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Raw and treated MSW stabilisation in laboratory scale bioreactor landfills

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Abstract

Bioreactor landfills (BLFs) are an effective and sustainable method for waste stabilisation. The process involves controlled recirculation of leachate back into the landfill, enhancing the biodegradation of municipal solid waste and thus increasing its efficiency. To manage large volumes of waste in a landfill, the waste undergoes pre-treatment, which has shown to yield superior results for biodegradation in a shorter time frame compared to untreated waste. This is because pre-treatment leads to lower biogas production and leachate pollution potential. This study focuses on two anaerobic bioreactors out of which one is filled with untreated municipal solid waste (MSW) and the other with windrow compost as treated MSW. The aim is to provide a comparative analysis to examine the effect of treatment on biodegradation and stabilisation in both untreated and treated MSWs. During the ongoing study period of about 10 months, data from the initial 3 months (13 weeks) is shared. Treated waste has shown better results compared to untreated MSW due to its lower pollution potential. It is hypothesized that treated waste will yield superior results throughout the entire study period in terms of environmental sustainability. Stabilisation of waste matrix in treated MSW is expected to be done in almost half duration as compared to that of raw MSW.

Keywords: Municipal solid waste, Windrow compost, biodegradation, Raw MSW, Treated MSW.

Introduction

World Bank data reveals that approximately 2.01 billion tonnes of municipal solid waste (MSW) is generated annually worldwide. Shockingly, at least 33 percent of this waste is not managed in an environmentally safe or sustainable manner[1]. In India, the situation is particularly noteworthy. The country produces roughly 160,038.9 tonnes of MSW daily. Of this, about 152,749.5 tonnes is collected, 79,956.3 tonnes is treated, and the remaining 29,427.2 tonnes ends up in landfills[2-4].

Bioreactor landfills, a type of waste management system, operate quite differently from traditional landfills. In these systems, known as municipal solid waste landfills with leachate recirculation, leachate is intentionally reintroduced in controlled amounts to enhance biodegradation. This process aids bacteria in breaking down the waste into smaller pieces. By adding both liquid and air, microbial processes are enhanced, leading to accelerated waste degradation and stabilization. It’s worth noting that the Kanjurmarg bioreactor landfill in Mumbai is India’s only bioreactor landfill, highlighting the need for wider implementation of this technology[5]. Bioreactor landfills are favored in waste management as they achieve waste stabilization in a much shorter time compared to conventional landfills, which can take years or even decades to completely stabilize wastes and yield maximum results. Bioreactor landfills reduce pollution potential in a limited time as wastes often undergo pre-treatment in anaerobic bioreactors followed by aerobic processes, primarily composting[6-10].

The method of anaerobic biodegradation, which involves the recirculation of leachate in regulated amounts, enhances the quality of leachate within a bioreactor. This, in turn, leads to a decrease in the costs associated with leachate disposal. While there are several types of bioreactor landfills, the underlying philosophy of operations and maintenance remains the same. As an alternative to traditional landfills, BLFs actively recirculate leachate through the waste matrix to enhance bio-stabilization of wastes while simultaneously collecting usable energy output[11-13].

The risks posed by these engineered systems include human safety and environmental health, which is why various engineering techniques are implemented to prevent disasters such as leachate leakages contaminating the groundwater table and waste mass destabilization from settlement, leachate, and gas pressures. These systems are largely considered experimental, and the body of knowledge governing bioreactor landfill operations continues to expand[14-17].

It has been observed that anaerobic bioreactor landfills loaded with raw MSWs face challenges with delayed methanogenesis because raw MSWs contain a high amount of organics, which create a barrier to methane-forming microbes due to the acidic environment[18]. The raw MSWs contain organics and during the hydrolysis and acidogenic phase, volatile fatty acids (VFAs) and long chain fatty acids accumulate within the system during anaerobic biodegradation, causing a reduction in pH and creating an environment where methane formers cannot survive.

This enhanced biodegradation results in a quicker and more effective stabilization of landfill waste compared to traditional landfills, which can take years or even decades to fully stabilize the waste. The lag phase is observed in many anaerobic bioreactors loaded with raw MSWs. To overcome this problem of delayed methanogenesis, it becomes necessary to treat the wastes before finally landfilling them[19-21]. Pre-treatment of wastes can be Mechanical-biological (MBT) involving shredding, mechanical volume reduction, thermal and biological processes like composting etc[22]. As wastes are pre-treated, the polluting potential is reduced and maximum yield in terms of gassing and bioenergy is attained prior to landfilling[23-25]. Gassing is observed to be more in raw wastes due to high organic content[26,27]. Also, due to mechanical volume reduction, large quantities of wastes can be placed in landfills, thereby saving large space and accommodation in landfill[28-30].

Materials and Methodology

Waste samples: In this investigation, about 25 kgs of both raw MSW as well as compost (treated MSW) were taken from A to Z waste processing plant near Sasni gate, Mathura Road, Aligarh. This plant is based on windrow composting which takes about 6 weeks for complete composting.

Particle size distribution of waste samples: Representative samples weighing 25 kilograms each from both raw MSW and treated MSW were taken for this study. To obtain these samples, quartering and coning method on the bulk sample was employed. Samples were then sieved through specific-sized sieves as per Indian standards. The resulting particle size distribution is depicted in Figure-1. Notably, the raw MSW showed a greater mass retention percentage in the 80 mm and 20 mm sieves

Waste composition: Each size fraction of both categories of wastes were sorted manually into different components expressed as dry weight percentages having average size of 35-50 mm classified as food wastes, plastic, paper etc. The unidentified category represents a mix of different components that could not be separated or segregated.

Table-1 gives the breakdown of different components of waste and their dry percentages after manual sorting.

Substrate and Inoculum in synthetic leachate: To enhance the anaerobic bacterial decomposition, a synthetic leachate recipe was formulated as shown in Table-2. This recipe included essential minerals and trace elements, as outlined by a study[26]. The study focused on treated wastes and yielded promising results, which were found to be somewhat similar to those obtained in this study.

Anaerobic sludge 10% (v/v**)** as inoculum was mixed in the synthetic leachate prepared for achieving rapid biodegradation in anaerobic media[18,26.]

Table-1: Composition of Raw and treated MSW analysed in laboratory expressed as dry weight percentages.

Raw MSW		Treated MSW	
Component	Percentage	Component	Percentage
Food Waste	42	Paper	1
Paper	15	Hard Plastic Soft Plastic	5 5
Plastic	16	Wood	1.5
Rubber	0.7	Textile	1.4
Metal	1.8	Rubber	0.1
Inert	17	Ceramics	5
Glass	2	Stone	14
Textile	0.5	Glass	7
Unidentified	5	Unidentified	60
Total	100	Total	100

Table-2: Substrate recipe.

Chemical Reagent as substrate	Chemical formula	Concentration (mg/l)
Potassium Phosphate Dibasic Trihydrate	($K_2HPO_4.3H_2O$)	330
Ammonium Chloride	(NH_4Cl)	280
Magnesium Sulphate heptahydrate	($MgSO_4.7H_2O$)	100
Calcium Chloride Dihydrate	($CaCl_2.2H_2O$)	10
Iron(II) Chloride Tetrahydrate	($FeCl_2.4H_2O$)	2
Boric Acid	(H_3BO_3)	0.05
Zinc Chloride	($ZnCl_2$)	0.05
Ethyl Diamine Tetra Acetic Acid	(EDTA)	1
Manganese Chloride Tetrahydrate	($MnCl_2.4H_2O$)	0.5
Copper Chloride Tetrahydrate	($CuCl_2.2H_2O$)	0.038
Ammonium Molybdate Tetrahydrate	($(NH_4)6MoO_{24}.4H_2O$)	0.05
Aluminum Chloride Hexahydrate	($AlCl_2.6H_2O$)	0.09
Nickel Chloride Hexahydrate	($NiCl_2.6H_2O$)	0.142
Disodium selenite hydrate	($Na_2SeO_3.5\ H_2O$)	0.164
Cobalt Chloride Hexahydrate	($CoCl_2.6H_2O$)	2

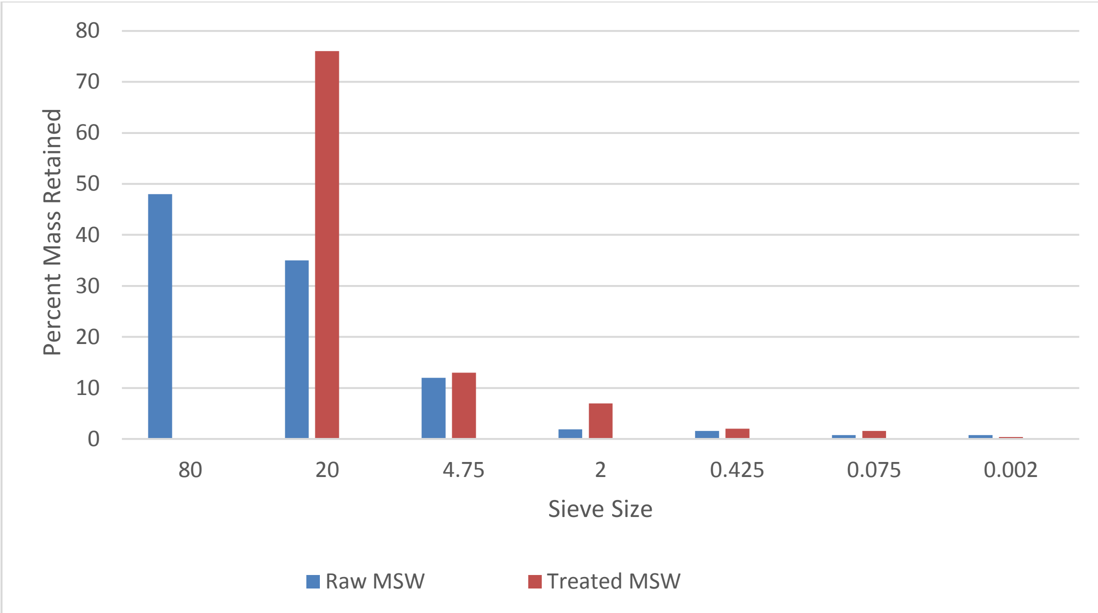

Figure-1: Particle size distribution of raw and treated MSW.

Simulated Bioreactor landfill Setup and operational procedure: The complete setup of two bioreactors loaded with raw and treated MSW has been represented in Figure-2. Raw fresh mixed municipal solid waste (MSW) and compost (achieved through Windrow composting) were each oven-dried at 70°C for 48 hours. Waste characterization was conducted to ensure that representative samples accurately represented the entire waste volume. The components of MSW were shredded to approximately 35mm uniform size. In each bioreactor (R1- raw and R2 - treated), a 10cm layer of gravel (10-12 mm) was placed at the bottom for filtration and drainage of leachate[6,10,11].

A 6-inch diameter Perspex glass membrane with 5mm perforations was positioned in both reactors. Approximately 5kg of representative samples (compost and raw) were layered in both R1 and R2, compacted thoroughly using a rammer. The densities of raw and treated MSWs were approximately 560 kg/m³ and 629kg/m³, respectively. The filling depth in R1 and R2 was approximately 50.5cm and 45cm, respectively. At the top of the waste layers in both reactors, a 5cm thick layer of gravel (10-12mm) was placed, separated by a Perspex glass membrane. This arrangement prevented clogging of recirculated leachate and ensured proper distribution from the top port as shown in Figure-2 both bioreactors were connected to peristaltic pumps (MICLINS PP30EX) for leachate recirculation. Adequate leachate pond level was maintained. A 3-way valve facilitated sample collection in the upper loop of each bioreactor setup. Synthetic leachate (20 liters, 10 liters per reactor) was prepared following a specific recipe[26].

Anaerobic sludge (10% by volume of leachate) was mixed into the prepared synthetic leachate[26].

The prepared leachate was poured into each reactor from bottom to top, filling it until it reached a few cm below the upper recirculation port, forming a stable leachate pond. Both reactors were properly sealed to prevent air entrainment and promote anaerobic environment. Tedlar bags for biogas collection were fixed thoroughly on the port fixed on the lid of both reactors. Leachate was recirculated from day 1 @ 1 litre per hour via MICLINS PP30 EX peristaltic pumps for 12 hours on a daily basis for 300 days at a minimum temperature of 26°C[11,15,16]. Heater was used in cold weather to maintain the optimum temperature range (26-35^{0}C). Synthetic leachate was also re-injected in order to compensate for the volume of sample grabbed from the reactor for analysis. Leachate parameters were analysed on a weekly basis. Quantity of biogas produced was measured daily after collecting it in tedlar bags.

Analytical Procedures: Leachate: The pH was measured using a HACH HQ30d digital pH meter. Temperature was recorded with a lab thermometer. To maintain temperatures between 26°C to 35°C during cold weather, a Double Rod Heater (2000 W) was employed. Chemical Oxygen Demand (COD) was determined using closed reflux method, following the guidelines from the “Standard Methods for Examination of Water and Wastewater. Volatile Fatty Acids (VFA) were analysed using the NUCON 5700 Gas Chromatograph equipped with a Flame Ionization Detector (FID). Ammonia Nitrogen (NH_3-N) levels were assessed using the HACH Direct ISE method 10001. This involved utilizing the Intellical ISENH3181 ammonia ISE probe and ammonia ISA powder pillows mixed into the samples.

Biogas: Biogas was collected on a daily basis in gas sampling bags and volume of biogas collected was measured by water-displacement method.

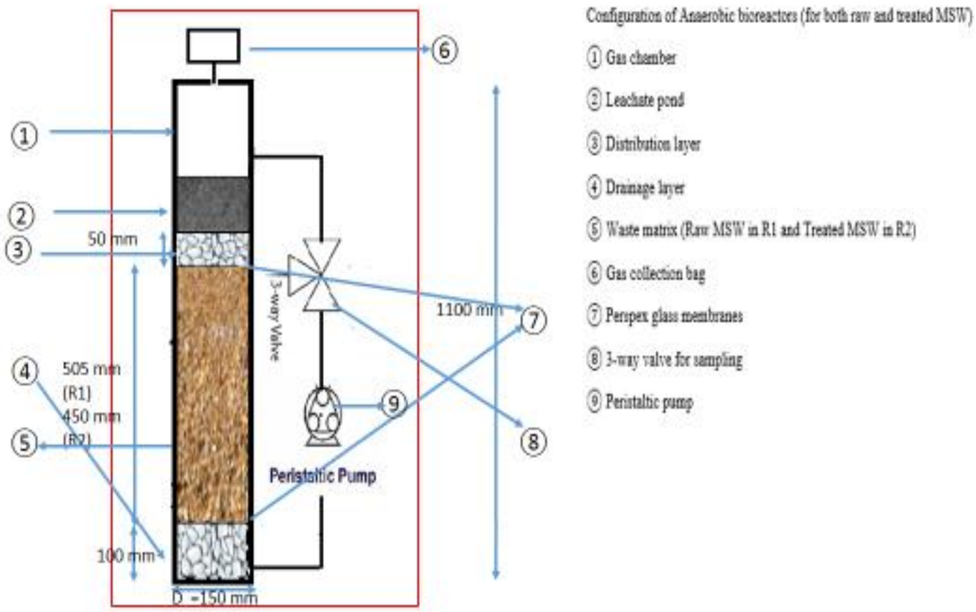

Figure-2: Schematic representation of simulated landfill bioreactor[8,11,21].

Results and Discussion

The major outcomes are being discussed below separately for both leachate quality and biogas. Leachate quality: The polluting potential of leachate is very low in case of windrow compost[14,23,25]. This is due to the fact that due to pre-treatment, the VFA is reduced and pH rises at a rapid pace giving way for methanogenesis and stabilisation process[16,18,28]. The pH of the leachate from raw municipal solid waste (MSW) was initially below 6 during the first 2 weeks. Subsequently, there was a gradual increase, and by week 5, it exceeded 6.8 due to the onset of methanogenesis as shown in Figure-3. In the treated MSW leachate, the pH remained above 6 and rose above 7.6 in the 2^{nd} week as gassing began[6,8]. pH of raw MSW leachate ranged between 6.45 to 7.42 in case of some previous studies[22].

As shown in Figure-4, the Chemical Oxygen Demand (COD) of the leachate increased steadily until week 5 in reactor R1, reaching a peak value till week 4 [9,14]. Afterwards, it declined due to the commencement of gassing. In reactor R2, the maximum COD value observed was around 2,900mg/l, followed by a decrease after one week. The COD concentration increases due to unavailability of oxygen in anaerobic media[28]. By week 13, COD in reactor R1 decreased to about 6,400mg/l, while in reactor R2, it reached approximately 450mg/l[10,12]. The maximum concentration of Volatile Fatty Acids (VFA) in reactor R1 was approximately 12,000mg/l similar to what has been seen in the case of consolidated anaerobic reactors[11,12,], whereas in reactor R2, it was around 800mg/l. VFA levels declined in reactor R1 after week 5 due to gassing, reaching about 4,300mg/l by week 13. In R2, VFA decreased to approximately 45mg/l during the same period as can be seen in Figure-5 and compared by few studies[8,10,24].

In Figure-6, Ammonia Nitrogen (NH3-N) in reactor R1 gradually increased due to the anaerobic environment, reaching about 650 mg/l by week 13. In R2, a lower trend was observed, starting from approximately 100mg/l and reaching around 160mg/l. The ammonia concentration remains on the higher side and accumulated for a longer time in case of both raw and treated MSW due to anaerobic environment as be seen from various studies like[8,10,25,27]. From the previous studies conducted like[6,8,12] it is seen that parameters are interconnected: the rise in pH above 6.5 marked the onset of the gassing phase in both reactors. VFA and COD exhibited similar trends, with slight differences. As methane-forming microorganisms consumed VFA and utilized COD, both parameters eventually declined. NH_3-N accumulated initially and then decreased after the methanogenic phase, showing minor fluctuations[10-28] Speculatively, in the next 3-4 months, COD and VFA levels in the raw MSW bioreactor will likely be below 1,000mg/l. NH_3-N concentrations are expected to fall within the range of 300-400 mg/l for reactor R1 and 50-100mg/l for R2[26,27].

Biogas: Biogas production commences just as the pH rises above 6.5 and VFA drops because high acidity is a barrier for onset of methanogenesis as can be noted from literature[13,22,27]. Reactor R1 loaded with raw MSW faced lag period of about 5 weeks due to the prolonged acidogenic phase caused by the accumulation of VFAs as raw MSW has about 40% food wastes (organics). The gassing quantity is higher in case of raw wastes due to high amount of biodegradables like in Ivanova[9,12]. Logically in case of treated wastes[25,28,30] the organics are degraded to a large extent and gassing observed is low in terms of quantity and the advantage is that there is virtually no acidogenic phase or if it is there then it will last for a week or 10 days.

By the end of week 13 it is seen that the trend is rising and it is expected that maximum gassing per day will be achieved in 14 or 15 weeks. Low pH caused inhibition to the methanogenic process. The treated MSW reactor R2 on the other hand faced very short duration of acidogenic phase of about 7 days and then methanogenic phase commenced. Gassing commenced after about one week and reached a maximum in about 25-30 days for German MBT[10]. Total period of gassing expected in case of R1 is about 4 months.

Gassing is almost complete in reactor R2 till 91 days and it is expected that very little amount of gas per day may continue till approximately 120 days. The trend of biogas production in both wastes can be seen in Figure-7. The lower polluting potential in case of treated wastes makes it an environmentally sustainable as well as safe option to be disposed in bioreactor landfill as it degrades at a double pace as compared to raw wastes and there are minimum chances of hazards in surrounding soil as well as groundwater.

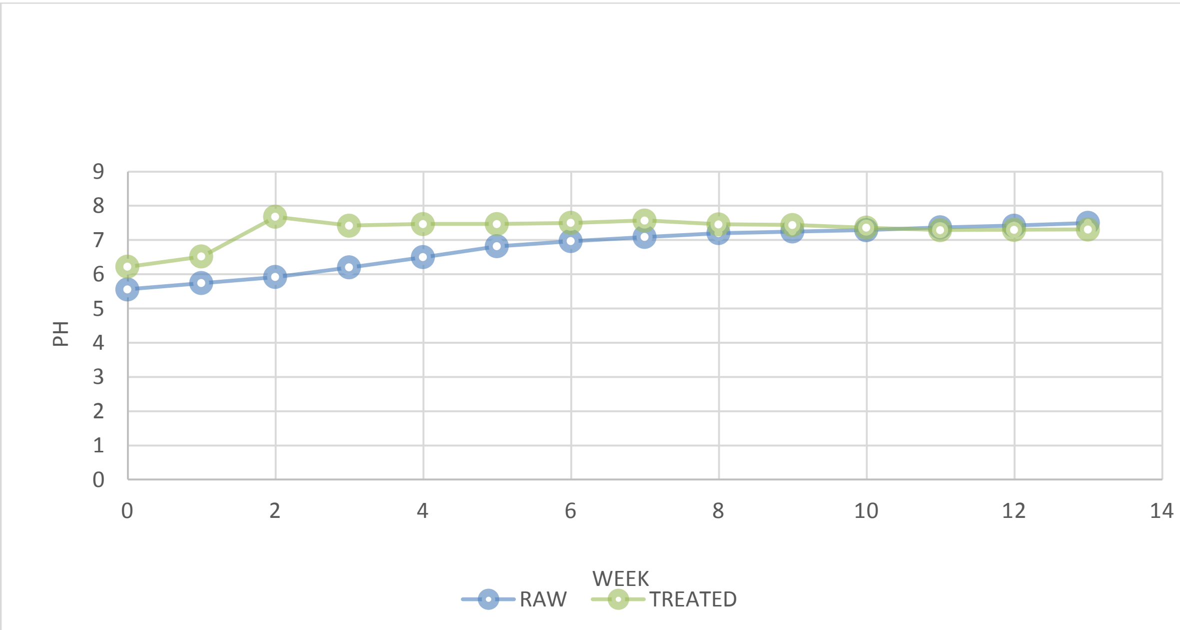

Figure-3: Leachate pH in raw and treated MSW.

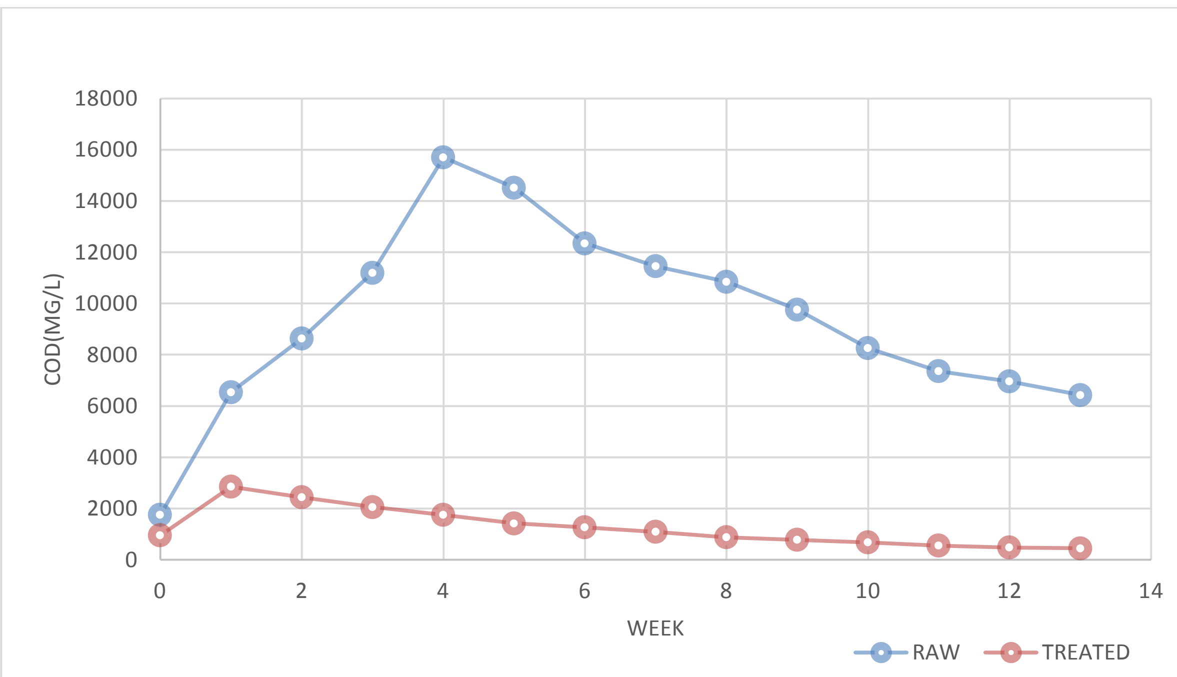

Figure-4: Leachate COD in raw and treated MSW.

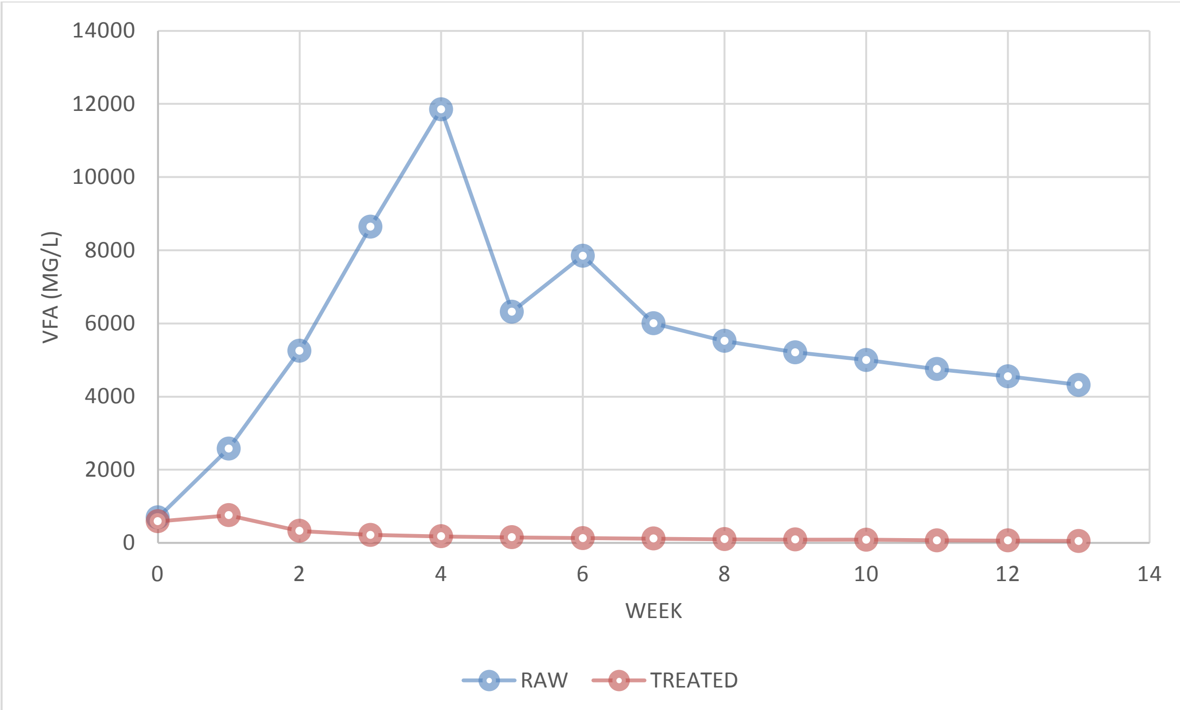

Figure-5: Leachate VFA in raw and treated MSW.

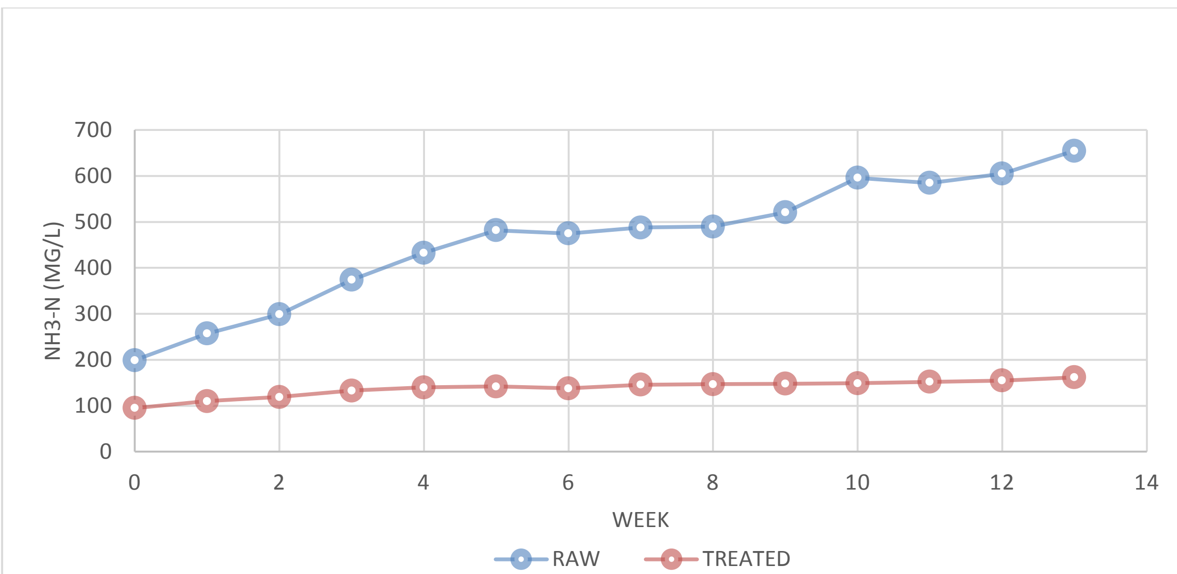

Figure-6: Leachate Ammonia nitrogen in raw and treated MSW.

Conclusions

The leachate characteristics and gassing potential of both raw municipal solid waste (MSW) and windrow compost were analysed for selected parameters. The treated MSW exhibited significantly better results, as expected. This improvement can be attributed to lower organic content and the effective pre-treatment achieved through aerobic decomposition using the windrow composting method. In terms of biogas production, the treated MSW reached its maximum volume by week 7, followed by a decline until week 13, where gassing was minimal. For raw MSW, it is anticipated that biogas production will continue to rise and reach a peak around week 14 or 15, given the higher gassing potential associated with raw MSWs. The organic strength of leachate from raw MSW is higher compared to that of treated MSW (windrow compost). Notably, the leachate from reactor R2 (treated MSW) has lower polluting potential compared to reactor R1 (raw MSW).

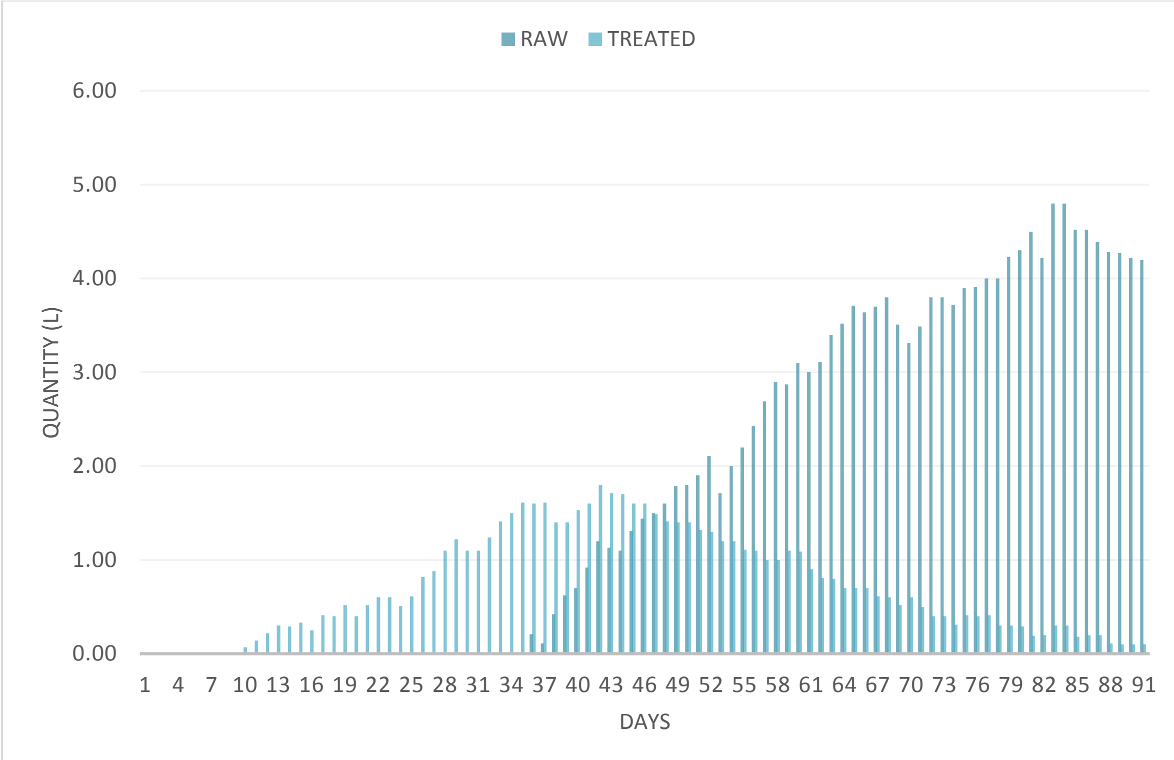

Figure-7: Daily biogas production for raw and treated MSW.

Predictions: It is predicted that the reactor R2 with treated wastes will give promising results as can been seen from the graphs and raw MSW reactor R1 will have higher values of leachate parameters and more biogas will be produced in R1 for about 2 more months. As far as the obtained results are concerned, it can be said that treated waste i.e. windrow compost in this case shows lower polluting potential as compared to raw waste as can be seen from the COD and VFA graphs. It is expected from relevant literature and on logical and scientific basis that windrow compost will achieve much quicker stabilisation in almost half time (~1/2) i.e. 50% as compared to raw waste due to initial treatment being given.

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