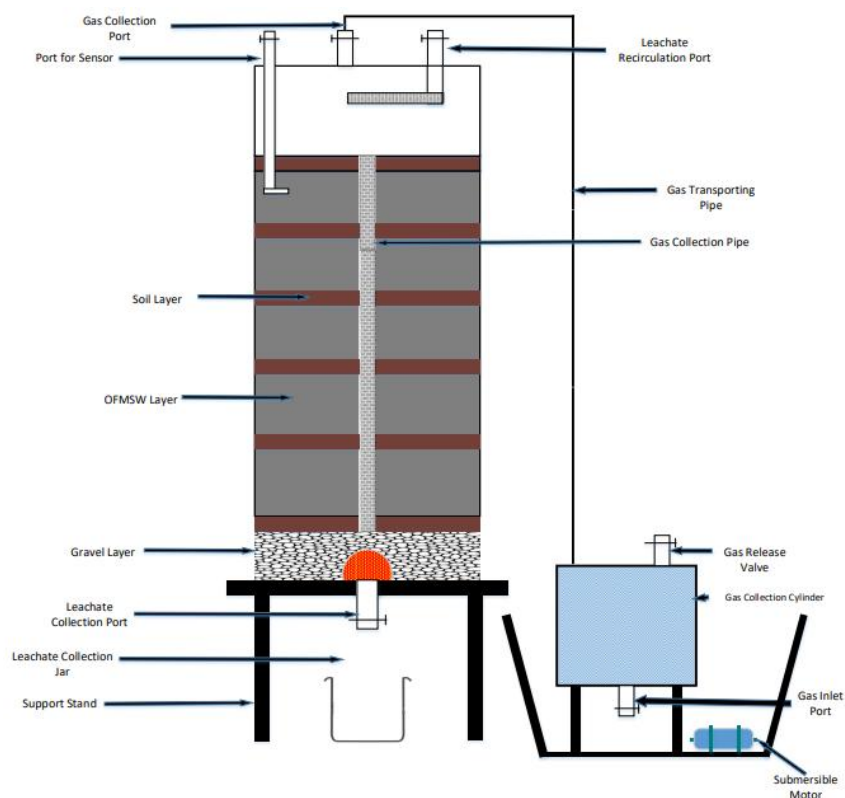


Fig. 2 Schematic diagram of Flushed Hybrid Bioreactor landfill simulator

The variation in the operation conditions in the reactors is done to compare the rate of biogas generation and rate of degradation between the conventional anaerobic bioreactor landfill with no enhancement (reactor AB)

with the proposed flushed hybrid bioreactors (FHB1, FHB2 and FHB3). Also, the operating conditions within the flushed hybrid bioreactors (FHB1, FHB2 and FHB3) are varied to understand the effects of enhancement parameters.

OFMSW used to fill the reactors was obtained from the Moshi Landfill in the Pimpri Chinchwad area of Pune City, India. The moisture content of the OFMSW sampled was 29.32%, and the TVS content was 682.45 gm/kg. The elemental analysis of the OFMSW depicted that it had 43.94 %, 6.67%, 2.94% and 0.331% of carbon, hydrogen, nitrogen and sulphur, respectively. The bromatological analysis suggested that the presence of proteins, fats and carbohydrates in the OFMSW was 14.47 (gm/100gm), 10.11 (gm/100gm) and 42.53 (gm/100 gm), respectively. The OFMSW was shredded manually to obtain a size of 0.03 - 0.05 m before filling in all the reactors. The approximate volume of the substrate in the reactor was 0.13 cubic meters, and the weight was approximately 22-23 kgs.

The OFMSW for the reactors AB and FHB1 was mixed with 2 Litres of anaerobically digested slurry (ADS) from the anaerobic digester of the 10 MLD Sewage Treatment Plant at Sanghvi, Pune. The ADS had a moisture content of 99.37% and consisted of 4.36 gm/kg of volatile solids. In both reactors, tap water of 1L per week was added to simulate rainfall & comply with 720 mm of rainfall in Pune City for three months. The reactors were sealed to maintain airtight conditions for anaerobic reactions. Leachate was recirculated as per the values decided.

For reactors FHB2 and FHB3, 250 ml of aerobic microbial culture was mixed with the shredded waste. The waste in the reactor FHB2 was aerated for 7.5 hours/daily for 10 days at the rate of 33 lpm. The waste in the reactor FHB3 was aerated in 3 cycles/day for 10 days at the rate of 33 lpm (each cycle consisting of 2.5 hours with a 0.5-hour gap). The aerated substrate in reactor FHB2 and FHB3 was then mixed with 2 Litres of ADS. The plastic media having enhanced surface area was mixed in both the reactors (6.25% v/v of the OFMSW volume). The plastic media was cylindrical in shape, made up of HDPE and was corrugated, having a surface area of 700 m²/m³. The reactors were then filled with alternate layers of waste and soil and were then sealed to maintain airtight conditions. The leachate recirculation in FHB2 was the same as that in reactors AB and FHB1 for the anaerobic process. The leachate recirculation rate for reactor FHB3 was higher for the first 30 days, then was reduced till 60th day and was further reduced till 109th day. For both reactors, pH was adjusted to the neutral range using NaOH during the recirculation.

Table No. 1 Operational parameters in the reactors

Sr. No.	Parameters	AB	FHB1	FHB2	FHB3
1	Working mode	Conventional Anaerobic Bioreactor Landfill		Flushed Hybrid Bioreactor	
2	Shredding of OFMSW	5-6 cm	5-6 cm	5-6 cm	5-6 cm
3	Addition of the media	NA	NA	6.25% of the v/v of OFMSW	6.25% of the v/v of OFMSW
4	Aeration in Hydrolysis Stage	No	No	7.5 hrs. daily @ 33 lpm for 10 days (10% of the total duration)	3 cycles per days Each cycle of 2 hrs. @ 33 lpm with 0.5 hrs. gap for 10 days (10 % of the total duration)
5	Addition of aerobic inoculum in Hydrolysis Phase	No	No	250 ml	250 ml
6	Leachate Recirculation rate		Same throughout the process		Varied leachate recirculation rate
7	pH adjustment of leachate during recirculation	No	No	Yes (by addition of NaoH)	Yes (by addition of NaoH)
8	Addition of anaerobically digested slurry after sealing of the reactors	No	No	0.42 % of the v/v of OFMSW	0.42 % of the v/v of OFMSW
9	Addition of aerobic inoculum post methanogenesis phase	NA	No	Yes	Yes
10	Aeration post methanogenesis phase	NA	No	Same as in Hydrolysis stage	Same as in Hydrolysis stage

The solubilization and establishment of the anaerobic population in the initial days is attributed to the higher recirculation rates. 150 ml of ADS was added in reactors FHB2 and FHB3 every time during the leachate recirculation to maintain the anaerobic population.

The process in Reactors FHB1, FHB2 and FHB3 was converted from an anaerobic to aerobic process as per the flushed hybrid bioreactor strategy. Reactor FHB1 was converted into the aerobic process, and no enhancement techniques were used. In the aerobic stage, the substrate in FHB2 was mixed with 150 ml of the aerobic inoculum to introduce aerobes into the reactor and was aerated continuously with the same strategy as in pretreatment. In reactor FHB3, in the aerobic stage, the substrate was added with 120 ml of aerobic inoculum and was aerated intermittently in 3 cycles with the same strategy as in pretreatment.

The settlement in the reactors was measured daily using a 2 m tape having a least count of 0.1 m pasted on each of the reactors. The biogas generated in each of the reactors was measured daily by using the water displacement method in the water container of 20 L volume having least count of 250 ml. The water used for the measurement of the biogas in the water displacement method was made acidic by adding 2 % (v/v) H₂SO₄. Leachate samples for the analysis were collected weekly in glass bottles and were preserved at 4°C in a refrigerator. Further, the chemical analysis of the collected leachate was done. The leachate was analyzed for pH, electrical conductivity, Oxidation Reduction Potential (ORP), Biochemical Oxygen Demand (BOD₅) and Chemical Oxygen Demand (COD) by standard methods APHA, 1998. The OFMSW was analyzed for carbon (C), Hydrogen (H), Nitrogen (N) and Sulphur (S) when the processes were converted from anaerobic to aerobic. The OFMSW was also analyzed for bromatological parameters like carbohydrates, proteins and lipids when the processes in the reactor were changed from anaerobic to aerobic.

2.4 Biogas Production Modelling

Gompertz Modified Growth Model and Modified logistic models were used to predict the cumulative volume of the biogas produced from the bioreactors according to their respective equations. These models have a sigmoid shape and provide a clear inflection point. These models are applied for representing the process of anaerobic digestion, study of microbial growth under different environments and formulation of other prediction models for fermentation microbiology [21]

As per Gompertz Modified Growth Equation, $BG = BGP \exp \left\{ -\exp \left[\frac{Rm \times e}{BGP} (\lambda - t) + 1 \right] \right\}$ (1)

$$\text{As per Modified Logistic Model Equation, } BG = \frac{BGP}{1 + \exp\left(\frac{4Rm}{BGP}(\lambda + t) + 2\right)} \quad (2)$$

Where BG is the cumulative biogas yield (mL/gm VS), t is digestion time (d), BGP is biogas yield potential (mL/gm of VS), Rm is maximal daily biogas yield (mL/gm of VS d), k is bacteria growth lag time (d), e is the mathematical constant (2.718) and λ is lag time.

3. Results and discussions

3.1 Daily Biogas Generation

Fig. 3a represents the daily biogas generation in the reactors over a period of time. Initial lower values of biogas production till the 44th day in AB, the 37th day in FHB1, the 29th day in FHB2 and FHB3 are attributed to the hydrolysis phase. The biogas generation rate then increased in the reactors in the acidogenesis phase. A rapid increase in the biogas generation was observed, indicating an increase in the rate of degradation in the reactors. Due to variable degradation rates in each of the reactors, the peak values of AB, FHB1, FHB2 and FHB3 observed were 34.25 litres (110th day), 34.25 litres (111th day), 55.5 litres (96th day) and 62.75 litres (46th day) respectively. As a result of the pretreatment strategy in FHB3, the hydrolysis stage (solubility of the substrate) is noticed to be reduced. This has resulted in the early beginning of the next phases and reduced the number of days required to achieve the peak value and increase in the volume of biogas generation. A progressive increase in biogas generation till peak value followed by progressive decline was observed in all reactors, which was also reported in the Babaei and Shayegan 2019 [22]. Stable readings of biogas generation for AB were observed from the 156th day, which indicated the start of the maturation phase. Reactors FHB1, FHB2 and FHB3 were converted into the aerobic process after complying with the criteria for conversion from the anaerobic process to the aerobic process after 129 days, 123 days and 111 days, respectively.

3.2 Cumulative Biogas Generation

The cumulative biogas generated in the reactors is presented in Fig. 3b. Cumulative biogas generation for AB is 2329.75 L (in 159 days), FHB1 is 2205.25 L (in 126 days), FHB2 is 3118.75 L (in 121 days), and FHB3 is 3461.5 L (in 111 days). The average daily biogas generation rate for reactor AB is 14.65 L /day, for FHB1 is 17.50 L /day, for FHB2 is 25.77 L/day and for FHB3 is 31.18 L /day. Reactor FHB3 has shown the highest biogas generation value of 3461.5 L and the highest biogas generation rate as well, depicting an accelerated degradation rate of 31.18 L/day because of the infused enhancement conditions resulting in a lowering of the hydrolysis phase, early start of the acidogenesis phase. Also, the strategies in FHB3 have inhibited the

conversion of OFMSW into some intermediate products and have accelerated the conversion to the end product which is biogas.

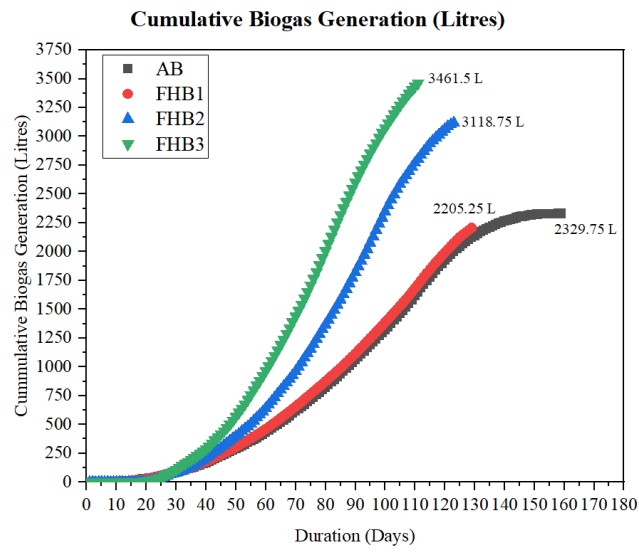


Fig. 3a Daily biogas generation with time

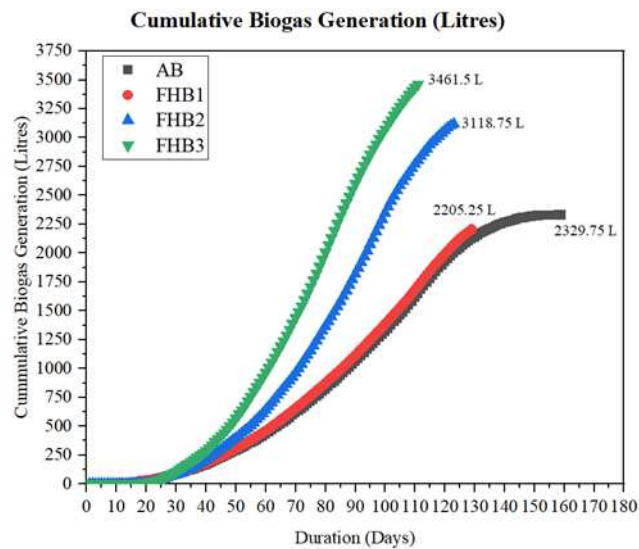


Fig. 3b Cumulative biogas generation with time

Table 2 depicts the time taken in the respective reactors to achieve the maximum biogas production rate, i.e., 241.56 L kg⁻¹ dry waste. The biogas production rate in the reactors FHB2 and FHB3 has shown a faster biogas production rate of 420.59 L kg⁻¹ volatile solids, which is higher than 202.8 L kg⁻¹ volatile solids [23] and 400 L kg⁻¹ volatile solids [8].

The achieved biogas production rate of 420.59 L kg⁻¹ of VS or 241.56 L kg⁻¹ of dry waste is greater than the biogas production rate achieved in similar studies [8, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33]. The flushed hybrid approach, which includes the use of enhancement techniques, has resulted in the achievement of a higher gas generation rate. The biogas generation rate achieved by FHB3 is 17.16 % more than that of the anaerobic bioreactor landfill. The increased biogas production will thus result in maximum extraction of the biogas and will result in the generation of more energy from the bioreactor landfill. The generation of more energy will indirectly help in improving the cost-economics of the bioreactor landfill, making it more economically viable.

Table No. 2 Biogas production rate

Biogas Production Rate (L kg ⁻¹ dry waste)	AB(Days)	FHB1	FHB2	FHB3
20	48	46	43	40
40	65	63	56	51
60	78	75	65	58
80	89	86	72	65
100	99	95	79	70
120	108	104	85	76
140	116	112	90	80
160	125	120	95	85
180	144	NA	100	90
200	NA	NA	105	96
220	NA	NA	112	102
240	NA	NA	122	111
Total Biogas produced at the end of anaerobic phase (L)	2329.75	2205.25	3118.75	3461.5
Average daily biogas generation (L)	14.65	17.09	25.44	31.18
Biogas production rate at the end of anaerobic phase				
(a) L Kg ⁻¹ dry waste	150.50	142.45	217.35	241.56
(b) L Kg ⁻¹ VS	357.32	355.68	412.18	420.59

3.2.1 Biogas Modelling

Both the Modified Gompertz Growth Model and Modified Logistic Model were used to predict the maximum values of the biogas yield in the reactors. The values of R^2 obtained are 0.99, suggesting that these models are well-fitted with the observed experimental results. Considering the Gompertz Growth Model, values of biogas yield potential predicted were 380.53 mL g VS⁻¹, 359.24 mL g VS⁻¹, 426.29 mL g VS⁻¹ and 428.88 mL g VS⁻¹, respectively, for reactors AB, FHB1, FHB2 and FHB3 respectively. The predicted values were 6.531 %, 1.046%, -3.466% and -1.959% higher than that of the experimental values in reactors AB, FHB1, FHB2 and FHB3, respectively.

Considering the Modified Logistic Model, the values of the biogas yield potential predicted were 368.30, 350.97, 413.70 mL g VS⁻¹ and 415.75 mL g VS⁻¹ for reactors AB, FHB1, FHB2 and FHB3, respectively. The predicted values were 3.108 %, -1.277 %, 0.393% and -1.163 % higher than that of the experimental values in reactors AB, FHB1, FHB2 and FHB3, respectively. The values of both methods are presented in Table 3.

Table No.3a Kinetic parameters of biogas yield estimated using the Gompertz Growth Model

Bioreactor	Retention time (RDR) (d)	Biogas yield potential (BGP) (mL g VS ⁻¹)	Maximal daily biogas yield (Rm) (mL g VS ⁻¹ d)	Correlation Coefficient (R ²)	Experimental Value (mL g VS ⁻¹)	Predicted Value (mL g VS ⁻¹)	% Difference in Expt. & predicted
AB	150	281.42	3.13	0.99	357.20	380.53	-6.531
FHB1	129	286.51	3.74	0.99	355.51	359.23	-1.046
FHB2	122	297.5	4.34	0.99	412.08	426.28	-3.446
FHB3	111	271.65	4.29	0.99	420.64	428.88	-1.959

Table No. 3b Kinetic parameters of biogas yield estimated using the Modified Logistic Model

Bioreactor	Retention time (RDR) (d)	Biogas yield potential (BGP) (mL g VS ⁻¹)	Maximal daily biogas yield (Rm) (mL g VS ⁻¹ d)	Correlation Coefficient (R ²)	Experimental Value (mL g VS ⁻¹)	Predicted Value (mL g VS ⁻¹)	% Difference in Expt. & predicted
AB	150	281.42	3.13	0.99	357.20	368.3	-3.108
FHB1	129	286.51	3.74	0.99	355.51	350.97	1.277
FHB2	122	297.5	4.34	0.99	412.08	413.7	-0.393
FHB3	111	271.65	4.29	0.99	420.64	415.75	1.163

3.3 Settlement

Settlement is attributed to the degradation in the reactors. Settlement values are represented in Fig. 3c. The early settlement in the reactors was noted to be in the range of 5-10 % and was attributed to the self-weight of the substrate. After the initial settlement, continuous settlement in the reactors was observed till the end of the anaerobic phase due to the degradation of the substrate in the reactors (duration and values). The percentage settlement in AB, FHB1, FHB2 and FHB3 at the end of the anaerobic process was 20.44 % in 156 days, 20% in 129 days, 24.44 % in 122 days and 28% in 108 days.

A higher settlement rate is attributed to the higher degradation rate. This confirms the cumulative effect of the enhancement parameters used in FHB3.

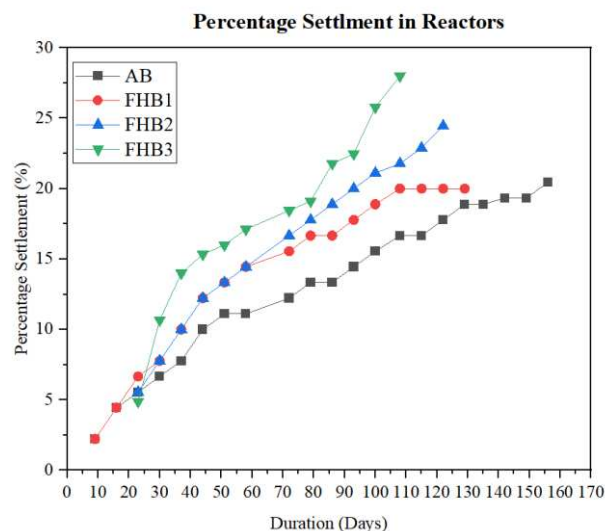


Fig. 3c Percentage settlement with time

3.4 pH

The variation in the pH is a function of the product formation by the acting microorganisms in the phases. Maintaining the targeted pH in the respective phases enhances the process of degradation of the substrate in the reactor. Observations of all the reactors depict the range of pH values between 5.5 and 8.19. The values of pH are represented in Fig. 4a. The average values considering all the reactors were noted in the range of 6.67 to 7.07, which is favourable for the anaerobic reactions [34]. The pH values of the leachate at the start of the anaerobic process for reactor AB, FHB1, FHB2 and FHB3 were 6.44, 6.13, 6.02 and 5.94. All reactors initially showed a decreasing trend in pH values relating to the reactors undergoing the hydrolysis and acidogenesis phase. The reduction in the pH for reactor AB, FHB1, FHB2 and FHB3 continued till the 79th day, 44th day, 37th day and 23rd day, respectively. Early drop in the pH value affirms the early end of the hydrolysis and early entry into the acidogenesis phase, which might have happened because of the pretreatment strategies used. Early rise of the pH in the reactors FHB2 and FHB3 was noted because of the adjustment of the pH of the leachate in the range of 7-7.5 before the leachate recirculation. After the initial drop in pH, the increase in pH was noted in all reactors, depicting the start of the acetogenesis and methanogenesis phase [35] and the same trend was also observed in other research [36,37,38]. The reactors with the addition of the media showed higher pH values (above 8.04) compared to the other reactors. Final pH values at the end of the anaerobic process for reactors AB, FHB1, FHB2 and FHB3 were 7.6, 7.7, 7.72 and 7.87, respectively. The neutral to slightly alkaline range of the pH in the bioreactor will assist in maintaining the required substrate treatment environment through reduction of corrosive and abrasive effects [35].

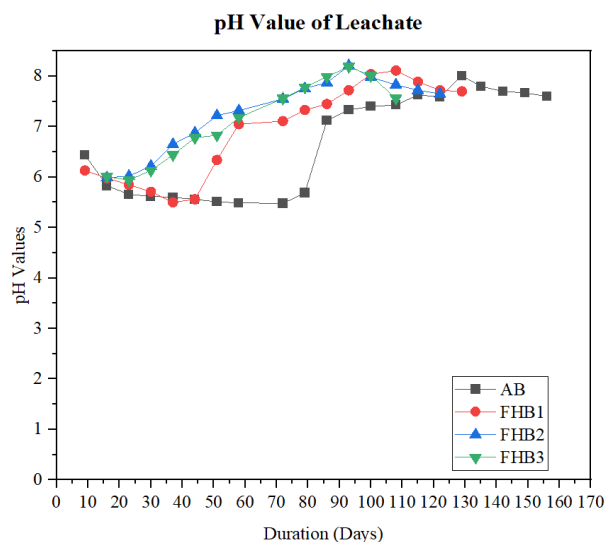


Fig. 4a pH variation with time

3.5 Chemical Oxygen Demand (COD)

COD values represent the oxygen requirement to degrade all the oxidizable material in the leachate. As the anaerobic reactions proceeded, the deficiency of oxygen increased the COD values. The COD values increased to achieve the peak value in each of the reactors and then decreased, which was also observed in other research [39, 40]. The values of COD are represented in Fig. 4b. Reactors AB, FHB1, FHB2 and FHB3 observed their peak COD value on the 72nd, 51st, 37th and 37th day, respectively. COD values decreased after attainment of the peak values. The percentage reduction in the COD values with respect to the peak value and the end value considering the anaerobic process for reactors AB, FHB1, FHB2 and FHB3 are 84.57% (in 156 days), 94.05% (in 129 days), 92.83% (in 122 days) and 94.55 % (in 108 days), respectively. Reactors AB, FHB1 and FHB2 have taken a longer time for the percentage reduction in COD values, suggesting the presence of higher organic content in leachate because of a relatively slower degradation rate than that of FHB3. Higher reduction of COD values can be attributed to the utilization of the organic matter from the leachate as well as the conversion of the organic matter to biogas.

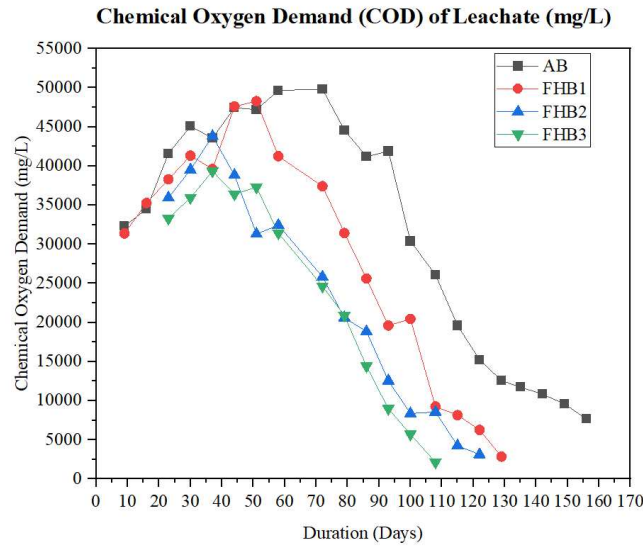


Fig. 4b COD variation with time

3.6 Biochemical Oxygen Demand (BOD₅)

BOD₅ values are a function of the quantity and quality of the organic matter in the reactor, and the leachate is used to ascertain the biodegradability of the leachate and for the identification of the degree of waste stabilization [41]. The values of BOD in reactors are represented in Fig. 4c. The peak values for the reactor AB, FHB1, FHB2 and FHB3 were noted on the 72nd day, 51st day, 37th day and 37th day, respectively. A decreasing trend of the values of the BOD₅ was observed for all the reactors. A slight increase in the BOD₅ compared to the previous values was also noted, but the decreasing trend then continued to progress. Considering the anaerobic process and with respect to the end values and peak values, the percentage BOD₅ reduction in the reactors AB, FHB1, FHB2 and FHB3 noted is 98.33 % (in 156 days), 99% (in 129 days), 98.41% (in 122 days) and 98.76% (in 108 days) respectively.

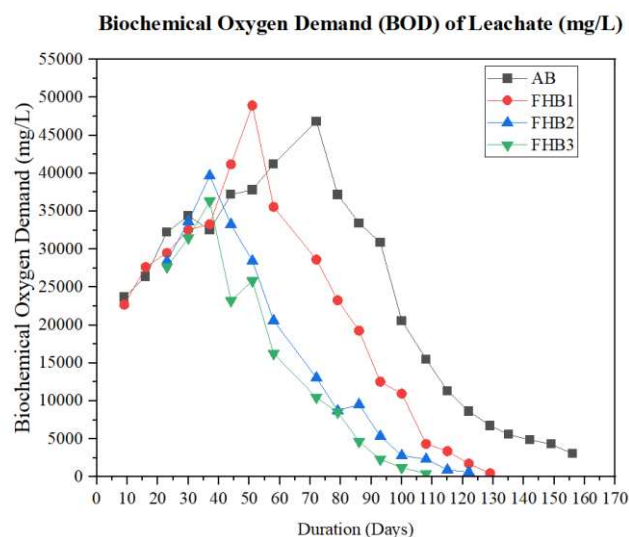


Fig. 4c 5 Day BOD Value with time

3.7 Electrical Conductivity (EC)

EC reflects the concentration of the ionic solute and is a measure of a solution's ability to convey electric current. The values of EC are represented in Fig. 4d. The initial values of the EC in mS/cm at the start for the reactors AB, FHB1, FHB2 and FHB3 were 15.1, 15.8, 14.8 and 13.1. The values of EC didn't follow any specific path during the anaerobic process in the reactors. Initially, the EC values in all the reactors were high. The EC values declined for some duration and gained nearly similar values [8]. The lowest EC in mS/cm noted for the reactors was 10.5 mS/cm, 13.2 mS/cm, 11.5 mS/cm and 10.3 mS/cm for reactors AB, FHB1, FHB2, FHB3 respectively. Regaining of similar values may be due to the flushing of the compounds in the reactor via leachate and then re-addition of these compounds back into the reactor as the leachate was recirculated. Compounds contributing to the EC in leachate are metals of lime, calcium, potassium, sodium, etc., with sulphates, chlorides, nitrites, etc., which are resultant of REDOX reactions in the reactor. The average values of the EC in the reactors were in the range of 11.53-14.59 mS/cm.

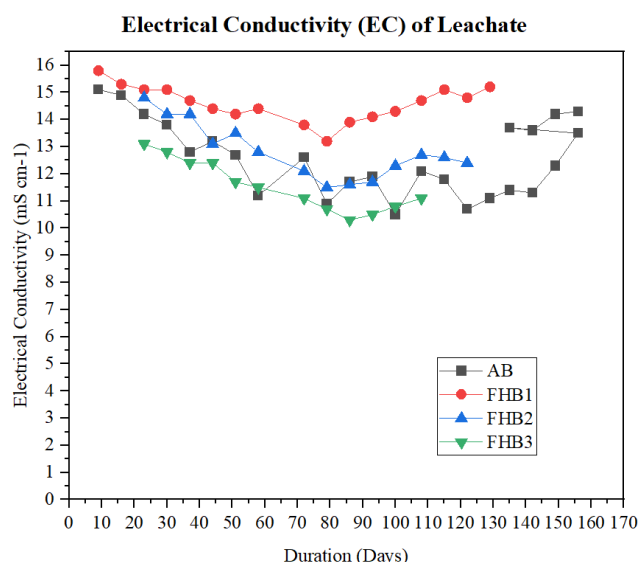


Fig. 4d Electrical conductivity variation with time

3.8 Oxidation Reduction Potential (ORP)

ORP checks the status of the biochemical degradation of the substrate and existence of redox conditions during the degradation process [42]. The ORP value of the leachate is very sensitive to the duration of the storage, and hence values were immediately measured after the sampling of the leachate was done. The values noted in the reactors are presented in Fig.4e. The average ORP values in the reactors were in the range of -135.90 to -143.42 mV, indicating that the ORP values were well within the range required for methanogenesis, i.e., -100 to -300mV [43, 34, 45]. Initial ORP values (in mV) observed in the reactors AB, FHB1, FHB2 and FHB3 were -32, -54, -154 and -133. Lower ORP values were noted in the reactors FHB2 and FHB3 where enhancement conditions prevailed. The final ORP values for reactor AB, FHB1, FHB2 and FHB3 noted were -112, -183, -195, -187. The initial decrease in the ORP values is associated with the decrease in the oxygen content in the reactors. As the microbial community disintegrates the organic substrate and converts it into methane, the EC value is found to decrease, indicating the shift of the acidogenesis phase to the methanogenesis phase.

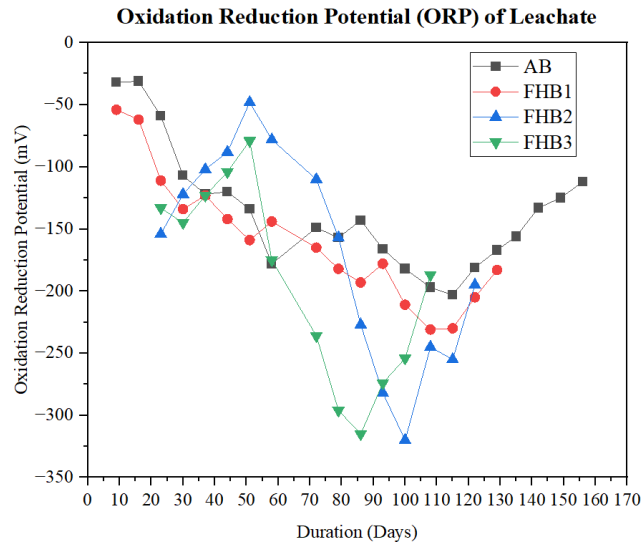


Fig. 4e Oxidation Reduction Potential variation with time

3.9 Identification of the Phases in the Reactors

The values of pH of leachate, COD of leachate and daily gas generation were studied to identify the approximate phase duration in the reactors. For reactor AB, the hydrolysis phase continued from the 1st to 44th day, acidogenesis phase continued from 45th to 86th day, the methanogenesis phase continued from 87th to 115th day, and the maturation phase was estimated to be from the 116th to 159th day. For reactor FHB1, it is estimated that the hydrolysis phase was between 1st and 37th day, acidogenesis phase between 38th and 79th day, methanogenesis phase from 80th to 129th day and further aerobic phase from 130th to 159th day. For reactor FHB2, the hydrolysis phase was estimated to be in between the 11th and 29th day, acidogenesis phase between the 30th and 79th day, methanogenesis between the 80th and 122nd day, and the aerobic phase started form 123th day till the 132nd day. For reactor FHB3, the hydrolysis phase is estimated between the 11th and 29th day, acidogenesis phase from the 30th to 58th day, the methanogenesis phase between the 59th and 108th day and the aerobic phase started from the 109th day till the 118th day.

3.10 Stabilization of the Organic Substrate

The initial and final characteristics of the OFMSW in the reactors AB, FHB1, FHB2 and FHB3 is presented in Table 4. The mass balance of the carbon was calculated on the basis of the dry weight and elemental analysis and is also presented in Table No. 4.

For mass balance, the initial carbon (C) was calculated from the values of the dry weight of waste and carbon percentage of the waste during sealing of the reactor. The values of C in CH₄ and C in CO₂ were calculated by

considering 56% methane and 37 % carbon dioxide in the generated biogas [46]. The value of C in COD was determined by the values of the leachate recirculated and the COD value of the leachate. The residual carbon in the reactor was calculated on the basis of the dry weight and carbon percentage of the residual waste. The percentage carbon recovery, as 67.73%, 77.77%, 97.71% and 83.29% in reactors AB, FHB1, FHB2 and FHB3, respectively. A similar kind of result was also observed by Mali et al., 2012 [8]. The unaccounted carbon can be associated with carbonate deposition within the drainage layers in the bioreactors, as the formation of the carbonates is pH-dependent, which governs the solid-liquid equilibrium in the bioreactors [19]. Also, the losses in the biogas during the collection and measurement process and also during the leachate recirculation may have led to unaccounted carbon.

Reduction in the values of C, H, N, and S was observed in the substrate due to utilization of these elements in the formation of the biogas consisting of methane, carbon dioxide, hydrogen disulphide, etc. Also, reduction in carbohydrates, proteins and lipids was observed as a result of the degradation process that they underwent.

Table No. 4 Initial and Final Characteristics of the OFMSW in the bioreactors

Parameters	AB		FHB1		FHB2		FHB3	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Dry waste, Kg	15.48	7.59	15.48	8.42	14.28	6.19	14.33	4.81
Moisture content, %	31.2	41.5	31.2	41.44	33.02	42.34	31.27	40.77
C^a	43.9	17.66	43.05	11.59	43.05	21.49	44.09	10.3
H^a	6.61	3.52	6.76	2.63	6.76	4.02	6.34	2.52
N^a	3.27	1.28	2.04	0.86	2.04	1.63	2.43	0.72
S^a	0.18	0.22	0.32	0.17	0.32	0	0.35	0.15
Carbohydrates^b	24.85	19.45	24.85	16.31	21.38	4.39	17.16	1.19
Proteins^b	10.99	4.62	10.99	3.82	8.24	4.58	14.17	5
Fats^b	6.21	2.09	6.21	1.58	3.74	1.33	10.13	1.22

^a As percentage dry weight; ^b As gm/kg of dry waste

C, H, N and S are among the building blocks of the organic matter. Initial percentages of the C, H, N and S get reduced as the degradation process continues. The complex chains of CHNS break as the anaerobic process continues its transformation from hydrolysis, acidogenesis and methanogenesis and simpler compounds are formed. The analysis of OFMSW for CHNS was done at the various instances: (a) Fresh OFMSW from Moshi landfill (Raw OFMSW) of reactors AB, FHB1, FHB2 and FHB3; (b) Pre-aerated OFMSW mixed with aerobic culture of reactors FHB2 and FHB3; (c) Substrate during sealing of the reactors for reactors AB, FHB1, FHB2 and FHB3; (d) Substrate after the anaerobic process for reactors AB, FHB1, FHB2 and FHB3 and (e) Substrate after the aerobic process for reactors FHB2 and FHB3. The sample in all these cases was collected after mixing the substrate properly. The mixed substrate was divided in approximate four portions, and samples were again collected from these four portions and were again mixed for getting the representative sample. The carbon reduction was considered to be an important parameter as it confirms the degradation of the organic substrate happening inside the reactors. The total carbon reduction for reactors AB, FHB1, FHB2 and FHB3 was 61.27%, 73.07%, 51.42% and 75.73%.

Proteins, fats and carbohydrates are biochemical molecules made of C, H, N, S, and Oxygen (O). These are the complex chains of CHONS which disintegrate in the hydrolysis phase to form less complex compounds like fatty acids, further into acetic acids in acidogenesis and further into methane in the methanogenesis phase. The analysis of proteins, fats and carbohydrates was done at various instances as enlisted: (a) Fresh OFMSW from Moshi landfill (Raw OFMSW) of reactors AB, FHB1, FHB2 and FHB3; (b) Pre-aerated OFMSW mixed with aerobic culture of reactors FHB2 and FHB3; (c) Substrate during sealing of the reactors for reactors AB, FHB1, FHB2 and FHB3 (d) Substrate after the anaerobic process for reactors AB, FHB1, FHB2 and FHB3 and (e) Substrate after the aerobic process for reactors FHB2 and FHB3. The sample in all these cases was collected after mixing the substrate properly. The mixed substrate was divided in approximate four portions, and samples were again collected from these four portions and were again mixed for getting the representative sample. For reactor AB, the content of proteins, fats and carbohydrates was reduced by 57.96 %, 67.63%, and 21.73 %. For reactor FHB1, the content of proteins, fats and carbohydrates was reduced by 65.24 %, 74.55%, and 34.36 %. For reactor FHB2, the content of proteins, fats and carbohydrates was reduced by 68.34 %, 86.84% and 90.08 %. For reactor FHB3, the content of proteins, fats and carbohydrates was reduced by 69.36 %, 89.62 % and 96.85 %. The reduction in proteins, fats and carbohydrates suggests the degradation of the organic substrate in each of the reactors and their quantities depict the extent of the degradation undergone.

4. Effect of the enhancement parameters on the process

4.1 Effect of Aeration

Substrate in reactors FHB2 and FHB3 were initially aerated before starting the anaerobic process as part of the pretreatment. Also, as a part of the proposed hybrid approach, these reactors were aerated after the anaerobic process. The aeration strategy, however, remained the same. Reactor FHB2 was aerated continuously for 7 hrs. at the rate of 33 lpm, and FHB3 was aerated intermittently for 2.5 hrs. and 0.5 hrs. for a total duration of 7 hrs. at the rate of 33 lpm. Intermittent aeration has resulted in the enhancement of the hydrolysis stage in the FHB3. This has resulted in an increased rate of the anaerobic process by 20.99 % and enhanced the rate of production of biogas from the reactor by 1.6%. Aeration as a strategy for pretreatment has helped in retarding the inhibition process due to accumulation of volatile fatty acids, reduction in the phase duration of acidogenesis and methanogenesis, providing a favourable growth environment for the microorganisms and the acceleration of the stabilization.

The intermittent aeration approach has contributed significantly in the post-anaerobic stage as well. The complex organic substrate that has shown resistance to the anaerobic reaction has degraded faster in the aeration process. Comparing the results of FHB2 and FHB3, percentage carbon reduction was 4.46 % higher in FHB3. Considerable reduction of proteins, fats and carbohydrates has been noted post-aeration, which has resulted in the early stabilization of the substrate. However, excess aeration will degrade the excess organic matter, which could have resulted in biogas, resulting in loss in biogas volume [47]. Insufficient aeration may also lead to excessive butyric-type acidification, which may inhibit the anaerobic process from starting [48]. The effect of the aeration process on the retardation of the inhibition due to the formation of volatile fatty acids in the anaerobic digestion was studied in earlier research. [49,50].

4.2 Effect of addition of microbial culture

Aerobic microbial culture was added as part of the pretreatment during the aeration of the substrate. The addition resulted in the development of the aerobes, which assisted the hydrolytic bacteria in breaking down the complex chain compounds at a faster rate than usual. This also further helped for the acidogens to process the substrate faster and develop acids. In the post-methanogenesis phase, the addition of the aerobic inoculum helped to develop the aerobes at a faster rate and accelerate the rate of degradation. The aerobic culture also helped to degrade the slowly degrading compounds faster, reducing the overall stabilization time of the substrate.

4.3 Effect of mixing of media in the substrate

Plastic media having larger surface area were mixed with the substrate in the reactors FHB2 and FHB3 in the proportion of 6.25 % of the total substrate volume in the reactor. The strategy to do so was to increase the availability of the surface area for microbial reactions and also increase the contact between the microbes and substrate. The plastic media have helped reactor FHB2 and FHB3 to increase the rate of generation of the biogas in these reactors, resulting in enhanced degradation rate and reduction in total stabilization time.

4.4 Effect of leachate recirculation and leachate recirculation rate

Reactors AB, FHB1 and FHB2 had the same recirculation rate throughout the process. However, a varied rate of leachate recirculation was adopted for the reactor FHB3. A higher recirculation rate at the start and then a lesser and then further reduction in the leachate recirculation rate were adopted, which helped in providing the essential environment and nutrients to microbes. A higher recirculation rate at the start helped in faster solubilization of the substrate, and draining of the unwanted parameters happened, resulting in a reduction of chances of inhibition. Distribution of the leachate through the entire mass would have helped dispersal of the necessary nutrients and moisture, accelerating the organic matter degradation rate [40].

4.5 Effect of addition of Anaerobically Digested Sludge

Addition of STP's anaerobically digested sludge with leachate recirculation in FHB2 and FHB3 has increased the microbial population inside the reactor. Also, the supply of methanogens through the sludge resulted in early gain of peak biogas generation, which also suggests a higher degradation rate. The enhanced degradation rate has resulted in a reduction in the stabilization time for these reactors. Earlier studies by the researchers have stated that the leachate recirculation with the adjustment of the pH and seeding of the anaerobically digested sludge have increased the rate of stabilization of the organic fraction in the leachate and have increased the quantity of biogas generation [45, 51, 52].

4.6 Effect of the Flushed Hybrid Bioreactor Concept

In comparison to the conventional anaerobic bioreactor landfill technology, the flushed hybrid bioreactor has better performance, which is evident from the results of FHB3. The larger time requirement for stabilization of the organic substrate in the reactor because of the rate-limiting maturation phase has been reduced. Considering reactor AB and FHB1, the stabilization time was reduced by 10.89 % (without usage of any enhancement technique). Though reactor AB was operated anaerobically for 159 days and reactor FHB1 was operated

anaerobically for 129 days, both the reactor has shown approximately the same biogas generation rate of 355.43 per kg of TVS, suggesting that very little gas is generated in the maturation phase. Also, the percentage reduction in the carbon content in FHB1 is 19.25 % more than AB. The percentage carbohydrate reduction in the reactor FHB1 was noted to be 58.12 % higher than that of AB. Comparing the results of reactor FHB3, where enhanced conditions were used with AB, FHB3 has its stabilization time 25.39% less, biogas generation rate 17.61 % higher, and percentage carbon reduction 23.6% higher.

4.7 Sensitivity Analysis

The sensitivity analysis for the parameters leachate recirculation rate, addition of the anaerobic sludge, addition of the plastic media and aeration with addition of the aerobic culture was carried out to investigate the effect of these parameters on biogas generation rate (BGR) and air space recovery (ASR). The sensitivity analysis was performed on the performance of two reactors, FHB2 and FHB3. The results of FHB2 and FHB3 are presented in Table 5.

Considering the operating parameters in FHB2, leachate recirculation was found to be contributing more sensitively to BGR and ASR. The other sensitive parameters in the sequence of more sensitivity are addition of plastic media, anaerobic sludge addition and continuous aeration with mixing of aerobic culture. Considering the operating parameters of the FHB3, the parameters in order of more sensitivity are varied leachate recirculation rate, addition of plastic media, addition of the anaerobic sludge and intermittent aeration with addition of the aerobic culture.

5. Conclusion

The study showed that the flushed hybrid bioreactor landfill approach has helped in enhanced reduction of carbon, carbohydrates, proteins and fats, which has directly reduced the stabilization time of the organic substrate by increasing the rate of biogas production rate by 17.61 %. The reduction in the stabilization time of the OFMSW observed was 26.16 % with respect to the conventional anaerobic bioreactor landfill. The combination of parameters that helped increase the rate of biogas production is shredding, intermittent aeration ($1\text{m}^3\text{ day}^{-1}\text{ kg}^{-1}$ of dry solids), and addition of media (6.25% of substrate volume), varying leachate recirculation rate (9% of the v/v of OFMSW), addition of anaerobic sludge during the leachate recirculation (0.42% v/v of the OFMSW) and addition of the plastic media (6.25% v/v of OFMSW).

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Declarations

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Data Availability Statement

The datasets generated during and/or analysed during the current study are not publicly available because they form part of an ongoing research programme and contain unpublished experimental data but are available from the corresponding author on reasonable request