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Simplicity Hits the Gas: A Robust, DIY Biogas Reactor Holds Potential in Research and Education in Bioeconomy

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Abstract: Biogas is a promising and robust renewable energy that holds potential as clean energy in the context of the current climatic emergency. Biogas has the immense advantage of coupling waste management and clean energy production. In other words, it is not only a renewable energy source, but also a central tool in recycling a vast range of waste products from the agroindustry. Despite its potential, the process is microbiologically complex and is usually carried out in both industrial and pilot laboratories, utilizing a variety of reactors and systems. In this work, we present a very simple, Do It Yourself (DIY) biogas fermenter that we have designed, operated, and characterized. We propose this technology as both an inexpensive proxy for biogas reactors in academic and private laboratories and as an effective dissemination tool to foster the knowledge and potential of biogas as a key technology to contribute to the development of a global bioeconomy.

Keywords: biogas production; dissemination tool; DIY biogas digester; renewable energy; science education; waste management

Citation: Vogel, F.W.; Carlotto, N.; Wang, Z.; González-Herrero, R.; Giménez, J.B.; Seco, A.; Porcar, M. Simplicity Hits the Gas: A Robust, DIY Biogas Reactor Holds Potential in Research and Education in Bioeconomy. *Fermentation* **2023**, *9*, 845. https://doi.org/10.3390/fermentation9090845

Academic Editors: Jay J. Cheng and Yaojing Qiu

Received: 28 July 2023
Revised: 23 August 2023
Accepted: 13 September 2023
Published: 15 September 2023

1. Introduction

There is an increasing demand for research on greenhouse gas (GHG) mitigation technologies and on renewable resources as a viable alternative to fossil fuels [1]. In addressing the climatic emergency, a holistic approach that includes research, science dissemination, and fostering of consensus is required. In this regard, universities, as educational and research institutions, have a pivotal role in science dissemination [2,3]. Within this context, the easy-to-grasp concept of biogas as renewable energy emerges as a powerful approach.

Biogas is a combustible gas generated through the anaerobic digestion (AD) of organic matter by a diverse microbial community, primarily composed of methane (CH_4; 55–75%) and carbon dioxide (CO_2; 25–45%) [4]. A large variety of biomass, including animal manure and food waste, can serve as substrates in the AD process, which is an energetic valorization practice that contributes to proper organic waste treatment [5]. Therefore, biogas production appears as an alternative solution for a waste-to-energy (WtE) process, being considered as an ecological fuel since it is produced through renewable sources with a potential for generating electricity, thermal energy, vehicular gas (biomethane) and organic fertilizer through the production of a digestate, a co-product of the process [6,7]. Despite its potential as an excellent alternative for both renewable energy generation and organic waste treatment, the high cost of the technology associated with biogas production presents a major hurdle in its widespread adoption [8]. Additionally, the microbiological process involved in biogas production remains elusive for scientists, often perceived as a black box [9–11].

The degradation of organic matter and the production of biogas take place inside of biodigesters. These biodigesters can be made with different materials (plastic, metal, brick, among others) and can also come in different shapes and sizes (industrial scale, pilot scale, domestic scale, and laboratory scale) [6,12]. Thus, selecting a biodigester model implies considering the investment level, type of substrate to be treated, and environmental conditions [6,13]. However, due to the technology applied, biodigesters present a very high cost, even for laboratory-scale models used for research. As a result, many researchers have been adopting the term DIY (Do It Yourself) for the construction of biodigesters with cost-effective materials.

Several publications report the use of this kind of biodigester both for research in academic labs and for teaching in schools. Brito-Espino et al. [14] introduced DIY sensors of pH, redox potential, pressure, and temperature for the indirect monitoring of the microorganism's growth in a lab-scale anaerobic digester, with the main objective of helping engineering students learn and understand the operation of an anaerobic digester. Eckert et al. [15] developed a laboratory-scale batch biodigester using alternative materials in order to disseminate techniques for the construction of biodigesters; although the economic viability was confirmed, the model presented flaws (i.e., methane losses). McGee et al. [16] developed a mathematical kinetic model to analyze the functioning of lab-scale digesters; however, they relied on data taken from the literature. Do Marques Do Carmo [17] performed workshops in elementary schools to construct homemade biodigesters during science lectures. Although the design and performance of the digester were not reported, it was concluded that the activity was highly accepted by the students as they could discuss the environmental impacts of this technology. In addition, Cassia Souza et al. [18] proved that homemade biodigesters in schools are useful to disseminate the United Nations Sustainable Development Goals #4 ("quality education"), #7 ("affordable and clean energies"), and #11 ("sustainable cities and communities"). Oliveira Duarte et al. [19] performed a bibliographic survey of the topics "biodigesters" and "environmental education" and reflected the value of the use of biodigesters to disseminate concepts of organic waste management and demonstrating the development of low-cost biodigester prototypes to engage students in a discussion about renewable energy and environmental education. Therefore, the importance of cost-effective biodigesters as instruments for disseminating environmental education in high schools and promoting scientific studies in universities is evident. However, a simple, economical, and robust biodigester for research and education purposes, highlighting in detail the step-by-step of its construction, together with a physical–chemical characterization of the AD process that validates the digester, is still missing.

Thus, the main objective of this study was to fully design a simple and economical DIY biodigester, with the aim of being easily replicated as well as validate its performance by characterizing the main physical–chemical parameters (TS, VS, CH_4 concentration, CH_4 volume, and pH) and fulfills both academic and educational requirements. This digester serves as a powerful science dissemination device in schools and can also be used in the academic field, because of the simplicity and thus ease of construction, conceptual link with bioeconomy and renewable energies, and dissemination potential as a very visual device.

2. Materials and Methods

2.1. Biodigester Design

In this study, a 20-L digester was designed and built to be operated in a batch and manually agitated [18,20]. The designed bioreactor can be grouped into 4 distinct parts: (1) the bioreactor itself, serving as the fermentation chamber; (2) the filter system; (3) the biogas storage system; and (4) the system for conducting the flame test, as depicted in Figure 1.

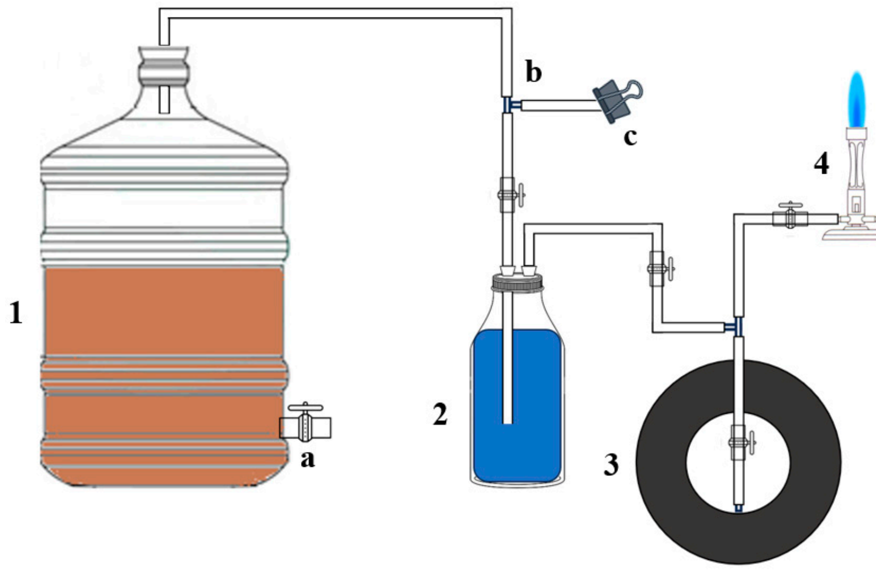

Figure 1. Schematic diagram of the DIY biodigester: (1) fermentation chamber; (2) filter system; (3) biogas storage system; (4) flame test system; (a) vales; (b) T-connector; (c) binder clamp.

Fermentation chamber: The biodigester itself, functioning as a fermentation chamber, was constructed using a 20-L recyclable plastic water bottle. To ensure sample collection for subsequent analysis, a valve was inserted through a 20 mm drilled hole near the bottom of the bottle, firmly secured with rubber rings (see Figure S1a). This setup allowed for regular weekly collection of liquid samples. The top opening of the bottle served as the feeding inlet, which was subsequently hermetically sealed using the bottle cap itself after feeding with substrate and inoculum. The cap featured a hole where a hose pipe was introduced, enabling a direct flow of biogas from the digester to the filter system, as illustrated in Figure S1b. To maintain an anaerobic environment within the biodigester, all the seals were carefully reinforced with an appropriate glue (Soudal T-Rex Flex, Soudal Química S.L., Alovera Guadalajara, Spain) to prevent any gas leakage. Before the filter, a T-connector was incorporated to allow biogas sampling for the analysis of CH_4 and CO_2 content.

Filter system: In order to purify the biogas and increase the methane content, a filter was developed using a 500 mL plastic container filled with a 3M sodium hydroxide (NaOH) solution [21]. CO_2 reacts with NaOH forming sodium carbonate (Na_2CO_3) with its subsequent depletion from the raw biogas, increasing the concentration of CH_4. The lid of the plastic container was drilled with two 20 mm holes, to which two nipples, two threaded sleeves, and two male hose pipe connectors were securely attached, as shown in Figure S2. Subsequently, pipes were connected enabling the biogas to reach the solution. To ensure a tight seal and prevent the biogas from leaking out, glue was applied around both the 2 nipples and the plastic container lid itself. The solution was supplemented with thymolphthalein to indicate an optimum pH between 8.2 and 10 with a blue color.

Biogas storage system: The biogas storage system was built using an adapted motorcycle air chamber, where the valve core of the chamber had to be removed to allow the biogas to pass into the air chamber (Figure S3).

Flame test system: The burning potential proof of the filtered biogas was built using a Bunsen burner attached to the piping system (Figure S4) which must be used with the air inlet closed to perform the flame test.

2.2. Biodigester Construction Materials

The materials used for the construction of the AD system are shown in Table 1, while the photos of each component are depicted in Table S1.

Table 1. Material list involved in the construction of the DIY biodigester.

Materials	Size	Quantity	Price (Euro)	Total Cost (Euro)
Water plastic bottle	20 L	1	20.00	
Plastic container	0.5 L	1	1.00	
Garden hose pipe	16 mm	2 m	7.60	
Silicon pipe	14 mm	1 m	9.99	
Ball valve tap	32 mm	1	3.99	
Plastic closure valves	16 mm	4	5.60	
T connector	16 mm	2	0.64	106.77
Nipple male–male	32 mm	2	1.94	
Threaded sleeve female	32 mm	2	12.00	
Female threaded hose connector	32 mm	2	16.00	
Bunsen burner	12 cm	1	19.40	
Binder clamp	-	1	1.12	
Glue *	-	1	7.49	

* Soudal T-Rex Flex.

2.3. Operation of the DIY Digester

Two batch experiments were conducted to verify the performance of the DIY biodigester. The first experiment focused on mono-digestion, where only buffalo manure was used as the substrate. In the second experiment, co-digestion was explored, using a combination of food waste and buffalo manure as the substrate. Besides the scientific experimental method used, this work also provides a standard operating procedure (SOP) (supplementary materials) in order to help students and teachers in the proper management of the DIY Biodigester.

2.3.1. Substrate and Inoculum

The buffalo manure was collected from the Bioparc Zoo (39°28′41.0″ N, 0°24′27.4″ W) located in Valencia, Spain, and stored in a cold room at 4 °C prior to use. The fresh food waste used in the co-digestion experiment was obtained from a cafeteria located at Universitat de València, Spain. Before being utilized, the food waste was crushed with a food processor. The inoculum was a liquid digestate collected from a mesophilic anaerobic digester in the lab, which was fed with buffalo manure as the sole substrate and operated over 6 months. The physicochemical characteristics of buffalo manure, food waste, and the inoculum are summarized in Table 2.

Table 2. Characteristics of buffalo manure, food waste, and digestate as inoculum *.

Parameters	Buffalo Manure	Inoculum	Food Waste
pH	7.3	7.6	4.9
TS (%)	17.8	5.3	30
VS (%)	15.1	3.4	28.5
VS/TS (%)	85.0	65.0	95

* TS, total solids; VS, volatile solids.

2.3.2. Batch Experiments

In this study, the inoculum-to-substrate ratio was selected as 1:1, based on volume, and the working volume of the digesters was set at 12 L. For mono-digestion, fresh buffalo manure was fed into the digester as the sole substrate and then diluted with distilled water to a final volume of 6 L to obtain a total solid (TS) content below 10% (usually called wet digestion). As for co-digestion, the mixing ratio between buffalo manure and food waste was 1:1 based on VS, and distilled water was also added to achieve wet digestion with the same final volume. An amount of 6 L of inoculum were added to each digester and then they were closed with the water bottle cap itself and sealed using glue (Section 2.1) to maintain anaerobic conditions. Subsequently, the assembled DIY digesters were placed in a chamber room with a constant temperature of 37 °C and manually mixed twice a day. The AD process was continued for around 35 days until biogas production became negligible. Throughout the process, a daily sample of 200 mL of biogas was taken and stored in a gas bag (Dalian Delin Gas Packing Co., Ltd., Dalian, China) for subsequent analysis of biogas composition. Additionally, liquid samples were periodically collected over time for further measurements.

2.3.3. Analytical Methods

TS and VS of the substrates and digestate were measured according to standard methods [22]. The pH was recorded using a pH/mV Temperature Bench-Top Meter (GONDO, Taipei, Taiwan). Biogas production was determined volumetrically by a simple method based on water displacement [23]. The measured volume was normalized to the volume under standard temperature and pressure (STP, 0 °C, and 101 kPa) based on the ideal gas law. The methane (CH_4) content in the produced biogas was analyzed by gas chromatography (GC 6890 N, Agilent Technology, Santa Clara, CA, USA) equipped with a single filament thermal conductivity detector (GC-TCD). For this application, the GC was configured with a gas-sampling valve and a restrictor valve. HP-PLOT Q (30 m × 0.32 mm × 20 µm) and HP-PLOT Molesieve column (30 m × 0.32 mm × 25 µm) were installed in series, both from Agilent Technologies, USA. Helium gas was used as the carrier gas at a flow rate of 20 mL/min.

2.3.4. Data Analysis

The VS removal rate (*VSR*) was calculated using the following Equation (1):

$$VSR(\%) = \frac{VS_{initial} - VS_{final}}{VS_{initial}} \times 100 \quad (1)$$

where $VS_{initial}$ and VS_{final} are the VS measured before and after the digestion process.

Two commonly used kinetic AD models were applied and assessed in this study: the first-order equation (FO) and modified Gompertz model (GM), which are shown in Equations (2) and (3), respectively [24].

$$P_{CH_4}(t) = P_{max} \cdot [1 - exp(-k \cdot t)] \quad (2)$$

$$P_{CH_4}(t) = P_{max} \cdot exp\left\{-exp\left[\frac{R_m \cdot e}{P_{max}} \cdot (\lambda - t) + 1\right]\right\} \quad (3)$$

where $P_{CH4}(t)$ represents the cumulative specific methane yield (SMY) at a certain incubation time (mL/g VS_{added}); P_{max} represents potential methane production (mL/g VS_{added}); k represents the hydrolysis rate constant (d^{-1}); t is the incubation time (d); R_m represents the maximum rate of methane production (mL/(g VS_{added}·d)); λ represents the lag phase duration (d); and e represents the Euler constant value, 2.71828.

All the statistical analyses and plotting of data were conducted using Microsoft Office 2016 (Microsoft, Washington, DC, USA) and OriginPro 2021 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Design for the DIY Biodigester

The described biodigester (Figure 2) was constructed offering a sturdy structure capable of handling significant organic matter loads. Utilizing readily available materials, the setup was cost-effective, making it accessible for educational institutions. In comparison to conventional laboratory-scale biodigesters used in scientific research [15,18,25], this biodigester was designed for simplicity in both construction and operation, making it ideal for implementation in school settings.

Figure 2. The DIY biodigester system.

The practical set of valves (open-and-close mechanism, and binder clip) for the easy collection of liquid and gaseous samples, offers an advantage over conventional low-cost biodigesters used in schools [17,20], making it well-suited for academic research purposes.

Additionally, the low-cost filter system ensures biogas purification quality assessment and efficient CO_2 absorption. Moreover, the biogas storage system allows for a safe and efficient storage of biogas, and the flame test system allows a simple demonstration of the potential use of purified biogas as a fuel.

3.2. Performance of the Digesters and System Stability

To characterize and validate the functioning of the DIY digesters, the methane production was measured under mono-digestion of buffalo manure and under co-digestion of food waste and buffalo manure for 35 days (Figure 3).

During the mono-digestion of buffalo manure, a slow initial methane production rate was observed (Figure 3a,b). This phenomenon was expected, as in batch conditions, the acceleration of the biogas production rate can be directly linked to the specific growth of methanogenic bacteria [26]. During the initial two-day observation period, the biogas production was relatively lower. However, between the 4th and 7th days of observation, a significant increase in methane production was observed, which can be attributed to the growth of methanogens, indicating their establishment and active participation in the AD process. On day 7, the highest methane production rate of 13.6 NmL/g VS_{added} was measured, indicating the peak performance of the AD process during mono-digestion of buffalo manure. However, around day 10, biogas production decreased considerably, primarily due to the depletion of organic matter in the system. The total cumulative methane produced during the mono-digestion of buffalo manure was measured to be 186.1 NmL/gVS_{added} (Figure 3b).

Figure 3c,d show the methane production and cumulative methane yield under co-digestion rates of the buffalo manure and food waste. In contrast to mono-digestion, the methane production of the first six days was considerably low, with a significant increase only after the 8th day which correlates with pH values below the optimum for methanogenic microorganisms, as can be seen in Figure 3a. However, after regulation of the pH, methane production increased, reaching the maximum production rate between 15.0 and 17.0 NmL/VS_{added} on days 13 to 15. A slight decrease in the rate of biogas production was observed for day 14 compared to day 13 and day 15; however, the production rate is still higher than the rest of the days and might be explained by lack of stirring. The cumulative total methane production in co-digestion of buffalo manure and food waste was higher compared to mono-digestion reaching 228.1 NmL/VS_{added} (Figure 3d), proving that co-digestion of substrates indeed improves methane production.

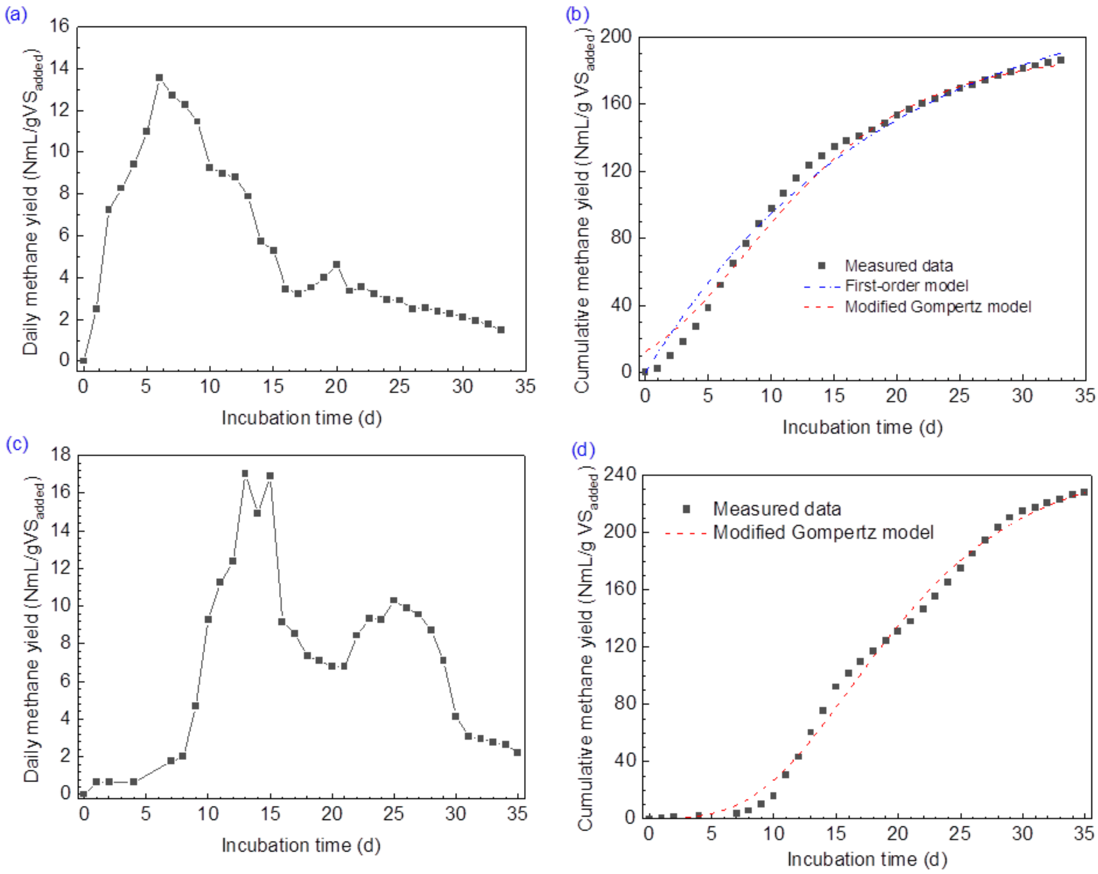

Figure 3. Daily and cumulative methane production for mono-digestion (**a**,**b**) and co-digestion (**c**,**d**).

The results obtained from methane production showed that throughout the operational period (35 days), the biodigesters functioned smoothly and comparable to other biodigesters in the same category (Table 3). Despite the variation in SMY for the different reports, this is normal for lab-scale biodigesters due to differences in inoculum, substrate and operation conditions, and the SMY of our digesters is in the range with the other digesters (Table 3).

Table 3. Comparison of this study with other reports to assess digester functionality *.

	Temperature (°C)	Digester Volume (L)	Working Volume (L)	Substrate	SMY (NmL/gVS)
Current study	37	20 L	12 L	BM	186.1
Current study	37	20 L	12 L	BM + FW	228.1
Sun et al., 2015 [27]	37	500 mL	400 mL	BM	308
Jarwar et al., 2023 [28]	37	500 mL	375 mL	BM	241.95
Cu et al., 2015 [29]	37	1.1 L	nd	BM	153.1
Carotenuto et al., 2020 [30]	37	280 mL	80 mL	BM	210

* BM, buffalo manure; FW, food waste.

To further characterize the functioning of our digesters in this study, methane production under mono-digestion and co-digestion scenarios were simulated using two commonly employed kinetic models: the first-order model and the modified Gompertz model (Figure 3b,d). Both the first-order and modified Gompertz kinetic models are commonly used for describing and predicting methane production. The parameters within these kinetic models offer more information regarding methane production, including the rates of chemical reactions, microbial activities and lag phase. This information helps digester operators understand the factors influencing methane production, assess potential outcomes, and develop strategies to mitigate its environmental impact or enhance its utility. The modelled kinetic parameters under mono- and co-digestion are shown in Table 4. The co-digestion process presents a methane production profile with a specific shape, displaying two distinct peaks (Figure 3c). While the first-order kinetic model demonstrated a good fit with the measured results for mono-digestion (with an R^2 value of 0.986), it proved to be unsuitable for representing the co-digestion process. The distinct behavior and specific shape of the methane production profile during co-digestion were not accurately captured by the first-order model. The parameter k (0.053 d^{-1}) obtained from the first-order model fitting for mono-digestion of buffalo manure indicates a slightly higher hydrolytic rate compared to the mono-digestion of pig manure (k = 0.023 d^{-1}) in the study conducted by [31]. This suggests that buffalo manure undergoes a more rapid hydrolysis process during mono-digestion.

Table 4. Modelled kinetic parameters under mono- and co-digestion.

	Parameters	Mono-Digestion	Co-Digestion
Measured data	SMY (NmL/g VS $_{added}$)	186.1	228.1
First-order model	P_{max} (NmL/g VS $_{added}$)	230.2	-
	k (1/d)	0.053	-
	Adj. R-Square	0.986	-
Modified Gompertz model	P_{max} (NmL/g VS $_{added}$)	191.1	249.1
	R_m (mL/g VS/d)	9.0	11.8
	λ (d)	0	8.4
	Adj. R-Square	0.992	0.994

The fitting results obtained from the Modified Gompertz model exhibited an excellent match with the measured data for both mono-digestion and co-digestion processes, achieving high R^2 values of 0.992 and 0.994, respectively. When comparing mono-digestion and co-digestion, it was observed that mono-digestion of buffalo manure showed no lag phase, indicating that buffalo manure is a favorable substrate for this process. However, co-digestion displayed a relatively long lag phase of 8.4 days, attributed to over-acidification at the beginning, likely due to an unsuitable ratio of food waste to buffalo manure. Despite the lag phase, co-digestion demonstrated a higher-than-predicted methane production and methane production rate when compared to mono-digestion. This outcome suggests the presence of synergistic effects during co-digestion, contributing to the increased methane production and rate observed in the process [31], and evidencing why co-digestion is widely recognized and commonly applied as a method to enhance AD processes. Based on the simulation of both mono-digestion and co-digestion using the modified Gompertz model, we concluded that the performance of our digesters is in accordance with the expected outcomes of mono and co-digestion processes

Figure 4 illustrates the evolution of CH_4 content over time for both mono-digestion and co-digestion. Throughout the entire operation, the methane content in the biogas remained at 60% for both digesters when they reached a relatively stable performance.

The pH during the incubation period of both mono-digestion and co-digestion processes is shown in Figure 5a. Throughout the mono-digestion of buffalo manure, the pH exhibited a stable evolution without significant fluctuations, consistently remaining within the acceptable pH range of 8.5 to 6.5. In contrast to the mono-digestion, the pH of the co-digestion of buffalo manure and food waste showed an abrupt drop in the first days, and remained relatively acidic until day 8, requiring pH regulation with sodium hydrogen carbonate ($NaHCO_3$). After regulation, the pH increased again reaching the optimal range for microorganisms. This pH drop may be a consequence of the rapid accumulation of volatile fatty acids (VFA) during the digestion process of food waste [32]. As these VFA accumulate, the pH of the digestion medium decreases, creating an acidic environment. Even though the mono-digestion of buffalo manure presents a more stable pH behavior than the co-digestion of buffalo manure and food waste, we demonstrated that the functioning of our digesters is robust enough to recover from a pH decrease after making the adjustment with $NaHCO_3$.

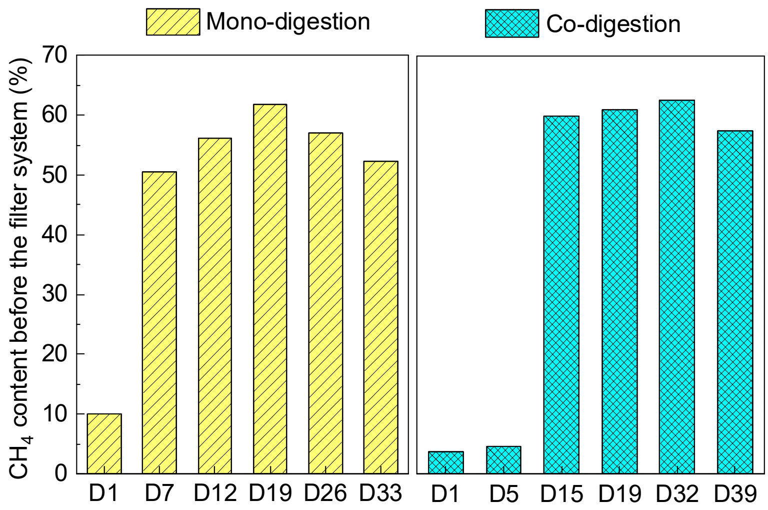

Figure 4. Evolution of CH_4 content over time for mono-digestion and co-digestion. D, day.

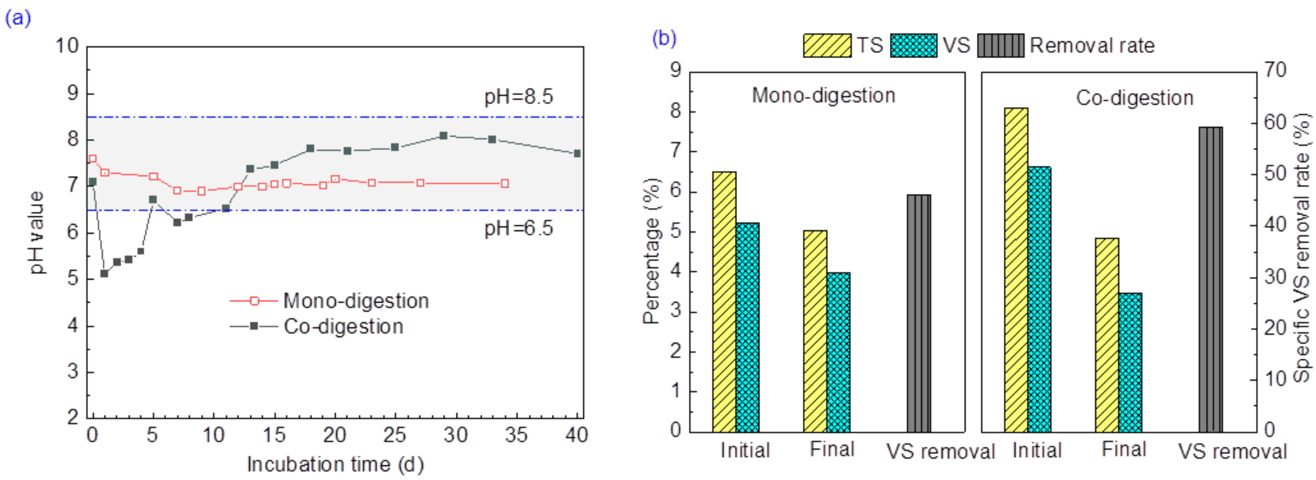

Figure 5. Evolution of pH (**a**) and VS removal (**b**) for mono-digestion and co-digestion. TS, total solids; VS, volatile solids.

Regarding the VS removal rate, it is clear to observe that the mono-digestion reached a maximum 46.0% while the co-digestion reached 59.3%, as shown in Figure 5b. This observation is in line with [33] and suggests that co-digestion of manure with food waste is generally expected to lead to higher removal rates of VS compared to mono-digestion of cow manure alone. The enhanced VS removal rate in co-digestion may be attributed to the synergistic effects arising from the combination of different substrates, contributing to more efficient biodegradation and decomposition processes. This result further probes that the outcomes from our DIY digesters are in line with the bibliography.

In conclusion, the operation of the DIY biodigester under both mono-digestion and co-digestion conditions demonstrated excellent performance, validating its suitability for academic use as intended. Moreover, co-digestion proved to be an effective strategy for enhancing the AD process, owing to the potential synergistic effects it provides.

3.3. Dissemination Activities

As part of dissemination activities, three speeches were delivered to different audiences. The first speech took place during the first annual meeting of the Micro4Biogas project held at the University Foundation-Business of the University of Valencia (ADEIT) from 24 May 2022 to 27 May 2022. The audience consisted of professionals from the biogas industry, professors from various disciplines, and university students, totaling 40 participants. The second speech took place at the Institute for Integrative Systems Biology (I2SysBio) in the University of Valencia Science Park on 14 June 2022. The presentation was given to a group of high school students and professors from the applied biotechnology course of the Colégio Internato dos Carvalhos (Portugal), with 35 participants in attendance. Lastly, the third speech, including a practical demonstration of the biodigester, was carried out during the Second predoc and postdocs seminar series at I2SysBio on 13 July 2023. This speech attracted participation from the academic community in the institute, with 22 participants. Additionally, in the frame of the Micro4Biogas project, a video was recorded in order to disseminate the construction of the DIY biodigester to the general public on social media called “Building a mini biodigester for schools” (Video S1).

In the first dissemination activity, participants showed a strong interest in the biodigester model presented as a study tool. Due to most of the audience being professionals in the field, some advice was given to improve the biodigester’s features, which were implemented and presented in this study. In the second dissemination activity, most students showed interest in the process of anaerobic digestion and the treatment of organic waste, mainly due to the practical demonstration of the flame test through the biogas flare. In addition, the teachers present liked the idea of implementing the biodigester as a study tool in their schools and asked for more information on how to set up the biodigester. In the third dissemination activity, the academic students present showed great interest in the process by asking several questions regarding how this digester could be implemented in schools, which safety measurements need to be taken to be handled by students, and what other substrates could be used to compare the gas production among them.

4. Discussion

4.1. Considerations Related to Making a DIY Digester

The DIY biodigester presents several features that make it a powerful and versatile device for science dissemination, environmental education, and academic studies. The simple and affordable construction using a 20 L plastic bottle and easily available materials make it a financially feasible solution for academic institutions with limited resources [17,20]. In addition, its ability to collect regular data from liquid samples for analysis allows students and researchers to monitor important parameters such as pH, gas production, and substrate degradation. This facilitates data collection and analysis, enabling the development of scientific skills.

The implementation of DIY biodigesters can represent significant savings compared to more sophisticated and commercial models [34]. The biodigester presented in this study had a maximum cost of EUR 106.77 with a relatively low manufacturing time of 1 h. Additionally, the low maintenance and operating costs ensure that the biodigester can be a durable and long-lasting device. The biodigester’s versatility is another important characteristic. Researchers and students can modify and adapt the biodigester design according to the specific study objectives, making it possible to investigate different parameters and scenarios.

In high school, the biodigester stands out as a demonstrative and hands-on learning device. Students can be actively involved in the construction, operation, and monitoring of the biodigester, which promotes a practical and concrete understanding of the concepts of anaerobic fermentation, bioenergy production, and environmental sustainability [35]. The biodigester developed in this study can also be applied in citizen science projects, involving the local community in monitoring the AD process and biogas production. This involved approach can broaden the reach of environmental education and awareness about the importance of sustainability in rural and urban communities.

However, when building and operating a DIY digester, there are several important considerations to keep in mind. First, selecting the appropriate substrate for the digester is crucial. As highlighted in the results section, co-digesting buffalo manure with food waste yielded a higher methane production than digesting buffalo manure alone. Specifically, the cumulative biogas production for the two DIY biodigesters was 186.1 NmL/gVS$_{added}$ using buffalo manure and 228.1 NmL/gVS$_{added}$ with buffalo manure combined with food waste. Another vital consideration is the disposal of the digestate, the residual material left post-biogas production. Rich in nutrients such as nitrogen, phosphorus, and potassium, and enriched with organic matter, the digestate is a prized byproduct of the anaerobic digestion process [6]. It thus stands as an outstanding natural fertilizer for agricultural applications.

Thus, the DIY biodigester under study offers numerous opportunities for education, research, and environmental awareness. Furthermore, the affordable construction and data collection capabilities provide a valuable platform to investigate and understand biogas production through anaerobic fermentation. As an educational instrument, it can promote science dissemination and encourages students' interest in renewable energy and sustainable practices.

4.2. Utilization of a Filter System

The absorption of CO_2 using alkali solutions is a well-established and effective method for capturing CO_2, a major component of biogas [36,37]. Widely employed in the biogas industry for upgrading biogas in plants [38], NaOH-based absorption filters offer an economically viable option to increase biogas purity, particularly in places with limited resources like schools and universities. The chemical reaction between CO_2 and NaOH results in the formation of sodium carbonate (Na_2CO_3), effectively scrubbing CO_2 from the biogas. The high solubility of CO_2 in the alkaline solution allows for efficient removal, leading to biogas purification and a higher methane content of over 95% and without any methane loss [21,39]. During the practical process, the CO_2 present in the biogas stream was rapidly absorbed when it came into contact with a 3 M NaOH solution. Thymolphthalein is introduced as an indicator into the main solution to monitor CO_2 absorption, as it changes color based on the pH of the solution (Figure S5). By monitoring the color change in thymolphthalein, it becomes possible to identify the critical point of the NaOH solution with CO_2 absorption [21,40].

When employing the biogas purification filter system, it is crucial to take into account the potential negative effect on the CO_2 removal rate caused by reducing the NaOH concentration during the AD process. Maile et al. [21] conducted a study illustrating that lowering the NaOH concentration (from 3 M to 1 M) resulted in a significant decline in both the CO_2 absorption rate and the overall CO_2 removal efficiency. Mel et al. [36] revealed that the utilization of a 3.5 M NaOH solution resulted in the highest removal efficiency (100% CO_2 removal) when compared to using 1.8 M and 1 M NaOH solutions. It is evident that in a continuous flow of biogas, the NaOH concentration gradually diminishes as it absorbs CO_2, leading to a decrease in removal efficiency and consequently resulting in a lower methane content. However, it is important to note that there is a lack of information regarding how the decrease in NaOH concentration affects CO_2 removal efficiency and whether the biogas flow rate influences this process. Therefore, further research is necessary to explore these aspects and enhance the CO_2 removal efficiency of the filter system.

4.3. Potential for Future Improvement

In the current design, three main points can be further improved: the automation and monitoring system, stirring system, and temperature control system.

Automation and monitoring system: Integrating sensors and control mechanisms, such as Arduino-based systems, can enable real-time monitoring of important parameters, such as temperature, pH levels, and gas production. In this case study, low-cost sensors such as DS18B20 (temperature sensor), MQ-4 (CH_4 sensor), and a pH sensor for Arduino could be easily integrated into the fermentation tank to help optimize the feeding process and adjust operating conditions for improved biogas production. Additionally, remote monitoring capabilities can provide real-time data for performance evaluation and early detection of any issues or abnormalities, leading to more efficient and reliable operations [14,41]. The main challenges that could arise from this are the design of the programming script and the calibration of the sensors. While the idea of keeping the design as simple as possible should be balanced with a more profound characterization of the AD process for a better understanding of the students, this task may be assigned to a third-party participant to assure a fast implementation of the sensors. Alternatively, if programming skills are part of the curricula in a school aiming to use the DIY digester, some parts or even the whole programming code could be designed by the students tutored by teachers.

Stirring system: Introducing a mixing or agitation system within the biodigester can enhance the digestion process by promoting better contact between the organic waste and microorganisms. This can lead to more efficient biogas production and reduce the risk of substrate stratification or settling. The agitation system can be designed using low-cost materials as described by [42] to maximize mixing efficiency, ensuring a uniform distribution of nutrients and microorganisms throughout the digester. The main challenge that could arise from a stirring system is the appearance of gas leakages either because more holes may appear in the digester or because of the manipulation, per se, of the system.

Temperature control system: For mesophilic or thermophilic digesters, the temperature needs to be carefully regulated to ensure consistent gas production. Advanced thermal management solutions, such as the use of phase-change materials (PCMs) as passive thermal energy storage, as mentioned in [43], can help maintain stable temperatures and extend the operational time of the digester designed in this study. The main challenge for this may be the costs associated with implementing the temperature control system, which could be detrimental to the affordability of the DIY digester.

4.4. Dissemination Strategies

Innovative dissemination using biodigesters could significantly enhance its impact on science education and society at large [20]. By integrating the biodigester into the science curriculum, students can actively engage in hands-on learning experiences that go beyond theoretical concepts. The biodigester's compact size, affordability, and simplicity make it a suitable tool for implementation in schools with limited resources, enabling a broader reach and accessibility to students from diverse backgrounds [35]. Moreover, the biodigester's ability to produce biogas from organic waste serves as an excellent example of sustainable technology and renewable energy production, empowering students to explore solutions to real-world environmental challenges [44].

Encouraging participation and collaboration in dissemination efforts is another crucial aspect. By involving students, teachers, and the broader school community in the biodigester project, a sense of ownership and responsibility toward sustainable practices can be fostered. Students can be invited to actively participate in assembling the biodigester, preparing different feedstocks, and monitoring biogas production, facilitating experiential learning and critical thinking skills [45]. Engaging with the wider community through open lab days, science cafés, and interactive workshops further promotes the biodigester's impact, sparking interest and curiosity among students and the public alike. Following these innovative dissemination strategies, the biodigester can become a powerful science education instrument that not only raises awareness about renewable energy and environmental conservation but also inspires the next generation of environmentally conscious citizens and scientists.

5. Conclusions

In this work, we present a straightforward and cost-effective DIY biogas fermenter that we have designed, operated, and characterized. This innovative technology serves as an affordable alternative for biogas reactors in academic and private laboratories while also acting as a valuable dissemination tool. Besides being simple and accessible, the characterization of our DIY biogas fermenter in terms of methane production, kinetic parameters, methane concentration, pH, and VS removal proved excellent functioning as an anaerobic digester. All these features hold great promise in advancing research and education in the field of renewable energy and environmental conservation, which is also a key technology to contribute to the development of a global bioeconomy. While the actual design of the digester can be already used for hands-on lessons in the curricula of schools, future research may be focused on the implementation of the proposed improvements together with a subsequent characterization of the next model of DIY digester with monitoring, stirring, and temperature control systems.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/fermentation9090845/s1. Figure S1: (a) Valve connected to the biodigester with the respective rings and screw nut; (b) Bottle lid showing the hose pipe connected after glue (T-Rex Flex the universal adhesive sealant, Soudal). Figure S2: Filter system assembly schematic. Figure S3: Air chamber and the valve core. Figure S4: Flame system with the air inlet open (a) and closed (b). Figure S5: Color changing of NaOH solution during the absorption process. Table S1: Material list and their respective images involved in the construction of the DIY biodigester. Video S1: Building a mini biodigester for schools.

Author Contributions: Conceptualization, F.W.V., M.P. and N.C.; Methodology, F.W.V., Z.W. and N.C.; Validation, F.W.V., Z.W. and N.C.; Formal analysis, F.W.V., Z.W. and R.G.-H.; Investigation, F.W.V., N.C. and R.G.-H.; Data curation, F.W.V., Z.W. and J.B.G.; Writing—original draft, F.W.V. and Z.W.; Writing—review and editing, M.P., Z.W., N.C., R.G.-H., J.B.G. and A.S.; Visualization, F.W.V. and Z.W.; Supervision, M.P.; Project administration, F.W.V. and M.P.; Funding acquisition, M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the European Union's Horizon 2020 research and innovation programme through the MICRO4BIOGAS project (grant agreement No 101000470).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful to the European Commission for funding the MICRO4BIOGAS project.

Conflicts of Interest: The authors declare no conflict of interest.

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