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Optimization of Anaerobic Co-Digestion of Mess Food Waste with Parthenium hysterophorus for Improved Biogas Yield

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Abstract

Mess food waste is an ever-present issue in institutional & hostel dining facilities. The increasing generation of mess food Waste can cause serious public health and environmental risks if it is improperly handled. Anaerobic digestion technology for biogas production through many organic the topic of substrates has garnered global attention. because of It's economic viability & simplicity of use. The potential of pretreatment parthenium was assessed in this investigation hysterophorus weeds as a Mixed feedstocks for the Mixed substrate digestion of mess food leftovers laboratory-scale anaerobic digesters operated at varying feedstock ratios (0:100, 30:70, 70:30, 30:70, 70:30, & 100:0 on a Total solid bases) For biogas generation, the efficiency of the anaerobic digestion process was analyzed based on Chemical oxygen demand (COD), carbon-to-nitrogen ratio, total level of solids and pH, & biogas yield capacity. The findings revealed that the maximum rate of biogas generation (558 mL L^{-1} d^{-1}) & total biogas production (5422 mL L^{-1}) were Obtained in the PCP2 co-digestion reactor, containing 70% mess food waste & 30% pr-treated Parthenium hysterophorus under static incubation at 32 ± 1 °C. Furthermore, A gradual reduction in volatile solids (VS), total solids (TS), the carbon-to-nitrogen (C/N) ratio, and organic matter content was noted during digestion process. The maximum organic matter removal effectiveness (37.8%) was achieved in the co-digestion reactor PCP2, which exhibited the greatest reduction in a 78% reduction in iCOD was recorded over a 60-day digestion period. The results demonstrate the feasibility of using Parthenium that has been prepared as a viable co-feedstock for enhancing biogas generation through digestion under oxygen-free conditions mixed substrate of mess food leftovers.

Keywords

Co-digestion of anaerobic Mess food waste, Parthenium, Pretreatment, Biogas Production

1.Intoduction

1.1. Theoretical context

Edible discards are classified as organic trash generated from several origins, including food manufacturing facilities, households, culinary establishments, mess facilities, dining establishments, & eateries [1]. Mess food wastes are

produced mainly in institutional and hostel dining facilities due to food preparation, serving [2], and leftover food, and represents a significant fraction of the organic waste generated in such establishments. Mess food waste mainly consists of leftover cooked food, vegetables, fruits, cereals, pulses, meat products, and other food residues, which are abundant in biodegradable biological substances, polypeptides, saccharides, fats, amino acids, vitamins, & essential nutrients [3,4]. The increasing number of educational institutions, hostels, hospitals, and other residential facilities with mess services has culminated in a substantial escalation in the production of disorder food wastes. Waste resulting from these sources can produce offensive odours, greenhouse gas emissions and other environmental and public health issues if they are not disposed of in an appropriate manner [5]. Hence, use of anaerobic digestion to convert waste food into biogas is a type of promising a solution to energy from renewable sources and waste management production [6]. As the food industry advances, so does the amount of food waste, which consists of various parts of the food product, including parts that are biodegradable and detrimental to the environment & general public health, including as animal by-products. Increase in population, urbanization, and changing food habits have created a significant quantity of food waste from households, restaurants, institutional kitchens and other food-service outlets, especially in India and Southeast Asia [7]. As eating habits continue to go up, so has how much food been wasted created. Given the elevated moisture content of wasted foods, conventional physical methods are usually not an energy conserving process to minimize food wastes [8]. Furthermore, the amount of food waste generated is putting a strain on municipal landfills, and can cause excess methane gas in uncontrolled decompositions [9]. Millions of Food waste in tons is disposed of landfills each year, posing environmental and management of waste problems [18,19]. According to FAO [2] the breakdown of food waste produces about 3.4Gt CO_2 equivalents of GHGs and estimated economic losses of approximately 752 billion US dollars. Hence, wasting food is among the most promising sustainable fuel is among the least utilized organic sources. wastes [12]. In addition, Parthenium hysterophorus, often known as parthenium weed, is an undesirable alien annual plant, found throughout Worldwide, tropical and subtropical regions. The impact of allelopathy and its adaptability to various climate conditions and lack of effective natural enemies make Parthenium hysterophorus a potential threat to the natural biodiversity in several parts of India such as Punjab, Kashmir and other areas affected by it [13]. Parthenium has allelopathic effects and also shares other plant resources such as nutrients, light and water. The presence of Parthenium hysterophorus can also cause allergic dermatitis and breathing issues in people [14]. The frequency with which Parthenium hysterophorus is present has been reported to be nearly 16–24% at the regional level, reaching up to 35% at some places [15]. Parthenium weed or Parthenium hysterophorus was once restricted to roadsides, wastelands and disturbed areas. However, it has greatly expanded in pastures and farmland since 2003 [15]. The parthenin, a toxic sesquiterpene lactone, present in this plant can cause harmful effects in livestock and crop production, making it a serious threat to agricultural production [16]. A wide variety of management strategies have been attempted over the years, but few have been successful in stopping it spreading. This has led to an increasing focus on biological and biotechnological approaches for degradation and utilization of parthenium biomass, which can not only mitigate its ecological impact but also provide opportunities for the production of beneficial products like bioenergy and bio-gas from this weed problem.

In anaerobic digestion (AD), Microorganisms break down organic materials in a setting devoid of oxygen, leading to in digestate and biogas, the two primary products. There are a number of advantages to this process such as being a sustainable energy source that lowers greenhouse emissions (GHG) emissions in comparison to landfill disposal, reducing contamination of water, and generating valuable revenue [20,22]. The generated biogas is usually 63–72% Methane as well as 33 - 37% CO_2, and Additionally, the digestate contains biosolids that are rich in water and nutrients. which can be separated & applied as a soil supplement or fertilizer. [23]. The potential benefits of anaerobic digestion are drastically lowering the amount of food garbage dumped in a landfill, and the generation of these byproducts, making Anaerobic digestion is a significant more effective way of dealing with Mess food waste than landfilling. There is a lot of moisture and organic stuff in the food waste and it is more suitable for anaerobic digestion process.

Several factors at each stage of the method of anaerobic digesting influence the output of biogas. Every one of the four crucial phases: hydrolysis, acidification, both methanogenesis and acetogenesis – is important and an increase in activity at one of the stages will lead to a rise in the generation of biogas. The first stage of anaerobic digestion is

hydrolysis. and is vital as it is the process which speeds up the production of biogas for the remainder of the procedure. Hydrolysis is suppressed in cases where the substrate is not easily broken down, particularly for high solids content wastes [24]. Therefore, it is essential to employ strategies to raise the pace of hydrolysis and boost the effectiveness of the system. Enhancing hydrolysis is one of the ways that can be achieved through physical pretreatment methods including heating, mechanical processing and microwave application. A very promising method is to use microwave irradiation in combination with high-pressure steam at 120°C and for 25 minutes, which provides for rapid and efficient heating and reaction kinetics [25,26]. However, any form of treatment that is selected should not be overly energy-intensive. The acidification phase is the one that generates the feedstock of volatile fatty acids (VFAs) in the phase of methane generation for the methanogens. There are two possible pathways for producing VFA's and increasing either of these two pathways increases the overall rate of acid production [27]. The composition and activity of various populations of microorganisms are also closely related to this stage. Acetic acid is one of the products formed, and due to its significant effect on methanogenesis, has received a lot of attention and has been optimized to be produced. By being capable to grow in different environments such as alkaline, saline and high temperature, acetogenic microorganisms can be utilized in hybrid systems which consist of several biological functions [28-30]. Last but not least, methanogenesis, a metabolic phase mainly carried out by methanogenic archaea, is the most critical step for maximizing the production of methane. Anaerobic microorganisms are strict anaerobes and their metabolic activity and growth can be affected even by slight environmental changes [31]. In addition to this sensitivity, other factors like the pH value and the ratio of carbon to nitrogen (C/N) can be major constraints to anaerobic digestion. When carbon sources are insufficient, methanogen activity declines, which in turn suppresses their growth and interferes with ammonia formation [32-35]. One way to address this is by introducing easily biodegradable co-substrates, like transient herbaceous plant material which can supply additional readily available carbon to support methane-producing metabolic pathways. Furthermore, boosting the population density of anaerobic bacteria can enhance both the capacity and overall efficiency of the treatment process [36].

To address these research gaps, the present study set out to evaluate whether Parthenium hysterophorus could serve for anaerobic co-digestion as a feasible co-substrate alongside Mess food wastes. In particular, to study examined how methods of pretreatment namely steam treatment and the co-processing procedure was impacted by parthenium microwave irradiation in an effort to enhance biodegradation. efficiency & boosting output of biogas. Additionally, changes occurring during the downstream digestion process, along with shifts in nutrient content and substrate solubility within the mixed feedstocks, were examined separately in order to identify the optimal proportion of the two substrates that are mixed.

2.Materials and Methods

2.1 Collection and Preparations of Substrates

Mess food waste used as substrate was sourced from three different locations: (1) MANIT Bhopal Hostel 8's kitchen trash (33° 37′ 52.14′ N, 72° 05′ 08.68′ E), (2) food waste from Kotra Tiwari Restaurant in Kotra Sultanabad, Bhopal (33° 37′ 13.16″ N, 72° 04′ 9.74″ E), & (3) waste of food from the MANIT Canteen (33° 38′ 15.22″ N, 73° 04′ 11.10″ E). Most of the Waste included cooked noodles, bread, rice, and tea bags., and a range of fruits and veggies. All three Specimens were collected & ground mechanically for a constant particle size of 3 mm for even distribution of organic matter and were then subjected to physicochemical examination.

The rationale behind choosing Parthenium hysterophorus was it is common, abundant in the area and has no effective natural predators to control it. Also, it is a highly branched, erect, herbaceous annual plant, suitable for hydrolysis. The whole plant including seed, flower, leaves, root and stem was collected from the MANIT Bhopal campus (33° 37′ 52.12″ N, 72° 04′ 09.74″ E) for their study. After that, the materials were gathered, let to air dry, and then ground in a blender.

2.2. Pre-treating the co-substrate partially

A method of partial physical pretreatment was chosen. irradiating and steaming, which will involve relatively low energy input and will improve the hydrolysis and nutrient release. All microwave irradiations were performed in a domestic microwave oven. Fifty (50g) of Parthenium hysterophorus that is dry (following a six-hour air drying period) was subjected to microwave treatment for 15 minutes in this process. This was followed by sterilizing using high-pressure steam, carried out at 120°C for 25 minutes.

2.3. Designing experiments and setting up bioreactors

Two anaerobic co-digestion systems operating in parallel were established, one using untreated parthenium weed (P) and the other using pretreated parthenium, each combined with Mess food waste at feed ratios of 30%, 40%, 60%, and 70% (see Table 1). As a control, mess food waste alone (100%, without any parthenium treated or untreated) was used. The experimental setup consisted of five identical bioreactors, each with a 2000 mL capacity and dimensions of 13 × 35 cm (Fig1). Each set had four reactors assigned to it the co-processing trials (marked CP1–CP4 for the untreated series and PCP1–PCP4 for the pretreated series), Although the fifth reactor acted as the regulator, containing 100% Mess food waste with no parthenium addition. Cow manure served as the inoculum, 305 g/L were added of the total reactor volume, approximately 1550 mL was allocated for the co-digestion mixture, leaving 550 mL of headspace for biogas accumulation. Each reactor was fitted with a biogas outlet tube connecting the reactor's top to the base of a liquid displacement unit containing 1.7% NaOH solution; this unit incorporated a control valve to maintain gas flow in a single direction. An installed sampling valve at the lowest part of every reactor permitted digestate to be withdrawn for analysis. All reactors were maintained at the lowest part of every reactor permitted incubator set to 30 ± 1°C throughout their experiment. The liquid displacement approach was used to track the production of biogas during a 45-day period, with gas volume calculated based on the amount displaced relative to the corresponding sampling time.

Table 1. For anaerobic co-digestion, different ratios of parthenium weed (co-substrate) and mess food wastes (substrate) are used.

Phrases	**Treatments Exp 1**		**Treatments Exp 2**
	Un treated parthenium	**Phrases**	**Pre-treated Parthenium**
Control (Mess. Waste)	100% mess food waste + 0% parthenium weed	Control (parthenium)	0% mess food waste + 100% parthenium weed
CP_1	70% mess food waste + 30% parthenium weed	PCP_1	70% mess food waste + 30% parthenium weed
CP_2	60% mess food waste + 40% parthenium weed	PCP_2	60% mess food waste + 40% parthenium weed
CP_3	30% mess food waste + 70% parthenium weed	PCP_3	30% mess food waste + 70% parthenium weed
CP_4	30% mess food waste + 70% parthenium weed	PCP_4	30% mess food waste + 70% parthenium weed

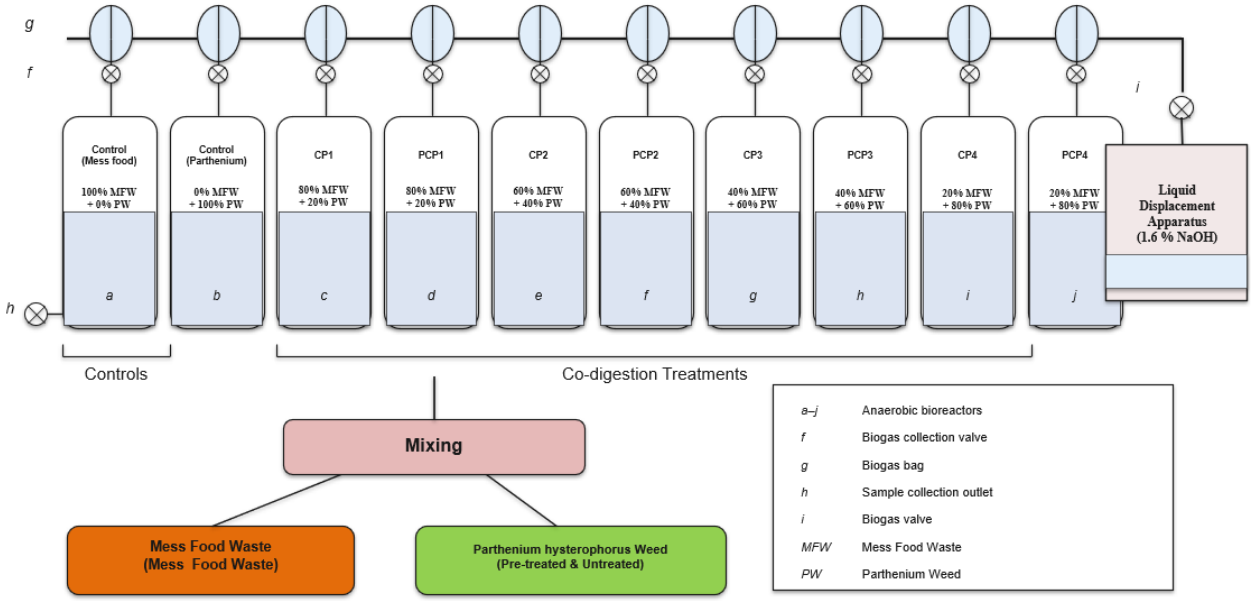


Fig 1 Diagrammatic representation of the bioreactor configuration during the anaerobic co-digestion of parthenium hysterophorus weed and mess food waste

2.4. Analytical measurements

The open reflux titrimetric method was used to calculate the chemical oxygen demand (COD) as described in the above-mentioned methodology [37]. COD values were calculated using Equation (1), as follows:

$$\text{COD (mg/L)} = (\text{X-B}) \times 7000/\text{Sample volume} \quad (1)$$

The volume (mL) of ferrous ammonium sulfate (FAS) ingested by the blank is represented by X in this equation. while B denotes the volume (mL) of FAS used for the actual sample. The milliequivalent weight of oxygen is represented by the constant 7000, while the FAS solution's molarity is denoted by M. The pH & Electric conductivity was measured using a CRISON Multi-meter (Model: CRISON MM-40+). The effectiveness of removing organic materials was determined using the formula below.

$$\mu\ (\%) = \frac{VS_{inf} - VS_{eff}}{VS_{inf}} \times 100 \quad (2)$$

The concentration of volatile solids in the raw feedstock is denoted by VSinf, while the concentration of volatile solids in the treated effluent at the conclusion of the treatment process is denoted by VSeff.

It was determined by dividing the sample's total mass of carbon (g) by its total mass of nitrogen (g). The Standard Method was used to calculate total solids (TS), fixed solids (FS), and volatile solids (VS). [38]. The liquid displacement method was used to assess the potential of biogas generated from the anaerobic co-digestion of food waste and parthenium. [39]. The total solids and the number of volatile solids was calculated using measuring the mass difference both prior to and following dry the sample at 110°C and 560°C respectively and the capacity of biogas produced from food waste that is co-digested anaerobically and Parthenium was identified. applying the method of liquid displacement [39]. The 45-day experimental period was conducted at a Biogas production was measured every three days at a constant temperature of 30°C.

2.5. Techno-economic assessment

A financial evaluation of the system for anaerobic co-digestion was performed using the ratio of benefits to costs (BCR) as the primary monetary indicator and market prices and currency values in India. The cost estimation for the co-digestion process was performed on an annual basis (6 reaction cycles/year, 45 days/cycle and in an industrial scale reactor of 1000 L). All the expenses related to the collection & transportation of mess food wastes, parthenium, energy use during co-substrate pretreatment and other labour costs were grouped under total input costs. The electricity tariff of 0.031232MJ was used for the calculation of energy costs, while the wages of general labour, skilled workers, drivers, supervisors and other personnel engaged were combined to calculate labour costs. The financial benefits of output materials, such as biogas and digestate, which reduce the cost of biofertilizer and are necessary for waste management in modern practice, were quantified. The energy conversion factor of 37.224MJ was used to determine the value of biogas.

3. Results

3.1. Physical-chemical properties of substrates

The physical-chemical properties of parthenium weed biomass and mess food waste are examined and recorded in Table 2. The examination of proximity revealed that the unstable matter Mess food waste included 806 g/L of feedstock, while parthenium biomass contained 621 g L−1. The two substrates' C:N ratio was very comparable, 21 ± and 22.20, respectively. The pH value was in acidic range for Mess food waste (pH 4.90) and the pH of parthenium biomass was found to be somewhat higher. (6.01). COD is an important parameter regarding the substrate's load of organic materials. Both substrates, Mess food waste and parthenium biomass, have high COD values (28.42 and 31.13 g L−1) and are suitable to facilitate anaerobic digestion. Additionally, the amount of water differential (17% in parthenium & 75% in Mess food waste) enhanced their appropriateness for use as complementary substrates & allowed for the modification of the water content needed for anaerobic digestion (see Table 2).

Table 2 Substrates' physicochemical properties

Characteristics	Mess food waste	Parthenium hysterophorus weed
pH	4.90 ± 0.02	6.01 ± 0.05
EC (μS cm^{-1})	103.6 ± 11.1	64.0 ± 8.5
Total dissolved solids (g L^{-1})	68.7 ± 0.19	54.4 ± 0.10
C: N	21 ± 1.2	22.20 ± 2.22
Water content (%)	76 ± 1.91	16 ± 0.07
$_{s}$COD (g L^{-1})	5.86 ± 0.21	4.59 ± 0.26
$_{i}$COD (g L^{-1})	28.42 ± 0.28	31.13 ± 0.91
Volatile solids (g L^{-1})	806 ± 18.9	621 ± 15.3
Total solids (g L^{-1})	330 ± 6.82	750 ± 7.02

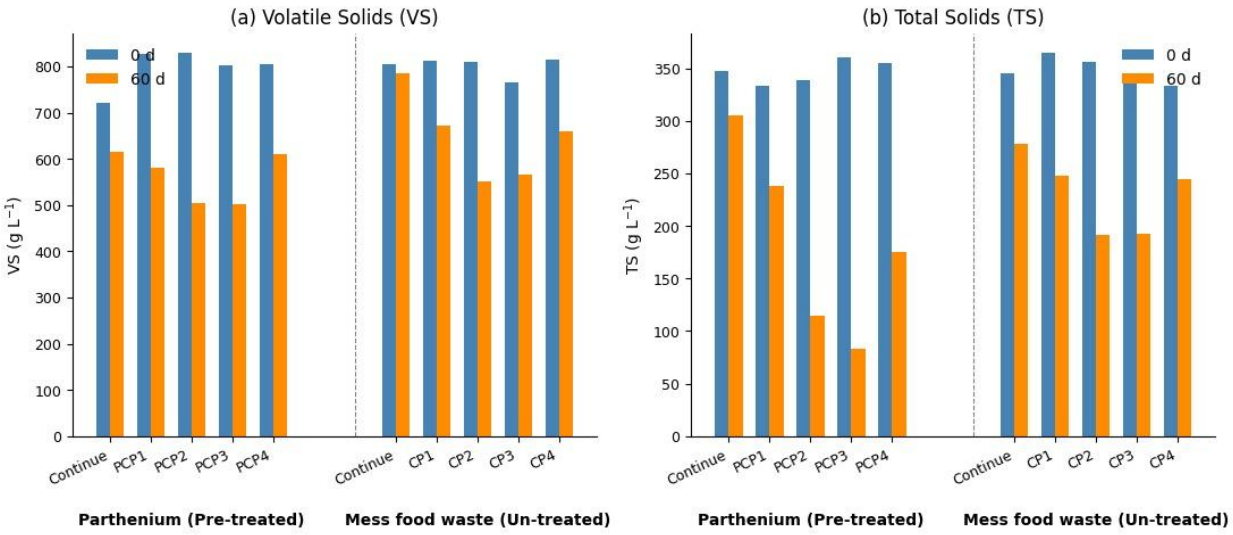


Fig 2. Variations between the beginning (0 d) and end (60 d) of the anaerobic digestion period in (a) volatile solids (VS) and (b) total solids (TS) of pretreatment Parthenium hysterophorus and untreated mess food waste digestion treatments.

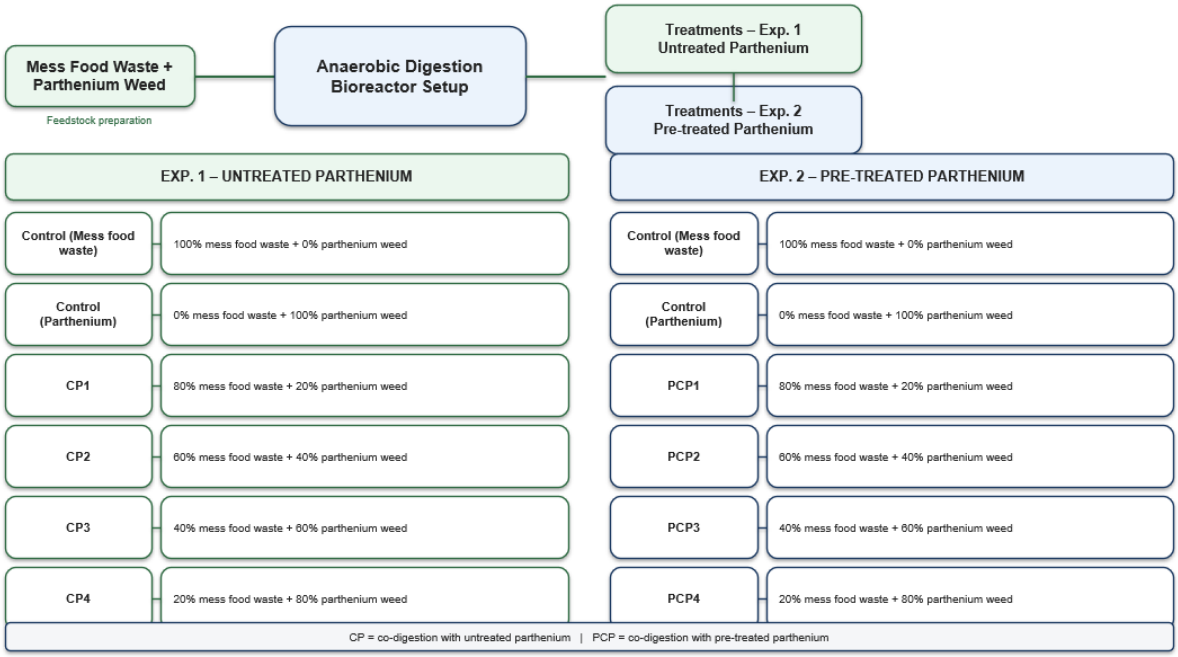


Fig. 3. Anaerobic codigestion of parthenium & Mess food waste results in the development of a schematic layout of the bioreactor setup.

3.2. Anaerobic digestion's impact on iCOD and sCOD

Figure 2 illustrates how anaerobic co-digestion affected COD levels in mixtures of Mess food waste and parthenium biomass. The data clearly show that combining Mess food waste using parthenium biomass that has been pretreated led to a significantly greater drop in insoluble COD (iCOD) than combining it using parthenium biomass that has not been treated (Fig. 2a). The biggest decrease in iCOD occurred in treatment PCP2 (a mix of 70% mess food wastes &

30% processed parthenium biomass), with values fell from 47.8 to 13.9 g L^{-1}. Close behind was PCP3 (30% mess food waste and 70% pretreated parthenium biomass), which saw iCOD drop from 45.5 to 13.1 g L^{-1} over the 60-day digestion period. Both treatments achieved the strongest iCOD reductions because they were particularly effective at boosting soluble COD (sCOD) partway through the process. PCP2 also produced the largest gain in sCOD overall: sCOD increased from 8.9 to 17.7 g L^{-1} after 30 days., before dropping sharply by day, to 3.6 g L^{-1} 60 (Fig. 2b). In contrast, sCOD levels were lower when untreated parthenium biomass was used in the digestion process compared to pretreated parthenium biomass. Total carbon in organic matter breakdown, measured as a whole COD (iCOD + sCOD), was markedly more PCP2 than in the different treatment combinations. Figure 3 shows that PCP2 achieved the greatest iCOD reduction, reaching 78%, whereas CP2 the equivalent mixture using untreated parthenium biomass removed only 54% of iCOD. Overall, treatments combining Mess food waste with pretreated parthenium biomass consistently outperformed those using untreated biomass in terms of insoluble COD removal, the best mixing ratios were found to be PCP2 and PCP3.

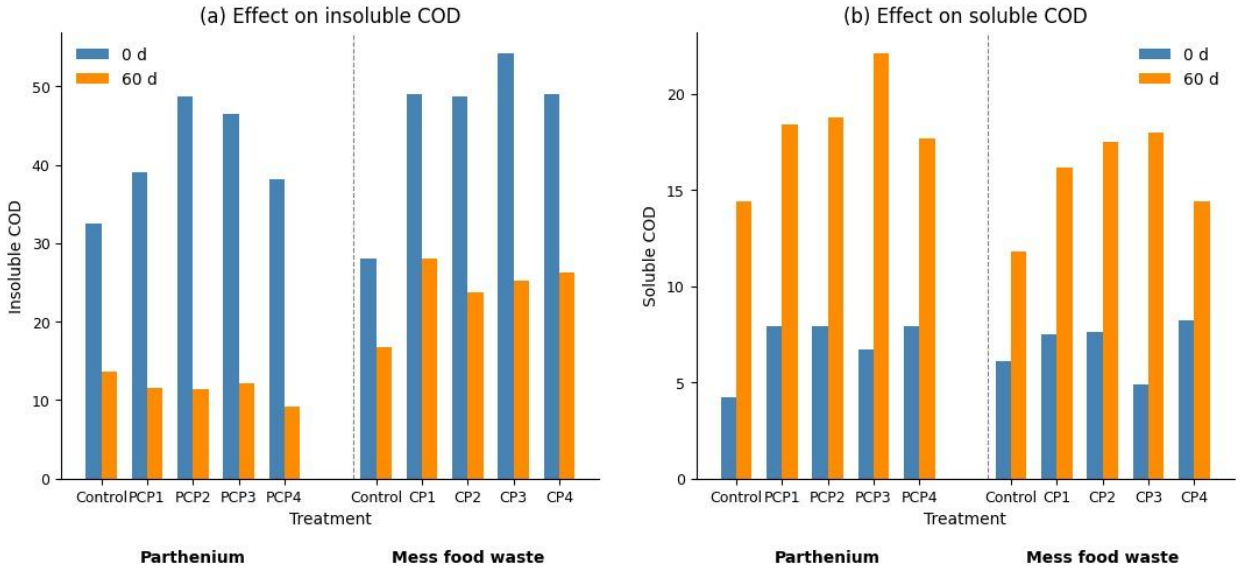


Fig 4. Changes in insoluble and soluble COD during anaerobic digestion of parthenium and mess food waste

3.3. Removal of VS and TS

Total solids (TS) and volatile solids (VS) in the substrate samples were measured to determine the solids content in the anaerobic co-digestion tests. Figure 4a presents the VS levels before and after digestion. Across all treatments, VS content declined over time, and mixtures containing pretreated parthenium biomass showed greater VS removal than those with untreated biomass. PCP2 achieved the highest VS removal, dropping from 828 to 503.8 g L^{-1} a 1.53-fold decrease following 60 days of digesting. Similarly, SV content decreased from 805 to 610 g L^{-1} for PCP3., representing a 1.21-fold decrease over the same period. When compared to the control experiments, it was evident that digesting parthenium biomass or Mess food waste alone resulted in the least VS degradation, with reductions of only 1.53 and 1.21 times, respectively.

TS content followed a pattern similar to that of VS content, with a marked decline observed particularly in interventions using pre-treated parthenium as a mixed feedstock (Fig. 4b). PCP2 and PCP3 both achieved the greatest reductions in TS. PCP3 recorded the highest removal, with TS falling from 360 to 83 g L^{-1} (a 3.87-fold decrease), PCP2 came next, where TS dropped based on 339 to 115 g L^{-1} (a 2.6-fold decrease) over the 60-day digestion period. By contrast, the control treatments & the Experimental co-digestion using Parthenium biomass that was not treated displayed no substantial TS removal relative to those using pretreated biomass. Among these, CP2 alone showed the most notable change, with a 1.7-decrease of fold in TS (from 356.4 -191 g L^{-1}) from the end of the breakdown of food.

3.4. Efficiency of organic matter removal

The productivity of Volatile Solids (VS) removes as a result of co-digestion of anaerobic Mess food wastes & parthenium Biomass was assessed during the process. When Mess Co-digestion of food waste with pretreated parthenium as compared to its co-digestion with untreated biomass, it was more efficient in the elimination of organic materials as indicated Fig. 6. The elimination of organic matter was the highest in PCP2 with 37.8% and the decrease in its Volatile Solid was of 830 - 503.8 g L-1 during digestion over 60 days. The minimum efficiency of Organic matter elimination (12%) received in the CP1 experiment on co-digestion using untreated parthenium biomass as a co-substrate. The pretreated parthenium in the control bioreactor biomass recorded somewhat greater elimination rate of 24% as compared to Concurrent digestion bioreactor using Parthenium biomass that has not been treated.

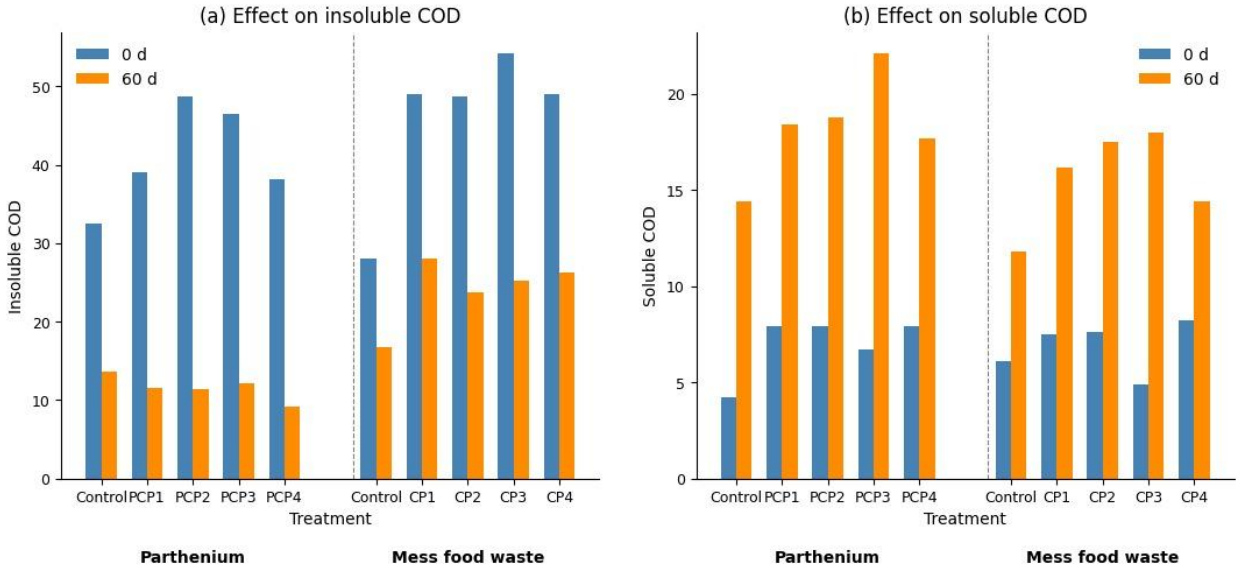


Fig 5. Effect of Anaerobic digestion on COD fractions (a) Effect of Anaerobic Digestion on Insoluble COD Reduction in Parthenium and Mess Food Waste (b) Effect of Anaerobic Digestion on Soluble COD Variation in Parthenium and Mess Food Waste

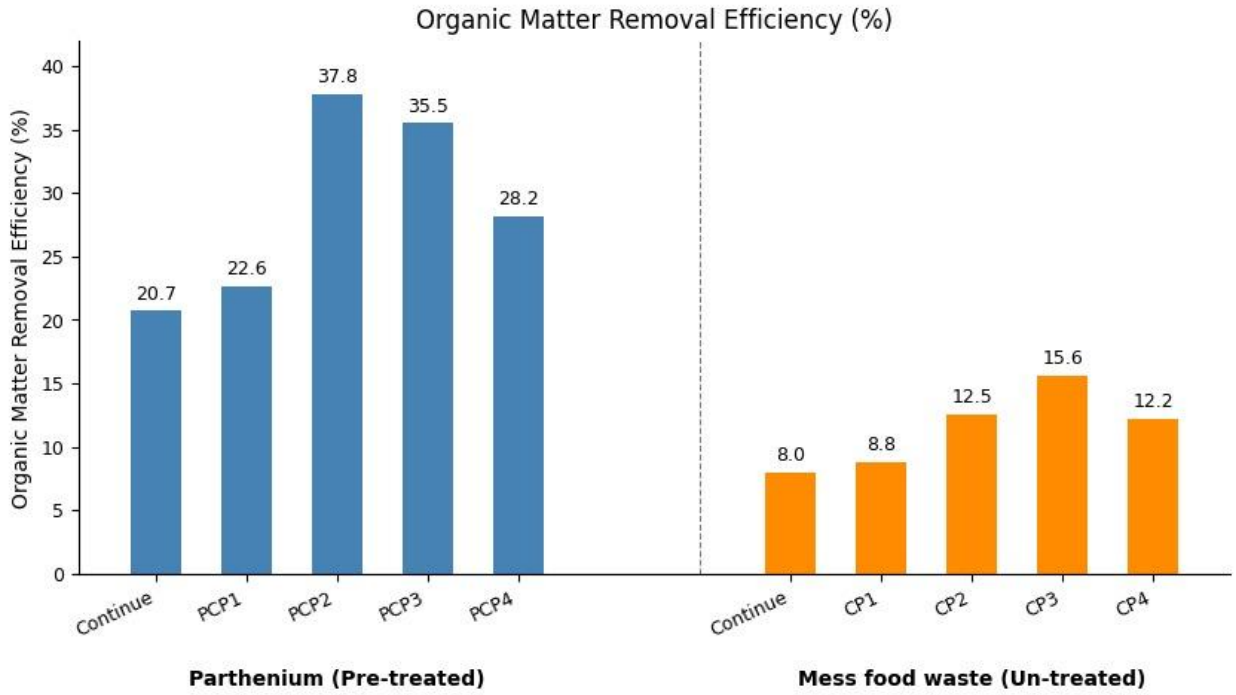


Fig 6. Organic Matter Removal Efficiency of Different Substrate Treatments

3.5. C/N Overview

The results are shown in Figure 7 on how C/N ratios were affected when co-digesting anaerobic Mess food wastes with parthenium biomass. The findings showed that pretreated parthenium Compared to untreated biomass, biomass enhanced the C/N ratio more successfully. during co-digestion. As established earlier (Figs. 3 and 4), PCP2 and PCP3 exhibited greater degradation potential, which corresponded to their ideal C/N ratios of 19.2 & 18.42, correspondingly. By contrast, the equivalent treatments using untreated parthenium biomass as co-substrate CP2 and CP3 showed considerably greater C/N ratios of 35.2 & 27.9, Accordingly, the highest C/N ratios overall, 35.0 and 33.0, were recorded in the control treatments (Mess food waste alone and parthenium biomass alone), reflecting their comparatively limited possibility of degeneration.

3.6. Biogas Production

Figures 7 and 8 present the synthesis of biogas data based on the co-digestion of anaerobic Mess food trash that contains parthenium biomass. When pretreated parthenium biomass was combined with Mess waste, all mixing ratios started with relatively poor generation of biogas, but PCP2 and PCP3 showed a marked increase after 17 - 19 days of digestion (Fig. 7a). By day 60, PCP2 recorded the maximum rate of biogas production at 558 ml L^{-1} d^{-1}, closely followed by PCP3 at 556 ml L^{-1} d^{-1}, both using their designated ratios of pretreated Mess food waste and parthenium biomass. In contrast, trials using untreated parthenium biomass showed declining biogas production, with CP3 showing the sharpest drop down to 390 ml L^{-1} d^{-1} after 30 days (Fig. 7b) and continuing to decline through the completion of the digestive process. The control bioreactors' biogas output was minimal & 285 ml L-1 d-1 for Mess food waste and 315 ml L-1 d-1 for parthenium biomass alone. In conclusion, co-digestion showed to increase the amount of biogas for all treatment combinations. The cumulative biogas production plotted in Fig. 8 indicated that the greatest total amount of biogas was produced. from PCP2 utilizing 5434 ml L-1 after 60 days of digestion. This was because PCP2 consistently produced the highest amount of biogas production rates as indicated in Fig. 8a. In contrast, among the reactors using untreated parthenium biomass, CP1 achieved the highest cumulative output at 3187 ml L^{-1} (Fig. 8b).

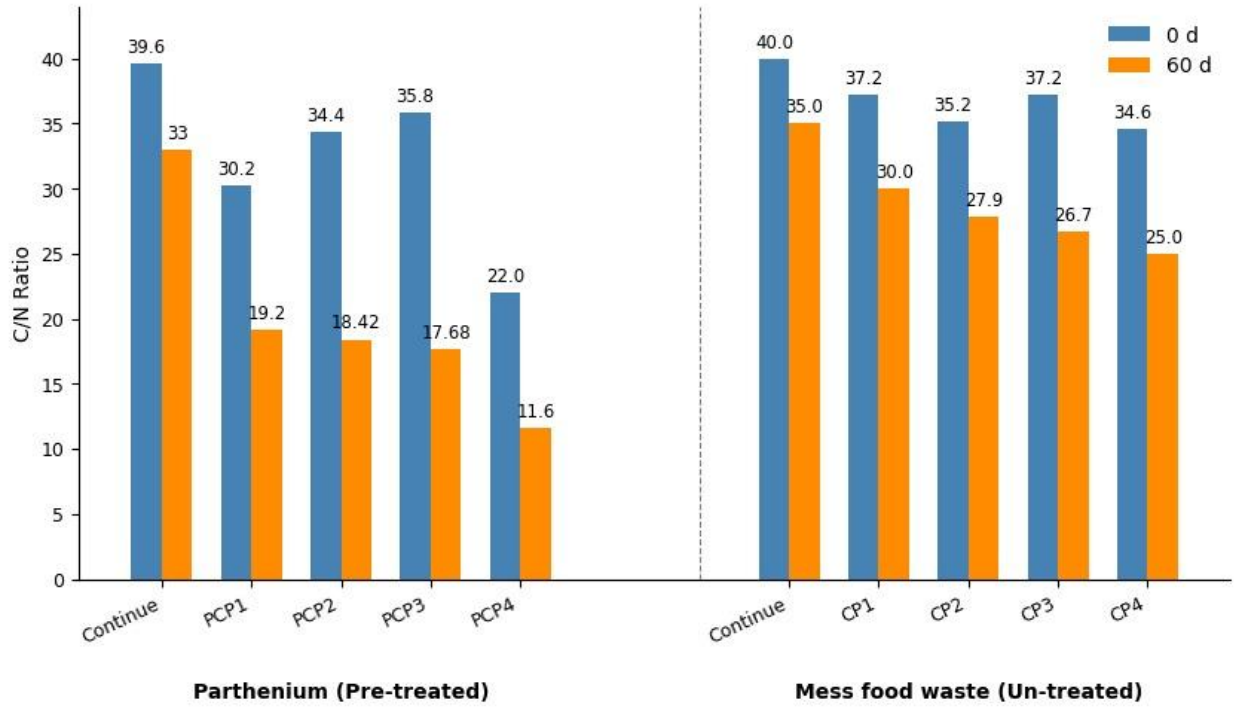


Fig 7. Changes in C/N ratio during the anaerobic breakdown of pretreated parthenium & mess food waste

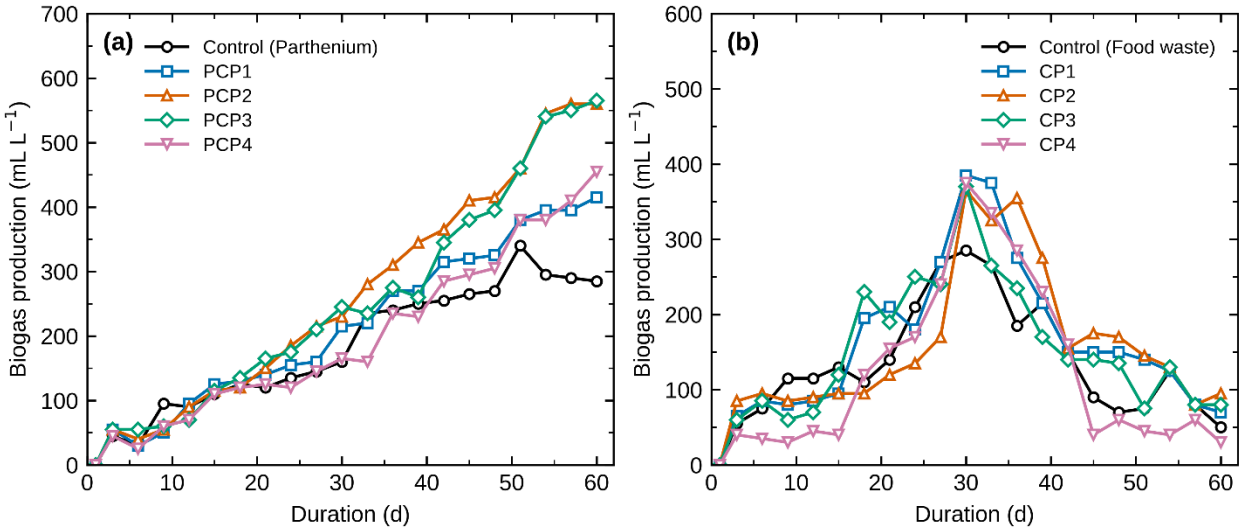


Fig 8. Biogas generation during the anaerobic breakdown of parthenium & mess food waste over 60 days

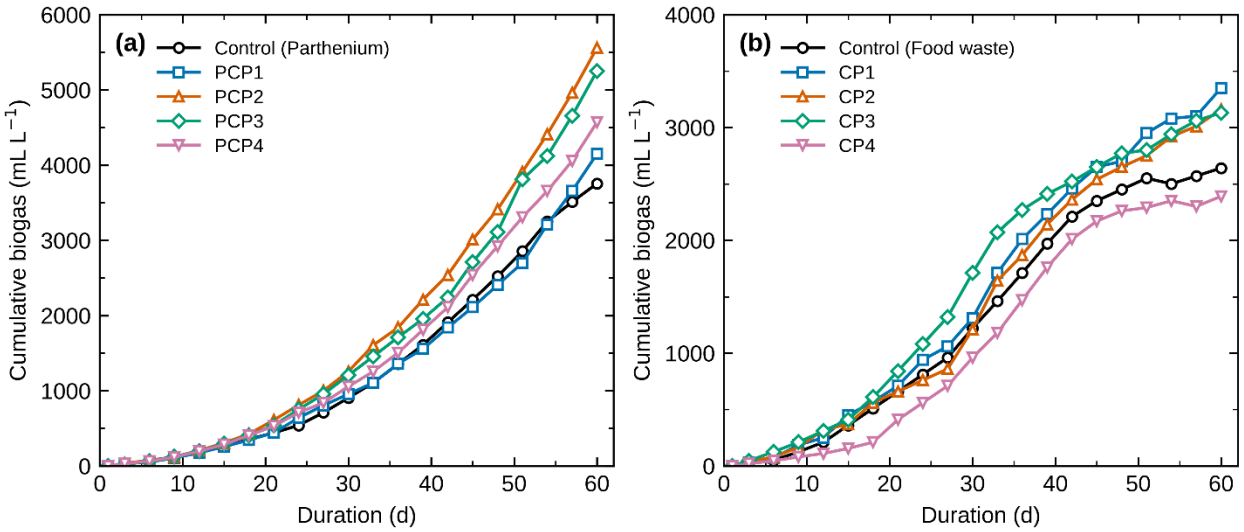


Fig 9. Cumulative generation of biogas while anaerobic digestion of parthenium & mess food wastes over 60 days

3.7. Variations in pH

During anaerobic co-digestion, the pH of the digestate was notably impacted by the disparate mixing ratios of parthenium biomass & Mess food waste (Fig.10). Co-digestion treatments using pretreated parthenium started with an initial pH between 7.4 and 7.9 (Fig. 10a), whereas those using untreated parthenium began at a comparatively lower range of 4.05–5.4 (Fig. 9b). Throughout digestion, pH values in all pretreated-parthenium treatments gradually declined. Despite this drop, the final pH after 60 days remained above 5.95 the level considered optimal for biogas production particularly in PCP2, which ended at pH 6.5. The untreated-parthenium systems were found to have a rising pH trend; however, they did not exceed the 5.95 level until about 30 days into the digestion. This delay suggests that the untreated biomass of parthenium is not more suitable for efficient biogas production as It requires a lot of longer time to reach the desired pH conditions of the biogas production process.

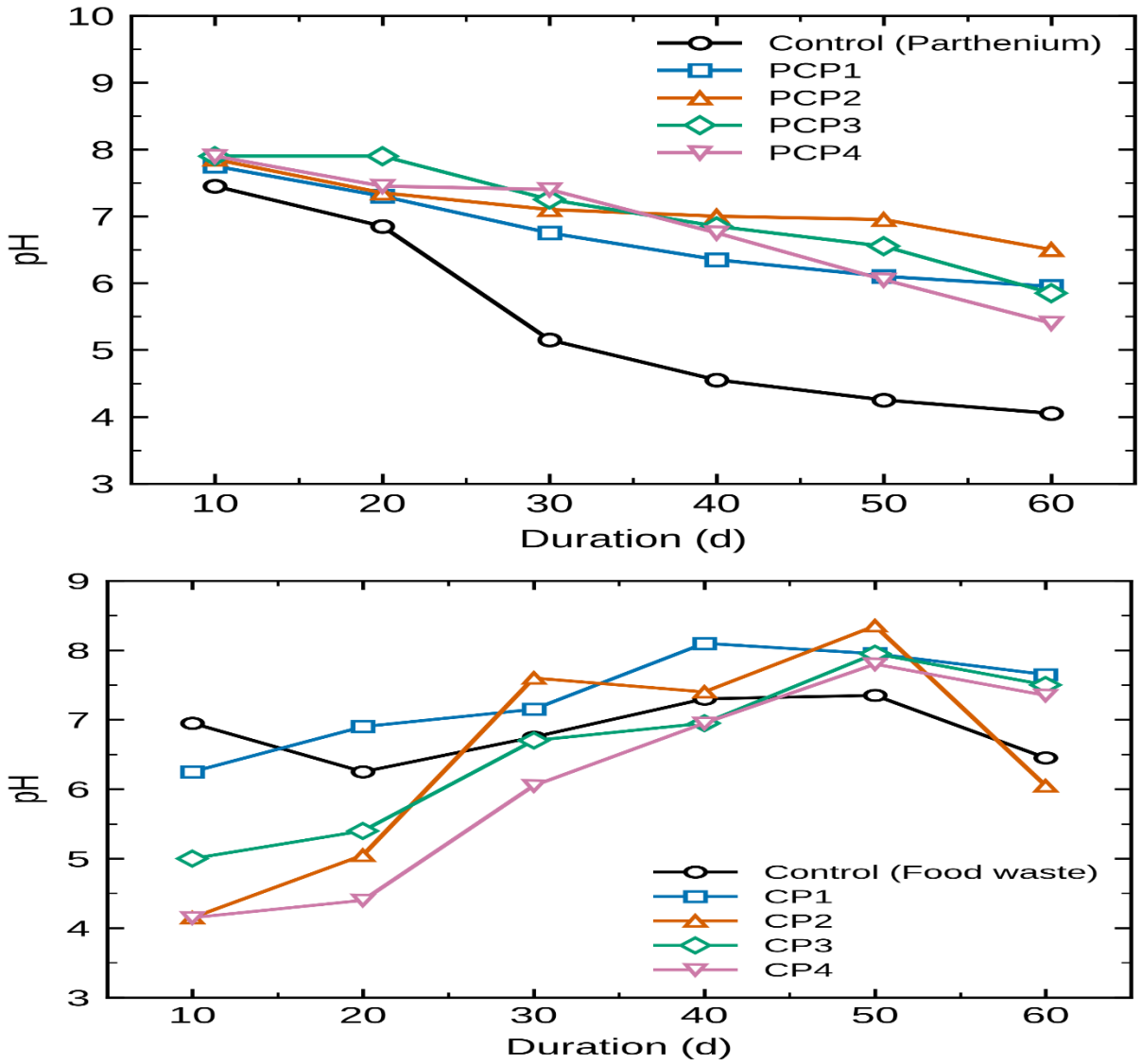


Fig 10. Changes in pH over 60 days of anaerobic digestion in (a) pretreated Parthenium hysterophorus treatments (Control, PCP1-PCP4) and (b) mess food waste treatments (Control, CP1-CP4).

4. Analysis

Various biogas production potential varied based on the proportion of Mess waste food to parthenium biomass (pretreated and un-pretreated) during anaerobic digestion process. Overall co-digestion performance bioreactors (Pretreated parthenium biomass combined with mess food waste) Table 3 provides a summary in comparison to the control reactors. PCP2 had the maximum potential for degradation with highest level of removal efficiencies for organic substances (38%) and iCOD (78%) among all treatments. The high reduction in iCOD because PCP3 was assigned in order to convert insoluble organic substances into dissolved organic matter (sCOD) which increased mineralization of organic materials as a result to increased availability for microbial degradation [41–43]. This is consistent with earlier research that reported the enhancement of nutrient degradation such as sCOD, TN and VS degradation due to pretreatment [44–46]. Overall, these findings imply that pre-treating the parthenium biomass raises the efficiency of the overall digestion process.

The substrate's nutritional content and the overall effectiveness of the anaerobic digestion process are gaged by the C/N ratio. [47,48]. Parthenium biomass that has been pretreated when used in combination with Mess food waste, allowed greater opportunity to achieve closer to the optimal range of C/N ratio by better degradation than when using untreated parthenium biomass. With C/N ratios, PCP2 and PCP3 have the greatest potential for deterioration of 19.02 and 18.42 respectively. The positive nutrient balance also probably resulted in increased microbial activity leading to better efficiency in the use of carbon for expansion [49,50]. For co-digestion treatments including untreated parthenium biomass, the C/N ratio was greater., suggesting a lesser ability to be degraded, which may be the result of an accumulation of free ammonia, an inhibitor of methanogenic bacteria. From these results, the conclusion is that the steam and microwave treatments methods used in pre-treatment of parthenium biomass facilitated the utilization of maximum carbon for microbial expansion during anaerobic breakdown [51,52].

One of the main variables affecting biogas yield and decomposition efficiency is pH. In this study, co-digestion treatments using pretreated parthenium biomass maintained a pH between 7.2 and 7.9 within the optimal range for methanogenesis whereas those using untreated parthenium biomass started at a notably lower pH, ranging from 4.2 to 6.8. This lower pH in the untreated treatments was probably brought on by the buildup of organic acids with elevated nitrogen levels [53,54]. Thermal pretreatment methods such as microwave and steam treatment have been shown in previous studies to effectively hydrolyze organic material, which in turn helps stabilize pH by promoting more efficient hydrolytic breakdown [55,56].

Enhanced degradation directly translates into more efficient biogas production. The PCP2 co-digestion setup achieved the highest cumulative biogas yield (5434 ml L^{-1}), which can be attributed to improved enzyme accessibility and an optimal C/N ratio that together promoted efficient digestion [57]. The increased biogas output observed in the pretreated parthenium–Mess food waste co-digestion setups appear to stem from greater accessibility of organic matter (volatile solids) to microorganisms. This suggests that thermal pretreatment of the substrate maximizes solid mineralization [58], thereby making organic material more readily available for biodegradation [59–61].

5. Economic performance of the co-digestion process

This study also included a short economic assessment, using the benefit-cost ratio (BCR) [62] along with the market value of the energy recovered as biogas (Table 4). The financial data is based on an average 6 batch cycles per year in a small-scale digester and a full year of operation of a co-digestion facility. When pretreated parthenium (56%) was digested together with Mess food waste (44%), the BCR came out at 1.24. A project is economically viable if its BCR is greater than 1 [63] and the result above indicates that the process is economically feasible. The process produced three valuable by-products: biogas, digestate and an alternative organic waste management process all with an economic value. The energy content of the methane fraction of the biogas is approximately 66.6828 MJ (from 1 m^3 CH_4 = 37.224 MJ), which can be used for natural gas used in the household or generating electricity. The digestate can be sold as a biofertiliser, thus decreasing the use of chemical fertilizers like DAP and urea, which are harmful for the environment and ecological systems. Net energy gain (NEG) was 166.83 (Gijzen). This positive balance indicates that more energy is generated than is used and the excess benefit is further. The results overall indicate that this can be used as a way to contribute the industrialization of anaerobic co-digestion, particularly in underdeveloped nations where low-cost solutions are needed.

Table 3. Economic Assessment of Commercial – scale Co-digestion of Mess Food Waste and Parthenium Anaerobically

Input Parameters	Cost/Run ($)	Cost/Year ($)	Energy Req./Run (kWh)	Energy Req./ Year (kWh)	Output Parameters	Benefit/ Run ($)	Benefit/Year ($)	Energy Prod./Run (kWh)	Energy Prod./Year (kWh)
Mess Food waste collection and transfer	1.75	10.33	–	–	Biogas	6.19	32.07	65.44	367.55
Cost of Parthenium harvesting and collection	2.16	14.07	–	–	Waste treatment	67.76	402.59	–	–
Energy cost	1.65	9.85	32.25	188.23	Digestate as biofertilizer	98.41	577.46	–	–
Stream pretreatment	0.95	6.47	18.26	104.24	Partheniu m management	245.66	1414.67	–	–
Microwave pretreatment	0.77	4.57	15.12	85.62	Man power	317.00	1880.02	–	–
Total Cost	325.01	1927.02	–	–	Total Benefit	404.83	2414.57	–	–

$1m^3$ CH_4 = 37.224 MJ

1 $ = 96.57 INR (2025)

Energy Price = 0.031232 $/MJ

6. Conclusion

Pretreated Parthenium hysterophorus with mess food waste can be a promising pathway for Biogas generation during anaerobic digestion. It also lowers the price of this invasive weed control and provides a clean and cost-effective energy source, together with environmentally friendly trash handling. Additionally, the economic research showed

that the procedure is economically appealing with positive net energy balance and with a high benefit-cost ratio. The energy crisis in India and huge amount of unused parthenium biomass and mess food waste. Given this scenario, co-digesting pretreated parthenium with mess food waste may be an effective waste management strategy that can be easily adapted to the nation's existing system. With its strong potential for industry and the economy & its capacity to generate bioenergy as a byproduct, the use of co-digestion technology can be further promoted.

Despite such huge quantities of parthenium biomass and mess food waste lying unused, Indian efforts are still underway to fill its energy deficit. In this context, use of pretreated parthenium along with mess food waste in co-digestion process seems to be a a workable waste management strategy that can be combined in the existing waste management infrastructure within the nation. Additionally, its commercial and economic feasibility, combined with the bioenergy that it can provide as a product with added value, can encourage co-digestion technology use even further.

Declarations

Conflict of interests The authors declare no competing interests

Data availability No datasets we are generated or analyzed during the current study

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