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Design and Implementation of a Biogas Pilot Plant for Bioaugmentation Strategies in a rural municipality

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Abstract. The transition towards renewable energy sources is imperative for achieving sustainability and mitigating climate change impacts. Among various renewable energies, biogas stands out for its dual role in waste management and energy production. This study introduces the design and implementation of a biogas pilot plant aimed at exploring bioaugmentation strategies to enhance biogas yield and quality. The pilot plant, located at Aras de los Olmos, features two independent 3.4m^3 digesters, allowing for parallel comparison between standard anaerobic digestion and digestion with microbial enhancements. The plant is equipped with monitoring and control systems for precise regulation of environmental conditions, such as temperature, and for real-time measurement of biogas composition. Some initial experiments using a mix of agricultural wastes demonstrated the plant's capability to adapt to varied feedstock. Despite suboptimal temperature conditions, preliminary results indicated a high methane content, suggesting significant potential for bioaugmentation to improve biogas production efficiency. The study highlights the importance of controlled environmental conditions and introduces a novel bioaugmented digestion approach using selected microbial consortia. This research contributes to the broader goal of enhancing biogas technology's efficiency and sustainability, offering insights into the practical application of bioaugmentation in biogas production.

Key words. biogas production, bioaugmentation, pilot plant design, renewable energy, microbial consortia.

1. Introduction

The challenge of addressing climate change and advancing towards global sustainability underscores the urgency of transitioning to cleaner and renewable energy systems. In this context, biogas emerges as a promising and versatile energy solution, offering multiple environmental and economic benefits. Through anaerobic digestion (AD) of organic matter, biogas production not only yields a methane-rich mixture [1] but also efficiently manages the treatment of organic waste, significantly contributing to the reduction of greenhouse gas emissions [2]. Moreover, biogas distinguishes itself by its ability to generate electricity and heat, control the power generated, and manage production independently of weather conditions, setting it apart from other renewable sources such as solar and wind. Recent advancements in bio-integrated carbon capture and utilization further highlight the potential of biogas systems to transform carbon dioxide gas streams into methane, offering a sustainable pathway to mitigate climate change impacts [3].

Within the framework of the European project MICRO4BIOGAS (M4B) titled Natural and Synthetic Microbial Communities for Sustainable Production of Optimised Biogas (ref.: 101000470) [4], an ambitious initiative has been undertaken to optimize the biogas production process. This project aims to improve the efficiency, quality, speed, and robustness of biogas production through bioaugmentation strategies that leverage natural microbial strains and artificial microbial consortia. These efforts are aligned with the EU Bioeconomy Strategy and the European Green Deal, highlighting the commitment to innovation in the bioenergy sector.

The M4B project is structured into eight work packages that range from the characterization and selection of microbial consortia to the laboratory-scale validation of bioaugmentation strategies [5]. This comprehensive approach provides a robust framework that integrates cutting-edge scientific research with practical, scalable solutions. The ultimate aim is to enhance the sustainability and operational efficiency of biogas systems, thereby reinforcing their position as a crucial, eco-friendly energy resource.

This article focuses on the experimental work carried out by the GEDER group from Universitat Politècnica de València (UPV), designing and building a pilot plant with two twin anaerobic digesters in Aras de los Olmos, that will work as a large-scale laboratory. This design allows for the testing and validation of various bioaugmentation strategies, marking a milestone in applied research in the field of biogas. The goal of this paper is to detail the design of the pilot plant, offer a guide for the construction and operation of similar prototypes, and justify the relevance of these innovations for the bioenergy industry. The significance of such initiatives is underscored by the growing body of

research on sustainable waste management practices, highlighting the critical role of innovative technologies in enhancing the environmental and economic sustainability of biogas production [6].
By integrating experimental and theoretical results, this study significantly contributes to the existing literature on biogas production and presents a replicable model for the optimization of biogas plants through bioaugmentation. Thus, this work not only reflects a significant scientific advance but also proposes practical solutions for contemporary energy challenges, reinforcing the role of biogas in the transition to a more sustainable energy future. In this vein, the methodology proposed by [7] for optimizing a hybrid biogas and photovoltaic system underscores the potential for sustainable power supply in rural areas, demonstrating significant reductions in energy costs and environmental impact for small rural populations. This aligns with the proposed research on enhancing energy autonomy through innovative bioaugmentation strategies in biogas production, further emphasizing the importance of integrated approaches to renewable energy system optimization in rural settings.
The paper is organised as follows. Section 2 presents the pilot plant designed for the experiments. Section 3 shows the initial experiment performed in the pilot plant. Then, Section 4 describes the future operation of the future plant. Finally, in Section 5, some conclusions of the presented work are drawn.

2. Description of the biogas plant

In the continuous search for sustainable solutions to address environmental challenges, the M4B project seeks to improve the biogas production process. Within this scope, the assembly of a small biogas plant where relevant tests can be carried out to quantify improvements in biogas production is of great importance. This section details the fundamental elements that make up the installation of a biogas plant, consisting of two independent digesters of 3.4 m^3 each.

A. Feedstock Tank

The feedstock tank allows for the accumulation and homogenization of organic waste, creating a constant flow of material for the digester. This initial step is crucial to ensure efficient anaerobic digestion.
This tank is designed to store animal manure, which is collected from farms in the municipality. The dimensions of this tank are 100 x 150 x 300 cm (DWH), allowing it to store a maximum of 4,500 L. The capacity of this tank not only translates into effective management of excrement but also facilitates the optimization of the digester load, thus contributing to the stability and optimal performance of the biogas plant.
Likewise, a grinder pump for wastewater is available to push the organic matter into the digesters. To perform its extraction and cleaning, a pulley system located above the feedstock tank has been installed. All this is shown in Figure 1.

B. Biogas Digesters

The anaerobic digestion process takes place in the digesters, a biological process where microorganisms break down organic matter producing biogas. This gas, primarily composed of methane and carbon dioxide, is stored and used as a valuable fuel source.

Fig.1. Feedstock tank in construction phase.

Specifically, there are two digesters with a total volume of 3.4m^3 each from Biogas Puxin. Of this volume, 2m^3 corresponds to the fermentation capacity (the amount of organic matter that can be stored) and a biogas storage volume of 1.4 m^3. Each digester has dimensions of 195x156x120 cm and is located within a thermally insulated enclosure from the outside as shown in Figure 2. Figure 2 corresponds to the assembly stage, where the structure can be clearly appreciated. Subsequently, the space where the digesters are located was completely enclosed. To ensure an optimal temperature of this enclosure, two ceramic thermal emitters were installed to keep the room at a temperature of above 30ºC, to ensure the growth of methanogenic bacteria. Likewise, gas sensors are available inside the insulated enclosure, in case there is a gas leak from any of the digesters, to deactivate all electrical and combustion equipment.

Fig.2. Thermally insulated enclosure where the digesters are located.

On the other hand, within the scope of the M4B project, it is intended to analyze the influence of new bacteria developed in improving biogas production. This is why it is important to have two independent digesters. The first one is used as a reference, where only organic matter is introduced. The second digester is used to introduce organic matter and the newly developed microbiome. Since both digesters use the same organic matter, as it comes from the same storage pond, and are in identical conditions, the only difference between them is the microbiome inoculated in the second digester. This allows for a correct analysis of the influence on biogas production. For this reason, although the organic matter is identical in both digesters, it is necessary to perform an independent filling and emptying installation for both digesters, to avoid any cross-contamination between them. Additionally, the biogas installations of both digesters are independent of each other to prevent any interaction between the biogas generated in either of the digesters. Figure 3 shows in detail one of the two digesters, where the storage bag for organic matter and biogas (blue) can be seen, as well as the filling pipe that connects to the storage pond.

Fig. 3. Biogas Puxin 3.4m^3 digester

C. Biogas Treatment and Storage

After the biogas is generated in the digesters, the next crucial step is to undergo a treatment process that improves its quality and facilitates its storage and use. This treatment consists of three essential stages: dehydration, desulfurization, and storage in bags.

1) Dehydration:

The biogas produced in the digesters contains a significant amount of water vapor, which can affect its quality and performance. To overcome this challenge, a dehydrator is implemented, which is a device that removes excess moisture from the biogas. This dehydration process not only improves the gas quality but also prevents corrosion in distribution and storage systems.

2) Desulfurization:

Another critical component in biogas treatment is the desulfurizer. Although biogas is a clean energy source, it often contains traces of sulfur compounds that must be removed to prevent corrosion and to meet environmental standards. The desulfurizer acts as a filter, efficiently removing sulfur from the biogas and improving its quality for broader applications. This desulfurizer is made of iron oxide (FE203) pellets.

3) Storage:

Once treated, the biogas is directed to a specialized 2 m³ storage bag. The bags allow for safe and efficient storage of the biogas before its use. The flexibility of the storage bags adapts to variations in biogas production, ensuring constant availability for utilization.
The combination of dehydration, desulfurization, and bag storage not only improves the quality of the biogas but also prepares it for use in various applications, such as electricity generation and heating.

Figure 4 shows the desulfurizers, storage bags, flow meters, and booster pumps of each digester. As aforementioned, each digester has an independent installation to avoid cross-contamination of the biogas.

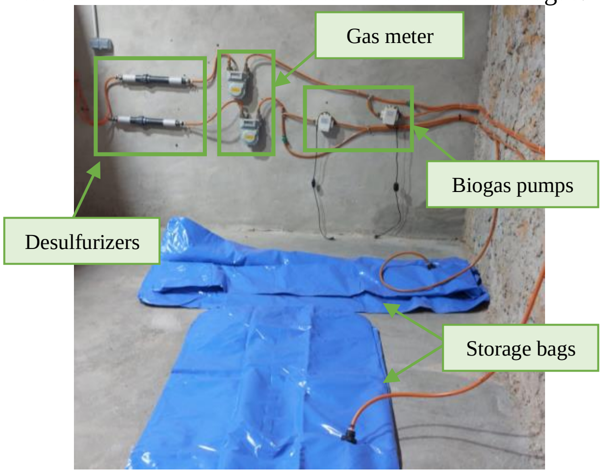

Fig 4. Desulfurizers, gas meters, biogas pumps and biogas storage bags.

D. Biogas Equipment

Once the biogas is treated and ready for use, it can be utilized in various equipment. Specifically, there is a burner and a biogas motor-generator available.
Prior to these devices, at the outlet of the storage bags, there is a flow meter and a 15 mbar biogas pump for each independent biogas installation. The flow meter measures and regulates the flow of biogas, ensuring a constant and controlled supply. On the other hand, the biogas pump ensures that the biogas is delivered to the burners or electrical generators at the correct pressure.

1) Burner:

Biogas burners play an essential role in the direct use of gas for applications such as heating or industrial processes. The burners allow control of the biogas flow, ensuring efficient combustion.

2) Biogas Electrical Generator:

For the generation of electricity from biogas, electrical generators are essential. These devices convert the energy contained in the biogas into usable electricity. The generated electricity can be used to power local facilities or integrated into the electrical grid, thus contributing to energy self-sufficiency and reducing dependence on traditional sources. For this purpose, there is a 1.5 kW PX1500EBG motor-generator, prepared to operate with biogas. Figure 5 displays the generator. In the vicinity of the generator, a CO (carbon monoxide) detector has been installed for safety purposes.

Fig 5. Biogas motor-generator.

E. Measurement Equipment

In addition to the practical use of biogas using the burner and the generator set, it is necessary to quantify the quality of this biogas. On the one hand, it is necessary to know the pH of the organic matter at all times during the anaerobic digestion process to ensure proper biogas generation. On the other hand, the quality of the generated biogas must be quantifiable through an analyzer, and the energy efficiency of the motor-generator depending on the biogas used.

1) pH Meter:

The pH meter is a vital instrument in the operation of the biogas plant. It is precisely introduced into the digesters to monitor and control the acidity or alkalinity level of the environment. This device plays a crucial role in ensuring that conditions are optimal for microbial activity in the anaerobic digestion process. By measuring the pH from inside the 3.4m³ digester, precise control over acidity is achieved, thus ensuring efficient decomposition of organic matter and constant production of biogas.
Specifically, the HI510 Universal Process Controller from Hanna Instruments is used in this pilot plant, which comes with a pH and temperature measurement probe. The pH probe must be calibrated using two solutions with pH values of 7.0 and 10.0 before taking measurements, and it should be cleaned with a special solution every 3 days.

2) Biogas Analyzer

The biogas analyzer is strategically positioned to measure and assess the quality of the produced biogas. For this purpose, a coupling to the pipes located at the exit of the storage bag is available. This device is essential for monitoring the gas composition, ensuring that it meets the required standards for efficient and sustainable use. By analyzing the proportion of components such as methane, carbon dioxide, and other gases present in the biogas, the analyzer provides critical information on its viability as an energy source.
The OPTIMA Biogas Analyzer is available as a measuring device, which includes measurements of O_2 (0-25%), H_2S (0-2,000ppm), CH_4 (0-100%), and CO_2 (0-40%).

3) Energy Analyzer

The energy analyzer used in the biogas plant is the Fluke 1777 (Figure 6), a sophisticated measurement tool designed to analyze and monitor the quality of the electrical energy generated from the biogas motor-generator. It facilitates precise measurements of parameters such as voltage, current, active power, reactive power, power factor, harmonics, and total harmonic distortion (THD). With these values, it is possible to analyze changes in the generator's performance based on the biogas used. This will allow for the evaluation of whether the microbiomes, in addition to enhancing biogas production, also improve its quality for energy generation purposes. This capability underscores the importance of not just increasing biogas quantity but also ensuring its quality meets the standards required for efficient energy production, marking a significant step towards optimizing renewable energy sources.

Fig 6. Energy Analyzer Fluke 1777

F. Plant Layout

In summary, the plant layout plan includes the arrangement of all the mentioned equipment, as depicted in Figure 7. This plan includes both the biogas and liquid organic matter installations within the pilot plant, ensuring the proper connection of all elements while preventing any cross-contamination.

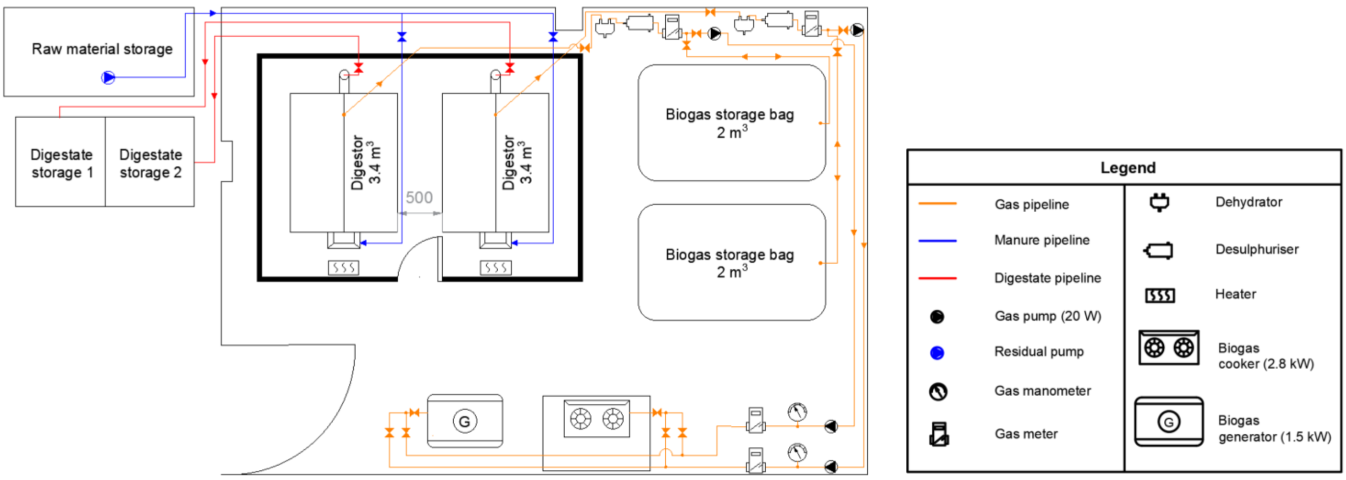

Fig 7. Layout of the biogas plant.

3. First test conducted

A first set of experiments was conducted only in one of the two digesters, when the heating system was not yet in place, so the temperature was ambient, to test that the process was properly carried out. Therefore, it must be taken into account that the production is not under optimal conditions but it is intended to improve these results both by implementing temperature control and by adding the M4B microbiomes.

For this initial test, 800L of pig excrement, 800L of rabbit excrement, and 400L of cow excrement were used. The latter is extremely useful, as it contains plant residues and starts the production more quickly. It is worth mentioning that the CH_4 value, despite not being under good conditions, is quite high. Therefore, high-quality biogas is expected in the next trials, having a more stable temperature and being able to experiment with the microbiomes. Figure 8 shows the evolution of biogas production (accumulated) and the temperature evolution during the first experiment. The composition in Figure 8 has been estimated from the final measurements regarding the composition of biogas, analyzed using the OPTIMA Biogas Analyzer. The results of the final biogas composition are presented in Table 1.

Table I. – Composition of the generated biogas.

Component	Value
CH_4	77.34 %
CO_2	20.60 %
N_2	2.00 %
O_2	0.06 %
H_2S	2,868 ppm

Analysing the results obtained from the first experiment, it is evident that the biogas produced is of high quality, as the percentage of CH_4 is significantly elevated. Typically, biogas comprises approximately 50-70% methane (CH_4) and 30-50% carbon dioxide (CO_2). However, the outcomes of this initial trial have shown higher than average CH_4 levels and lower CO_2 levels, translating into a more efficient utilization of the stored energy in the biogas.

Nevertheless, the biogas sample exhibited a high concentration of hydrogen sulfide (H_2S). Such a level is unacceptable, as it can be toxic and may significantly reduce the lifespan of the engine. A second stage of desulfurization was necessary for the use of the generated biogas. This additional treatment step is crucial for ensuring the biogas's safety and efficacy, highlighting the importance of comprehensive gas quality management in optimizing biogas for energy applications.

4. Discussion and future operation of the pilot plant

The design of the biogas pilot plant represents a functional milestone, validated through initial operational tests. This discussion outlines the critical design decisions made, providing a summary of essential points and advice for future prototypes. Additionally, it elaborates on how the plant will be utilized for bioaugmentation tests.

A. Design Decisions:

Digesters Size: The chosen size aims to mimic a real plant scenario, accommodating larger input/output of material than what laboratory-scale containers allow, yet manageable by one or two persons. This balance ensures a practical scale for experimentation while maintaining relevance to real-world applications.

Storage Pond Size: The storage pond is sized to correspond with the capacity of the two digesters, ensuring sufficient storage of feedstock for continuous operation without frequent refilling.

Storage Bag Size: Designed to store the estimated biogas production for 2-4 days, acknowledging that the plant might not be operated daily. This consideration is crucial for a pilot plant operated by a limited number of personnel.

Safety Equipment: Safety measures include CO alarms near the motor and CH_4 alarms near the digesters, emphasizing the importance of maintaining a safe working environment.

Dual Digesters: The installation of two digesters facilitates comparative studies between bioaugmented and non-bioaugmented processes. This necessitates the

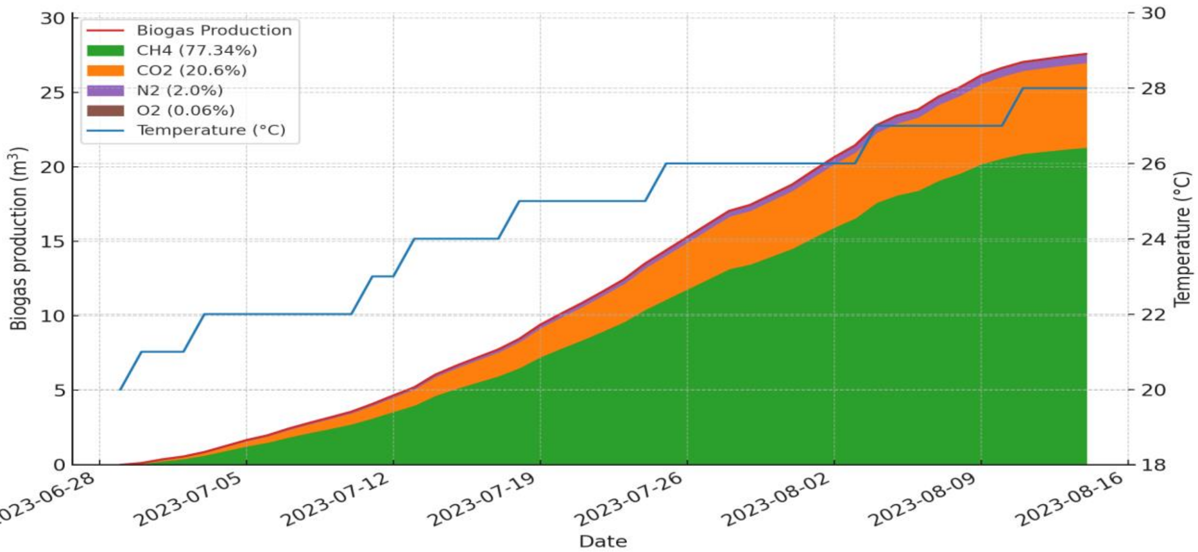

Fig 8. Evolution of accumulated biogas production (including its estimated composition) and temperature evolution during the first test.

duplication of gas installations to independently manage each digester's biogas output, allowing for a controlled comparison of bioaugmentation effects.

Burner and Generator Size: The capacities of the burner and generator are selected to allow for experiments lasting 2-3 hours, yielding significant operational parameters.

Measurement Equipment: The selection of pH and biogas analyzers is guided by the typical ranges observed in biogas digesters. Devices that accurately measure within these expected ranges are critical for monitoring the digestion process and evaluating the bioaugmentation impact.

B. Application for Bioaugmentation Tests:

The pilot plant is strategically designed to assess the effectiveness of bioaugmentation in boosting biogas production. By featuring two digesters, the setup facilitates a comparative analysis of biogas yield and quality from both standard operations and bioaugmented processes. This side-by-side evaluation is crucial for evaluating the impact of introduced microbial consortia on biogas enhancement. Furthermore, the design of the plant embodies scalable and practical operational aspects, making it an exemplary framework for translating bioaugmentation research from the lab to real-world applications.

Additionally, the comparison extends beyond the two digesters at this pilot plant. Results will be juxtaposed not only before and after the implementation of bioaugmentation strategies within this facility but also against outcomes from other small/medium-sized pilot plants involved in the M4B project. This broader comparison will enrich the understanding of bioaugmentation's effectiveness across different settings and scales, providing a more comprehensive perspective on its potential in the biogas sector.

The ongoing monitoring and detailed analysis of each digester's performance will ensure a nuanced understanding of bioaugmentation's impact over time, enabling a dynamic assessment rather than a static comparison at the end of the experiment.

In sum, the pilot plant's sophisticated design and operational functionality mark a significant advancement in biogas research, especially in exploring bioaugmentation's potential. With careful consideration given to the size of the digesters, storage capabilities, safety protocols, and measurement precision, this facility offers a robust and insightful environment for conducting pivotal bioaugmentation experiments. The knowledge gleaned from this pilot study, enriched by comparative insights from other plants in the project, will be instrumental in refining biogas production techniques, highlighting the pivotal role of bioaugmentation in advancing renewable energy solutions.

5. Conclusions

This paper has detailed the technical components of a 6.8m³ biogas plant, which can be replicated by any user by providing information on the equipment used, its connections, and layout. By sharing these details, we aim to contribute to the broader application and understanding of biogas plant operations, offering a template for future projects and research in renewable energy sources.

In this study, the challenges encountered during the initial trial and the subsequent improvements made to ensure the plant operates under optimal conditions have also been discussed. These adjustments highlight the iterative nature of experimental research, where each trial provides valuable insights that contribute to the overall efficiency and effectiveness of the process.

Looking ahead, this biogas plant will serve as a crucial tool for analyzing the impact of bioaugmentation strategies within the framework of the M4B project in the coming months. The anticipation is that these strategies will significantly influence the quality and quantity of biogas production, providing a sustainable solution to energy generation and waste management. The findings and the plant's design not only contribute to the scientific community's understanding of biogas production but also offer practical insights for enhancing renewable energy resources through innovative approaches such as bioaugmentation.

In conclusion, the development and optimization of this biogas plant represent a significant step forward in renewable energy research, particularly in the context of bioaugmentation. The insights gained from this work lay the groundwork for future studies, aiming to further enhance the efficiency sustainability, and applicability of biogas technology in the broader context of renewable energy systems.

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