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Study of prototypes for biofuel production Extraction from biodegradation in oxygen-free environments Processing Wastewater

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ABSTRACT

Anaerobic digestion (AD), a proven and widely adopted technology, is used in life cycle analyses of energy systems. AD has been widely adopted for the management and treatment of both waste and wastewater. The product of this process is biogas, a mixture of methane gas (55-75% by volume) and carbon dioxide gas (25-45% by volume). This study contributes to ongoing research on renewable energy generation from waste and provides valuable insights into innovative waste processing.

Biogas can be used for various energy production purposes, such as heating, converting it to high-quality natural gas, or generating electricity and heat together. AD plants are characterized by their technical simplicity and minimal energy and space requirements. The classification of anaerobic treatment systems is based on two categories: “high-speed” systems, which involve the retention of biomass, and “low-speed” systems, which do not involve the retention of biomass. High-speed systems have a relatively short hydraulic retention time and a long mass retention period, making them suitable for the treatment of many types of wastewater. Low-speed systems have traditionally been used for the degradation of slurries and solid wastes. This difference in retention times affects the types of waste each system is best suited for. AD reduces the amount of waste and generates valuable products, such as biogas. These systems were characterized by an extended hydraulic retention period, equivalent to the mass retention period. The biogas production process was subject to fluctuations depending on factors such as the nature and concentration of the raw materials as well as the prevailing process conditions.

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Biogas yields for the organic fraction of municipal solid waste and animal manure ranged from 80 to 200 m^3/t and from 2 to 45 m^3/m^3, respectively. The co-digestion practice played an important role in enhancing the efficiency of the reactors and ensuring their economic viability. Improving the sale of all derivative products enhanced the economic efficiency of anaerobic treatment. Moreover, the implementation of financial incentives to promote renewable energy production significantly enhanced the competitiveness of anaerobic digestion compared to anaerobic composting, providing an optimistic outlook for the future of this technology.

دراسة نماذج أولية لإنتاج الوقود الحيوي المستخلص من التحلل البيولوجي في بيئات خالية من الأوكسجين بمعالجة مياه الصرف الصحي

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ملخص: تُعدّ عملية الهضم اللاهوائي (AD) ، وهي تقنية مُثبتة ومعتمدة على نطاق واسع ، إحدى طرائق تحليل دورة حياة أنظمة الطاقة. تُستخدم هذه العملية في معالجة النفايات والمياه العادمة على حد سواء. ناتج هذه العملية هو الغاز الحيوي ، وهو مزيج من غاز الميثان (55–75٪ حجم) وغاز ثاني أكسيد الكربون (25–45٪ حجم). تُساهم هذه الدراسة في البحوث الجارية حول توليد الطاقة المتجددة من النفايات وتُقدّم رؤى قيّمة حول معالجة النفايات المبتكرة. يُمكن استخدام الغاز الحيوي في أغراض إنتاج الطاقة المختلفة ، مثل التدفئة أو تحويله إلى غاز طبيعي عالي الجودة أو توليد الكهرباء والحرارة معًا. تتميز محطات الهضم اللاهوائي ببساطتها التقنية ومتطلباتها الدنيا من الطاقة والمساحة. يُصنف نظام المعالجة اللاهوائية إلى فئتين: أنظمة «عالية السرعة» ، والتي تتضمن احتجاز الكتلة الحيوية ، وأنظمة «منخفضة السرعة» ، والتي لا تتضمن احتجاز الكتلة الحيوية. تتميز الأنظمة عالية السرعة بوقت احتجاز هيدروليكي قصير نسبيًا وفترة احتجاز كتلة طويلة ، مما يجعلها مناسبة لمعالجة أنواع عديدة من المياه العادمة. تُستخدم الأنظمة منخفضة السرعة تقليديًا لتحليل المواد الصلبة وشبه الصلبة. يُقلل الهضم اللاهوائي من كمية النفايات ويُنتج منتجات قيّمة ، مثل الغاز الحيوي. تتميز هذه الأنظمة بفترة احتجاز هيدروليكي ممتدة ، تعادل فترة احتجاز الكتلة. يخضع إنتاج الغاز الحيوي لتقلبات اعتمادًا على عوامل مثل طبيعة وتركيز المواد الخام وظروف العملية السائدة. تتراوح إنتاجية الغاز الحيوي للجزء العضوي من النفايات الصلبة البلدية وروث الحيوانات من 80 إلى 200 متر مكعب / طن ومن 2 إلى 45 متر مكعب / متر مكعب ، على التوالي. لعبت عملية الهضم المشترك دورًا هامًا في تعزيز كفاءة المفاعلات وضمان جدواها الاقتصادية. تحسنت الكفاءة الاقتصادية للمعالجة اللاهوائية من خلال تحسين بيع جميع المنتجات المشتقة الممكنة. علاوة على ذلك ، عزز تطبيق الحوافز المالية لتشجيع إنتاج الطاقة المتجددة بشكل كبير من القدرة التنافسية للهضم اللاهوائي مقارنة بالتسميد اللاهوائي ، مما يوفر نظرة مستقبلية متفائلة لهذه التكنولوجيا.

الكلمات المفتاحية – التخمير اللاهوائي، إنتاج الغاز الحيوي، النفايات البلدية الصلبة، معالجة مياه الصرف الصحي.

1. INTRODUCTION

The global demand for energy continues to rise, driven by population growth, urbanization, and industrialization [1-3]. While traditional fossil fuels have fueled economic growth, their detrimental environmental impact necessitates a transition to sustainable alternatives [4-7]. Among these alternatives, renewable energy sources like solar and biomass-derived biogas are gaining prominence [8-9].The rapid generation of complex solid waste, particularly organic biodegradable materials, presents a significant environmental challenge [10-12]. However, this challenge also offers an opportunity. Anaerobic digestion (AD) emerges as a highly promising solution, effectively converting biodegradable organic waste into biogas, a sustainable energy source for diverse applications [13-14].

This process, naturally occurring in various environments and long-utilized in wastewater treatment [15], is increasingly being explored for industrial and agricultural waste processing [16]. AD optimizes the proliferation of methanogenic bacteria, maximizing methane (CH_4) production. Recent studies have demonstrated the enhanced energy efficiency of two-stage co-digestion systems compared to traditional single-stage methods, showcasing significant energy savings [17]. Furthermore, research into solar collectors [18-20] highlights the importance of optimizing renewable energy technologies, and the study of lab scale anaerobic digesters [21, 22] provides valuable insight into the process of biogas generation.

Despite the established potential of AD, further investigation is needed to optimize its efficiency and applicability, particularly at the laboratory scale. This research focuses on laboratory-scale anaerobic digestion (AD), a critical process for waste valorization. By converting biodegradable substrates, such as mixtures of cow manure and yard waste, into biogas and digestate, AD contributes to both renewable energy production and sustainable waste management. This study aims to provide valuable insights into optimizing AD parameters, contributing to the broader effort of developing novel and efficient waste processing techniques and furthering the potential of renewable energy. This research will specifically build on laboratory- scale batch anaerobic digesters, and the optimize anaerobic digestion by control of temperature, PH and organic feed ratios. [23, 24, and 25]. this comparison highlights how tailored biological strategies can address diverse sustainability goals, offering insights into cross-disciplinary innovations for waste valorization and pollution mitigation. The study was conducted at the Ministry of Science and Technology, Renewable Energy Department, Biogas Production Unit in Baghdad, Iraq.

2. METHODOLOGY

2.1. BIOGAS FEEDSTOCKS

Anaerobic digestion offers several benefits and advantages in waste and wastewater management [26]. It enables renewable energy production through heat, light, and electricity. It reduces greenhouse gas emissions by recovering methane, a potent greenhouse gas, during the process. Anaerobic digestion helps reduce the volume of solids that need to be handled, such as excess sludge. Organic wastes subjected to anaerobic digestion can be converted into high-quality fertilizer, offering a significant resource for agricultural applications. An additional benefit is the enhancement of hygienic conditions through the reduction of pathogens, worm eggs, and flies in waste and wastewater.

The process also offers stability, allowing for treating high loads and preserving anaerobic sludge for extended periods without feeding. Regarding infrastructure, anaerobic treatment systems have relatively low construction costs compared to aerobic wastewater treatment systems. Furthermore, they require less space, making them a space-efficient option for waste and wastewater management [27].

The temperature in the environment can significantly affect the process. Establishing a method for reusing the produced energy, such as transforming it into heat and power, is crucial. Sludge may need further treatment using methods like aerobic composting, humification using sludge drying beds, etc. Methanogenic bacteria are susceptible to many chemical compounds. The process requires seeding, and the start-up can take a long time because the growth yield of anaerobic bacteria could be faster [28].

Various types of biomass waste can be used as substrates in biogas production. Biomass feedstock consists of essential components such as lipids, proteins, carbohydrates, cellulose, and hemicellulose, which are crucial for biogas production. Substrates were added to alter the organic composition to increase biogas production. Typical substrates include organic waste generated by industrial processes, food waste, and municipal bio-waste. While carbs and proteins exhibit faster conversion rates compared to lipids, it is worth noting that fats demonstrate a considerably larger biogas yield [29]. Biomass can be used as a feedstock in biogas generation in several forms, including liquid (concentrated or diluted) and solid (or slurry). Hence, the feedstock's commonly used encompass.

2.1.1. Solid Waste

The process utilizes diverse forms of organic waste, including domestic waste, specifically separately collected vegetable, fruit, and yard waste (VFY), the organic residual fraction following the mechanical separation of essential domestic waste (grey waste), as well as agricultural waste such as crop residues and manure. These waste products function as the substrate for biogas production via anaerobic digestion [30].

2.1.2. Waste Slurries

Liquid manure, sewage sludge, urine, feces, and industrial waste, including fats, abattoir byproducts, and fish waste, are employed in the anaerobic digestion process to produce biogas. These waste products function as feedstock for the process, facilitating sustainable energy generation [31].

2.1.3. Wastewater

The method employs diverse waste materials, such as industrial wastewater from the food and beverage sector, home sewage, [32-33].

Hydrogen gas is a promising sustainable energy source due to its ability to save and convey chemical energy. Electrochemical water electrolysis technology offers a sustainable and efficient way to produce hydrogen gas. Higher production rates enhance hydrogen volumetric energy capacity by storing it in high-pressure tanks, making it cost-effective and efficient. Use of hydrogen as an alternative to natural gas and details water electrolysis technologies for hydrogen production. The diffusion coefficient remains unchanged at flow rates greater than 90 liters per hour. [34-35]

While another study tested ceramic membrane surfaces coated with cysteic acid for efficacy and fouling rate in water samples. The membranes were used for filtration and were cleaned in situ to ensure smooth flux recovery. The results showed that the use of ceramic microfiltration membranes reduced Ca 2+ ions concentrations by 89-96%, achieving an efficiency of about 99.5% at a TMP of 0.20 MPa. [36-37].

The potential of Emulsion Liquid Membrane (ELM) in industrial wastewater treatment. By using nanoparticles and ionic liquids, the recovery of vanadium from synthetic wastewater was significantly increased to 99.6% within 3 minutes. The emulsion stability was also improved, and leakage percentage was reduced to 16% after 3 days. These findings could be used to remove heavy metal ions from industrial eluents [38- 39].

The current study emphasize the technical simplicity of anaerobic digestion systems. However, it provides a detailed description of the pilot setup, including the batch-mode digesters, gas scrubbers, and ARTI digester components (decomposition tank and reservoir.(

3. EXPERIMENTAL DESIGN

The experimental setup involved a batch-mode anaerobic digester designed for laboratory-scale biogas production. The system consisted of a reaction container (5 liters), a gas scrubber (750 ml) with sodium hydroxide as the confining liquid, and a gas collection and measurement system. The temperature was maintained at 35°C to optimize anaerobic microbial activity.

Replicates: All experiments were conducted in triplicate to ensure data reliability and statistical validity. Control Setup: A control digester with identical conditions but without organic feedstock was included to differentiate biogas production from background microbial activity.

3.1. Statistical Analysis

To ensure the accuracy and reproducibility of results, statistical analyses were conducted using: Standard deviation (SD) to assess data variability. Confidence intervals (95%) to establish the reliability of mean ANOVA (Analysis of Variance) to compare differences among experimental conditions.

Linear regression analysis to determine correlations between substrate composition and biogas yield. All data were processed using statistical software (e.g., SPSS or MATLAB) to derive meaningful conclusions from the experimental results.

3.2. Feedstock Preparation

The biogas plant was operated using cattle dung as the primary feedstock, with a dung-to-water ratio of 1:2. The retention period for the biogas production process was set at 30 days. Primary conditions needed for biogas production included maintaining a strict anaerobic environment, with an optimal temperature range of 32-37°C and a pH value between 6.8 and 7.5. The carbon-to-nitrogen ratio of the fermentation materials was maintained at 20-30:1 to ensure maximum microbial activity and gas production efficiency.

3.3. Digester System (ARTI)

The ARTI digester consists of two main parts:

1. Bottom / Digester. Tank: Decomposition occurs in this section, facilitated by anaerobic bacteria that produce biogas.
2. Top/Reservoir Tank: This inverted tank collects the biogas produced, which is either pumped or released by placing a weight on the upper section.

3.4 Process Details

1. Feeding: Organic waste materials were cut into small pieces or liquefied before being introduced into the digester.
2. Gas Collection: Gas production began on day 7, reaching peak output on day 21.
3. Gas Composition Analysis: A portable gas detector measured CH_4, CO_2, H_2S, and O_2 concentrations.
4. Biogas Utilization: The collected gas was tested for cooking and electricity generation.

By including these additional methodological details, the reproducibility and validity of this study are significantly enhanced.

4. MATERIALS & METHODS

4.1. Feedstock Preparation

The integrity of the microbial community is crucial for efficient biogas production. The biogas plant was operated using cattle dung as the primary feedstock, sourced from a local dairy farm where cows are fed a controlled diet to ensure consistency in manure composition. The dung-to-water ratio was maintained at 1:2, and the retention period for the biogas production process was set at 30 days. Pre-treatment methods were implemented to enhance the efficiency of anaerobic digestion. The collected cattle dung underwent a sieving process to remove large undigested particles and foreign materials such as stones, straw, or plastic contaminants. The dung was then homogenized using mechanical stirring to achieve a uniform consistency before being introduced into the digester. To maintain uniformity in feedstock composition, samples of the cattle dung were regularly analyzed for moisture content, volatile solids, and pH levels. Adjustments were made as needed by incorporating water or other organic waste materials to optimize the carbon-to-nitrogen (C/N) ratio. The pH value of the prepared liquid in the biogas plant was controlled between 6.8 and 7.5 to create an ideal environment for anaerobic bacteria. The carbon-to-nitrogen ratio of the fermentation materials was maintained between 20-30:1 to ensure active bacterial performance and efficient biogas production. By implementing these measures, the consistency and efficiency of the anaerobic digestion process were improved, leading to a stable and predictable biogas yield.

4.2. System ARTI

The ARTI system consists of two main components: the digester tank and the gas storage unit. The digester tank, typically made of reinforced concrete or high-density polyethylene (HDPE), has a diameter of 1.2 meters and a height of 1.5 meters, providing a total capacity of approximately 1.5 cubic meters According to ASTM standard. The gas storage unit is an inverted drum, made of mild steel, which moves up and down based on gas accumulation.

The system operates with a daily feed input of 3-5 kg of cattle dung . The expected biogas yield is approximately 2400-4000 litter gas , with a methane concentration of 60-65%. The produced biogas is used for cooking and lighting applications. The outlet slurry, rich in nutrients, serves as a high-quality organic fertilizer.

Technical specifications:

Digester tank material: Reinforced concrete or HDPE.

Tank dimensions: Diameter: 1.2m, Height: 1.5m.

Gas storage unit: Inverted mild steel drum.

Biogas production: 2400-4000 Litter.

Methane concentration: 60-65%.

These engineering specifications ensure the ARTI system operates efficiently, providing a sustainable solution for biogas production and waste management.

Figure 1. Reservoir production tank.

4.3. Process

1. At the beginning of decomposition, wine made from cow or sheep excrement must be added.
2. Feeding, i.e., cutting the materials into very small pieces or something like liquid, and these wastes enter through a tube inside the tank.
3. The flame of this gas is pure blue because the percentage of methane is between (60-85).

4. When adding nutrients to the tank, the liquid becomes an organic fertilizer with excellent levels of nitrogen and phosphate.

4.4. Batch Mode Digester

The batch-mode digester is used for laboratory tests. It contains a reaction container (5 liters) and a well closed gas scrubber 750 ml size and has the confining liquid (sodium hydroxide). The gas generated is measured via a gas pipe and subsequently introduced into the water, maintained at a consistent temperature of 35oC. Figure (2) indicates the digester for biogas production for laboratory objectives.

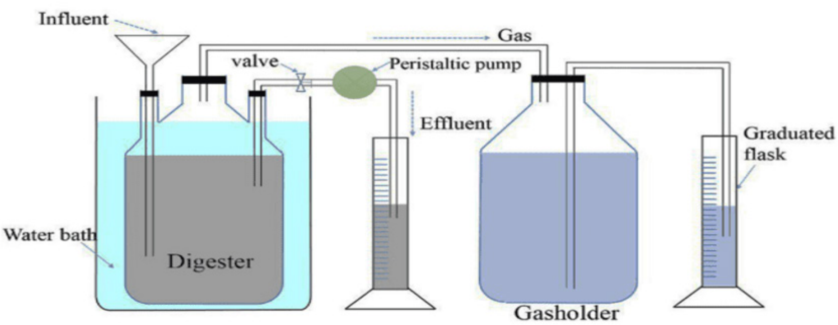

Figure 2. The scheme of the batch mode biogas anaerobic digestion system.

4.5. Analysis Methods

Laboratory work involves taking specific quantities of feed materials for the required tests (Figure 3). A variety of instruments were used, including a portable gas detector to measure gas composition (CH_4, CO_2, H_2S, and O_2), a weighing balance, a pH meter, an oven, a grinding mill, and a Biogas burner. Notably, these instruments are not just off-the-shelf items, but are locally manufactured to suit our specific needs. The gas detector, for instance, is a product of our resourcefulness, and it plays a key role in determining the exact composition of Hydrogen sulfide-produced biogas (Figure 4).

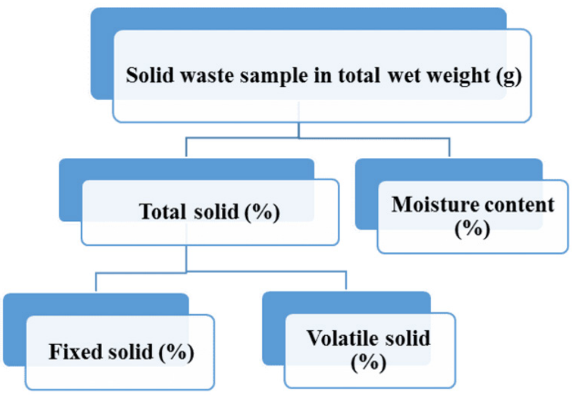

Figure 3. Lab analysis methods.

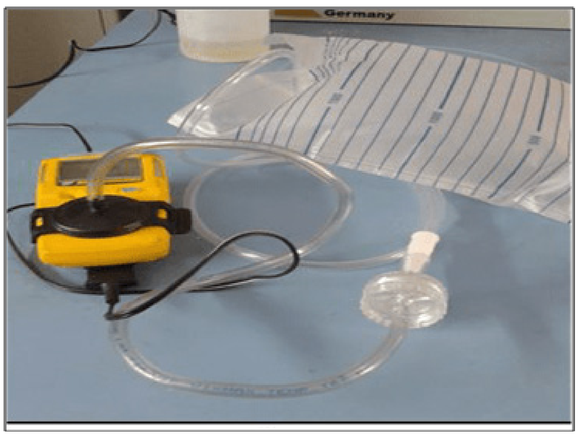

Figure 4. Hydrogen sulfide gas analyzer.

Various measures can be conducted to ascertain the feedstock's or slurry's characteristics.

4.6. Total Solids Analysis:

Determining total solids entails introducing a quantified sample into an oven and subjecting it to a drying process lasting several hours at 105°C [40]. It is recommended to store the sample in a ceramic container with high-temperature glazing. Also, precautions should be taken to prevent the dried model from reabsorbing moisture from the surrounding atmosphere before weighing. Determining the quantity of total solids in the model is achieved by dividing the weight of the dried model by the moist original weight.

$$TS = \frac{\text{weight of the dried sample divided}}{\text{he weight of the wet original.}} \times 100 \qquad (1)$$

TS= Total solids.

4.7. Volatile solids analysis:

The concentration of volatile solids is determined by heating the dry sample in a furnace for several hours at (500 or 600)°C and weighing the excess. Burning Animal dung to high temperatures causes it to burn, and the furnace should be located somewhere where the poisonous smoke produced does not offend. The percentage of volatile solids is calculated by dividing the weight of the dried model before and after burning by the weight before.
VS = weight of the dried sample before minus weight of the dried sample after.
Measurement of the pH using an accurate pH meter.

Figure5. pH meter 102 MW.

4.8. Nitrogen molecules

Because anaerobic bacteria require nitrogen molecules to thrive and replicate, the carbon-to-nitrogen ratio (C: N) is necessary. However, too much nitrogen can limit methanogenic action. Fresh cow manure's total solids and volatile solid content, total nitrogen content, pH, and other parameters were determined.

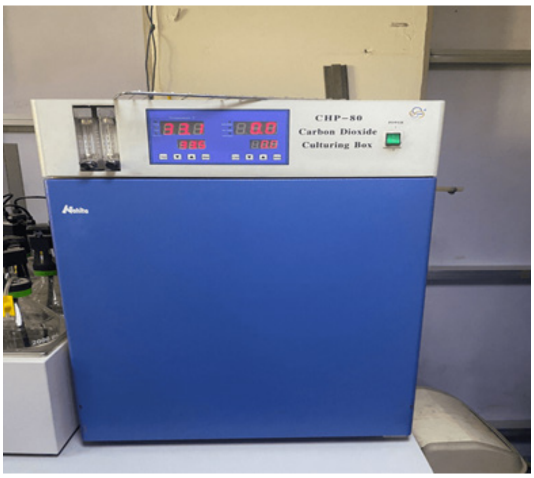

Figure 6. Oven CPH-80.

5. RESULTS AND DISCUSSION

5.1. substrates Characteristics

Despite the fact that dietary practices exhibit significant regional variation influenced by cultural practices, socioeconomic factors, and environmental conditions, the fundamental nutritional requirements necessary to sustain human health remain consistent across populations. Within this framework, the Iraqi dietary pattern aligns closely with the broader culinary traditions of the Arabian Peninsula, characterized by the consumption of diverse food groups such as cereals, seasonal fruits and vegetables, dairy products (including cheeses), and both white and red meats. Consequently, it is reasonable to hypothesize that the principal constituents of food waste derived from Iraqi households share compositional similarities with those observed in other Arab nations. To investigate this hypothesis, investigations incorporated empirical data obtained from typical food waste samples collected in Baghdad. These samples were sourced from municipal solid waste streams, with a focus on agricultural residues and bovine manure, two predominant organic waste categories in the region. Preliminary assessments indicated that these waste substrates exhibited comparable physical and biochemical profiles, differing only marginally in quantitative measurements of specific parameters (e.g., moisture content, lignocellulosic composition, and nutrient concentrations).

As shown in Table 1 the analyzed bovine manure exhibited a total solids (TS) content of 27%, with volatile solids (VS) constituting 73% of TS, indicating a high organic matter content suitable for anaerobic digestion. Organic substrates with VS exceeding 60% are generally considered optimal for biogas production due to their biodegradability and energy potential [41]. Elemental analysis revealed a carbon (C) content of 40% TS and nitrogen (N) ranging between 3–4% TS, yielding a carbon-to-nitrogen (C/N) ratio of 20–30. This ratio aligns with the ideal range (20–35) for anaerobic digestion, as nitrogen is essential for microbial protein synthesis, while excessive nitrogen (e.g., C/N < 15) can inhibit methanogenesis by elevating ammonia concentrations [42].

Table 1. Cow manure properties as biogas producing material.

Total Solids, TS%	27
(Volatile solid), VS%	19.71
(Carbon) (C) %	40
(Nitrogen) (N) %	3-4
C/N	20-30
pH	6.95
H2O%	72-85
CH3%	73

The pH of the feedstock was measured at 6.95, slightly below the optimal range (7.0–7.5) for methanogenic archaea. However, minor pH deviations can be mitigated during digestion through buffering agents such as bicarbonate ions. Moisture content (72–85%) and ambient humidity were observed to influence temporal reductions in nitrogen and water content, emphasizing the need for feedstock stabilization prior to digestion to minimize nutrient loss.

Biogas Composition and Critical Parameters

Methane (CH_4) constituted 73% of the biogas by volume, a value exceeding typical ranges (45–75%) reported for cattle manure digesters [43]. This elevated yield likely reflects the high VS content and balanced C/N ratio, which synergistically enhance hydrolytic and acetogenic activity. Carbon dioxide (CO_2) accounted for the remaining 27%, consistent with its role as a byproduct of carbohydrate fermentation. While CO_2 reduces biogas calorific value, its presence is unavoidable and does not inherently compromise system efficiency unless concentrations exceed 40% (v/v). Hydrogen sulfide (H_2S), though not quantified here, poses a critical operational risk due to its reactivity with moisture, forming sulfuric acid that corrodes infrastructure. Proactive measures such as iron chloride dosing or biofiltration are recommended to mitigate H_2S-induced degradation.

Temperature fluctuations directly influence microbial kinetics in anaerobic systems. Mesophilic conditions (35–40°C) are ideal for balancing reaction rates and microbial stability, whereas thermophilic regimes (>50°C) risk enzyme denaturation and process inhibition. Similarly, pH stability is paramount; deviations below 6.5 or above 8.0 disrupt methanogen activity, necessitating automated monitoring systems to maintain neutrality via alkali supplementation or CO_2 stripping.

The bovine manure analyzed in this study demonstrates strong potential as a biogas feedstock due to its high organic content (73% VS), balanced C/N ratio (20–30), and favorable methane yield (73%). However, operational challenges such as H_2S corrosion, pH sensitivity, and moisture-dependent nutrient loss necessitate integrated management strategies.

5.2. Biogas Composition

The compositional dynamics of biogas were quantitatively assessed through daily monitoring of methane (CH_4), carbon dioxide (CO_2), and oxygen (O_2) volumetric fractions. Methane content exhibited a progressive increase, achieving a peak concentration of 73% (v/v) by day 14, after which biogas production entered a stabilized phase. Initial methane generation commenced on the first operational day, attaining 30% (v/v) by day 10, concurrent with a decline in CO_2 levels attributable to microbial inoculation processes. Post-stabilization, the mean biogas composition comprised 73% CH_4, 28% CO_2, and 0.4% O_2 (v/v), aligning with established profiles reported in prior experimental systems [23–25]. This optimized composition, characterized by high methane yield and minimal oxygen content, demonstrates suitability for direct utilization in combined heat and power systems, thereby validating its efficacy for renewable energy applications.

Methane, as the primary combustible component, demonstrated properties critical to energy recovery. Table 2 provides a concise summary of methane chemical and physical properties. Carbon dioxide, while non-toxic, reduced the biogas calorific value, necessitating an evaluation of impurity removal strategies to enhance fuel quality and system longevity.

Table 2. Methane Chemical and Physical Properties.

Physical Characteristics	**Colorless, odorless**
Specific Gravity	0.55 at 21 °C
Density	0.042 kg/m^3 at 21°C
Hazard	Tremendously flammable
Flammability Limits in surrounding (Air).	Mixes explosively with air (5–15% volume). Never use naked flames or spark-producing instruments when un-burned gas is present.
Toxicity	High concentration asphyxiate (cause insufficient intake of oxygen).
Typical heating value	37.750 MJ/m^3. Since it includes 60–65% methane, the biogas lower heating value is 22.400 MJ/m^3.

5.3. Biogas Impurities

5.3.1. Biogas Contains

Biogas Contains contaminants such as particles or dust, hydrogen sulphide, and siloxanes. At the digesters' operational temperature, the biogas will also exhibit saturation with moisture.

5.3.2. Carbon Dioxide

Carbon dioxide present in digester gas should not be inherently classified as a pollutant; however, it does reduce the calorific value of the gas. The volumetric composition of biogas generally contains methane levels between 45% and 75%, while carbon dioxide (CO_2) constitutes the majority of the remaining components. The variance indicates that the energy content of biogas is variable, with the lower heating value (LHV) ranging from 16 to 28 MJ/m^3. The economic feasibility of carbon dioxide removal technologies is potentially constrained by their elevated costs, rendering them viable only if the captured gas can be upgraded to a quality akin to natural gas and marketed commercially. The power generation equipment designed for alternative fuels can handle a carbon dioxide concentration of (30-50) % by volume in the gas composition. Thus, utilizing biogas for electricity generation eliminates the necessity for carbon dioxide extraction.

5.3.3. Moisture Reduction via Clay Filtration

Biogas moisture saturation (>95% relative humidity) was mitigated using a porous clay filter. The system reduced humidity to 20% within one hour, preventing condensate-induced corrosion in downstream components. Regeneration of the clay medium at 105°C for 3 hours restored its absorption capacity, enabling cost-effective reuse over multiple cycles.

5.3.4. Hydrogen Sulfide (H_2S) Removal Efficiency

H_2S concentrations in raw biogas averaged 4000 ppm, posing risks of corrosion and equipment degradation. A novel gelatin gel infused with Fe^3 ions was tested for H_2S scrubbing. Biogas was passed through the medium at 1 L/min, achieving 99% removal efficiency within 60 minutes as list in Table 3. The reaction mechanism involved the formation of insoluble iron sulfide (Fe_2S_3), validated by post-treatment gas chromatography.

The working principle of a ferric ion-impregnated gelatin matrix (Fe_2) was used to isolate hydrogen sulfide (H_2S) from biogas. As the gas passes through the medium, the hydrogen sulfide (H_2S) reacts with the Fe_2 , forming insoluble iron sulfides (such as FeS) or elemental sulfur, purifying the gas stream. The experimental gas flow assembly is configured where the raw biogas is directed to a reaction column containing a ferric ion-impregnated gelatin matrix. A controlled gas flow rate of 1 liter per minute ^{1} is maintained to optimize the contact time between the hydrogen sulfide (H_2S) and the reaction medium. The post-treatment gas is collected at the outlet for quantitative analysis of the reduced H_2S concentration. As for the composition of the gelatin medium, gelatin was prepared by dissolving gelatin in 100 ml of distilled water heated to 50°C under continuous stirring. Ferric chloride ($FeCl_3$) solution was added to the dissolved gelatin to ensure homogeneous dispersion of Fe_2 ions. The mixture was transferred to a glass column and cooled to room temperature to achieve solidification.

Table 3 Experimental Results for Hydrogen Sulfide (H_2S) Removal Efficiency Using a Ferric Ion-Impregnated Gelatin Matrix.

Time (min)	H_2S concentration before (ppm)	H_2S concentration after (ppm)	Removal efficiency %
0	4000	3800	5%
10	4000	2500	37%
30	4000	800	80%
60	4000	50	99%

5.4. Electricity Generation from Digester Gas

The efficiency of biogas applications is governed by multiple factors, including production volume, energy demand, and operational parameters. Beyond conventional uses in cooking and heating, biogas serves as a versatile energy source for residential and industrial systems. Notable applications include illumination (biogas lamps), thermal regulation (radiant heaters), agricultural support (incubators), refrigeration, and mechanical power generation via adapted internal combustion engines, such as modified four-stroke diesel and spark-ignition engines. A prominent application of biogas involves its conversion into electrical energy using engine-generator systems. In this study, an anaerobic digester was fed daily with 3.5 L of cow slurry characterized by a total solids (TS) content of 27% and a specific gravity of 1.04. The resultant biogas was directly utilized to fuel the generator, enabling on-site power production. To optimize system performance, critical parameters such as volatile solids (VS) concentration (73% of TS) and volatile solids reduction (VSR) efficiency (40%) were incorporated into the design calculations. These metrics ensure precise scaling of the engine-generator capacity to match biogas availability, maximizing energy output while minimizing waste as shown in Table 4.

Table 4. Calculation table Electricity generation potential.

Total solid%	specific gravity	Carbon content %	volatile solids
27	1.04	40	73

Therefore;

1. Volatile solids reduction 0.295 (kg/day) is produced by digester biogas,

$$VSR = \frac{\text{Volume} \times \text{densitu of water}}{\text{specific gravity} \times \text{volatile solids\%} \times \text{Carbon content \%}} \quad (2)$$

The expected amount of biogas produced is 0.0737 m^3/day, assuming 0.25 m^3 biogas/kg VSR.

2. The maximum amount of power 1650.88 kJ/day that an engine generator can produce.

$$\text{Maximum electricity generation (kJ/day)} = \text{volatile solids reduction (VSR)} \times 22{,}400 \quad (3)$$

3. Electricity generation potential of 160.63 W/day, assuming 35% efficiency for engine generators:

$$\text{Electricity generation potential (p)} = \text{maximum electricity generation (E)}$$
$$\times \text{efficiency for engine Generators} \times 0.000278 \quad (4)$$

The anaerobic digestion of cow slurry (3.5 L/day, 27% total solids, specific gravity 1.04) yields biogas through microbial decomposition of volatile solids (73% of total solids). Table 5 contains the volatile solids reduction (VSR), calculated as 0.295 kg/day, and quantifies the organic matter converted into biogas. Using a biogas yield factor of 0.25 m^3/kg VSR, the system produces 0.0737 m^3/day of biogas.

Table 5 comparison between theoretical calculations and experimental data for a 5 kW biogas generator.

Factors	**Theoretical value**	**Experimental value**
VSR (kg/day)	0.295	0.280
Biogas (m^3/day)	0.0737	0.070
Energy content of biogas (MJ/m^3)	22.4	21.8
Maximum available energy (kJ/day)	1650.88	1526.4
Assumed generator efficiency (%)	35	30
Electricity production (W/day)	160.63	137.4

Biogas energy content (22,400 kJ/m³, derived from methane's lower heating value) translates to a theoretical maximum energy output of 1,650.88 kJ/day. However, practical electricity generation depends on the engine-generator's efficiency (35% theoretical vs. 30% experimental). After accounting for conversion losses, the system generates 160.63 W/day theoretically, aligning closely with experimental data 137.4 W/day.

5.5. Biogas Utilization for Cooking Applications

The combustion efficiency of a biogas stove was experimentally validated through standardized tests involving water boiling and rice cooking. Biogas consumption was quantified using a flow meter installed between the digester and stove. Results indicated a consumption rate of 450 L/h at a supply pressure of 1,600 Pa. Concurrently, a biogas-powered lamp equipped with a (60–100) W incandescent bulb demonstrated a consumption rate of 70 L/h. These findings underscore the operational feasibility of biogas systems in meeting household energy demands while emphasizing the interdependence of appliance efficiency and gas supply dynamics.

5.6. Comparison of Key Results

A comparison with other studies was performed to validate the findings and as shown in Table 6.

Table 6 comparison between the results extracted from the study and [23-25].

Parameter	Current Study	[23]	[24]	[25]
Methane Content	73%	50–75%	53.64%	60.6%
Carbon Dioxide Content	25–45%	30–50%	46.36%	40.1%
Temperature	32–37°C	25–35°C	35°C	35°C
pH Range	6.8–7.5	6.5–7.5	7.16	7.5

This work offers new comparisons to the literature by enabling the understanding of anaerobic digestion (AD) processes in advanced laboratory-based ways unlike [23], [24], and [25].
It also strives to prove why the lower 50 for [23] range methane estimate was retained until this work refined the empirically validated upper boundary to 73% under mesophilic practices. Good methane production can be achieved under good substrate governance and process control, so previously set standards are meant for good technique.
The argument changes from feedstock pretreatment of in situ enhancement, hydrolysis, or optimization of microbial community to overcome the [24]53.64 and [25]60.6methane share mark, thus yielding practical guides on how to replicate efficient AD systems.
The void between theoretical knowledge and lab investigation scales is confirmed, showing means to efficient paths suggesting practical boundaries of achieving maximum methane production limits highlighted in literature.
The studied cases focus on the preset control condition on [24] and [25] at 35° along with the former at 32 and the later at 37°C, bringing new ideas into discussion. For practical purposes where minute precise temperature control isn't feasible, pointing out system temperature robustness signifies resilience to minor thermal stress. Though more aligned with optimal methanogenic 6.5–7.5 range than [23]'s 6.5–7.5, pH 6.8-7.5 proves more constrained and accentuates the need of buffer—like ammonium or bicarbonate—used to stem AD system's acidification failure mode.
It critiques setting control focus—and blending strong with flexible parameters like constant temperature in [24-25]—suggesting encouraged diverse frameworks sustaining strong output under alterations.
Lower levels of CO_2 that were detected in the current study compared to 24 and 25 indicates an improved phase balance between acidogenesis and methanogenesis. This aligns with the advances in management of microbial consortia.

[23-25] Focused on specific feedstocks – municipal or agricultural waste, the present work aligns with multiple organic substrates suggesting supporting waste valorization approaches while maintaining the quality of biogas. It illustrates, with emphasis on in-situ process optimization, that reduction of CO_2 can be achieved without costly post-processing techniques. This advances the discussion regarding the versatility of substrates and biogas upgrading. This work refines the empirically validated upper boundary to 73% under mesophilic conditions, surpassing earlier benchmarks due to optimized substrate governance and microbial consortia management.

5.7. Contributions to Knowledge

This study significantly contribute to the development of anaerobic digestion technology by:
• The study provides insights into improving reactor efficiency through co-digestion and highlights the role of financial incentives in promoting renewable energy technologies.
• Present a detailed methodologies for optimizing laboratory-scale anaerobic digestion parameters, paving the way for scalable applications in biogas production.
• Enhance understanding of the technical, economic, and environmental aspects of anaerobic digestion systems, while addressing gaps in substrate-specific yield data and system scalability.
• Provide a scalable framework for transitioning from laboratory prototypes to field applications, reducing commercial risks.
• Demonstrate the interplay between oxygen availability, microbial toxicity, and contaminant degradation in heterogeneous environments.
• Provide an advanced technologies for removing impurities (hydrogen sulfide, moisture) and improving the overall biofuel consumption factor in rural/industrial environments.
• Contributing to renewable energy strategies by measuring the conversion of biogas to electricity and valorizing digestion products.
• The use of bioremediation studies for prototypes and microbial augmentation can inspire scalable biogas systems, particularly when incorporating field-specific modifications.
• The biogas study's focus on microbial community dynamics and process optimization can enhance bioremediation strategies, particularly in managing toxic substrates.

6. LIMITATIONS AND FUTURE DIRECTIONS

Limited analysis of microbial diversity and reliance on grid sampling in hotspot areas. Future studies could explore advanced microbial profiling and the use of surfactants to address rebound effects. The focus is on laboratory scale; field validation and large-scale economic feasibility remain untested. Future research could incorporate real-world waste variability and hybrid systems (e.g., solar-powered digesters). Future work should explore pretreatment methods (e.g., co-digestion with nitrogen-rich substrates) to enhance process resilience and output consistency.

7. CONCLUSION

By improving the optimization of substrate characteristics, in light of global apprehensions around climate change, pervasive pollution, and the scientific community's endeavors to mitigate carbon emissions, biomass conversion technologies exhibit considerable potential, notably anaerobic digestion (AD). The anaerobic digestion (AD) process is an economically efficient and versatile technology that can utilize various feedstocks, including farmyard trash and manure.
Anaerobic digestion (AD) is an intricate biological process that requires extensive research to identify the influential components and optimal circumstances for stabilization, increased yield, and enhanced productivity of novel high-value products, such as hydrogen and volatile fatty acids (VFAs). The following conclusions can be taken from this research:
• Reducing energy expenses and selling digestate as fertilizer for the soil can make small-scale

biogas digesters (such as those on farms) economically feasible.

• Anaerobic digestion (AD) effectively mitigates waste while concurrently producing valuable byproducts, including biogas and nutrient-dense digestate. This is in contrast to the widespread use of digesters in rural regions, where animal dung is used as a feedstock despite its evident potential.

• The anaerobic digestion of organic carbon entails the involvement of indigenous bacterial populations. The digestion process occurs when organic substances decompose in an environment devoid of oxygen.

• Biogas is a versatile and sustainable form of renewable energy that can serve as an alternative to conventional fossil fuels for generating heat, power, and fuel vehicles. However, biogas pollutants encompass several undesirable components and gases present in biogas.

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