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Evaluating the Potential of Renewable Energy Sources in a Full-Scale Upflow Anaerobic Sludge Blanket Reactor Treating Municipal Wastewater in Ghana

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Abstract: Wastewater management remains a major challenge in developing countries due to the lack of adequate infrastructure, making the need for economically viable and efficient technologies that can be sustained by emerging economies imperative. The upflow anaerobic sludge blanket (UASB) reactor represents an efficient and low-cost technology that produces by-products from which valuable resources can be recovered. This study assessed the energy recovery potential in the form of electricity from biogas and sludge by-products produced by a full-scale UASB reactor. Biogas production rate and composition were monitored to determine the biogas energy recovery potential. Dehydrated sludge from sludge drying beds was likewise quantified and characterised for its elemental composition, immediate composition, gross calorific value and net calorific value to estimate sludge energy recovery potential. The average daily biogas production was found to be 611 ± 275 Nm^3/d, with 65% methane in the biogas output. Average sludge dry matter production was determined to be 358.24 TS kg/d. The net energy recovery potential was estimated to be 534.1 MWh/yr, 36% more than the yearly energy demand (392.7 MWh/yr) of the entire plant. Conservative energy recovery at a UASB-based municipal wastewater treatment facility could serve as a self-supply energy option to support its operations.

Keywords: anaerobic digestion; biogas production; energy recovery; municipal wastewater treatment; sludge production; UASB reactor

Citation: Arthur, P.M.A.; Konaté, Y.; Sawadogo, B.; Sagoe, G.; Dwumfour-Asare, B.; Ahmed, I.; Bayitse, R.; Ampomah-Benefo, K. Evaluating the Potential of Renewable Energy Sources in a Full-Scale Upflow Anaerobic Sludge Blanket Reactor Treating Municipal Wastewater in Ghana. *Sustainability* **2023**, *15*, 3743. https://doi.org/10.3390/su15043743

Academic Editors: Xinzhe Zhu, Ruohong Li and Lianpeng Sun

Received: 19 December 2022
Revised: 9 February 2023
Accepted: 13 February 2023
Published: 17 February 2023

1. Introduction

Basic sanitation in developing countries such as Ghana still requires huge investment to meet the growing population demand [1]. This makes the study of technologies that can facilitate the deployment of wastewater treatment systems imperative. The upflow anaerobic sludge blanket (UASB) reactor has been identified as one of the most efficacious and economically viable wastewater treatment technologies which could be deployed in developing countries towards the attainment of sustainable wastewater management in these regions [2]. The UASB reactor has the added advantage of its ability to handle high-strength wastewater at relatively shorter hydraulic retention times (HRTs) and controlled odour problems [3,4]. Additionally, the UASB reactor allows the recovery of renewable energy via the production of methane-rich biogas, whilst the recovery of biosolid by-products as nutrient and/or energy sources provides economic and environmental benefits, such as saving on the cost of using landfills and a significant reduction in greenhouse gas

(GHG) emissions [4]. The benefits associated with the use of UASB reactors for sewage treatment have greatly increased their application within the last few decades in most developing countries, with several full-scale plants installed, especially in Latin America and India [4,5].

Various studies have reported on resource recovery from wastewater treatment systems as a means of attaining sustainable wastewater management via the application of eco-friendly technologies and modern circular-economy concepts [6,7]. Recovery of energy from biogas and sludge in the form of electricity from wastewater treatment systems could replace fossil-fuel-based energy sources used for plant operations [8]. For anaerobic systems, such as the UASB reactor, which has lower energy requirements, the recovery of energy from biogas and sludge by-products could offset the entire energy demands of plants [9]. Noyola [10] opined that a UASB reactor that could generate biogas with 75% methane gas presents the potential for a high energy value of at least 26.9 MJ/m^3. Sewage sludge generated from these systems likewise has a high potential for energy recovery by the applications of either biochemical conversion methods coupled with co-digestion or thermochemical conversion methods [8]. Energy recovered from these systems could be employed for electricity generation or the heating of digesters. This would enable wastewater treatment facilities to subsequently reduce their energy costs, become energy neutral or go energy-positive [11].

With the recent persistent global outcry over the depletion of fossil reserves, GHG emissions and the severe climate change menace [12], the recovery of clean renewable energy from wastewater biogas and sludge would promote the attainment of the sustainable development goals (SDGs) on affordable and clean energy (SDG 7) and climate change (SDG 13), which aim to lessen the impacts of climate change by regulating and promoting the utilisation of clean, renewable energies [13]. The climate-change policy developed by the United Nations advocates the use of renewable energy sources as alternatives to traditional fossil-based fuels. Thus, sustainable wastewater management through energy recovery can contribute to the generation of clean renewable energy [14]. Energy recovery from wastewater biogas and sludge could allow the replacement of plant energy sources from the national grid with self-supply and clean renewable energy and consequently reduce the carbon footprints of wastewater treatment plants (WWTPs) to support the global campaign to halt climate change [8].

Energy recovery from wastewater treatment systems has become a budding enterprise for industry players as it provides a means to achieve sustainable wastewater management, promoting the concept of "sanitation financing sanitation" [15]. This phenomenon is commonly employed in the developed world, with more plants in these regions becoming energy self-sufficient through energy recovery from biogas and sludge. Nonetheless, there have been progressions in some developing countries as well [16,17]. Despite the advancement in some developing countries towards the recovery of energy from WWTPs, this phenomenon is non-existent in Ghana. To the best of the authors' knowledge, there are currently no studies that have evaluated the energy recovery potential of the few full-scale WWTPs operating in the country. This notwithstanding, as the government aims to expand the coverage of population served by sewage treatment plants, with the commencement of construction of full-scale WWTPs in some regions across the country having already been seen, it would be prudent for research to be conducted on the few existing plants to evaluate their energy recovery potentials. This would support assessment of the feasibility of this concept and inform policymakers on the advantages of incorporating energy recovery systems at the new plants that are being constructed. This paper seeks to evaluate the energy recovery potential of biogas and sewage sludge produced from the operations of a full-scale UASB-based WWTP treating municipal wastewater to assess the possibility of the full-scale plant becoming energy self-sufficient.

2. Materials and Methods

2.1. Description of the Wastewater Treatment Plant Used in the Study

This research was conducted at the Mudor WWTP located in Accra, Ghana's capital city (latitude 5°36′53.3448″ N, longitude 0°12′21.1464″ W). The city has a bimodal rainfall pattern, with major dry and wet seasons typically experienced from mid-November to April and from May to October, respectively [18]. Ambient temperature ranges from 22.7 °C to 33.8 °C [19]. Constructed in 2000, the Mudor WWTP was shut down after a few years of operation because of poor maintenance and limited financial injection to sustain operations. Later, in 2017, it became operational after major rehabilitation and expansion works were carried out. The treatment facility accepts and treats wastewater from office buildings, households and commercial centres within Accra's central business district (CBD) and its environs connected to a sewer network. Currently, the plant is projected to serve roughly 100,000 residents, based on a projection of 60,000 people served at the time of construction [20], with an applied 2.1% per annum population growth rate [21]. No industrial effluent was known to terminate at the plant at the time of the study.

The Mudor WWTP consists of six (6) UASB reactors, three trickling filters (TFs), and two clarifiers for post-treatment and sludge drying beds (Figure S1a). The modular-shaped UASB reactors operate in parallel, with a total volumetric loading capacity between 16,000 and 18,000 m^3/d. The circular-shaped TFs and clarifiers also operate in parallel. The six UASB reactors were in operation at the time of the study, treating an average flow rate of 176 ± 36 m^3/h.

The plant receives typically low-strength sewage [22] pumped from the Central Accra Pump Station (CAPS) on the same premises (about 50 m away). At the CAPS, coarse solid waste materials (>20 mm) in the sewage are trapped by installed primary screens. Grit and other fine materials are removed by physical separation systems (i.e., vortex grit units and 5 mm-mesh fine screens) before the sewage enters the UASB reactors. The TFs receive effluent from the UASB reactors for additional biological treatment and subsequent settling in the clarifiers. Effluent from the clarifiers is released into the Korle Lagoon. Occasionally, UASB reactor excess sludge is released into the sludge thickeners for physical sludge dewatering. Upon thickening, the sludge is pumped onto the conventional sand drying beds for dehydration and further processing, whilst the supernatant is recycled back into the wet well, where it combines with incoming wastewater. Biogas generated by the UASB reactors is directed to a gas-flaring unit for flaring (Figure S1b). Table 1 illustrates the major characteristics of the Mudor WWTP. The Mudor WWTP is designed with gravity driving most of the material flow, thereby minimising pumping and electricity consumption and the associated costs. Further description of the WWTP, sewage characteristics and performance are presented in Arthur et al. [23].

Table 1. Major characteristics (hydraulic, organic load, and geometric) of the Mudor WWTP.

Characteristics	UASB Reactors	Trickling Filters	Secondary Clarifiers
Population equivalent (Inhab)	100,000		
Flow (m^3/h)	180.5	90.2	-
Hydraulic retention time (h)	47.6	-	18.1
Organic loading rate ($kgBOD_5/m^3/d$)	0.81	0.19	-
Hydraulic loading rate ($m^3/m^2//h$)	-	0.19	-
Number of Units	6	3 *	2
Shape	Modular	Circular	Circular
Dimension of each unit (m)	20 × 10	D = 24.5	D = 24.5
Depth of each unit (m)	6.5	3.0	4.2
Volume of each unit (m^3)	1300.0	1414.0	1540.0

Source: Arthur et al. [23]. D = Diameter. * One unit not functioning during the study period.

2.2. Biogas Quantification and Characterisation

The volumetric production of biogas was monitored daily during the study period (January 2021 to December 2021). Biogas reading was carried out with an automatic ultrasonic flow measuring device (Prosonic Flow B (Endress + Hauser, Switzerland)), situated inside the gas line prior to the flaring unit. Gas flow was measured at standard temperature (273 °K) and atmospheric pressure (1 atm).

Furthermore, the characterisation of biogas was carried out to substantiate the methane content and hence the energy potential of the biogas. Grab samples of biogas were collected by connecting Tedlar bags (1 litre) to the biogas sampling units positioned at the top of the gas hoods using the two-way valves. Biogas was sampled from all six UASB reactors and conveyed to the laboratory of the Institute of Industrial Research (IIR) for characterisation. This exercise was carried out over 10 weeks (2 July to 15 September 2021). Constituent gases, namely, methane (CH_4), oxygen (O_2), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and nitrogen (N_2), were measured using a portable FM 406 Gas Analyser (Gas Data, Coventry, UK).

2.3. Excess Sludge Quantification and Characterisation

2.3.1. Sludge Quantification

Plant operators monitored the system for excess sludge production during the study period. Excess build-up of sludge was defined by the observation of effluent concentrations for total suspended solids (TSS), biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Effluent deterioration of these parameters was indicative of excess sludge build-up [24]. Sludge discharge ports sited at the sides of the UASB reactors were opened using designated valves, which allowed excess sludge to be discharged first into the sludge thickeners and subsequently onto the sludge drying beds. Sludge withdrawal was conducted once every two weeks, with the discharged sludge volume being approximately 30% of the volume of the sludge thickener. Based on these projections, the volume of discharged sludge was estimated for this study.

2.3.2. Sludge Characterisation Technique

Sludge samples were characterised to determine their physical and chemical composition. With regard to the ultimate analysis, elemental analysis for the determination of nitrogen (N), carbon (C), hydrogen (H) and sulphur (S) contents was performed. Proximate analysis was also carried out to measure immediate components: moisture (MC), volatile matter (VM), fixed carbon (FC) and ash contents. These analyses were conducted following standard methods [25].

- Proximate Analysis

Proximate analysis was conducted to quantify the solids (total, volatile and fixed solids) and moisture contents. MC was determined by measuring the weight loss observed in the substrate after the water content had been evaporated. A quantity of 5 g of sludge aliquot was placed in a porcelain crucible, which had been preconditioned by heating in an oven heated to 105 °C for 1 h, cooled in a desiccator containing magnesium perchlorate desiccant and weighed to determine the empty weight of the crucible. The sample in the crucible was kept in the oven for 24 h. The dried sample was removed from the oven and placed again in a desiccator to cool. MC was determined immediately after sample collection to avoid sample drying, which could have affected the authenticity of the results. Equation (1) was used to calculate MC, based on the percentage weight (wt%).

$$MC(\%) = (W_{wet} - W_{dried})/M_{wet} \times 100 \quad (1)$$

where W_{wet} is the weight of the initial wet sample and W_{dried} is the weight of the oven-dried sample.

The dry residue is expressed as the total solids (TS) or dry matter (DM). This is expressed by Equation (2).

$$TS(\%) = 100 - MC \quad (2)$$

The VM represents the organic compounds in the sludge sample. After the TS analysis, the same specimen was used for the VM analysis. After recording the TS value, the specimen was sent to a furnace preheated to 550 °C to be ignited for 2 h. The ignited sample was kept in the furnace to allow the temperature to drop reasonably before being transferred to the desiccator for cooling. VM was determined afterwards using Equation (3).

$$VM(\%) = \left(M_{dried} - M_{ignited}\right) / M_{dried} \times 100 \quad (3)$$

where M_{dried} is the sample mass after drying at 105 °C for 24 h and $M_{ignited}$ is the sample mass after ignition in the furnace.

The ash content was computed with $M_{ignited}$ in Equation (3), and the mass left in the dish after the ignition is represented by the equation below:

$$Ash(\%) = M_{ignited} / M_{dried} \times 100 \quad (4)$$

The FC content was determined as the mass difference and was computed according to the following equation:

$$FC(\%) = 100 - VM(\%) - Ash(\%) \quad (5)$$

- Ultimate Analysis

For the elemental analysis, S was determined turbidimetrically using a spectrophotometry method adapted from Singh et al. [26], with di-acid (HNO_3-$HClO_4$) for digestion. H was measured by the titrimetric method employed by Mclean [27], using sodium hydroxide and phenolphthalein indicator as reagents. N was measured employing the Kheldahl method as explained by Bremner and Mulvaney [28], using ammonia-free-grade concentrated H_2SO_4, NaOH, Boric acid solution and selenium as reagents. C was characterised by the Walkley–Black wet oxidation method described by Nelson and Sommers [29]. Oxygen (O) was estimated as the difference in CHNS and ash values [15,30].

- Calorific Value (CV) Analysis

The laboratory procedure for the calorimetry analysis for energy content determination followed the methods described in the Parr oxygen bomb calorimeter manual (Parr 1342 manual, No. 204M), as outlined by ASTM E711-87 (2004) [31]. Air-dried sludge samples were weighed, pelletised and combusted in a pressurised (30.0 atm) oxygen atmosphere. A quantity of 1.0 g of sludge pellets was used to ensure that the rising temperature within the water jacket provided a safe combustion environment that did not exceed the thermometer optimum range. Benzoic acid was employed as the standard solution for the determination of the heat capacity of the bomb. Experiments were carried out in duplicate. The calculation of gross and net calorific values (GCV) and (NCV) were carried out based on directives provided by the Parr manual.

The theoretical energy values for the sludge were determined based on the model proposed by Galhano dos Santos and Bordado [32] and have been employed in similar studies [6,15] to evaluate the theoretical heating values of sewage sludge. They allow comparison of actual and theoretical values and permit the determination of the energy values of a substrate based on elemental composition in the absence of a bomb calorimeter [15]. The theoretical GCV was estimated using Equation (6).

$$GCV = \left[337.3 \times C + 1418.9 \times \left(H - \frac{1}{8}O\right) + 93.1 \times S + 23.3\right] / 1000 \quad (6)$$

where GCV is the gross calorific value (MJ/kg), dry basis; C is % carbon in the sludge, dry basis; H is % hydrogen in the sludge, dry basis; O is % oxygen in the sludge, dry basis; S is % sulphur in the sludge, dry basis; and N is % nitrogen in the sludge, dry basis.

The theoretical NCV was estimated using Equation (7).

$$\mathrm{NCV} = [(\mathrm{GCV} - \lambda \times (r + 0.09 \times \mathrm{H})) \times (100 - W_t)/100] \quad (7)$$

and

$$r = W_t/(100 - W_t) \quad (8)$$

where NCV is the net calorific value (MJ/kg), dry basis; GCV is the gross calorific value (MJ/kg), dry basis; λ is the latent heat of water (2.31 MJ/kg at STP); r is the solids content and dehydrated sludge moisture ratio; H is % hydrogen in the sludge, dry basis; and W_t is the solids content in dehydrated sludge (%), moist basis.

2.4. Evaluation of Energy Balance at the Mudor WWTP

The energy balance was estimated as the difference between the energy recovery potential from the biogas and sludge by-products and the actual energy needs of the plant [9]. The Mudor WWTP's energy demand is the power consumption level of the plant, which is primarily the power consumed by the wastewater pumping stations (PS). The energy potential correlates with the all-out energy that could be recovered from biogas and sludge produced by the plant.

2.4.1. Energy Demand at the Mudor WWTP

The energy demand of the plant was estimated from data on the monthly energy consumption of the facility (in kWh/month) during the study period. The energy consumption data collected covered all activities, departments, unit operations and processes that depended on energy usage at the plant, i.e., administration, lighting, laboratory and pumps, including the cost of the diesel used to power standby generators during interruptions to the main power supply from the national grid. According to the facility operators, about 95% of the entire energy demand at the Mudor WWTP could be ascribed to the operations of four pump stations (PS-1, PS-2, PS-3 and PS-4) employed for the daily running of the plant. PS-1 comprises the lift pumps at the CAPS that pump raw sewage to the UASB reactors. The PS-2 pumps pump sludge from the clarifiers into the sludge thickeners, while the PS-3 pumps transfer sludge from the thickeners to the sludge drying beds. The PS-4 pumps distribute clean water to various parts of the plant for daily cleaning activities. The main characteristics of the pumping stations have been presented in Table S1.

2.4.2. Energy Recovery Potential of the Mudor WWTP Biogas and Sludge By-Products

As indicated earlier, the Mudor WWTP's energy recovery potential corresponded to the sum of the energy potentials of the system's by-products: biogas and sludge. For the methods applied to characterise the by-products, refer to Section 3.2 and 3.3. The equations used to determine the energy recovery potential of the Mudor WWTP are presented below, as reported by Rosa et al. [15].

$$\mathrm{EP}_{\mathrm{Total}} = \mathrm{EP}_{\mathrm{Biogas}} + \mathrm{EP}_{\mathrm{sludge}} \quad (9)$$

where $\mathrm{EP}_{\mathrm{Total}}$ is the total energy potential (MJ/d), $\mathrm{EP}_{\mathrm{Biogas}}$ is the biogas energy potential and $\mathrm{EP}_{\mathrm{sludge}}$ is the sludge energy potential (MJ/d).

$$\mathrm{EP}_{\mathrm{Biogas}} = \mathrm{Q}_{\mathrm{biogas}} \times \mathrm{C}_{\mathrm{CH_4}} \times \mathrm{E}_{\mathrm{CH_4}} \quad (10)$$

where EP_{Biogas} is the biogas energy recovery potential (MJ/d), Q_{biogas} is the biogas production rate (m^3/d), CCH_4 is the concentration of CH_4 in biogas (%) and ECH_4 is the NCV of CH_4 combustion (35.9 MJ/m^3).

$$EP_{Sludge} = P_{sludge} \times NCV_s \tag{11}$$

where EP_{Sludge} is the sludge energy potential (MJ/d), P_{sludge} is the production of dry sludge matter (kg/d) and NCV_s is the NCV of sludge (MJ/kg).

3. Results and Discussion

3.1. Wastewater Characteristics and Biogas Energy Recovery Potential

The characteristics of the raw sewage, the production levels and the constituents of the biogas generated by the UASB reactors during the study period are presented in Table 2. The results show that the raw sewage inflows ranged from 1572 to 6054 m^3/d, with a mean flow of 4096 ± 837 m^3/d (47.4 ± 9.69 l/s); this flow is approximately one-fourth of the design capacity of the plant (18,000 m^3/d), which indicates that the plant currently operates under capacity [22]. Regarding the flow received at the plant, the Mudor UASB reactors can be classified as small-scale WWTPs based on the classifications reported in the literature [6]. The volumetric biogas production ranged from 100 to 1809 Nm^3/d, with an average value of 611 ± 275 Nm^3/d. The biogas was found to consist of 65% methane (CH_4), the major constituent, with an average CH_4 flow of 391.2 ± 176 Nm^3/d. The other biogas constituents were: nitrogen (N_2), carbon dioxide (CO_2) and oxygen (O_2), reported at mean portions of 24.6%, 4.7% and 5.7%, respectively. Hydrogen sulphide (H_2S) was found to be in minute concentrations between 78 and 314 ppm.

Table 2. Descriptive statistics of some major parameters: wastewater flow, biogas production and composition.

Descriptive Statistics	Raw Sewage (m^3/d)	COD_{inf} (mg/L)	COD_{rem} (kg/d)	Biogas Flow (Nm^3/d)	CH_4 (%)	N_2 (%)	CO_2 (%)	O_2 (%)
Maximum	6054	8150	34,194	1809	76.5	28.2	9.1	14.6
Minimum	1572	450	889	100	54.0	19.9	3.2	1.4
Average	4096	2007	6303	611	65.0	24.6	4.7	5.7
SD *	837	1061	4826	275	9.0	3.1	2.2	4.6

* Standard deviation; COD_{inf} = Influent COD concentration; COD_{rem} = COD removed.

Although the CH_4 fraction of the biogas observed in this study was relatively lower than that reported in a similar study by Noyola et al. [10], with 70–80% of CH_4, the other biogas components observed corroborate the results obtained by the same authors—10–25% N_2 and 5–10% CO_2—for UASB reactors treating domestic wastewater. According to Noyola et al. [10], the high nitrogen content in the biogas could be ascribed to the dissolved N_2 in influent wastewater. Chernicharo et al. [4] and Souza et al. [33] likewise reported higher percentages (70–85%) of CH_4 in biogas for UASB reactors treating domestic sewage. The seemingly lower methane component observed in the study could be attributed to such factors as plant loading and sludge activity.

The energy potential of the biogas (EP_{biogas}) was estimated to be 14,044.59 MJ/d, culminating at 3901.27 kWh/d (1423.96 MWh/yr). Comparing the daily biogas energy recovery potential obtained for this study (14.04 GJ/d) to that reported by Lopes et al. [6] for small-scale UASB-based WWTPs observed for a typical scenario (380 GJ/d), the estimate for the Mudor plant is far lower. This could be ascribed to the fact that the Mudor UASB reactors currently operate under capacity, as stated earlier. However, with envisioned population growth in the near future, the biogas energy recovery potential of the plant is likely to be higher due to subsequent increases in sewage flows. Again, the lower biogas energy potential observed in this study could be ascribed to the low organic loading rate

(OLR) applied to the plant, as reported in a previous study [23], buttressing the assertion by Ahmed et al. [22] that the Mudor plant receives typical low-strength sewage.

Unitary Relationships between CH_4, Biogas and Energy Generation for the UASB Reactors

Unitary relationships between CH_4, biogas and the energy recovery potential of the Mudor WWTP were estimated based on the monitoring data presented in Table 2. The results obtained were compared with the model results reported by Lobato et al. [34] for ideal UASB reactors treating domestic sewage under optimised conditions. As presented in Table 3, most of this study's results were closer to the ranges predicted by the model.

Table 3. Unitary relationships of CH_4, biogas and energy production for the UASB reactors.

Unit Relationships	Units	Current Study	Simulated Values *
CH_4 volume per volume of sewage	m^3CH_4/m^3 sewage	0.09	0.07–0.14
Specific CH_4 yield	$m^3CH_4/kgCOD_{removed}$	0.10	0.11–0.19
Biogas volume per volume of sewage	m^3biogas/m^3 sewage	0.17	0.06–0.10
Specific biogas yield	m^3biogas/$kgCOD_{removed}$	0.14	0.16–0.24
Energy production potential per kg of COD removed	$MJ/kgCOD_{removed}$	2.19	4.10–7.00
Energy production potential per volume of sewage	MJ/m^3 sewage	3.37	1.50–2.90
Energy production potential per volume of biogas produced	MJ/m^3 biogas	20.17	25.1–28.7

* Range reported by Lobato et al. [34].

The relative similarity between the unitary relationship values obtained for the Mudor plant and the model predicted by Lobato et al. [34] proves that the Mudor UASB reactors operate under optimum conditions and have a high potential for biogas energy recovery. Moreover, this result is comparable to that obtained by Rosa et al. [15] in their study conducted on a full-scale UASB reactor treating domestic sewage in Brazil. Chernicharo et al. [4] likewise reported the same model in their studies.

3.2. Characteristics of Sewage Sludge for Energy Recovery Potential Evaluation

The results for the essential parameters considered in the evaluation of sludge applicability for thermal conversion processes for energy recovery for sludge produced by the dewatering unit are presented in Table 4. As reported by Syed-Hassan et al. [35], proximate and ultimate analyses are useful for evaluating the thermochemical conversion characteristics of fuel. Chiang et al. [36] similarly opined that proximate and ultimate analyses provide estimations of feedstock efficiency for generating power as well as the yield of fuel by-products employed in thermal conversion systems. Proximate analysis revealed that MC ranged from 63 to 82%. VM was between 50.5 and 80.9%. FC and ash contents were found to be in the ranges of 2.4 - 5.2% and 19.0–49.5%, respectively. These values were found to be comparable to the results reported in similar studies [35,37]. Moreover, regarding the elemental constituents, the average percentage values for C and H were found to be 28.5 $\pm$ 5.27% and 11.8 $\pm$ 0.64%, respectively, and the values for N, S and O were found to be 3.33 $\pm$ 0.33%, 1.14 $\pm$ 0.32% and 27.5 $\pm$ 6.5%, respectively (Table 4). The results obtained for the elemental components of sewage sludge from the Mudor UASB reactors were found to be comparable to the ranges of values reported in the literature [35,37] in diverse studies conducted to assess the applicability of sewage sludge for energy recovery through the adoption of thermochemical conversion processes.

Table 4. Proximate and ultimate analysis of dewatered sludge at Mudor WWTP.

Parameter	Current Study Range	Current Study Average	Reported Ranges in the Literature	References
Proximate Analysis				
Moisture content (wt %)	63.00–82.00	75.00 ± 2.60	73.40–86.40	[38]
Volatile matter (wt %) [a]	50.50–80.90	62.90 ± 5.50	21.70–82.30	[35,37]
Ash content (wt %) [a]	19.00–49.50	36.60 ± 5.10	10.80–76.80	[35]
Fixed carbon (wt %) [a]	2.40–5.20	3.10 ± 1.20	1.81–21.80	[35]
Ultimate Analysis				
Carbon (wt %)	22.30–32.80	28.5 ± 5.27	32.1–69.3	[35,37]
Hydrogen (wt %)	11.02–12.69	11.8 ± 0.64	3.85–8.60	[35,37]
Nitrogen (wt %)	2.68–3.82	3.33 ± 0.33	2.25–9.08	[35]
Sulphur (wt %)	0.31–1.56	1.14 ± 0.32	0.60–2.05	[35]
Oxygen (wt %)	15.9–36.20	27.50 ± 6.50	18.20–56.30	[35,37]

[a] Dry basis; wt = weight.

A calorific value analysis of biomass fuel provides information on the energy content of the biomass [36]. From the results on sludge heating values (Figure 1), it was observed that the theoretical gross calorific value GCV(t) and theoretical net calorific value NCV(t) were higher than the actual values, GCV(a) and NCV(a), obtained from the bomb calorimetry analysis. The average GCV(a) was found to be 14.6 ± 1.1 MJ/kg, against the average GCV(t) of 16.3 ± 1.4 MJ/kg. The same pattern was obtained for the net heating values, with an average NCV(a) of 9.8 ± 1.1 MJ/kg, whilst the average NCV(t) was 13.8 ± 1.3 MJ/kg, as shown in the figure. Comparatively, the GCV and NCV values obtained for this study were far higher than those recorded in a similar study in Brazil by Rosa et al. [15]. The Brazilian study reported average values of 8.7 ± 1.2 MJ/kg and 7.4 ±1.4 MJ/kg for the actual and theoretical GCVs, respectively. They also reported actual and theoretical NCV values of 2.0 ± 0.8 MJ/kg and 1.7 ± 1.8 MJ/kg, respectively.

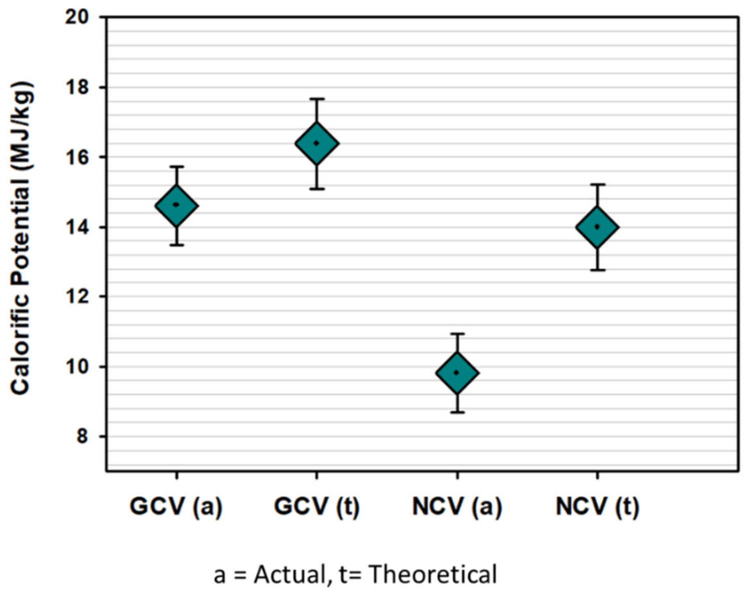

Figure 1. Actual and theoretical GCVs and NCVs for the dehydrated sludge of the Mudor WWTP.

Singh et al. [39] asserted that higher VM contents resulted in higher energy values of sludge, and this pattern was evident in this study, where VM ranged from 50 to 80%, resulting in higher heating values. Several other studies have reported actual GCV values for sewage sludge ranging from 11 to 22 MJ/kg [38,40,41]. The wide variation in sewage sludge calorific values (CVs) could be attributed to such factors as the sludge treatment processes applied. Different types of sludge, such as raw primary sludge, activated sludge and anaerobically digested sludge, were found to have different heating values, ranging from 8.9 to 23 MJ/kg [42]. Galhano et al. [32] investigated the correlation between ultimate analysis parameters and GCVs. They concluded that higher C and H contents were the most significant elemental constituents and represented a higher energy content for the fuel. Comparing their assertion with the C and H percentages by weight obtained in this study, it can be concluded that the H values (11.02–12.69%) are higher compared to the range (3.85–8.60%) reported in the literature. Despite the C values (22.30–32.80%) not being as high as those reported in the literature (32.10–69.30%), the actual GCV obtained falls within the reported range.

3.3. Sewage Sludge Energy Generation Potential

Over the study period, it was estimated, based on the volume of dewatered sludge sent to the drying beds biweekly, that sewage sludge dry matter production was 358.24 TS kg/d (130.76 tonnes/yr). Employing an average sludge NCV of 9.81 MJ/kg (Figure 1), the total daily energy recovery potential for sewage sludge (EP_{sludge}) was estimated to be 3514 MJ/d (3.5 GJ/d), culminating at 356.31 MWh/yr for energy recovery by thermochemical processes. Comparing this study with that conducted by Rosa et al. [15], they reported a filter-pressed dehydrated sludge mass of 3759 TS kg/d, which translated into an energy recovery potential of 7518 MJ/d—far higher than that reported for this study. In a similar study by Lopes et al. [6], it was reported that, for a typical scenario, the energy recovery potential of full-scale UASB reactor sewage sludge dehydrated with drying beds ranged from as low as 15 GJ/d to over 100 GJ/d. From the same study, the worst scenarios for small-scale WWTPs were characterised by a sludge energy recovery potential as low as 0.2 GJ/d. Several factors, including the population served, influent sewage characteristics, the sludge retention times applied and the sludge dehydration methods employed, can influence sludge production volume and consequently the energy recovery potential of sewage sludge [42].

It is worth noting that, as promising as the energy recovery potential of sludge generated by the Mudor UASB reactors may be, it is an undeniable fact that the low volume of sludge generated by the plant gives in return low energy recovery potential; this notwithstanding, another possibility to maximise the energy recovery potential of sewage sludge is the utilisation of anaerobic digestion (AD). Different authors have reported on the possibility of recovering energy from sewage sludge through this process. Qi [43] was of the view that AD of sewage sludge was more profitable for WWTPs with capacities larger than 22,000 m^3/d, as it provides larger volumes of sludge for energy recovery. Bachmann [44] reported the sewage sludge energy potential from AD to range from 42 GWh/yr to as high as 3050 GWh/yr for some WWTPs in North America, Europe and some Asian countries. Other authors have likewise reported that co-digestion of sewage sludge with organic feedstock, such as livestock manure and intestines, food waste, plant biomass, etc., allowed the generation of improved biogas with high methane content for energy recovery purposes [45,46]. Thus, with the abundant availability of organic feedstocks in Ghana [47,48], it would be prudent for co-digestion to be employed as the most sustainable way to recover energy from the sludge generated by the Mudor UASB reactors.

3.4. Actual Energy Demand of the Mudor WWTP

The actual energy demand of the Mudor WWTP has been estimated based on the energy consumption (electricity and fuel) of the plant. As has been stated early on, the running of the four sets of pumps (PS-1, PS-2, PS-3 and PS-4) accounts for about 95% of the total energy consumption at the plant. Administration activities, lighting and laboratory consumption were responsible for barely 5% of the energy costs. This finding confirms a parallel study conducted in Brazil [9], in which it was reported that the energy demand of a full-scale UASB-based treatment plant was entirely dedicated to the pumping stations of the plant. Due to the method of sludge treatment employed (using drying beds), the energy consumption of the plant due to sludge treatment during the study period was reported to be zero. From Figure 2, the actual energy demand at the plant, comprising electricity usage and fossil fuel consumed by standby power generators, was found to range from 28,836 kWh/month for the month of November 2021 to 38,442 kWh/month for the month of May 2021—the highest consumption observed during the study period. The average energy consumption was 32,722 kWh/month, and the overall consumption was 392.66 MWh/yr. Wastewater flow likewise ranged from 108,236 to 144,526 m^3/month.

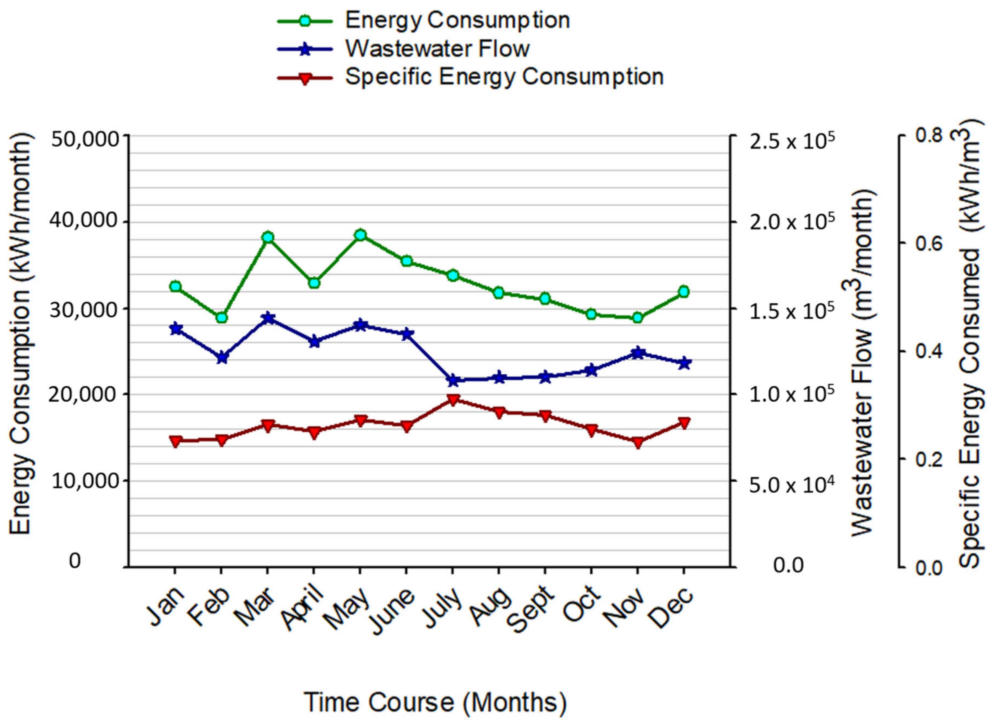

Figure 2. Plot showing wastewater flow and energy consumption during the study period.

A correlation analysis was conducted to evaluate the relationship between sewage flow and energy consumption. Pearson's correlation coefficient analysis presented a moderate correlation between the two variables ($R = 0.6471$). This is confirmed by the graph presented in the figure. The lowest sewage flow, recorded in July, did not result in that month having the lowest energy consumption; rather, the highest specific energy consumption during the study period was recorded for July. This observation could be ascribed to the energy source employed to run the pumps during that period, that is, whether the energy came from the national electricity grid or diesel fuel during power cuts. Again, this can be ascribed to the concept of economies of scale. It has been reported in the literature that larger wastewater treatment plants generally have lesser unit costs of treatment compared to smaller-capacity plants. The authors of [49] mentioned that economies of scale were more applicable to energy-intensive technologies. The authors stated that pump efficiency was linked to the size of the treatment plant. This means that increased flow rate with increased pipe diameters leads to decreased frictional losses, which allows energy economies of scale to be attained. Additionally, this finding is consistent with the assertion by Vaccari et al. [50] that higher energy efficiency in WWTPs is associated with large plant capacity.

Maktabifard et al. [51] reported that specific energy consumption (in kWh/m^3) is the key performance indicator (KPI) most commonly used to evaluate WWTPs' energy performance. The specific energy consumption of the Mudor WWTP ranged from 0.23 to 0.31 kWh/m^3, as presented in the figure. Highly variable values ranging from 0.02 kWh/m^3 to as high as 3.75 kWh/m^3 have been reported for WWTPs in several European, North American and Asian countries [52]. A review published by Gu et al. [8] reported that the energy consumption of WWTPs varied across regions, with consumption in developed countries being far higher due to the energy-intensive technologies employed in these regions, whilst consumption in developing countries is relatively lower. For instance, the authors reported that in the USA the specific energy consumption of WWTPs was approximately 0.52 kWh/m^3. However, in South Africa it was found to be between 0.079 and 0.41 kWh/m^3, mainly due to the wide implementation of low-energy-intensive technologies, such as TFs and lagoons. In similar studies, it was revealed that energy consumption levels in three Asian countries—Korea, Japan and China—were 0.243, 0.304 and 0.31 kWh/m^3, respectively, which levels were also lower compared to those of highly developed regions [53,54]. Several authors have reported that the energy consumption for a plant is dependent on factors such as plant size (population equivalent and hydraulic and organic load), location, type of treatment process, effluent quality requirements, plant age and operator experience, etc. Moreover, aerobic-based systems, especially conventional activated sludge (CAS) processes, and also treatment processes for advanced nutrient removal are characterised by higher energy consumption [53,55]. Thus, the lower specific energy consumption values obtained for the Mudor plant attest to the fact that anaerobic WWTPs consume less energy compared to energy-intensive aerobic processes.

3.5. Energy Self-Sufficiency of the Mudor WWTP through Biogas and Sludge Energy Recovery

Energy recovery from biogas and sewage sludge is one of the surest ways by which the Mudor WWTP can become energy self-sufficient. EP_{biogas} and EP_{sludge} were estimated based on monthly CH_4 and sludge dry matter production values. The monthly estimates were made assuming a 30% conversion efficiency of the power generators, as reported in the literature [6,15]. The total energy potential (EP_{Total}) was calculated as the sum of EP_{biogas} and EP_{sludge}.

A graph of EP_{biogas} and EP_{sludge} values plotted against the actual energy demand of the plant during the study period is presented in Figure 3. The EP_{biogas} was found to range from 18,408 kWh/month to 52,515 kWh/month. A constant EP_{sludge} of 8770 kWh/month was estimated for the entire study period based on the biweekly excess sludge withdrawal from the UASB reactors. Biogas energy recovery constituted the majority (80%) of the total by-product energy recovery potential, whilst sludge energy potential accounted for only 20%. Correspondingly, Lopes et al. [6] reported values between 65 and 74% biogas energy recovery potential for small-, medium- and large-scale WWTPs, as against sludge energy recovery potential. Additionally, they found that the WWTPs employing sludge drying beds had an average biogas energy recovery potential of 64% of the total by-product energy recovery potential. Similar trends were observed by Rosa et al. [9] in their study, where sewage biogas energy recovery constituted 59.3% of the total by-product energy recovery potential against 41% potential from sludge energy recovery. The report by Bachmann [44] likewise revealed, in a study conducted on WWTPs in some European countries, that 7–49% of total biogas production was accounted for by sewage sludge. The authors concluded that their finding was indicative that other biogas sources dominated the overall energy recovery balance. These assertions made by previous authors are comparable to the findings of this study.

Presented again in Figure 3 is the EP_{Total} plotted against the actual energy demand of the plant. It can be seen from the graph that, for each month, except the month of October, energy recovery from both by-products could offset the entire energy demand of the plant. Percentage energy self-sufficiency was found to range from 94% for the month of October to 186% for the month of February for energy recovery from biogas and sludge. It was also observed that the EP_{biogas} estimated for January through June could offset the entire energy demand for these periods. Again, it was observed that EP_{biogas} dropped consistently from June through to December, which is highly attributable to the drop in biogas production during these periods. The drop in biogas from June to December has been ascribed to a reduction in sewage flow to the plant during these periods. This is attributed to the channelling of influent sewage mixed with stormwater (due to the use of combined sewer lines for stormwater and domestic sewage) via a bypass directly into the Korle Lagoon during the rainfall seasons (June to September) to eliminate the cost of pumping high volumes of highly diluted sewage from the wet wells up into the UASB reactors. Reduction in biogas flow from October to December is likewise attributed to the acute water shortages usually experienced in some parts of Accra in the months preceding the dry seasons. Moreover, in about the same period, a media house reported that the Ghana Water Company Limited (GWCL) was to cut water supply to some parts of Accra, which included the Dansoman and Korle Bu suburbs, for maintenance activities [56]. These two communities are among the suburbs whose sewage is received by the Mudor WWTP. This explains the significant drop in sewage flow observed during this period. Notwithstanding the reduced EP_{Total} observed for some of the months, the overall EP_{Total} recorded for the entire study period (534.1 MWh/yr) could offset the entire energy demand (392.7 MWh/yr). Thus, the Mudor WWTP can move from being energy neutral to being energy positive through biogas and sludge energy recovery. This provides evidence of the plausibility of sanitation financing sanitation through sustainable wastewater management practices in a developing country such as Ghana.

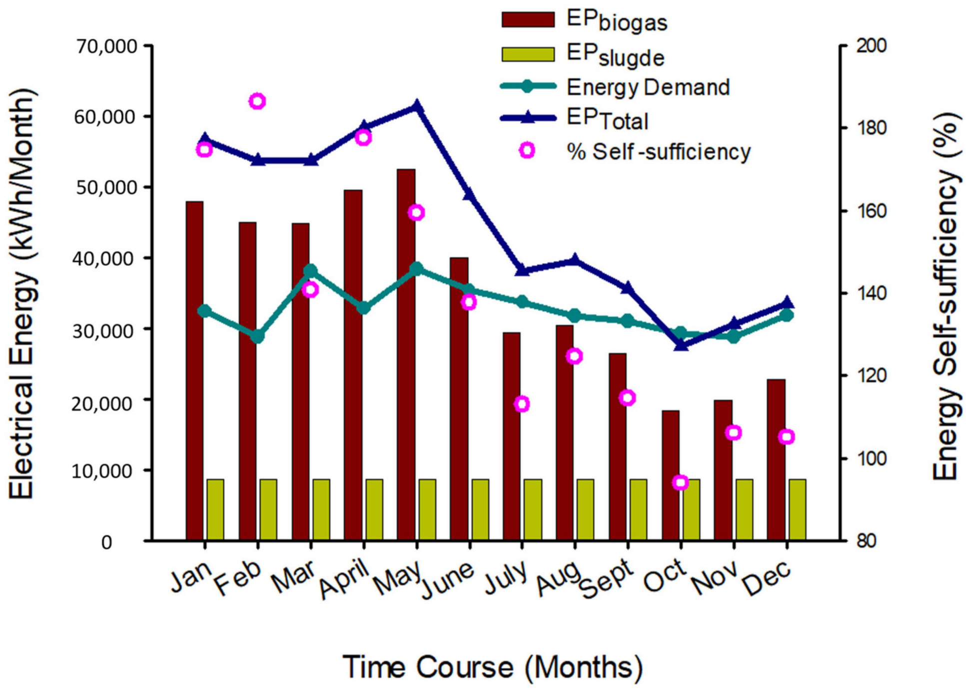

Figure 3. Energy recovery potential from biogas and sludge.

The potential of the Mudor WWTP to be energy self-sufficient, as discovered in this study, agrees with many other reports from different parts of the world. Several authors have reported studies in which complete energy self-sufficiency of WWTPs has been attained, especially in North American and European countries, such as the USA, Germany and Austria, through biogas and sludge energy recovery [8,51]. Similar studies carried out in developing countries, such as India and Brazil [39,57], have reported the possibility of offsetting at least 75% of the energy demand of WWTPs through biogas and sludge energy recovery. It should be iterated that if the Mudor WWTP, which currently operates at approximately one-fourth of its design capacity, has the potential to offset its entire energy needs, then should the plant be operated at full capacity (as anticipated in the near future), the Mudor WWTP can provide significant surplus energy to augment the national electricity grid, which could ameliorate the persistent energy crises in the country.

3.6. Perspectives on Energy Recovery from Full-Scale WWTPs in Ghana

With the expected rise in the number of WWTPs in Ghana, which will see the progressive expansion of sewage networks across the country, the relevance of energy recovery from biogas and sludge is evident. Notwithstanding the demonstrated energy potential of biogas and sludge from full-scale wastewater treatment facilities, the proven energy self-sufficiency of these systems and the economic feasibility, there are several factors which could limit this practice in Ghana.

First to be considered is the investment cost. Several studies have reported—and this has been proven beyond doubt—that the operational costs of high-rate anaerobic-based wastewater treatment systems are relatively low compared to CAS systems [4,58]. For a plant in which material flow is mostly gravity-driven, as it is in the Mudor UASB plant, the operational cost in terms of energy consumption by pumps is lower. However, the initial investment cost can be very high, running to several millions of euros. This initial cost could hamper the intended building of these systems across the country. Additionally, financial commitment on the part of key stakeholders is paramount for the successful operation of WWTPs. Ahmed et al. [22] previously reported that the Mudor WWTP had broken down in the early stages of operation and was not functional due to a lack of financial commitment; this fact cannot be disregarded if these systems are going to operate successfully and enhance energy recovery potential in Ghana.

Compounding the issue of initial investment cost is the investment cost of the energy recovery infrastructure, which has not been considered in this study. Currently, biogas generated by the Mudor UASB reactors is flared, whilst the sludge is piled up on drying beds. Pilot studies on the feasibility of recovering biochar pellets from sludge through pyrolysis are ongoing. Pelletised biochar could replace the charcoal that is predominantly used in the country, which usage, among other things, is leading to the uncontrolled cutting of trees. There have been recent outcries against this practice. Thus, regardless of whatever resources are desired to be recovered, there must be willingness on the part of stakeholders to invest in the resource recovery equipment and structures.

Finally, most WWTPs have failed to obtain the desired effluent quality due to the lack of skilled and qualified personnel to design and manage such complex systems. Moreover, competent personnel are needed to operate these systems. This means that building capacity of operators is relevant to successful plant operations. Again, most WWTPs in developing countries fail due to poor maintenance cultures prevailing among operators. Lopes et al. [6] highlighted some engineering practices that would maximise biogas recovery. The authors reported that some upgrading in terms of system design and the construction and operation of UASB reactors could be helpful. Some of the needed upgrades include the installation of three-phase separators, water- and air-tight gas hoods and biogas pipes, scum removal, and dissolved methane recovery from the effluent. One challenge observed at the Mudor WWTP was the leakage of biogas through the gas hoods. Biogas leakage reduces the energy potential of a system and poses safety risks due to its flammable gas constituents [33,59]. Hence, a proper maintenance culture and good practices are relevant to the successful operation of WWTPs to enhance energy recovery.

4. Conclusions

This study evaluated the electrical energy recovery potential of two by-products, biogas and sludge, produced by a full-scale UASB reactor treating municipal wastewater in Accra, Ghana. The study showed that the high-rate anaerobic system produces biogas with a high methane content. The dried sludge produced was likewise found to have a high heating value. This finding reveals a wastewater treatment system with high potential for energy recovery from its by-products. Considering the socio-economic status of an emerging economy like Ghana's, the implementation of UASB reactor technology, with the valorisation of biogas and sludge by-products, would, besides enabling the production and usage of clean renewable energy, introduce a wastewater treatment system with lower operational costs. From the perspective of promoting collective sustainable urban sanitation systems, the findings of this study will be informative for sector leaders and stakeholders in their bids to promote sustainable wastewater management in Ghana.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15043743/s1, Figure S1: (a) General view of the Mudor wastewater treatment plant (WWTP); (b) Biogas flaring unit. Table S1: Characteristics of pumping stations operating at the Mudor WWTP.

Author Contributions: Conceptualisation: P.M.A.A. and Y.K.; Methodology: P.M.A.A., Y.K., B.S., G.S., B.D.-A., R.B. and K.A.-B.; Data Acquisition: P.M.A.A., I.A., R.B. and K.A.-B.; Data Curation: P.M.A.A.; Formal Analysis: P.M.A.A., G.S. and B.D.-A.; Writing—Original Draft Preparation: P.M.A.A.; Writing—Review and Editing: P.M.A.A., Y.K., G.S., B.D.-A., B.S., R.B. and K.A.-B.; Visualisation: P.M.A.A., G.S., B.D.-A., R.B. and K.A.-B.; Resources: Y.K., I.A.; Supervision: Y.K., B.S., I.A., R.B. and K.A.-B.; Validation: Y.K., B.S., I.A., B.D.-A., G.S., R.B. and K.A.-B.; Funding Acquisition: Y.K. and B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Nelson Mandela Institutes–African Institutions of Science and Technology and supported by the African Development Bank (project no.: P-Z1-IA0-013, grant no.: 2100155032824).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available upon reasonable request from the corresponding author.

Acknowledgments: The authors acknowledge the professional and technical assistance received from the management and staff of Sewerage Systems Ghana Limited (SSGL), Zoomlion Ghana Limited (ZGL), the Jospong Academy Scholarship Scheme and the Institute of Industrial Research (IIR) during the various stages of this research.

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

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