water

MDPI

Article

Peering into a Simplified Digestor for Households: Performance, Cost and Carbon-Neutral Niche

Xiaoqin He [1,†], Sayed Mohammad Nasiruddin [1,2,†], Xiaoqin Zhou [1,*], Zifu Li [1,*], Heinz-Peter Mang [1], Roman Ryndin [1], Humayun Kabir [3] and Sayed Mohammad Nazim Uddin [4]

1 School of Energy and Environmental Engineering, Beijing Key Laboratory of Resource-Oriented Treatment of Industrial Pollutants, University of Science and Technology Beijing, Beijing 100083, China; uwo_cas@163.com (X.H.); smnasiruddin85@gmail.com (S.M.N.); hpmang@t-online.de (H.-P.M.); romanryndin@gmx.de (R.R.)
2 Program of Natural Resource and Environmental Studies, University of Northern British Columbia, Prince George, BC V2N 4Z9, Canada
3 Faculty of Agricultural Economics and Rural Sociology, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh; hkabir75@yahoo.com
4 Environmental Sciences Program, Asian University for Women, 20/AM M Ali Road, Chattogram 4000, Bangladesh; sayed.uddin@auw.edu.bd
* Correspondence: zhouxiaoqin025@163.com (X.Z.); zifulee@aliyun.com (Z.L.)
† These authors contributed equally to this work.

Abstract: In this study, a black-shading cylindrical water tank made of high-density polyethylene was locally manufactured as a household digestor for treating cow manure in Bangladesh. Effluent slurry instead of water was reused for manure dilution under manure-to-slurry ratios of 1:2 and 1:1, to assess this small prototype's production efficiency and feasibility. The specific biogas production at both ratios matched well, by 0.12 m^3/kg VS and 0.14 m^3/kg VS, respectively, while the former slurry dilution operation outperformed in daily and accumulative biogas production by 16% and 57%, correspondingly, referring to 0.49 Nm^3/d on average and 8.55 Nm^3 in total, potentially meeting a 2 h household cooking energy requirement. From a nationwide viewpoint, slurry dilution was proven to be a great initiative to conserve water amounting to 50,286,751 m^3 for 114,810 households of 6 person-equivalents annually, while cutting chemical costs by USD 32,720,684/yr and trimming annual greenhouse gas emission by 1.8 million tons of CO_2e. This study revealed that a small prototype digestor could be an alternative energy source for cost-effective and eco-friendly household applications.

Keywords: anaerobic degradation; low-cost household digestor; manure-to-slurry ratio; biogas production; carbon emission reduction

check for updates

Citation: He, X.; Nasiruddin, S.M.; Zhou, X.; Li, Z.; Mang, H.-P.; Ryndin, R.; Kabir, H.; Uddin, S.M.N. Peering into a Simplified Digestor for Households: Performance, Cost and Carbon-Neutral Niche. *Water* **2024**, *16*, 36. https://doi.org/10.3390/w16010036

Academic Editors: Jae-Kyu Yang, Jeong Hyub Ha and Afshin Maleki

Received: 17 November 2023
Revised: 11 December 2023
Accepted: 13 December 2023
Published: 21 December 2023

1. Introduction

In Bangladesh, natural resources are the primary energy source, yet only 58 percent of rural residents have access to them. Furthermore, 70% of the population has relied on abundant biomass to meet their daily energy consumption [1]. In addition, approximately 65% of the total population needs access to the national power supply connection and uses natural waste such as agricultural waste, woody biomass, and animal dung as primary energy sources for cooking and lighting. However, WHO reported that 3.2 million deaths in 2020 were caused by harmful household air pollution through cooking using open fires or inefficient biomass or coal. Converting the fuel by other means into cleaner/less harmful energy for cooking, such as biogas, to reduce household air pollution and protect health is essential. Nevertheless, the renewable energy share of Bangladesh is only 0.65% of the total energy mix, in contrast to the global renewable energy share of 13.47% of the total energy consumption by 2021, which leaves Bangladesh far behind India (9.31%) and China (14.95%), respectively. Developing a continuous flow of clean and secure energy would be a promising approach and is an urgent requirement for sustainable development, and Bangladesh has plenty of renewable resources. For example, Bangladesh had 1.48 million buffaloes, 24.086 million cattle, 26.10 million goats, and 3.47 million sheep in 2019 [2]. Manure from livestock is a potential substrate for renewable energy, which can partially replace the dependency on fossil fuels by developing low-cost, environmentally friendly technologies [3].

Anaerobic digestion (AD) of biomass could contribute to meeting our daily energy needs and help us sustainably manage our waste, reduce greenhouse gas (GHG) emissions, and reduce soil and groundwater contamination. AD is widely regarded as the most cost-effective and environmentally benign technology for producing biogas as an energy source and utilizing effluents as a soil enrichment, for its rich contents of nitrogen and phosphorus [4,5]. Mono-digestion using cow manure, sheep mature, swine manure, co-digestion with domestic organic waste and agricultural waste, has been frequently investigated at both lab-scale and pilot operations [6–9]. Compared with large biogas projects, household biogas project is considered a clean and environmentally friendly technology to help rural communities to meet their energy needs for lighting, cooking, and improving living conditions. Moreover, household biogas is also an effective solution for improved sanitation. Many developing countries have designed and constructed small and large-scale simple, inexpensive fixed-dome or plastic tubular portable household digestors for bioenergy production. Luo Guo Rui initially developed the concrete digestor in 1920 in Taiwan, China, and now it has become "China's model of biogas digestor" worldwide. It is usually built in a standard size and has been introduced to India, Latin America, and other countries across the globe [10–12]. However, the fixed-dome digestor was frequently reported to be under-performing due to some limitations, including lack of user awareness, unskilled engineering design, high construction cost, training, and poor management by the associated service provider [1,13]. Plastic tubular digestors, including tubular polyethylene or polyvinyl chloride (PVC) bags, have also been attractive. In particular, small-scale plastic tank-modified digestors are famous for biogas production in rural and decentralized settings. The performance of such digestors can be affected by various factors, including the feedstock, the feedstock-to-water ratio, and the operating temperature (T).

Cow manure typically has higher total solids (TS) and volatile solids (VS) contents than slurry, affecting digestion and biogas production. Thus, dilution of the raw substrate is required to avoid clogging, and adding water to dilute is a common strategy but enlarges the digestor volume and digestate amount [14,15]. Liquid digestate recirculation has been proven to be productive in biogas production and substrate dilution as well [16,17]. Using digestate instead of water for manure dilution can be an option, but only limited information is available [18]. Thus, it is challenging to adopt the approach at the household level, since finding an economical and straightforward strategy for substrate dilution should be considered. In the case of cow manure and slurry feeding ratios, the performance of the digestor will depend on the characteristics of the feedstock, such as their TS and VS contents and their nutrient composition. To optimize the performance of the digestor, it is essential to balance the feedstock-to-water ratio, which can affect the system's hydraulic retention time (HRT). A longer HRT can result in higher biogas production but may also increase the risk of digestor failure due to the accumulation of organic and volatile fatty acids. The temperature of the digestor is also a critical factor for optimal performance. Mesophilic temperatures between 25–40 °C are most common, but some systems operate at thermophilic temperatures above 50 °C. Higher temperatures can increase biogas production rates and reduce HRT, but they also require more energy to maintain and can be more sensitive to changes in feedstock characteristics. Overall, the performance of a small-scale plastic tank-modified digestor under cow manure and slurry feeding ratios for biogas production can be optimized by carefully balancing the feedstock-to-water ratio, operating at an appropriate temperature, and monitoring the digestor performance regularly to avoid any issues.

Obviously, diluting manure substrate with recirculated liquid digestate could avoid the freshwater consumption throughout the AD process. What is more, reusing liquid digestate could downsize the net slurry discharge, lowering pollution loading to the downstream disposal units. Digestate has been reported to be environmentally hazardous due to the high concentration of oxygen-consuming content, defined as chemical oxygen demand (COD) [17,18]. Disposal via decontamination and stabilization is required before discharging slurry to the receiving water, generally including solid–liquid pre-separation, reduction of the solid fraction and biological treatment of the liquid fraction [19]. Over the decontamination disposal chain, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have been reported to be inevitably generated and make the main contribution to GHG emissions [20,21]. Life cycle analysis (LCA) has been widely used for evaluating the climate impact throughout the AD process of the commercial fixed-dome or tubular types [22,23]. However, it is laborious indeed to carry out LCA for an AD process operated with recirculated slurry dilution, due to limited information and failure to cover a cost estimate. It was more feasible to conduct a step-by-step estimation of the cost and environment impact by referring to a handbook [19,24] or project output [20,21].

In this study, we investigated the biogas production performance using cattle manure and slurry at two different mixture ratios in a pilot-scale digestor, a prototype of a low-cost technology modified and constructed from a locally available high-density polyethylene (HDPE) water tank container. The digestor performance was also evaluated to determine whether the production efficiency obtained under this strategy is feasible at the household level for biogas production and consumption. Therefore, to assess the production efficiency and feasibility of this small prototype for treating a single substrate, our main objectives were to investigate the feeding pattern of cattle manure and slurry at a 1:1 and 1:2 ratio instead of water to achieve higher biogas efficiency and usability of the prototype for rural household application.

2. Materials and Methodology

2.1. Source of Cattle Manure and Liquid Slurry

Cattle manure was collected from the dairy farm located at the Bangladesh Agricultural University at regular intervals. Subsequently, large objects and particles were manually removed using protective gloves to avoid clogging and disruption while feeding the manure into the digestor. For the dilution of the manure, digestate was used instead of water as a feeding strategy. The effluent used in this study was regularly collected from a portable fixed-dome digestor (Configuration: V-7m^3, HRT-55d as per 4 d interval feeding) previously employed to handle solely animal manure, a single biogas substrate. The main characteristics of the raw cattle manure and slurry, mainly including TS, VS, Volatile Fatty Acid (TVFA), temperature (T) and pH, are listed in Table 1.

Table 1. Characterization of feedstock composition.

Components	TS (%)	VS (%)	VFA (mg/L)	Slurry T (°C)	pH
Feedstock composition	10.5	8.7	279	31.3	6.8

Note: estimated average.

2.2. Configuration of Plastic Tank Modified Digestor

A cylindrical water tank made of HDPE coated with black paint is locally manufactured and used as a water tank. The specific design of the reactor has been described in our previous study, with double the volume [13]. Hence, the volume capacity of the digestor in this study is 1 m^3, with a width of 104 cm and a height of 135.3 cm. The diameter of the inlet and the outlet pipes was 11 cm. For gas collection and storage, gas sampling is via a hose pipe attached to a gas valve. It is assumed that the tank can easily retain the digestor temperature due to its materials and cylindrical shapes while exposed to sunlight. As mentioned previously, the construction and design of this prototype do not generate high costs and require only limited skills and training for maintenance and operation during household application. For data collection, the produced gas was burned in a cooking stove using a gas meter, and data were recorded instantaneously (L/min). The operation ran from July to August, and the ambient temperature was mainly above 30 °C.

2.3. Substrate Feedings

Initially, the digestor was fed regularly with dairy manure and slurry uniformly. In this case, around 28 kg of feedstock was subjected to loading regularly. In the first phase, the digestor was fed with cattle manure, and the slurry was mixed evenly at 1:1 and observed for two weeks (from day 1 to 15) to check and monitor whether the digestor had been clogged by overloading. It was found that the substrates were partially diluted using an equal ratio of slurry and cow manure. It can be noted that the digestor was clogged due to higher TS content and lower moisture in the feeding ratio of 1:1. As a result, the feedstock slurry ratio was altered to 1:2 for better dilution and degradation for biogas production and operated for 20 more days. To analyze the TS and VS, samples were collected at regular intervals and subjected to the TS transformed into biogas over the experimental periods. Biogas produced from the digestor was analyzed to observe the efficiency throughout the operation. For VFA, the samples were collected weekly and measured as a total of volatile fatty acids using the titrimetric method to indicate different pH endpoints and estimated in mg per liter [25]. From day 1 to 15, at a feeding ratio of 1:1, the TS and VS for feed were 9.07% and 7.50% and increased to 11.90% and 9.98% when the cattle manure and liquid digestate ratio was increased to 1:2. The TS increased with the proportion of slurry, which was different from the situation when the cattle manure was diluted with water. This is because of the re-precipitation of solids in the slurry with the addition of cattle manure. A TS value of 10% is considered the upper limit of wet digestion, and the high TS could limit the mass transfer and reduce the degradation efficiency. The slurry's pH was around 6.8, favorable for AD.

2.4. Analytical Approach

For quantitative analysis, a muffle furnace (Model: JSMF-30T, JSR, China) was used to analyze the TS and VS of the feedstock and digested. For pH measurement, a pH meter (PHS-25, China) was used in both influent and effluent slurry and adjusted accordingly. Ambient temperature was recorded daily using a thermometer sensor (DL-200T, VOLTCRAFT). The temperature was monitored regularly by dropping the thermometer sensor into the digestor. For VFA analysis, the samples were collected from an effluent pipe and centrifuge at 10,000 rpm to filter the suspended solids. The supernatant was analyzed to measure the volatile fatty acids by the method suggested by [25]. The biogas composition of methane (CH_4) and carbon dioxide (CO_2) was measured using the gas analyzer (3200 p, cubic, China). The biogas volume was recorded by a gas flowmeter and converted into standard temperature (Kelvin) and pressure (normal atmosphere).

All data from the field experiment were analyzed per methodology and subjected to statistical analysis using "origin pro 9" and a Microsoft Excel datasheet.

2.5. Evaluation of Economic and Environmental Efficiency

Diluting raw cow manure to a favorable TS concentration was conducted by recycling digestate effluent instead of water, in the hope of reducing net slurry discharge and disposal volumes. Decontamination disposal was required before discharging slurry to the receiving water, including solid–liquid pre-separation and biological treatment of the liquid fraction, as shown in Figure 1. Along with the decontamination chain, GHG emission was inevitable because of the bio-generation of CH_4, CO_2 and nitrous oxide (N_2O). Therefore, two scenarios, dilution with water (scenario A) and recycled digestate (scenario B), respectively, were weighed up to evaluate the economic and environmental efficiency nationwide in Bangladesh.

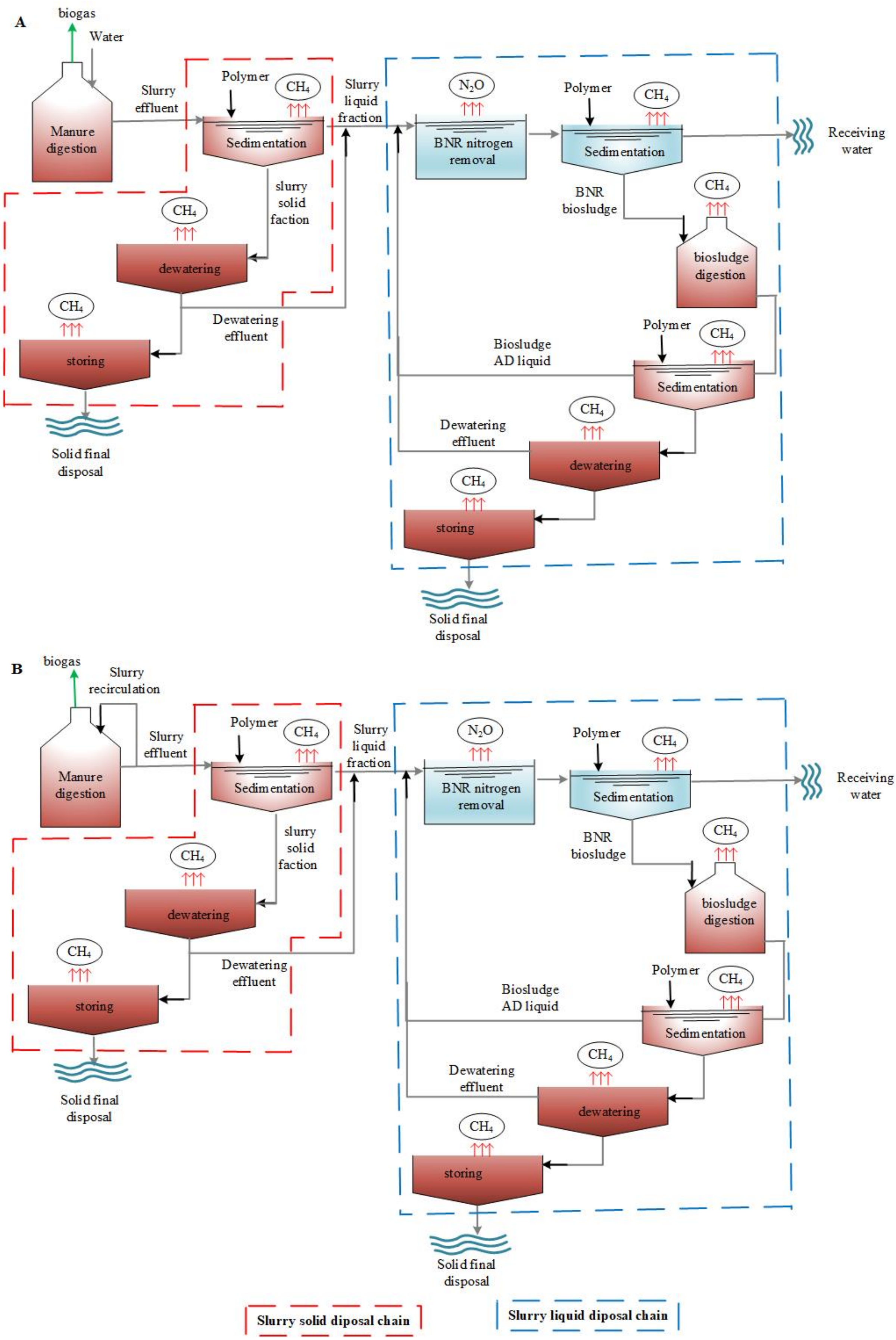

Figure 1. A Diagram of GHG emission evaluation in scenario A (**A**) and scenario B (**B**).

Bangladesh currently has 24.086 million heads of cattle, generating 25.14 million tons (MT) of manure waste annually (http://www.bbs.gov.bd/WebTestApplication/userfiles/Image/Arg-YearBook11 (accessed on 16 November 2023)), and, correspondingly, 22.06 MT of dry organic substrate ($M_{manure-solid}$) per year, from 2.86 kg of cattle manure generated by each animal per day at 12.28% moisture in the manure [26]. A dilution ratio of 1:2 was chosen to calculate the water requirement volume (V_{water}) based on Equation (1). According to the instruction of the US EPA [24], AD realized a two-fold volume decrease via a solid substrate destruction of 50 percent, with the manure digestion slurry volume ($V_{slurry-AD}$) being calculated by assuming a solid concentration of 3 percent in slurry (Equation (2)). The solid content of the digestate was further concentrated to 20 percent as solid cake via polymer coagulant-assisted solid–liquid separation and de-watering, followed by storing before typical landfilling or composting as final disposal. However, the final disposal of the thickened solid waste lies outside the scope of this work because of data scarcity. As suggested by Metcalf and Eddy (2003), 6 kg of polymer coagulant was required per ton of dry solids at USD 3.50 per kg of polymer [24]. Therefore, the polymer amount ($M_{manure-polymer}$) and cost ($Cost_{manure-polymer}$) of thickening solid content in slurry is determined based on Equations (3) and (4).

$$V_{\text{water}}\left(\frac{m^3}{yr}\right) = \frac{2 \times M_{manure-solid}\left(\frac{MT\ ts}{yr}\right)}{1.0\left(\frac{ton}{m^3}\right)} \times 10^6 \tag{1}$$

$$V_{slurry-AD}\left(\frac{m^3}{yr}\right) = \frac{0.5 \times M_{manure-solid}\left(\frac{MT\ ts}{yr}\right)}{0.03 \times 1.0\left(\frac{ton}{m^3}\right)} \times 10^6 \tag{2}$$

$$M_{slurry-polymer}\left(\frac{ton}{yr}\right) = 0.5 \times M_{manure-solid}\left(\frac{MTts}{yr}\right) \times \left(\frac{6\ kg\ polymer}{ton\ ts}\right) \times 10^3 \tag{3}$$

$$Cost_{slurry-polymer}\left(\frac{\$}{yr}\right) = M_{slurry-polymer}\left(\frac{ton}{yr}\right) \times \left(\frac{\$3.5}{kg\ polymer}\right) \times 10^3 \tag{4}$$

The manure digestion slurry was characterized by high organic compounds as total chemical oxygen demand (TCOD = 7.0−98 g/L) and nitrogen as total nitrogen (TN = 1.0−6.5 g/L) [27]. After separating the solid content, the liquid fraction was predominantly of soluble chemical oxygen demand (SCOD) under a C/N ratio of 0.9, and a typical SCOD concentration of 1532 mg/L [28] was applied to calculate organic loading (OL_{BNR}) and nitrogen loading (NL_{BNR}) based on Equations (5) and (6). Treatment based on the biological nutrient removal (BNR) process was chosen to decontaminate the slurry by virtue of eco-harmoniousness, assuming a bio-sludge amount (Equation (7)) with a typical biosolid yield of 0.3 g VS/g COD [24]. Two steps were taken to estimate the bio-sludge amount: first, using the observed biosolid yield for the scenario and the COD removal under the calculated organic loading to determine the VS mass along the BNR process; second, the waste activated sludge was assumed to have a VS mass amounting to up to 70% of the total solid fraction to determine the TS amount ($M_{BNR-biosludge}$) for further estimation of polymer cost and GHG emission. After volume reduction via AD, the same solid-waste treatment chain was applied to the bio-sludge as to the manure digestion slurry solid fraction, including thickening with polymer, de-watering and storing. The polymer requirements were determined by the same method as for thickening bio-sludge, while using only half of the original bio-sludge amount due to the 50% destruction in the anaerobic digestion stage. Thus, the total polymer amount ($M_{biosludge-polymer}$) and cost ($Cost_{biosludge-polymer}$) for the whole thickening treatment of bio-sludge is determined based on 1.5 times the total dry biosolid produced over the BNR process based on Equations (8) and (9).

$$OL_{\text{BNR}}\left(\frac{ton\ COD}{yr}\right) = V_{manure-ads}\left(\frac{m^3}{yr}\right) \times SCOD\left(\frac{g\ COD}{m^3}\right) \times \frac{1}{10^6} \tag{5}$$

$$NL_{\text{BNR}}\left(\frac{ton\ N}{yr}\right) = OL_{\text{BNR}}\left(\frac{ton\ COD}{yr}\right) \times \frac{1}{0.9} \quad (6)$$

$$M_{BNR-biosludge}\left(\frac{ton\ ts}{yr}\right) = OL_{\text{BNR}}\left(\frac{ton\ COD}{yr}\right) \times 0.3\left(\frac{g\ VS}{g\ COD}\right) \times \frac{1}{0.7} \quad (7)$$

$$M_{bioslude-polymer}\left(\frac{ton}{yr}\right) = 1.5 \times M_{BNR-biosludge}\left(\frac{ton\ ts}{yr}\right) \times \left(\frac{6\ kg\ polymer}{ton\ ts}\right) \times \frac{1}{10^3} \quad (8)$$

$$Cost_{bioslude-polymer}\left(\frac{\$}{yr}\right) = M_{bioslude-polymer}\left(\frac{ton}{yr}\right) \times \left(\frac{\$3.5}{kg\ polymer}\right) \times 10^3 \quad (9)$$

Alongside the decontamination process, GHG emission did contribute to the climate impact over the treatment of both solid and liquid waste fractions, mainly including polymer coagulant-assisted solid–liquid separation, de-watering, anaerobic digestion, solid-waste storing and BNR denitrification [20]. As the global warming potential (GWP) standardizes CO_2 as the reference gas of GHG, the calculation of the climate impacts of CH_4 and N_2O was usually performed as equivalent carbon dioxide (CO_2e) by applying a GWP of 25 kg CO_2e/kg CH_4 and 298 kg CO_2e/kg N_2O, and, for the polymer, 2.62 kg CO_2e/kg active polymer addition substance [20]. As for bio-sludge volume reduction via AD, both CH_4 and N_2O are released to create a climate impact through the GHG effect. As well, the emission amount ($GHG_{biosludge-AD}$) was calculated based on Equation (10), assuming a biogas production rate of 0.38 N m^3/kg TS with bio-sludge as substrate in AD, with biogas being composed of a CH_4 content of 60% and CO_2 content of 30%. The GHG emission amount was calculated by Equation (11) over polymer addition ($GHG_{slurry-polymer}/GHG_{biosludge-polymer}$).

$$\begin{aligned} &GHG_{biosludge-AD}\left(\frac{MT\ CO_2e}{yr}\right) \\ &= M_{BNR-biosludge}\left(\frac{ton\ ts}{yr}\right) \times 0.38\left(\frac{m^3\ biogas}{kg\ ts}\right) \times \left(0.6\left(\frac{m^3\ CH_4}{m^3\ biogas}\right) \times 0.717\left(\frac{kg}{m^3}\right) \times 25\left(\frac{kg\ CO_2e}{kg\ CH_4}\right)\right. \\ &\left. +0.3\left(\frac{m^3\ CO_2}{m^3\ biogas}\right) \times 0.9295\left(\frac{kg}{m^3}\right) \times 1\left(\frac{kg\ CO_2e}{kg\ CO_2}\right)\right) \times \frac{1}{10^6} \end{aligned} \quad (10)$$

$$GHG_{slurry-polymer}\left(\frac{MT\ CO_2e}{yr}\right) = M_{slurry-polymer}\left(\frac{ton}{yr}\right) \times 2.62\left(\frac{kg\ CO_2e}{kg\ polymer}\right) \times \frac{1}{10^6} \quad (11a)$$

$$GHG_{biosludge-polymer}\left(\frac{MT\ CO_2e}{yr}\right) = M_{bioslude-polymer}\left(\frac{ton}{yr}\right) \times 2.62\left(\frac{kg\ CO_2e}{kg\ polymer}\right) \times \frac{1}{10^6} \quad (11b)$$

Two steps were taken to quantify the GHG emission over the de-watering stage ($GHG_{slury-dewatering}/GHG_{biosludge-dewatering}$) and the solid cake storing stage ($GHG_{slurry-storing}/GHG_{biosludge-storing}$), with reference to a CH_4 emission factor (EF) of 4.5% and 2% of CH_4 production in the following AD, respectively. First, the quantification of CH_4 production ($M_{slury-CH_4}$) was fulfilled in AD using the slurry solid fraction as substrate, outputting a biogas production rate of 0.3 N m^3/kg TS [26] with 60 percent of CH_4 at a density of 0.717 kg/m^3, as Equation (12). Second, calculating $GHG_{slurry-dewatering}$ and $GHG_{slurry-storing}$ is further carried out based on Equations (13) by multiplying CH_4 production with EF. The same calculation procedures were applied to the GHG emission along the bio-sludge treatment chain to compute $M_{bioslude-CH_4}$, $GHG_{biosludge-dewatering}$ and $GHG_{biosludge-storing}$ according to Equations (14) and (15), assuming a biogas production rate of 0.38 N m^3/kg TS with bio-sludge as substrate in AD.

$$\begin{aligned} &M_{slurry-CH_4}\left(\frac{ton\ CH_4}{yr}\right) \\ &= 0.5 \times M_{manure-solid}\left(\frac{ton\ ts}{yr}\right) \times 0.3\left(\frac{m^3\ biogas}{kg\ ts}\right) \\ &\times 0.6\left(\frac{m^3\ CH_4}{m^3\ biogas}\right) \times 0.717\left(\frac{kg}{m^3\ CH_4}\right) \end{aligned} \quad (12)$$

$$GHG_{slurry-dewatering}\left(\frac{MT\ CO_2e}{yr}\right) = M_{slurrry-CH_4}\left(\frac{ton\ CH_4}{yr}\right) \times 0.045 \times 25\left(\frac{kg\ CO_2e}{kg\ polymer}\right) \times \frac{1}{10^6} \quad (13a)$$

$$GHG_{slurry-storing}\left(\frac{MT\ CO_2e}{yr}\right) = M_{slurry-CH_4}\left(\frac{ton\ CH_4}{yr}\right) \times 0.02 \times 25\left(\frac{kg\ CO_2e}{kg\ polymer}\right) \times \frac{1}{10^6} \quad (13b)$$

$$M_{biosluge-CH_4}\left(\frac{ton\ CH_4}{yr}\right) = M_{BNR-biosludge}\left(\frac{ton\ ts}{yr}\right) \times 0.38\left(\frac{m^3\ biogas}{kg\ ts}\right) \times 0.6\left(\frac{m^3\ CH_4}{m^3\ biogas}\right) \times 0.717\left(\frac{kg}{m^3\ CH_4}\right) \quad (14)$$

$$GHG_{biosludge-dewatering}\left(\frac{MT\ CO_2e}{yr}\right) = M_{biosluge-CH_4}\left(\frac{ton\ CH_4}{yr}\right) \times 0.045 \times 25\left(\frac{kg\ CO_2e}{kg\ polymer}\right) \times \frac{1}{10^6} \quad (15a)$$

$$GHG_{biosludge-storing}\left(\frac{MT\ CO_2e}{yr}\right) = M_{biosluge-CH_4}\left(\frac{ton\ CH_4}{yr}\right) \times 0.02 \times 25\left(\frac{kg\ CO_2e}{kg\ polymer}\right) \times \frac{1}{10^6} \quad (15b)$$

Calculating the amount of N_2O emissions was performed via multiplying nitrogen loading by a N_2O emission factor in the BNR process (Equation (16)). Parravicini et al. (2016) analyzed the carbon footprint of eight wastewater treatment plants, charting a negative relation of N_2O emission to nitrogen removal efficiency in the BNR process [20]. As the curve shows [20] an EF of 0.075 is chosen to calculate the N_2O emission amount over the BNR process in scenario A with water dilution, under which nitrogen removal efficiency was lowered to below 90%. In contrast, an EF of 0.005 was applied in scenario B, due to BNR nitrification and denitrification, and realized more than 90% nitrogen removal under the higher COD bio-availability favored by recycled digestate.

$$GHG_{BNR-denitrification}\left(\frac{MT\ CO_2e}{yr}\right) = NL_{BNR}\left(\frac{ton\ N}{yr}\right) \times EF\left(\frac{kg\ N_2O}{kg\ N}\right) \times 298\left(\frac{kg\ CO_2e}{kg\ polymer}\right) \times \frac{1}{10^6} \quad (16)$$

3. Results

3.1. Biogas Yield

Figure 2 shows the daily and accumulated biogas production throughout the experimental days at different feeding ratios. The summation of the daily output is estimated based on the daily feeding during the digestor operation. It can be observed that the daily biogas production decreased in the first week and then increased in the second week. The daily biogas production reached its first peak on day 10. On day 15, the feeding ratio was changed to 1:2, there was a sudden increase, and the daily biogas showed overall growth for two weeks but declined from day 32 until the end. From day 1 to 15, at a feeding ratio of 1:1, the estimated average biogas production was 0.42 Nm^3/d. When the cattle manure and slurry ratio increased to 1:2, the average daily biogas production improved to 0.49 Nm^3/d, equivalent to a 16% increase compared with the feeding ratio of 1:1. For the cumulative biogas production, it gradually increased during the operation day, and the curve showed that the feeding balance of 1:2 created a faster rate. From day 1 to 15, with a feeding ratio of 1:1, the cumulative biogas was observed to be 5.42 Nm^3. From day 16 to 35, the cumulative biogas production was 8.55 Nm^3, corresponding to a 57% increase compared with the feeding ratio of 1:1. However, it should be mentioned that the operation day was 5 days longer in the second phase. Meanwhile, the pump performance of biogas was recorded to be 0.16 Nm^3/L with a biogas production rate of 2.62 L/m for the first phase and changed to 0.17 Nm^3/L with a biogas production rate of 2.88 L/m for the second phase.

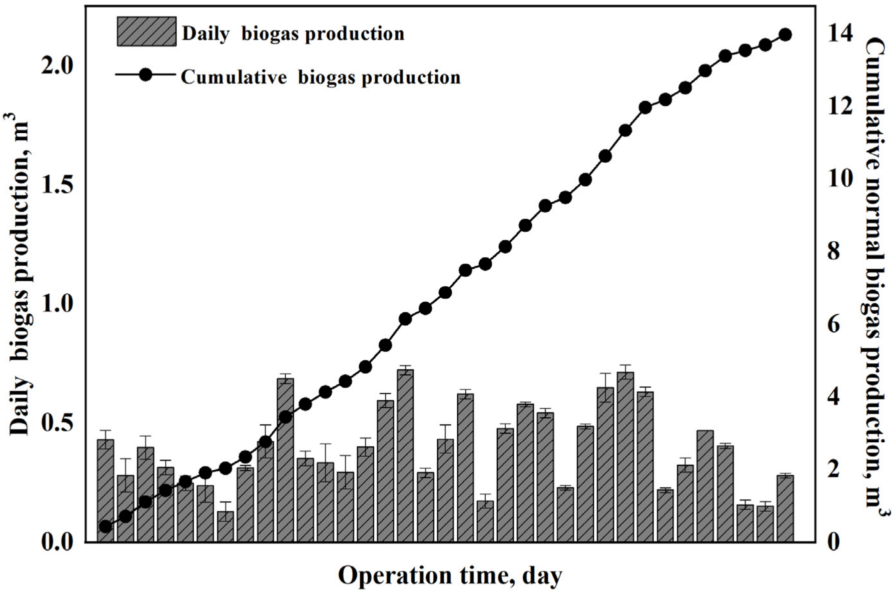

Figure 2. Daily and accumulated biogas production in the operation days.

3.2. Biogas Characterization

The percentage of CH_4 and CO_2 versus time during the operation is presented in Figure 3. Initially, the rate of CH_4 reached as high as 66.1% on the first day and decreased to 52.6% on day 5 but increased after that and remained stable. From day 1 to 15, the average CH_4 and CO_2 contents were 60.63% and 39.37%, respectively. When the cattle manure and slurry ratio increased to 1:2 on day 16, the CH_4 percentage suddenly decreased to 55% and slightly improved but was still lower than in the first phase. It should be mentioned that the CO_2 percentage surpassed the CH_4 rate from day 32 and persisted to day 34. The CH_4 percentage increased to 62.5% on day 35. This phase's average CH_4 and CO_2 contents were 54.33% and 45.67%, respectively. The CH_4 content declined in the second phase, but the CO_2 content increased. However, it is reasonable, since the lower percentage of cow manure was fed during the second phase, and the methane content was highly dependent on the type of feeding materials. Accordingly, the accumulative CH_4 productions were 3.29 Nm^3 and 4.72 Nm^3 for the feeding ratios of 1:1 and 1:2, respectively. Although the CH_4 content was somewhat lower in the second phase, the biogas production increased, resulting in a higher accumulative CH_4 output. Meanwhile, hydrogen sulfide (H_2S) concentrations were recorded to be 20 mg/L, 20 mg/L, 30 mg/L, 10 mg/L, 20 mg/L, and 10 mg/L on days 2, 7, 11, 19, 24, and 31, respectively, referring to an average of 23.33 mg/L in the first phase and an average of 12.5 mg/L in the second phase. The increased CO_2 content may cause a low H_2S concentration during the second phase, and the emission of H_2S should be stressed in practice.

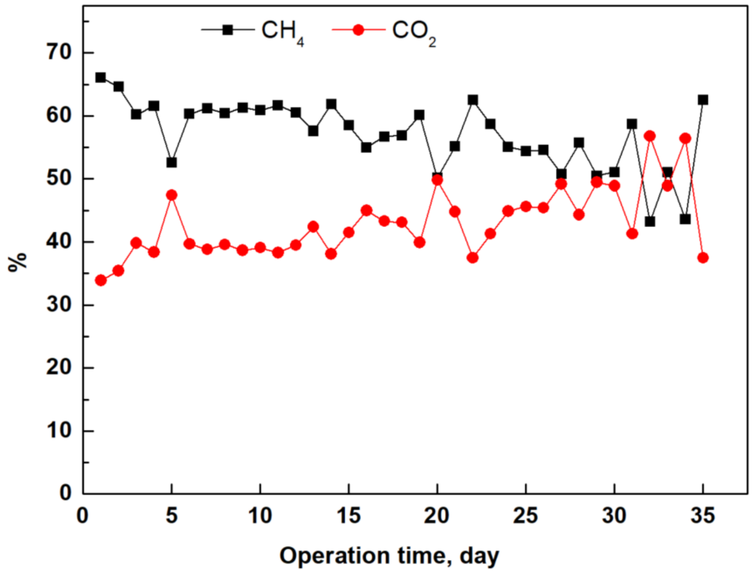

Figure 3. The percentage of CH_4 and CO_2 versus time during the operation.

3.3. Temperature, Volatile Fatty Acid Variation

The digestor ambient temperatures recorded in this field experiment are shown in Figure 4. Initially, the digestor temperature is lower than the ambient temperature, which may reflect the start of the process. The digestor temperature changed during the testing period from 28.90 to 37.8 °C, corresponding to an average temperature of 31.24 °C. It can be stated that the operated process meets mesophilic digestion but is lower than the optimum temperature for biogas production (32–37 °C). Although the ambient temperature decreased in the second phase of the experimental time (30.14 °C on average), the digestor temperature was maintained, indicating the stable operation of the digestor. It is known that temperature is the main parameter affecting biogas production. The methanogenic population would be enhanced with optimum temperature. This study's Pearson correlation coefficient analysis revealed a significant correlation between temperature and daily biogas production. Daily biogas production was positively correlated with temperature (r = 0.98, $p < 0.001$).

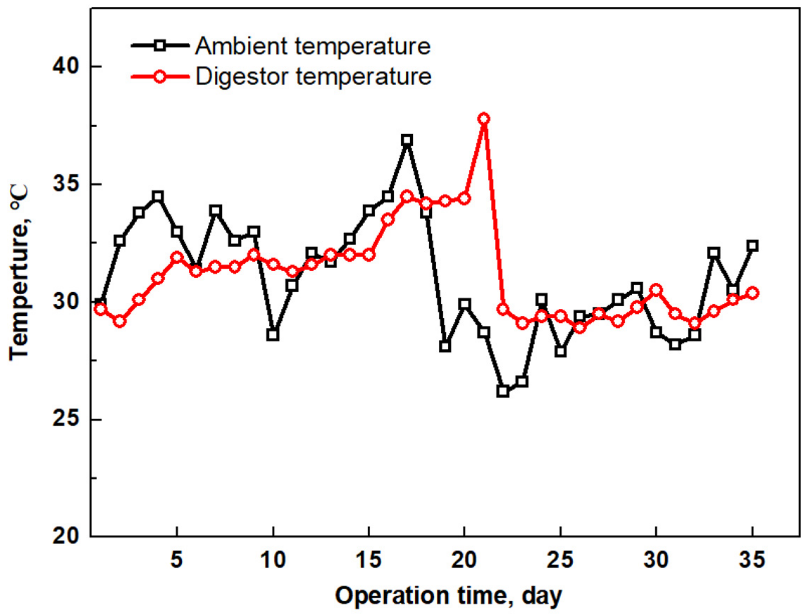

Figure 4. Digestor temperature during operation.

Thus, the decline of methane yield in the second phase may be partly due to the decreased digestor temperature. It should be noted that the temperature was recorded at a single time point during the daytime rather than being continuously monitored, and the temperature drop during the night was ignored. The VFA concentrations (Figure 5) measured on days 1, 8, 15, 22, and 35 were 232 mg/L, 241 mg/L, 365 mg/L, 246 mg/L, 234 mg/L, and 362 mg/L, respectively. VFA is an intermediate product produced during the microbial degradation of feedstock materials. A higher VFA content indicated poor biogas production performance, since acidification may occur if the high VFA cannot be further utilized and the methanogenic bacteria activity is inhibited. After that, the VFA concentration in this study was relatively low, indicating good utilization of VFA by methane bacteria.

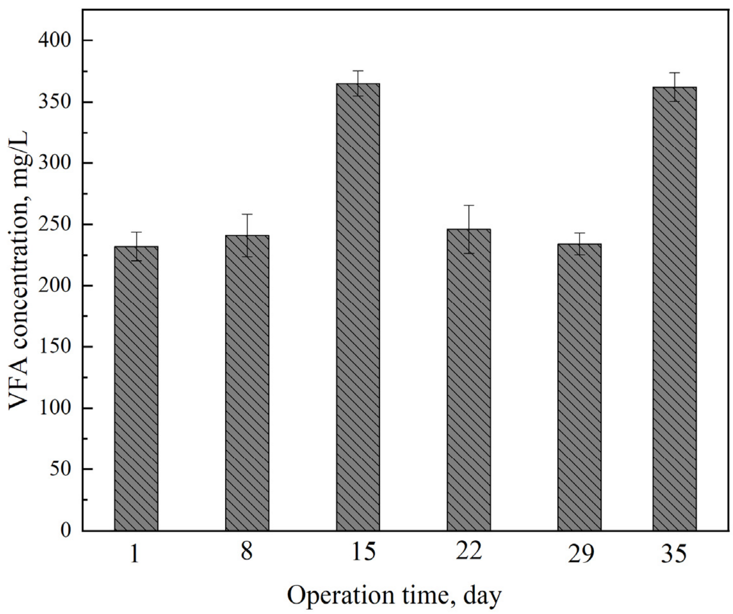

Figure 5. Volatile fatty acids variation during operation.

3.4. Economic and Environmental Efficiency

Compared with scenario A, in which water dilution, with an annual water requirement of 50,286,751 m^3 that was expected to be reduced by diluting raw cow manure with recycled digestate effluent, as shown in Table 2, recycling slurry decreased the digestate effluent discharge volume by 50,286,751 m^3 per year, and correspondingly cut 1.51 MT of to-be-disposed solid waste from the manure anaerobic digestion process. Polymer cost, thus, saw a reduction of USD 31,680,653 each year over the manure solid-waste treatment chain. Throughout the digestate solid disposal, 340,103 fewer tons of GHG were emitted in this scenario due to slurry discharge volume reduction. Specifically, the major contribution (64.4%) to the GHG emission reduction came from the de-watering stage by cutting 219,037 tons of CO_2e, followed by 97,350 tons of CO_2e over the storing stage and 23,715 tons of CO_2e for polymer addition.

As for the digestate liquid fraction, the manure digestion slurry recycle reduced organic loading to wastewater treatment plants by 13.68%. Organic content was further removed over the BNR process, generating 33,017 tons less bio-sludge in scenario B. With regard to solid-waste thickening, the recycled slurry dilution had an advantage in economic efficiency by reducing the polymer used both in liquid–solid separation and de-watering to 297 tons in total, saving USD 1,040,031 each year. Unlike the solid disposal chain of the liquid fraction in slurry, the GHG emission over the liquid–solid separation stages was less than 30,000 tons of CO_2e each year in the bio-sludge treatment, while BNR denitrification and bio-sludge anaerobic digestion were the major GHG emission sources. In the bio-sludge anaerobic digestion stage, the GHG emission was in a positive proportion to the bio-sludge mass and diminished by 134,835 tons of CO_2e each year in scenario B, profiting from OL reduction for the bio-sludge generation. A significant reduction was seen in BNR denitrification, lowering GHG emissions by 1.32 MT CO_2e due to lower nitrogen loading NL_{BNR} discharged from AD in scenario B.

Table 2. Cost and GHG emission.

		Scenario A	Scenario B	Equation Sources
$M_{manure\text{-}solid}$	(MT ts/yr)	22.06	22.06	
Dilution ratio		1:2	1:2	
V_{water}	m^3/yr	50,286,751	−50,286,751	Equation (1)
$V_{slurry\text{-}AD}$	m^3/yr	367,596,148	317,309,398	Equation (2)
$M_{slurry\text{-}solid}$	(MT ts/yr)	11.03	9.52	
$M_{slurry\text{-}polymer}$	ton polymer/yr	66,167.31	57,115.69	Equation (3)
$Cost_{slurry\text{-}polymer}$	$/yr	231,585,573	199,904,920	Equation (4)
$GHG_{slurry\text{-}polymer}$	MT CO_2e/yr	0.17	0.15	Equation (11a)
$GHG_{slurry\text{-}dewateriing}$	MT CO_2e/yr	1.60	1.38	Equation (13a)
$GHG_{slurry\text{-}storing}$	MT CO_2e/yr	0.71	0.61	Equation (13a)
OL_{BNR}	ton COD /yr	563,157	486,118	Equation (5)
NL_{BNR}	ton N/yr	625,730	540,131	Equation (6)
$M_{BNR\text{-}biosludge}$	ton ts/yr	241,353	208,336	Equation (7)
$GHG_{BNR\text{-}denitrification}$	MT CO_2e/yr	1.40	0.08	Equation (16)
$GHG_{biosludge\text{-}AD}$	MT CO_2e/yr	1.01	0.87	Equation (10)
$GHG_{biosludge\text{-}storing}$	MT CO_2e/yr	0.01	0.01	Equation (15a)
$GHG_{biosludge\text{-}dewatering}$	MT CO_2e/yr	0.02	0.02	Equation (15b)
$M_{biosludge\text{-}polymer}$	ton polymer/yr	2172.18	1875.03	Equation (8)
$Cost_{biosludge\text{-}polymer}$	$/yr	7,082,608	6,562,593	Equation (9)
$GHG_{biosludge\text{-}polymer}$	MT CO_2e/yr	0.005	0.005	Equation (11b)
GHG_{total}	MT CO_2e/yr	3.38	3.13	
$Cost_{total}$	$/yr	222,827,855	206,467,513	

4. Discussion

The daily biogas production rates were 0.42 and 0.49 Nm^3/d for ratios of 1:1 and 1:2, which were higher when compared with the performance of reported small-scale digestors (0.03–0.7 Nm^3/d) at high attitudes (Pérez et al., 2014) [23]. An evaluation of a plug-flow tubular PVC digestor operated in Cajamarca reported that the biogas production was about 0.53 m^3/d, which could support about 2 h of cooking every day [29]. Thus, it is predictable that the biogas generated from the digestor developed in this study could supply the fuels needed for household usage. A semi-continuous experiment conducted on household biogas in the cold region of China harvested an average biogas production of 0.95 m^3/d. Still, the feed in the substrate was dry sheep manure with TS of 74.36%, and solar heating was employed [30]. Moreover, the CH_4 content achieved in this study is comparable. On the one hand, it should be noted that the CH_4 content recorded in this study was relatively lower than in similar previous research that used a tubular digestor for cow manure digestion with TS of 3.5% and 9% in two regions of the Peruvian Andes. The achieved CH_4 content was 63–67% [14]. Meanwhile, a study using swine manure and cooking grease co-digestion by 12 plug-flow digestors of 250 L each in Costa Rica reported a range of CH_4 content from 63.2 to 69.9% [31]. On the other hand, a study conducted at Tikathali in the Lakitpur district also used a 1 m^3 capacity water storage tank for a digestor where its upper part was removed to place the gasholder; the average CH_4 content was 56.34%, and the maximum was 57% [32]. Typically, the proportion of CH_4 ranges from 50% to 70%, and CH_4 > 60% is better suited for heating and cooking [31,33]. Thus, the CH_4 percentage in this study can be satisfied. However, the specific biogas production yields at ratios of 1:1 and 1:2 in this study were estimated to be 0.12 Nm^3/kg VS and 0.14 Nm^3/kg VS, respectively, which were lower than for the reported low-technology digestors designed for similar conditions (0.32–0.36 m^3/kg VS). This may be due to the low VS content in the feedstock, which was below 10%. Moreover, HRT is an essential parameter for biogas production, and a lower stability of the digestor was observed at reduced HRT [34]. Usually, the HRT for mesophilic microorganisms ranges from 10 to

40 days, and for household biogas digestors the suggested HRT is typically 60 days, or 30–40 days in some cases. In this study, the HRT was set at 35 days, which was adequate but needed further research for better performance.

The study was emphasized to investigate the efficiency of biogas production using two different ratios for cattle manure and slurry. It is known that anaerobic digestion involves four distinct phases to produce biogas [35]. Under the mutual performance of the bacteria and archaea communities, some internal factors affecting degradation can be influenced by overloading, resulting in lower digestor efficiency. Under a high feeding ratio of 1:1, the organic loading rate (OLR) was 2.11 kg VS/m^3/d. When the ratio changed to 1:2, the OLR decreased to 1.11 kg VS/m^3/d. OLR is a critical design criterion for pilot biogas production [36]. In our previous batch investigation, co-digestion using household organic waste with dairy manure using the same digestor showed an OLR of 1.2–1.8 kg VS/m^3/d, and an average of 1.4 kg VS/m^3 was the suitable operation parameter [13]. The performance of the digestor in the operational conditions with a feeding ratio of 1:1 was suppressed due to overfeeding of the organic solids, which may be due to limited mass transfer and degradation by anaerobic microorganisms; the higher loading rates are not conducive, as they increase the solid contents on the feeding substrates and inhibit the transitions of the organic matter for microbial degradation. Thus, the biogas and methane yields increased when operated with a feeding ratio of 1:2, as we observed. In another study, cow manure diluted with water at ratios of 1:2 to 1:3, referring to an OLR above 1 kg VS/m^3/d, has been reported as the suggested dilution [14]. It can be foreseen that slurry instead of water could promote the biogas process at a higher OLR. This study used digestate instead of water to dilute the raw substance. In practice, the liquid digestate from the digestor could be returned and formed liquid digestate recirculation, which has been proven effective in biogas promotion by improving the buffer capacity and stability of the digestion system and further increasing the hydrolysis and fermentation microorganism population. A biogas rate 33.3% higher than the maximum volume was achieved by 50% of the digestate being recircled to the digestor in a lab-scale study, and liquid digestate recirculation was also influential in a two-phase digestor system [17,18]. It was detected that about 50% of the biogas was produced from the returned liquid digestate [16]. Thus, the slurry is returned to the digestor and forms a circulation that can be operated in practice, and 70% was the suggested recirculation ratio for the digestor developed in this study. Moreover, launching liquid–solid separation is not needed if the slurry is directly returned to the digestion unit, which could simplify the process. More research on process optimization should be carried out in the future. It should be mentioned again that there was no stirring device inside the digestor. Thus, the non-homogeneous environment may limit the degradation process. Predictably, the performance could be enhanced if heating and stirring are considered in the future, but the cost-effectiveness should also be balanced.

This work aimed at a cost-efficient and environmentally friendly prototype modified and constructed from a locally available HDPE water tank for the AD process. The cylindrical shape and HDPE material were believed to favor biogas production of this work, as listed in Table 3. The black-shading HDPE digestor was installed on site on the ground, where it absorbed solar radiation easily, and the HDPE material is superior in holding heat in to maintain a mesophilic temperature (around 37 °C), shortening HRT to far lower levels than in previous works. In spite of the lower HRT, the HDPE digestor met a higher OLR of 1.11–2.11 kg VS/m^3/d than fixed-dome and tubular digestors, with a comparable biogas production rate of 0.42–0.49 Nm^3/m^3/d. Conventional commercial digestors (fixed-dome or plastic tubular PE or PVC) were typically constructed with volumes of over 2.4 m^3 and operated under 25 °C, limiting OLR due to a long HRT. Comparatively, the HDPE digestor was utilized more efficiently, improving cost efficiency in the construction stage. Regarding the operation stage, this small prototype adopted digestate recirculation to dilute the manure substrate to avoid clogging. On the one hand, 50,286,751 m^3 of water annually could be saved in modified manure dilution by recirculated digestate (Scenario B) instead of water (Scenario A), potentially meeting the annual water demands of 114,810 households of 6 person-equivalents in Bangladesh. On the other hand, polymer costs over the solid treatment chain were trimmed by USD 1,040,031 each year, due to the reduced net slurry discharge to the downstream disposal units. Ioannou-Ttofa et al. (2021) also performed LCA for a 100-year GPW for a fixed-dome digestor [22] and found that GHG emission over the operation stage made a major (89.1%) contribution to the environmental impact over the construction stage. In this work, the GHG emission-related energy consumption over dilution operation made far less difference than the downstream disposal of the net discharged digestate. Thus, emphasis was put on the latter. For the solid treatment chain, the polymer cost mainly came from the solid thickening of the slurry by 96.82%, regardless of the dilution choice. Taking a broad view of the slurry decontamination, CH_4 and N_2O emissions significantly impacted the CO_2e balance during digestate solid de-watering, BNR denitrification and bio-sludge AD stages in scenario A. In contrast, in scenario B with slurry dilution, only solid disposal had a climate impact greater than its N_2O emission, which could be explained by the advantage of higher TN removal performances benefiting from a more available fraction of soluble carbon alongside the recycled manure digestate. Digestion slurry was often used as an external carbon source for nitrogen removal enhancement in previous works [37–39], confirming the favorable bio-availability to alleviate the N_2O impact.

This work confirmed the feasibility of this small prototype as an alternative to the widely used fixed-dome or tubular digestors across the country in Bangladesh. Still, more effort should be made to put the HDPE digestor into application. Plastic tubular digestors were found to be advantageous over fixed-dome digestors, due to straightforward operation and low investment cost [22]. In contrast, standard construction and manipulation enabled the fixed-dome digestors popular in developing countries [10–12], such as Vietnam, India and China. There is a need for developers and promoters to construct user-friendly operation for the HDPE digestor. Apart from GHG generation, CH_4 leakage and intentional release have been proven to be challenges with regard to environmental impacts over widely used fixed-dome digestors in practice [22]. More effective closure could be taken into consideration to improve eco-efficiency. Monitoring and discharge regulation by government could be also necessary to encourage the HDPE to be applied for reasons of sustainability. Moreover, removal of emerging pollutants could also be emphasized following the COVID-19 epidemic [40].

Table 3. Performance of small-scale digestors.

Digestor	Feedstock	Dilution	T	V	HRT	OLR	Biogas Production Rate	CH_4	Reference
			(°C)	(m^3)	(d)	kg VS/m^3/d	$Nm^3{}_{biogas}/m^3{}_{digestor}$/d	(%)	No.
Cylindrical HDPE	Cow manure	Recirculated digestate	37	1	35	1.11–2.11	0.42–0.49	54–61	This work
Tubular PE or PVC	Cow manure	water	<25	2.4–7.5	60–90	0.22–1.29	0.07–0.47	65	[14]
Tubular PVC	Pig manure	water	<25	7.5	75	0.59	0.04	60	[29]
Tubular PVC	Cow/pig manure	water	<25	7.5	60–90	0.34–1	0.03–0.12	55–60	[41]
Tubular neoprene	Cattle dung	water	<25	1.2	55	<1	0.50	55	[42]
Fixed dome							0.68		
Fixed dome	Cattle dung	water	<25	2.4	55	<1	0.4–0.7	55–60	[43]
Fixed dome	Cattle dung	water	<25	2	55	<1	0.35–0.45	55–60	[44]
Fixed dome	Cattle/sheep dung	water	<25	9.5	45	0.38	0.34–0.5	60	[45]

5. Conclusions

In this study, a household HDPE digestor achieved biogas production yields of 5.42 Nm^3 and 8.55 Nm^3 in accumulation under dilution operation with cattle manure and slurry at feeding ratios of 1:1 and 1:2, respectively. Biogas production rates were

0.42 Nm^3/d and 0.49 Nm^3/d, and specific biogas production yields were 0.12 m^3/kg VS and 0.14 m^3/kg VS, accordingly. Although the average CH_4 content declined from 60.63% to 54.33% when operating at a manure-to-slurry ratio of 1:2, biogas products potentially met a 2 h household cooking energy demand. Compared with the cattle manure AD process with water dilution, manure dilution with slurry re-circulation for biogas production exhibited a great potential to cut chemical costs by USD 32,720,684 per year and weaken GHG impact on the climate by 1.8 MT CO2e annually. From a nationwide scope, it suggested the feasibility of this small prototype as a cost-effective alternative to commercial digestors for household energy sources in rural Bangladesh.

6. Highlights

- Field observation on a locally manufactured household digestor was carried out.
- The cattle manure-to-slurry ratio was optimized during operation.
- Biogas production efficiency and feasibility were revealed.
- The prototype's cost-efficiency and carbon-neutral niche was evaluated in nationwide scope.
- Theoretical support was provided for low-cost anaerobic digestor development.

Author Contributions: Methodology, X.H.; Software, X.H.; Formal analysis, R.R., H.K. and S.M.N.U.; Investigation, S.M.N.; Writing—original draft, X.H. and X.Z.; Writing—review & editing, X.H., S.M.N. and X.Z.; Supervision, Z.L. and H.-P.M.; Project administration, Z.L.; Funding acquisition, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National key research and development plan (2021YFC3201305), the Research Fund Program of Guangdong Provincial Key Laboratory of Environmental Pollution Control and Remediation Technology (2020B1212060022), the World Bank (WB) and German Developmental Bank (KFW), incorporated Infrastructure Development Company Limited (IDCOL) to project fund (package No: S-32, RefNo: IDCOL/REREDPII/S-32/2015/03) with the involvement of Bangladesh Agricultural University (BAU).

Data Availability Statement: We all authors would like to share our work with other peers, and the data presented in this study can be available on request both from the corresponding author Xiaoqin Zhou (zhouxiaoqin025@163.com) and the first author He (uwo_cas@163.com).

Acknowledgments: The authors thank the National Environment and Energy International Cooperation Base for their support. We thank Alimul Islam, Bangladesh Agricultural University, for his project assistance.

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

Abbreviations

HDPE	High-density polyethylene
AD	Anaerobic digestion
TS	Total solids
VS	Volatile solids
HRT	Hydraulic retention time
VFA	Volatile fatty acid
TCOD	Total chemical oxygen demand
SCOD	Soluble chemical oxygen demand
BNR	Biological nutrient removal
OL	Organic loading
NL	Nitrogen loading
LCA	Life cycle analysis
GHG	Greenhouse gas
GWP	Global warming potential
EF	Emission factor
MT	Million ton
OLR	Organic loading rate

References

1. Salam, S.; Parvin, R.; Salam, M.A.; Azad, S.M. Feasibility study for biogas generation from household digesters in Bangladesh: Evidence from a household level survey. *Int. J. Energy Econ. Policy* **2020**, *4*, 23–30. [CrossRef]
2. Siddiki, S.Y.A.; Uddin, M.N.; Mofijur, M.; Fattah, I.M.R.; Ong, H.C.; Lam, S.S.; Kumar, P.S.; Ahmed, S.F. Theoretical calculation of biogas production and greenhouse gas emission reduction potential of livestock, poultry and slaughterhouse waste in Bangladesh. *J. Environ. Chem. Eng.* **2021**, *9*, 105204. [CrossRef]
3. Tasnim, F.; Iqbal, S.A.; Chowdhury, A.R. Biogas production from anaerobic co-digestion of cow manure with kitchen waste and Water Hyacinth. *Renew. Energy* **2017**, *109*, 434–439. [CrossRef]
4. Huang, X.; Yun, S.; Zhu, J.; Du, T.; Zhang, C.; Li, X. Mesophilic anaerobic co-digestion of aloe peel waste with dairy manure in the batch digester: Focusing on mixing ratios and digestate stability. *Bioresour. Technol.* **2016**, *218*, 62–68. [CrossRef] [PubMed]
5. Xiao, B.; Zhang, W.; Yi, H.; Qin, Y.; Wu, J.; Liu, J.; Li, Y.-Y. Biogas production by two-stage thermophilic anaerobic co-digestion of food waste and paper waste: Effect of paper waste ratio. *Renew. Energy* **2019**, *132*, 1301–1309. [CrossRef]
6. Li, R.; Chen, S.; Li, X. Biogas Production from Anaerobic Co-digestion of Food Waste with Dairy Manure in a Two-Phase Digestion System. *Appl. Biochem. Biotech.* **2010**, *160*, 643–654. [CrossRef] [PubMed]
7. Okuo, D.O.; Waheed, M.A.; Bolaji, B.O. Evaluation of Biogas Yield of Selected Ratios of Cattle, Swine, and Poultry Wastes. *Int. J. Green Energy* **2016**, *13*, 366–372. [CrossRef]
8. Wang, X.; Li, Z.; Zhou, X.; Wang, Q.; Wu, Y.; Saino, M.; Bai, X. Study on the bio-methane yield and microbial community structure in enzyme enhanced anaerobic co-digestion of cow manure and corn straw. *Bioresour. Technol.* **2016**, *219*, 150–157. [CrossRef]
9. Zhang, L.; Lee, Y.; Jahng, D. Anaerobic co-digestion of food waste and piggery wastewater: Focusing on the role of trace elements. *Bioresour. Technol.* **2011**, *102*, 5048–5059. [CrossRef]
10. Chen, Y.; Yang, G.; Sweeney, S.; Feng, Y. Household biogas use in rural China: A study of opportunities and constraints. *Renew. Sustain. Energy Rev.* **2010**, *14*, 545–549. [CrossRef]
11. Garfí, M.; Martí-Herrero, J.; Garwood, A.; Ferrer, I. Household anaerobic digesters for biogas production in Latin America: A review. *Renew. Sustain. Energy Rev.* **2016**, *60*, 599–614. [CrossRef]
12. Raha, D.; Mahanta, P.; Clarke, M.L. The implementation of decentralised biogas plants in Assam, NE India: The impact and effectiveness of the National Biogas and Manure Management Programme. *Energy Policy* **2014**, *68*, 80–91. [CrossRef]
13. Garfí, M.; Martí-Herrero, J.; Garwood, A.; Ferrer, I. Assessment of organic loading rate by using a water tank digester for biogas production in Bangladesh. *J. Clean. Prod.* **2020**, *265*, 121688.
14. Ferrer, I.; Garfí, M.; Uggetti, E.; Ferrer-Martí, L.; Calderon, A.; Velo, E. Biogas production in low-cost household digesters at the Peruvian Andes. *Biomass Bioenergy* **2011**, *35*, 1668–1674. [CrossRef]
15. Jeppu, G.P.; Janardhan, J.; Kaup, S.; Janardhanan, A.; Mohammed, S.; Acharya, S. Effect of feed slurry dilution and total solids on specific biogas production by anaerobic digestion in batch and semi-batch reactors. *J. Mater. Cycles Waste* **2022**, *24*, 97–110. [CrossRef]
16. Jeppu, G.P.; Janardhan, J.; Kaup, S.; Janardhanan, A.; Mohammed, S.; Acharya, S. Solid anaerobic digestion batch with liquid digestate recirculation and wet anaerobic digestion of organic waste: Comparison of system performances and identification of microbial guilds. *Waste Manag.* **2017**, *59*, 172–180.
17. Xue, S.; Qiu, L.; Guo, X.; Yao, Y. Effect of liquid digestate recirculation on biogas production and enzyme activities for anaerobic digestion of corn straw. *Water Sci. Technol.* **2020**, *82*, 144–156. [CrossRef]
18. Hendroko, S.R.; Sasmito, A.; Adinurani, P.G.; Nindita, A.; Yudhanto, A.S.; Nugroho, Y.A.; Liwang, T.; Mel, M. The Study of Slurry Recirculation to Increase Biogas Productivity from Jatropha curcas Linn. Capsule Husk in Two Phase Digestion. *Energy Procedia* **2015**, *65*, 300–308. [CrossRef]
19. Metcalf and Eddy, Inc. *Wastewater Engineering, Treatment and Reuse*, 4th ed.; McGraw-Hill: New York, NY, USA, 2003; pp. 714–732.
20. Parravicini, V.; Svardal, K.; Krampe, J. Greenhouse gas emissions from wastewater treatment plants. *Energy Procedia* **2016**, *97*, 246–253. [CrossRef]
21. Solomon, S. IPCC: Climate change the physical science basis. In Proceedings of the AGU Fall Meeting Abstracts, San Francisco, CA, USA, 10–14 December 2007.
22. Ioannou-Ttofa, L.; Foteinis, S.; Moustafa, A.S.; Abdelsalam, E.; Samer, M.; Fatta-Kassinos, D. Life cycle assessment of household biogas production in Egypt: Influence of digester volume, biogas leakages, and digestate valorization as biofertilizer. *J. Clean. Prod.* **2021**, *286*, 125468. [CrossRef]
23. Pérez, I.; Garfí, M.; Cadena, E.; Ferrer, I. Technical, economic and environmental assessment of household biogas digesters for rural communities. *Renew. Energy* **2014**, *62*, 313–318. [CrossRef]
24. USEPA. *Estimating Sludge Management Costs*; USEPA: Cincinnati, OH, USA, 1985; pp. 687–699.
25. Drosg, B. *Process Monitoring in Biogas Plants*; IEA Bioenergy: Paris, France, 2013.
26. Khan, E.U.; Martin, A.R. Review of biogas digester technology in rural bangladesh. *Renew. Sustain. Energy Rev.* **2016**, *62*, 247–259. [CrossRef]
27. Akhiar, A.; Guilayn, F.; Torrijos, M.; Battimelli, A.; Shamsuddin, A.H.; Carrère, H. Correlations between the composition of liquid fraction of full-scale digestates and process conditions. *Energies* **2021**, *14*, 971. [CrossRef]
28. Akhiar, A.; Battimelli, A.; Torrijos, M.; Carrere, H. Comprehensive characterization of the liquid fraction of digestates from full-scale anaerobic co-digestion. *Waste Manag.* **2017**, *59*, 118. [CrossRef]

29. Garfí, M.; Ferrer-Martí, L.; Velo, E.; Ferrer, I. Evaluating benefits of low-cost household digesters for rural Andean communities. *Renew. Sustain. Energy Rev.* **2012**, *1*, 575–581. [CrossRef]
30. Feng, R.; Li, J.; Dong, T.; Li, X. Performance of a novel household solar heating thermostatic biogas system. *Appl. Therm. Eng.* **2016**, *96*, 519–526. [CrossRef]
31. Lansing, S.; Martin, J.F.; Botero, R.B.; da Silva, T.N.; da Silva, E.D. Wastewater transformations and fertilizer value when co-digesting differing ratios of swine manure and used cooking grease in low-cost digesters. *Biomass Bioenergy* **2010**, *34*, 1711–1720. [CrossRef]
32. Lungkhimba, H.M.; Karki, A.B.; Shrestha, J.N. Biogas Production from Anaerobic Digestion of Biodegradable Household Wastes. *Nepal J. Sci. Technol.* **2010**, *11*, 167–172. [CrossRef]
33. Náthia-Neves, G.; Berni, M.; Dragone, G.; Mussatto, S.I.; Forster-Carneiro, T. Anaerobic digestion process: Technological aspects and recent developments. *Int. J. Environ. Sci. Technol.* **2018**, *15*, 2033–2046. [CrossRef]
34. Shi, X.S.; Dong, J.J.; Yu, J.H.; Yin, H.; Hu, S.M.; Huang, S.X.; Yuan, X.Z. Effect of Hydraulic Retention Time on Anaerobic Digestion of Wheat Straw in the Semicontinuous Continuous Stirred-Tank Reactors. *BioMed Res. Int.* **2017**, *2017*, 2457805. [CrossRef]
35. Awasthi, S.K.; Joshi, R.; Dhar, H.; Verma, S.; Awasthi, M.K.; Varjani, S.; Sarsaiya, S.; Zhang, Z.; Kumar, S. Improving methane yield and quality via co-digestion of cow dung mixed with food waste. *Bioresour. Technol.* **2018**, *251*, 259–263. [CrossRef] [PubMed]
36. Mel, M.; Suhuli, N.M.; Avicenna; Ihsan, S.I.; Ismail, A.F.; Yaacob, S. Effect of Organic Loading Rate (OLR) of Slurry on Biogas Production Quality. *Adv. Mater. Res.* **2015**, *1115*, 325–330. [CrossRef]
37. Deng, L.W.; Cao, W.P.; Sun, X.; Li, S.L.; Chen, Z.A. Impact of proportion of adding raw wastewater on post-treatment of digested piggery wastewater. *Environ. Sci.* **2007**, *28*, 588–593.
38. Dębowski, M.; Szwaja, S.; Zieliński, M.; Kisielewska, M.; Stańczyk-Mazanek, E. The influence of anaerobic digestion effluents (ADEs) used as the nutrient sources for *Chlorella* sp. cultivation on fermentative biogas production. *Waste Biomass Valorization* **2017**, *82*, 1153–1161. [CrossRef]
39. Chong, C.C.; Cheng, Y.W.; Ishak, S.; Lam, M.K.; Lim, J.W.; Tan, I.S.; Show, P.L.; Lee, K.T. Anaerobic digestate as a low-cost nutrient source for sustainable microalgae cultivation: A way forward through waste valorization approach. *Sci. Total Environ.* **2022**, *803*, 150070. [CrossRef] [PubMed]
40. Azqandi, M.; Shahryari, T.; Fanaei, F.; Nasseh, N. Green construction of magnetic $MnFe_2O_4$/ZIF-8 nanocomposite utilizing extract of *Melissa officinalis* plant for the photo-degradation of tetracycline under UV illumination. *Catal. Commun.* **2023**, *185*, 106798. [CrossRef]
41. Garfí, M.; Ferrer-Martí, L.; Perez, I.; Flotats, X.; Ferrer, I. Co-digestion of cow andguinea pig manure in low-cost tubular digesters at high altitude. *Ecol. Eng.* **2011**, *37*, 2066–2070. [CrossRef]
42. Kanwar, S.S.; Guleri, R.L. Performance evaluation of a family-size, rubber-balloon biogas plant under hilly conditions. *Bioresour. Technol.* **1994**, *50*, 119–121. [CrossRef]
43. Kalia, A.K.; Kanwar, S.S. Long-term evaluation of a fixed dome Janata biogas plant in hilly conditions. *Bioresour. Technol.* **1998**, *65*, 61–63. [CrossRef]
44. Kanwar, S.S.; Gupta, R.K.; Guleri, R.L.; Singh, S.R. Performance evaluation of a 1 m^3 modified, fixed-dome Deenbandhu biogas plant under hilly conditions. *Bioresour. Technol.* **1994**, *50*, 239–241. [CrossRef]
45. Tasdemiroglu, E. Review of the biogas technology in Turkey. *Biomass* **1988**, *17*, 137–148. [CrossRef]