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Enhanced Biogas Production and Pathogen Reduction from Pig Manure Through Anaerobic Digestion: A Sustainable Approach for Urban Waste Management in Abidjan, Côte d'Ivoire

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Abstract

In Abidjan, the treatment of pig waste is becoming a priority given the continued growth of pig farms, which readily reuse manure as organic fertilizer. This study evaluated the effectiveness of anaerobic digestion for simultaneous biogas production and pathogen reduction from pig farm residues. Two 1600 L biodigesters were installed at pig farms in Port Bouët (PBk) and Abobo (Ab). They were fed with pig manure and water (1:4 ratio) and monitored over 56 days. The total biogas production was 22.63 m^3 and 16.31 m^3 for the PBk and Ab digesters, respectively, with peak production occurring between days 14 and 28. Following biofilter treatment, the methane content increased to 80–82%, yielding potential energy outputs of 2.32–3.29 kWh/d, with optimal production occurring at a pH of 7.28–7.76. The COD, BOD_5, organic acid, and total nitrogen levels decreased progressively in the biodigesters, while the mineral element content remained almost unchanged. Complete elimination was achieved for most of the bacteria tested (*E. coli*, *Enterococcus*, *Salmonella*, etc.). However, *Bacillus* and *Clostridium* were able to persist, albeit with significant reductions of between 3.11 and 5.79 $\log_{10}$. Anaerobic digestion is an effective method of combining waste treatment and energy recovery. It eliminates major pathogens while producing valuable biogas. This makes it a sustainable waste management solution for urban agricultural systems.

Keywords: anaerobic digestion; pig farm residues; biogas production; pathogen reduction; sustainable waste management

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1. Introduction

The expansion of intensive animal farming has led to large volumes of livestock and poultry waste being produced, and this is now considered a primary contributor to non-point source agricultural pollution [1]. This issue is particularly acute in regions with dense concentrations of farming operations, where such waste represents a significant environmental burden. In developing regions, inadequate waste management infrastructure

exacerbates environmental pollution and public health risks, particularly in peri-urban areas where agricultural intensification coincides with rapid urbanization [2,3].

Sub-Saharan Africa faces unique challenges in livestock waste management due to limited regulatory frameworks, insufficient treatment facilities, and widespread reliance on untreated animal manure as agricultural fertilizer [4]. In Côte d'Ivoire, the use of raw animal manure in agriculture is becoming increasingly common due to a lack of economic resources, despite the associated health risks. This widespread application of untreated waste creates pathogen transmission pathways that threaten both agricultural workers and consumers through contaminated produce [5].

Untreated pig manure contains high concentrations of pathogenic microorganisms, including *Escherichia coli*, *Salmonella* spp., and antibiotic-resistant bacteria, which can persist in soil for extended periods [6]. Organic load, characterized by very high chemical oxygen demand (COD) values (sometimes in excess of 100 g/L), contributes to the eutrophication of water bodies and greenhouse gas emissions when poorly managed [7]. Also, in livestock farming, spreading manure can increase nitrate leaching and contribute to groundwater contamination when management is inadequate [8]. Furthermore, pig manure, often enriched in Cu and Zn due to feed additives, leads to a progressive accumulation of metals in the soil and their transfer to crops, with manure constituting a major source of metal inputs to agricultural soils [9,10].

Anaerobic digestion (AD) has emerged as a promising technology for simultaneous waste treatment and energy recovery from organic materials. First documented by Alessandro Volta in 1776 through his studies of marsh gas, AD harnesses microbial communities to decompose organic matter in oxygen-free environments, producing methane-rich biogas and stabilized digestate [11]. Depending on the characteristics of the substrate and the operating conditions, modern anaerobic digestion systems typically convert 40 to 70 per cent of the biodegradable fraction into biogas [12]. The process offers multiple benefits: pathogen reduction through thermophilic conditions and pH changes, greenhouse gas mitigation through methane capture, and production of high-quality organic fertilizer with improved nutrient availability [13,14]. Recent advances in biogas purification technologies have enhanced methane concentrations to >95%, making AD-derived biogas competitive with conventional energy sources [15].

Despite global advances in anaerobic digestion technology, research into its application to the management of swine waste in developing countries, particularly in West Africa, is limited. High ambient temperatures, variable feedstock quality and economic constraints create unique operational challenges in these regions. Previous studies have primarily focused on temperate regions with different climatic conditions and waste characteristics [16–19].

In Abidjan, Côte d'Ivoire's economic capital, rapid urban expansion has intensified peri-urban pig farming, creating concentrated waste generation that overwhelms traditional management approaches [20]. The city's tropical climate (average 28–33 °C) may affect AD performance compared to temperate systems, while local bacterial communities and feedstock composition require specific evaluation [21].

This research addresses critical knowledge gaps by evaluating AD performance for pig waste treatment under West African conditions, with specific focus on biogas production efficiency and energy potential from local pig waste, pathogen reduction effectiveness for major foodborne and zoonotic pathogens, digestate quality for safe agricultural reuse and process optimization under tropical conditions. The study provides essential data for the implementation of sustainable waste management systems in rapidly urbanizing African cities, thus contributing to environmental protection and the United Nations' Sustainable Development Goals (SDGs).

2. Materials and Methods

2.1. Study Sites and Experimental Design

2.1.1. Site Selection and Characterization

Two pig farms in Abidjan were selected to represent different scales of operation and management practices common in peri-urban West African contexts. Site selection criteria included: (i) minimum 50 pigs for adequate waste generation, (ii) accessible location for equipment installation and monitoring, (iii) representative farming practices and (iv) farmer cooperation agreement.

Site 1 (Port-Bouët Kamboukro—PBk): a semi-intensive farrow-to-finish operation housing approximately 500 pigs and piglets of mixed breeds. The farm operates modern housing systems with concrete flooring and waste collection channels. Geographic coordinates: 5°15′ N, 3°56′ W; elevation: 15 m above sea level.

Site 2 (Abobo Dokui—Ab): a traditional smallholder farm managing approximately 80 fattening piglets of local and crossbred varieties. The farm represents typical small-scale operations common in the region. Geographic coordinates: 5°25′ N, 4°01′ W; elevation: 45 m above sea level. Both sites experience tropical climate conditions with average temperatures of 28–32 °C, relative humidity of 75–85%, and bimodal rainfall patterns typical of the region.

2.1.2. Biodigester Setup and Operation

Commercial domestic biodigesters (PUXIN Soft Biodigester PX-2.65, Shenzhen Puxin Technology Co., Ltd., Shenzhen, China) with 1600 L working capacity were installed at each site following manufacturer specifications. The selection of this biodigester model was based on suitability for small-scale operations, proven performance in tropical conditions, integrated gas storage and purification systems and cost-effectiveness for regional applications.

Each biodigester was loaded with 320 kg fresh pig manure mixed with 1280 L water, achieving a 1:4 solid-to-liquid ratio. This ratio was selected based on optimal viscosity for mixing and gas production efficiency. It corresponds in fact to approximately 5.4% of dry matter, calculated from the DM content of ≈27% for solid pig manure, as reported for this substrate [22]. Thus, this dilution places the feed in the "wet digestion" range (<10–15% TS) where the viscosity remains moderate and the mixture is effective in supporting biogas production [23,24]. Initial pH was adjusted to 6.8–7.0 using lime ($Ca(OH)_2$) when necessary. Both digesters operated under ambient temperature conditions (28–32 °C) representing typical mesophilic digestion. No external heating was applied to evaluate performance under realistic field conditions. The 56-day retention time was selected based on previous studies indicating optimal pathogen reduction [25].

2.2. Sampling Strategy and Schedule

Samples were collected from both biodigesters on days 0, 14, 28, 42, and 56 to monitor temporal changes throughout the digestion process. Sampling times were selected to capture initial conditions (day 0), peak gas production phase (days 14–28), declining production phase (days 42–56). For each sampling event, 500 mL of slurry was collected from three different depths (10 cm, 50 cm, 100 cm) using a sterile sampling probe, then homogenized to obtain representative samples. Samples were immediately divided into portions for different analyses: 100 mL for physicochemical analysis, 50 mL for microbiological analysis, and 20 mL for elemental analysis. Physicochemical analysis samples were stored at 4 °C and analyzed within 24 h. Microbiological samples were processed immediately or stored at −80 °C for DNA extraction. Elemental analysis samples were acidified with HNO_3 (pH < 2) and stored at 4 °C.

2.3. Biogas Production and Composition Analysis

2.3.1. Gas Volume Measurement

Biogas production was monitored continuously using ultrasonic flow meters (BF-2000, Shenzhen Puxin Technology Co., Ltd., Shenzhen, China) installed between biodigesters and gas outlets. Flow meters were calibrated weekly using standard gas volumes to ensure measurement accuracy (±2%). Daily gas production data were recorded at 8:00 am to maintain consistency.

2.3.2. Gas Composition Analysis

Biogas composition was determined using a portable multi-gas analyzer (Dräger X-am 2500, Drägerwerk AG & Co. KGaA, Lübeck, Germany) calibrated for methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S) detection. Measurements were performed before and after biogas passage through the integrated biofilter system to evaluate purification efficiency. Gas samples were collected using gastight syringes and analyzed immediately. Three replicate measurements were taken per sampling point, and results were expressed as volume percentages for CH_4 and CO_2, and parts per million (ppm) for H_2S.

2.3.3. Energy Potential Calculation

The energetic potential (EP) of biogas is a function of the methane content in the biogas and the lower calorific value (LCV). While the LCV of methane is 9.94 kWh/m^3 or 35,784 kJ/m^3, that of the biogas is obtained by multiplying the proportion of methane in the total biogas by 9.94. The energy potential (EP) of produced biogas was calculated using the following equation:

$$EP = P_{biogas} \times \%\, CH_4 \times LCV_{CH4}$$

where

EP: Energetic potential of biogas (in kWh/d, or in kJ/d with 1 kWh = 3600 kJ)
P_{biogas}: Daily production of biogas (in m^3/d)
% CH_4: Percentage of methane
LCV_{CH4}: LCV of methane (in kWh/m^3, or in kJ/m^3 with 1 kWh = 3600 kJ)

2.4. Physicochemical Analysis

2.4.1. pH Measurement

pH was measured using a calibrated multi-parameter probe (TetraCon 325, Multi-Line® Multi 3510 IDS, Xylem Analytics Germany GmbH—WTW, Weilheim, Germany) following electrometric methods. Twenty milliliters of homogenized sample were stirred magnetically for 5 min, allowed to settle, and pH measured in the supernatant. Calibration was performed daily using standard buffer solutions (pH 4.0, 7.0, 10.0).

2.4.2. Organic Load Parameters

Chemical Oxygen Demand (COD) was determined using Hach Lange LCK-514 cuvette tests (100–2000 mg O_2/L range), HACH LANGE GmbH, Düsseldorf, Germany. Samples were diluted 1:100 with Milli-Q water, filtered through 0.45 µm PTFE filters, and digested at 148 °C for 2 h. Measurements were performed using a Hach Lange DR 3900 spectrophotometer, HACH LANGE GmbH, Düsseldorf, Germany. Biochemical Oxygen Demand (BOD_5) was measured using Hach Lange LCK-555 kit following standard protocols. Samples were diluted 1:300 with manufacturer-supplied dilution water and incubated for 5 days at 20 ± 1 °C in darkness. Total organic acids were quantified using Hach Lange LCK-365 cuvette tests. Samples were diluted 1:25, filtered through 0.45 µm filters, and analyzed

spectrophotometrically. And finally, total ammonia nitrogen was determined using Hach Lange LCK-438 cuvette tests following manufacturer protocols.

2.4.3. Elemental Analysis

Mineral element concentrations (P, K, Cu, Zn, Pb, Cr, Hg, Fe, Cd) were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Samples were directly injected without chemical pre-treatment and analyzed using UV laser ablation coupling. Quality control included certified reference materials and duplicate analyses for 10% of samples.

2.5. Microbiological Analysis

2.5.1. Microbial Enumeration

Standard culture techniques were employed for microbial quantification using selective media. Target microorganisms included: *Escherichia coli*, *Enterococcus* spp., *Pseudomonas* spp., *Salmonella* spp., *Staphylococcus aureus*, *Yersinia* spp., *Bacillus* spp., *Clostridium* spp., molds, and total mesophilic aerobic bacteria (MAB). Serial decimal dilutions (10^{-1} to 10^{-8}) were prepared in sterile phosphate-buffered saline. Triplicate plating was performed for each dilution level. Plates were incubated at 37 °C for 24–48 h (bacteria) or 25 °C for 3–5 days (molds). Colony counts between 15 and 150 (bacteria) or 30–300 (MAB) were used for microbial load calculations according to the formula below:

$$N = \frac{\sum \text{Colonies}}{V(n_1 + 0.1n_2)d}$$

where

N = Microbial load (CFU/g)
ΣColonies = Sum of counted colonies
V = Inoculum volume (mL)
d = Lowest dilution considered
n_1, n_2 = Number of plates at first and second dilutions considered

2.5.2. Molecular Identification

Representative isolates (n = 5) from each morphological group underwent molecular characterization. DNA extraction utilized the ZymoBIOMICS™ DNA Miniprep Kit, followed by 16S rRNA gene amplification using VWR Red Taq DNA Polymerase Master Mix with universal primers (Forward: 5′-AGAGTTTGATCCTGGCTCAG-3′; Reverse: 5′-ACGGCTACCTTGTTACGACTT-3′). Sequencing employed MinION Mk1C (Oxford Nanopore Technologies) with Native Barcoding Kit 24 V14 (SQK-NBD114.24) for amplification-free multiplexed analysis of 24 samples. Bioinformatics processing utilized Galaxy Australia platform tools including FastQC (quality control), MultiQC (report aggregation), Fastp (adapter trimming), Porechop (barcode removal), and Kraken 2 (taxonomic classification). Phylogenetic trees were constructed using iTOL v7.2.2 software.

2.6. Statistical Analysis

All measurements were performed in triplicate unless otherwise specified. Data were expressed as mean ± standard deviation. Statistical analysis was performed using R software (version 4.2.0). One-way ANOVA followed by Tukey's HSD test was used to compare means between sampling times and digesters. Pearson correlation analysis was applied to examine relationships between variables. Statistical significance was set at $p < 0.05$.

3. Results

3.1. Biogas Production Performance

3.1.1. Temporal Production Patterns

The two biodigesters exhibited distinct biogas production profiles over the 56-day operational period (Figure 1). The PBk biodigester achieved a total biogas production of 22.63 m^3, with an average daily production rate of 0.40 m^3/day. The Ab biodigester produced 16.31 m^3 total biogas, averaging 0.29 m^3/day. Peak production rates reached 0.72 m^3/day (PBk) and 0.53 m^3/day (Ab), occurring during weeks 2–4 of operation. Production dynamics showed characteristic phases: an initial lag period (days 0–3), rapid increase phase (days 8–21), peak production plateau (days 14–28), and gradual decline (days 29–56). The PBk biodigester maintained higher production rates throughout the experimental period, with peak production extending until day 28, while the Ab biodigester showed earlier production decline after day 21.

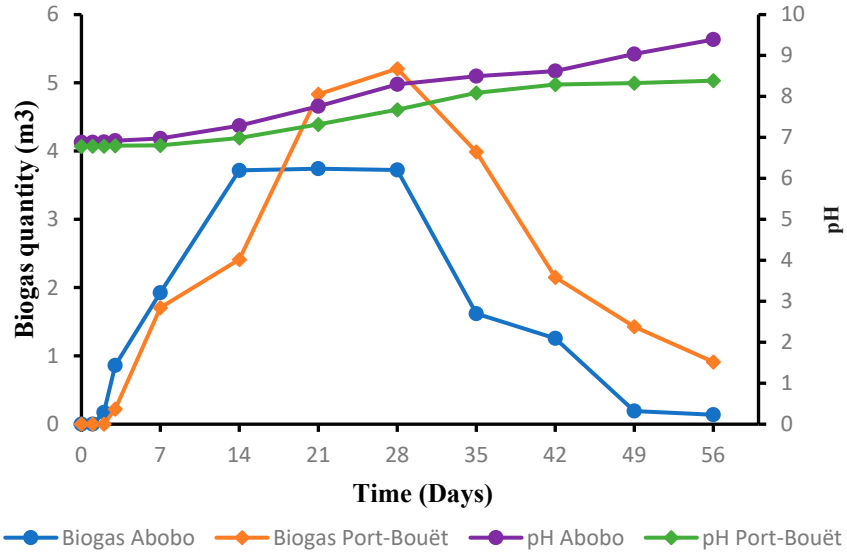


Figure 1. Variation in biogas production and pH during anaerobic digestion of pig manure on two farms of Abobo and Port-Bouët.

3.1.2. Biogas Composition and Energy Potential

Raw biogas composition varied between sites, with methane concentrations of 65–76% (Table 1). The PBk biodigester consistently produced biogas with higher methane content (72–76%) compared to the Ab biodigester (65–71%). Carbon dioxide comprised 20–30% of total biogas volume, while hydrogen sulfide concentrations ranged from 82.63 to 99.48 ppm. Biogas purification through the integrated biofilter system significantly enhanced methane concentrations to 80–82%, representing a 7–11% improvement. Concurrently, H_2S levels were reduced to 4.85–6.43 ppm, achieving >90% removal efficiency. The energy potential of raw biogas ranged from 1.88 to 3.05 kWh/day, increasing to 2.32–3.29 kWh/day after purification. Daily energy production averaged 3.25 ± 0.028 kWh/day (PBk) and 2.34 ± 0.035 kWh/day (Ab) for purified biogas.

Table 1. Estimated Energy Potential from biogas production during anaerobic digestion of pig manure on two farms of Abobo and Port-Bouët.

Study Site	Total Production (m^3)	Daily Production (m^3)	Energy Potential (kWh/d)			
			65% CH_4	76% CH_4	80% CH_4	82% CH_4
Abobo	16.31	0.29	1.88	2.20	2.32	2.37
Port-Bouët	22.63	0.40	2.61	3.05	3.21	3.29

3.2. Process Chemistry and pH Dynamics

3.2.1. pH Evolution and Production Correlation

pH values showed systematic evolution throughout the digestion process (Figure 1). Initial pH values of 6.78 (PBk) and 6.88 (Ab) gradually increased, reaching 8.34 and 9.39, respectively, by day 56. The optimal biogas production period (days 14–28) corresponded with pH values between 7.28 and 7.76 across both systems. A strong negative correlation ($r = -0.87$, $p < 0.01$) was observed between pH values above 8.0 and biogas production rates. The Ab biodigester reached inhibitory pH levels (>8.3) earlier than the PBk system, coinciding with its earlier production decline.

3.2.2. Organic Load Reduction

Substantial reductions in organic pollution parameters were achieved in both biodigesters (Figure 2). Unless stated otherwise, each value is the mean ± standard deviation of three ($n = 3$) technical replicates per sampling point and site. COD decreased from 123.300 ± 5.656 to 39.150 ± 1.343 g/L (68.3% reduction) in the PBk biodigester and from 142.450 ± 12.091 to 44.600 ± 5.091 g/L (68.7% reduction) in the Ab biodigester. BOD_5 concentrations declined from 66.672 ± 8.349 to 34.464 ± 2.307 g/L (48.3% reduction) in PBk and from 84.336 ± 3.190 to 41.184 ± 8.281 g/L (51.2% reduction) in Ab. The biodegradability index (COD/BOD_5) remained favorable throughout the process, ranging from 1.08 ± 0.35 to 1.13 ± 0.11, indicating continued biological activity. Total organic acid concentrations decreased progressively in both systems, with reductions of 73.2% (PBk) and 69.8% (Ab) by day 56. Total ammonia nitrogen levels declined by 45.6% (PBk) and 52.3% (Ab), reflecting microbial assimilation processes (Figure 3).

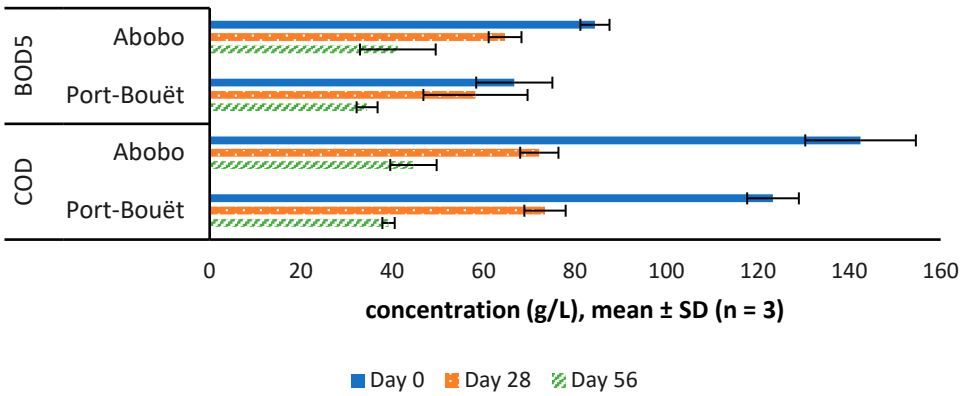


Figure 2. Evolution of COD and BOD_5 during methanization of pig manure from the two Ivorian pig farms under study.

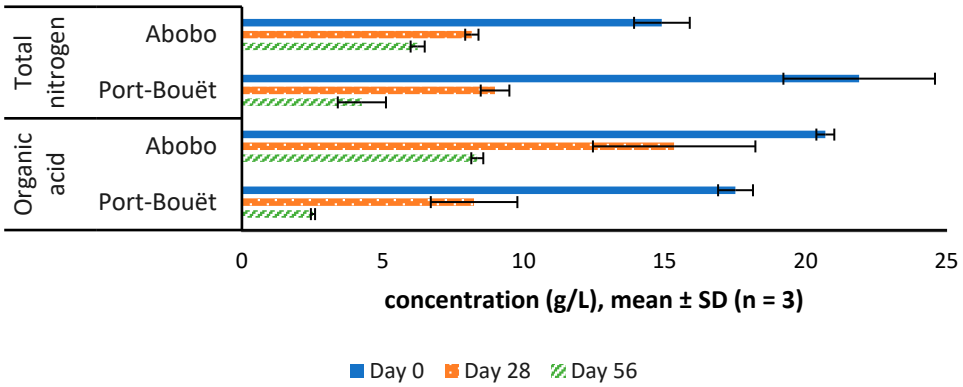


Figure 3. Evolution of Organic acid and Total nitrogen during methanization of pig manure from the two Ivorian pig farms under study.

3.3. Mineral Element Dynamics

The concentrations of essential mineral elements remained relatively stable throughout the anaerobic digestion process (Table 2). In the PBk biodigester, phosphorus, potassium, and iron concentrations showed minimal variation (<10% change). The Ab biodigester exhibited slight increases in copper (15.3%), zinc (12.7%), phosphorus (8.9%), and iron (11.2%), while potassium concentrations decreased by 6.8%. Heavy metal concentrations (Pb, Cr, Hg, Cd) remained below 10 mg/L throughout the process in both systems, with no significant temporal variations observed. However, in the Ab biodigester, Pb concentrations ranged from 22.1 ± 1.41 mg/L to 23.5 ± 5.52 mg/L. These low concentrations suggest minimal risk for agricultural applications of the resulting digestate.

Table 2. Evolution of mineral elements during methanization of pig manure from the two Ivorian pig farms under study.

Studied Parameters	Localities	Concentration (mg/L) by Time (Days)		
		Day 0	Day 28	Day 56
Cd	Abobo	<10	<10	<10
	Port-Bouët	<10	<10	<10
Hg	Abobo	<10	<10	<10
	Port-Bouët	<10	<10	<10
Pb	Abobo	23.5 ± 5.52 ^{a}	22.1 ± 1.41 ^{a}	22.9 ± 1.70 ^{a}
	Port-Bouët	<10	<10	<10
Cr	Abobo	42.65 ± 1.63 ^{a}	39.8 ± 0.14 ^{a}	38.3 ± 2.12 ^{a}
	Port-Bouët	11.3 ± 0.99 ^{a}	<10 ^{b}	13 ± 1.41 ^{a}
Cu	Abobo	22.9 ± 2.54 ^{b}	42.25 ± 1.06 ^{a}	38.6 ± 2.12 ^{a}
	Port-Bouët	45 ± 14.7 ^{a}	49.95 ± 11.48 ^{a}	65.7 ± 7.07 ^{a}
Zn	Abobo	96.9 ± 2.40 ^{b}	182.5 ± 14.84 ^{a}	166 ± 5.65 ^{a}
	Port-Bouët	413.5 ± 62.93 ^{a}	392 ± 7.07 ^{a}	500.5 ± 88.39 ^{a}
Fe	Abobo	16,820 ± 1555.63 ^{b}	25,400 ± 1357.64 ^{b}	24,235 ± 162.63 ^{a}
	Port-Bouët	3520 ± 212.13 ^{a}	3295 ± 827.31 ^{a}	4130 ± 848.53 ^{a}
K	Abobo	4325 ± 134.35 ^{a}	4960 ± 183.85 ^{a}	3415 ± 162.63 ^{b}
	Port-Bouët	17,395 ± 1562.71 ^{a}	12,785 ± 1831.41 ^{a}	16,185 ± 2807.21 ^{a}

Table 2. *Cont.*

Studied Parameters	Localities	Concentration (mg/L) by Time (Days)		
		Day 0	Day 28	Day 56
P	Abobo	8460 ± 721.25 [b]	16,115 ± 1831.41 [a]	18,650 ± 28.28 [a]
	Port-Bouët	20,560 ± 3408.25 [a]	25,335 ± 1166.73 [a]	24,910 ± 5515.43 [a]

In the same row, values followed by the same alphabetical letter are not statistically different ($p > 0.05$) and the results are presented in this form: mean ± SD ($n = 3$).

3.4. Pathogen Reduction and Microbial Dynamics

3.4.1. Complete Pathogen Elimination

Seven microbial groups showed complete elimination during the 56-day digestion period (Figure 4a,b). *Escherichia coli* and *Staphylococcus aureus* populations were undetectable by day 28 in both biodigesters, representing >8 $\log_{10}$ reductions from initial loads of 10^7–10^8 CFU/g. Mold populations were completely eliminated by day 28, while *Pseudomonas* spp. showed variable patterns: complete elimination by day 28 in the Ab biodigester and 3.2 $\log_{10}$ reduction followed by elimination in the PBk biodigester by day 42.

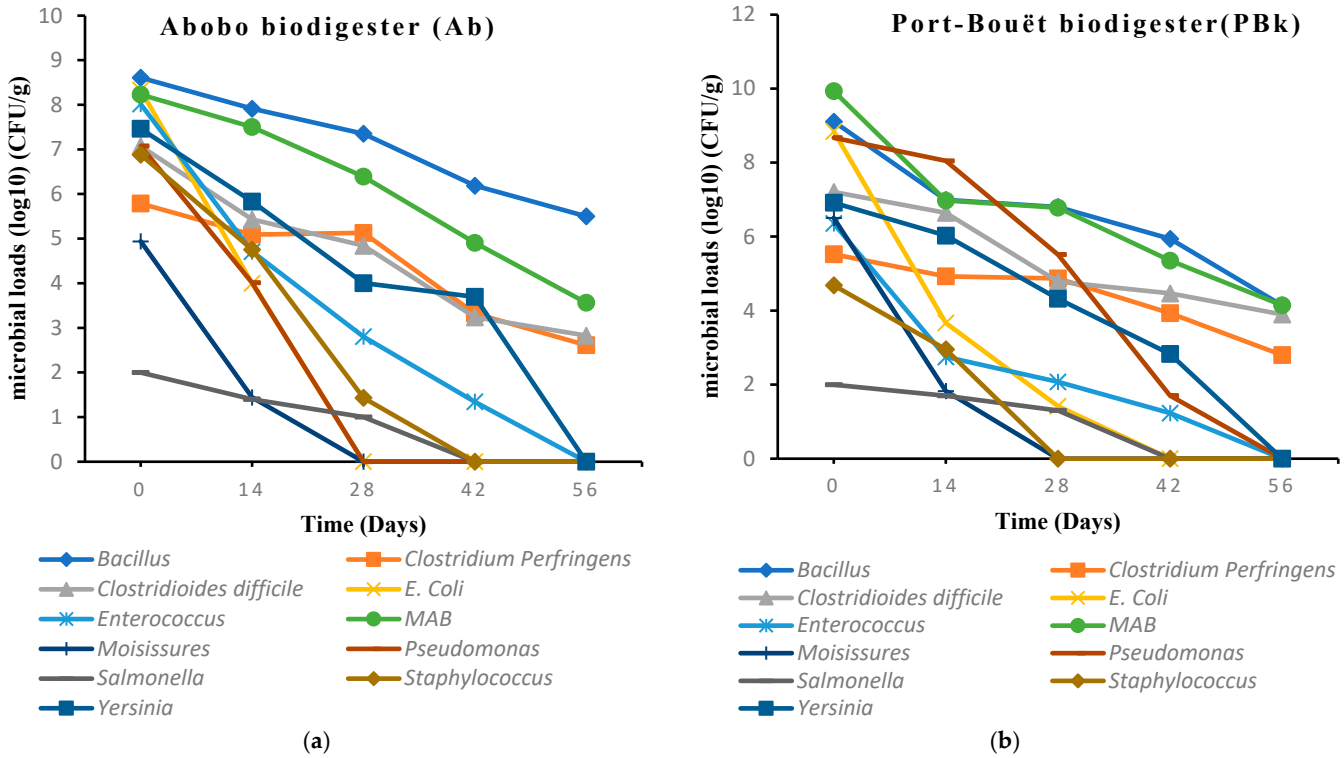


Figure 4. Monitoring of germs during methanization: (**a**) Abobo biodigester (Ab); (**b**) Port Bouët biodigester (PBk).

Salmonella spp. persisted until day 42 before complete elimination, while *Yersinia* spp. and *Enterococcus* spp. required the full 56-day period for complete removal in both systems.

3.4.2. Resistant Microbial Populations

Three microbial groups demonstrated resistance to anaerobic digestion conditions but showed substantial population reductions (Figure 4a,b). *Bacillus* spp. populations decreased by 4.97 $\log_{10}$ (PBk) and 3.11 $\log_{10}$ (Ab). *Clostridium perfringens* loads were reduced by 2.72 $\log_{10}$ (PBk) and 3.17 $\log_{10}$ (Ab), while *C. difficile* showed 3.31 $\log_{10}$ (PBk)

and 4.24 $\log_{10}$ (Ab) reductions. Total mesophilic aerobic bacteria (MAB) demonstrated the greatest reductions among persistent groups, with 5.79 $\log_{10}$ (PBk) and 4.66 $\log_{10}$ (Ab) decreases from initial populations.

3.5. Microbial Diversity and Ecophysiological Correlations

3.5.1. Phylogenetic Characterization of Bacterial Isolates

Phylogenetic analysis of representative bacterial isolates from pig manure revealed significant taxonomic diversity among culturable bacteria (Figure 5). 16S rRNA gene sequencing of 5 isolates from each morphological group using MinION Mk1C enabled the molecular identification and phylogenetic positioning of the dominant culturable bacterial taxa. The phylogenetic tree illustrates the taxonomic relationships among isolated bacteria, with representatives distributed across several major bacterial phyla.

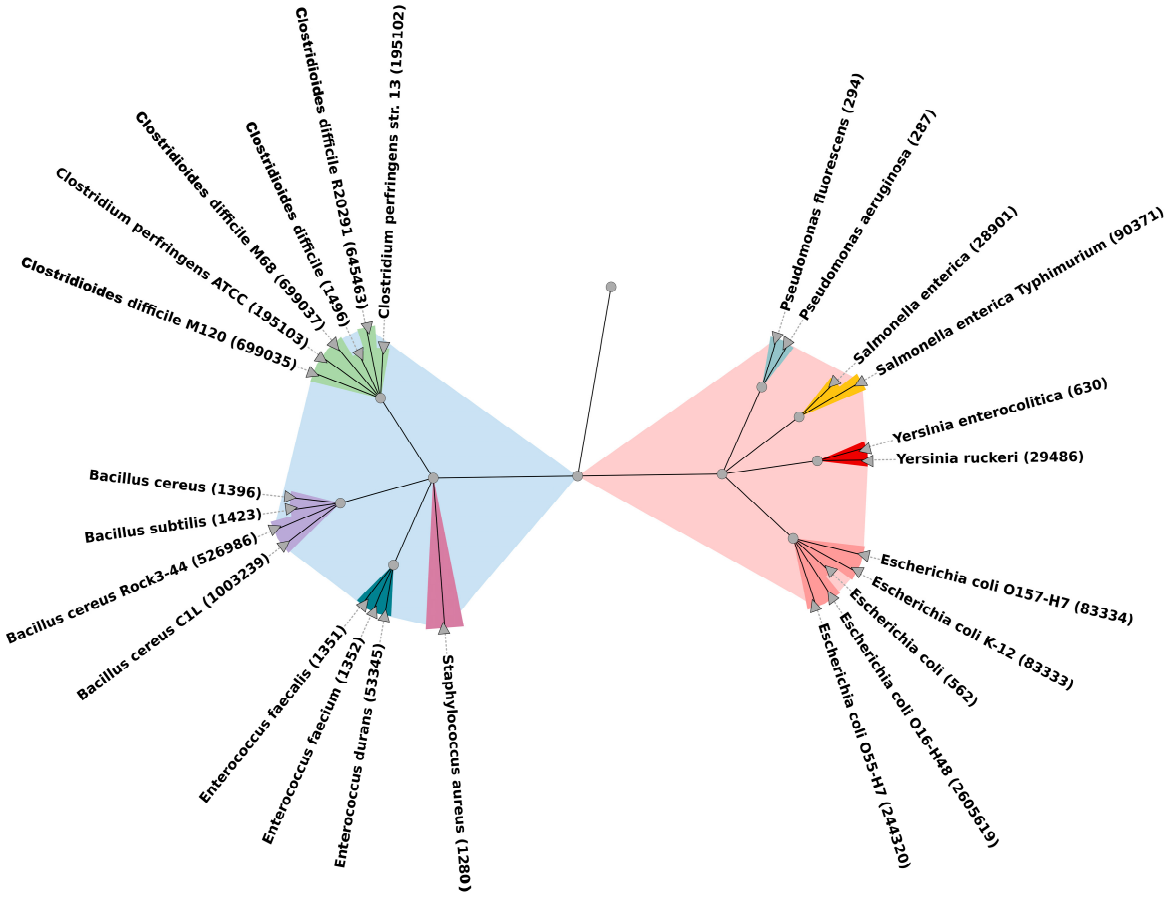


Figure 5. Phylogenetic tree of bacteria identified in pig manure, illustrating the taxonomic diversity and distribution of the main microbial phyla. Taxname (TaxID).

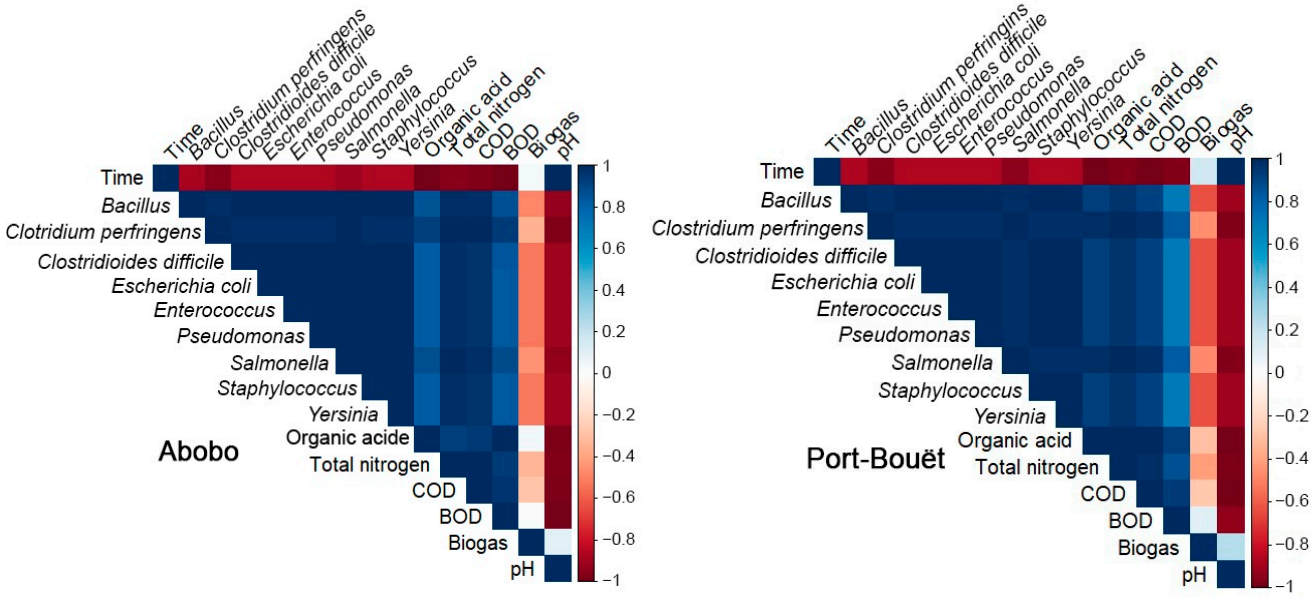
The Firmicutes phylum was well-represented among the isolates, including the spore-forming genera *Bacillus* and *Clostridium* that demonstrated marked resistance to the anaerobic digestion process. Several Proteobacteria isolates were identified, encompassing pathogenic enterobacteria (*Escherichia*, *Salmonella*) as well as *Pseudomonas* and *Yersinia* species that were monitored during the digestion process.

The phylogenetic analysis confirmed the molecular identity of key microbial groups detected through culture-based methods, providing taxonomic validation for the pathogen reduction results. The diversity of isolated bacteria reflects the complex microbial ecosystem present in pig manure, with representatives spanning Gram-positive and Gram-negative bacteria, aerobic and anaerobic species, and both pathogenic and environmental strains. This molecular characterization supports the comprehensive microbiological monitor-

ing approach and validates the identification of specific bacterial targets for pathogen reduction assessment.

3.5.2. Relationships Between Microbial Load and Physicochemical Parameters

Correlation analyses between microbial loads and physicochemical conditions of pig manure revealed significant relationships that illuminate survival and elimination mechanisms of different microbial groups (Figure 6a,b).



(**a**) (**b**)

Figure 6. Correlations between microbial load and physico-chemical conditions of pig manure during biodigestion (**a**) Abobo biodigester (Ab); (**b**) Port Bouët biodigester (PBk).

A strong negative correlation (r = −0.78 to −0.85, $p < 0.01$) was observed between pH evolution and survival of vegetative pathogenic bacteria (*E. coli*, *Salmonella*, *Staphylococcus aureus*). This relationship confirms that progressive alkalinization of the medium (pH > 8.0) constitutes a major elimination factor for these pH-sensitive microorganisms. Conversely, spore-forming bacteria (*Bacillus*, *Clostridium*) showed weaker correlation with pH (r = −0.45 to −0.55), explaining their relative persistence in the system.

Organic load reduction (COD, BOD_5) presented moderate positive correlation with microbial elimination (r = 0.62 to 0.71), suggesting that nutritional competition and modification of trophic conditions contribute to microbial community selection. Organic acid concentrations showed significant negative correlation (r = −0.69) with pathogen survival, indicating potential inhibitory effects of these metabolites on certain microbial groups.

The analysis also revealed positive correlation between ammonia nitrogen concentrations and reduction in Gram-positive bacterial populations (r = 0.58), suggesting toxic effects of free ammonia on these microorganisms. These relationships enable identification of microbial control mechanisms in anaerobic digestion systems and optimization of operational conditions to maximize pathogen elimination while preserving methanogenic activity.

4. Discussion

The biogas yields achieved in this study (22.63 and 16.31 m^3 from 320 kg substrate over 56 days) represent significant advances for small-scale anaerobic digestion under West African conditions. These results establish the first comprehensive dataset for pig waste digestion under ambient tropical temperatures (28–32 °C), filling a critical knowledge gap

for technology transfer to similar climatic regions. With daily production rates ranging from 0.29 to 0.40 m^3/day from 1600 L digesters, corresponding to outputs of 0.18 to 0.25 m^3/m^3 reactor/day or 0.91–1.25 L/kg/day of manure, these results demonstrate the economic viability of decentralized biogas systems for small and medium-sized pig farms in sub-Saharan Africa. Furthermore, the review article by Tolessa [26] indicates that a household of five people requires approximately 1.5 to 2.4 m^3/d of biogas to provide two meals. This benchmark puts our results into perspective and highlights that, correctly deployed, this sector can contribute to reducing the energy deficit of low-income households. Previous studies have primarily focused on temperate conditions or industrial-scale operations, which limits their applicability to predominant smallholder farming systems in African regions. However, recent analyses conducted in sub-Saharan Africa by Gbadeyan et al. [27] show that the sustainability of small digester use depends primarily on the cost per kWh, financing mechanisms, and supportive policies, rather than a universal daily production threshold. In this context, daily yields of 0.29–0.40 m^3 of biogas obtained from low-cost, easy-to-maintain domestic digesters are economically viable in rural areas. In this sense, Robin and Ehimen [28] demonstrate that anaerobic digestion could significantly impact the lives of low-income households in sub-Saharan Africa by improving their access to energy and providing an income through selling biogas and digestate. Moreover, the observed production patterns, with peak performance during weeks 2–4, align with established methanogenic kinetics but occur more rapidly due to higher ambient temperatures [29]. This accelerated timeline enables predictive management of gas supply for cooking and lighting applications, directly addressing energy poverty in rural communities as documented by the International Energy Agency's rural energy access reports [30].

The demonstrated energy potentials of 2.32–3.29 kWh/d after purification represent substantial renewable energy generation capacity for rural communities. In this context, the average daily energy production could more than meet the farmers' essential energy needs, especially if the quantities of methanized manure are higher. This energy production capacity is all the more significant given that biogas currently accounts for only a small proportion of renewable energy in Côte d'Ivoire and most other West African countries [31], despite having enormous development potential.

The successful application of simple biofilter purification under field conditions achieved >90% H_2S removal and 7–11% methane enhancement, demonstrating that high-quality biogas can be produced using locally maintainable technology. Similar purification efficiencies have been reported using low-cost materials like iron oxide and wood chips [32,33], confirming the scalability of such approaches across the region.

The integration of biogas production with waste management creates multiple value streams that enhance economic viability. Carbon credit mechanisms under international climate frameworks could provide additional revenue streams, with typical biogas projects generating 2–4 tCO_2e credits per household system annually [34,35].

The complete elimination of major foodborne pathogens (*E. coli*, *Salmonella*, *S. aureus*) within 28–42 days represents a paradigm shift for safe organic waste management in regions where raw manure application is widespread. This discovery addresses the practice of Ivorian market gardeners using untreated animal manure head on. It could prevent thousands of cases of foodborne illness each year, particularly given that the WHO estimates that unsafe food causes 600 million cases of illness worldwide each year, with the most severe impact being felt in developing countries [36].

Furthermore, the reductions in pathogens achieved are considerably higher than the international standards for pathogen reduction in organic waste treatment, as established by the EPA for Class A biosolids [37]. This level of pathogen inactivation transforms hazardous waste streams into safe agricultural inputs, thereby breaking the cycle of transmission of

zoonotic diseases which disproportionately affect vulnerable populations in developing regions, as previously noted [38]. On the other hand, identifying specific high-risk strains such as *E. coli* O157:H7 and *Salmonella Typhimurium* highlights the importance of proper waste treatment for public health. These pathogens cause serious foodborne illnesses, including hemorrhagic colitis and hemolytic uremic syndrome, which have high fatality rates among vulnerable populations [39].

The differential susceptibility of pathogens to anaerobic digestion conditions sheds light on the mechanisms of inactivation. Vegetative bacteria such as *E. coli*, *Salmonella* and *Staphylococcus* showed rapid elimination, likely due to unfavorable pH conditions, nutrient competition and the production of potential antimicrobial compounds by methanogenic communities. The prolonged presence of *Enterococcus* and *Yersinia* (with complete elimination occurring after 56 days) is consistent with their recognized environmental resistance traits, offering valuable guidance on the timing of safe digestate application. However, the persistence of spore-forming bacteria (*Bacillus* and *Clostridium*) despite a significant reduction reflects their inherent resistance mechanisms. Although complete elimination was not achieved, reductions of 3–5 $\log_{10}$ represent a substantial reduction in risk. The presence of residual spore-forming bacteria, albeit at greatly reduced levels, highlights the importance of adhering to proper digestate handling protocols and ensuring correct application timing to prevent resurgence of pathogens.

In addition, while antibiotic resistance genes were not directly quantified in this study, the dramatic reductions in bacterial populations suggest significant potential for reducing antibiotic-resistant bacterial loads commonly found in pig waste. Recent studies have shown that anaerobic digestion can reduce the number of antibiotic resistance genes by more than 1.5 $\log_{10}$ [40–42], which is a significant step in the fight against antimicrobial resistance. This is particularly relevant given the increasing use of antibiotics in pig farming across sub-Saharan Africa, where regulatory oversight remains limited [43].

Moreover, the identification of optimal pH ranges (7.28–7.76) and inhibitory thresholds (>8.3) provides actionable parameters for process control in low-tech environments. The strong correlation between pH management and biogas production ($r = -0.87$) establishes pH monitoring as a simple but powerful optimization tool accessible to smallholder farmers. This finding aligns with established anaerobic digestion principles, where pH values between 6.8 and 7.2 are considered optimal for methanogenic activity [44,45]. The observed alkalosis phenomenon from ammonia accumulation, leading to production decline, highlights the importance of nitrogen management strategies [46–48]. The earlier pH inhibition in the Ab system suggests higher nitrogen content or different buffering capacity in the substrate. Studies have shown that free ammonia concentrations above 80–150 mg/L can inhibit methanogenic bacteria [49,50], suggesting opportunities for process optimization through C:N ratio adjustment or co-digestion strategies.

The substantial COD reductions (68.3–68.7%) and BOD_5 reductions (48.3–51.2%) demonstrate effective organic matter conversion while maintaining favorable biodegradability indices (1.08–1.13). These results indicate that the remaining organic matter is readily biodegradable, suggesting potential for extended digestion periods or two-stage systems to achieve higher treatment efficiency. Indeed, the 73% reduction in organic acids reflects efficient methanogenic conversion, while the 45–52% reduction in ammonia nitrogen indicates effective nitrogen cycling. The balance between organic matter removal and nutrient conservation creates optimal conditions for producing high-quality biofertilizer.

The stability of essential mineral elements (P, K, Fe) during digestion, combined with controlled ammonia nitrogen reduction, creates optimal nutrient profiles for crop production. Unlike thermochemical treatments that can volatilize nutrients, anaerobic digestion preserved fertilizer value while eliminating pathogens. Several previous studies

have shown that anaerobic digestion retains almost all of the phosphorus and potassium in the digestate, unlike composting systems, which experience significant nutrient loss [51–54]. In the same vein, the observed improvement in certain fertilizing elements suggests the potential for agronomic recovery of digestates. However, the literature reports risks of copper (Cu) and zinc (Zn) accumulation in digestates derived from pig and cattle manure, requiring monitoring and controlled inputs [55]. This risk was not identified in our study. The mineralization processes during digestion often improve nutrient availability compared to raw organic matter [56,57]. Moreover, the maintenance of low heavy metal levels (<10 mg/L) ensures long-term soil health protection, remaining well below international standards for organic fertilizers. EU regulations limit heavy metals in organic fertilizers to 100–400 mg/kg for various elements [58], while our digestate values were 10–50 times lower, addressing concerns about micropollutant accumulation from repeated applications.

By combining waste treatment, energy production, and fertilizer generation, this study demonstrates integrated bioeconomy solutions particularly relevant for resource-constrained settings. The preserved mineral content enables closed-loop nutrient cycling that reduces dependence on imported synthetic fertilizers while managing environmental pollution. This aligns with FAO's promotion of circular bioeconomy approaches for sustainable agriculture in developing countries [59]. Techno-economic analyses and life-cycle assessments using economic allocation suggest that digestate valorization could account for several tens of percent (up to 45%, depending on the context) of the economic value of co-products and generate significant revenue when sold [60,61]. Thus, the integration of waste treatment and nutrient recovery represents a paradigm shift from linear waste management to circular resource utilization models increasingly advocated for sustainable development as stated by Ellen [62].

Furthermore, the successful operation under ambient tropical temperatures (28–32 °C) without external heating demonstrates climate-appropriate technology adaptation. This eliminates major capital and operational costs associated with temperature control, making the technology financially accessible to small-scale operations. Temperature stability in tropical climates provides operational advantages over temperate regions, where seasonal variations can significantly impact biogas production. Studies comparing heated versus ambient temperature digesters in tropical regions have shown that cost savings from eliminated heating often outweigh production losses [63,64].

Phylogenetic analysis revealed diverse microbial communities adapted to tropical conditions, predominantly consisting of Firmicutes and Proteobacteria. The successful establishment of methanogenic conditions despite high pathogen loads demonstrates the resilience of anaerobic digestion systems in challenging environments. Correlating microbial dynamics with process parameters provides insight into optimizing system performance through community management strategies.

Also, using commercially available biodigesters (PUXIN systems) with locally sourced materials demonstrates immediate scalability and eliminates the need for complex technology transfer. Similar technologies have been successfully deployed in several countries under various climatic conditions [65,66]. The methodology can be replicated across similar agro-ecological zones in West Africa, potentially impacting thousands of pig farming operations. Indeed, successful biogas programs in neighboring countries provide valuable lessons for scaling. Under the Africa Biogas Partnership Program, several thousand household biogas plants were deployed in Burkina Faso in 2018. Meanwhile, Ghana implemented approximately 400 biogas systems under its national initiative, which supports the installation of 200 systems in key institutions within a few years [67,68]. These experiences highlight the importance of combining technical training with financial support mechanisms and after-sales service networks.

Beyond individual farm benefits, widespread adoption could stimulate rural energy markets, create maintenance service opportunities, and develop value chains for digestate marketing. Studies in Nepal have shown that biogas programs can generate several indirect jobs per installation through maintenance, procurement of raw materials, and manufacturing of equipment [69]. Indeed, the technology addresses multiple Sustainable Development Goals simultaneously (SDG 7: Clean Energy, SDG 11: Sustainable Cities, SDG 12: Responsible Consumption, SDG 3: Good Health), justifying integrated development programming. This aligns with recent assessments that map and quantify the contributions of anaerobic digestion across multiple SDGs and targets, thereby supporting integrated development programming [70].

While this study provides crucial baseline data, several limitations should be acknowledged. Long-term performance monitoring beyond 56 days is needed to assess system durability, seasonal variations, and maintenance requirements. Incorporating local cost structures, including capital costs, operational expenses, and revenue streams, into an economic feasibility analysis would strengthen arguments for adoption. Also, future research priorities should include ammonia management strategies through co-digestion with carbon-rich substrates to optimize C:N ratios; digestate processing optimization through solid–liquid separation and nutrient concentration; integration studies with crop production systems to quantify agricultural productivity improvements; life cycle assessment to quantify environmental benefits compared to current waste management practices and participatory research approaches engaging farmers in system design and optimization. Regional adaptation studies should investigate variations in performance across different agroecological zones, pig breeds and feeding systems that are common in West Africa. Economic modeling that incorporates carbon credit potential, fertilizer value, energy savings and social benefits would provide a comprehensive business case analysis for different stakeholder groups.

However, the dual benefits of pollution control and energy generation that have been demonstrated provide strong economic incentives for policy support. Integrating the technology with existing agricultural extension services could accelerate its adoption, while partnerships with microfinance institutions could address barriers to capital investment. Commercial deployment would be facilitated by regulatory frameworks supporting digestate quality standards and biogas safety protocols. Developing local manufacturing capacity for biogas equipment and spare parts would reduce costs and ensure the long-term sustainability of interventions. Therefore, these results support the development of evidence-based policies for sustainable waste management in rapidly urbanizing African cities, contributing to environmental protection and renewable energy development goals. If successful, the Abidjan model could be replicated across similar urban–agricultural interfaces throughout the region.

5. Conclusions

This study demonstrates that anaerobic digestion is a robust, multifunctional solution for managing pig manure in urban farming settings, such as in Abidjan. Over a 56-day period, the process produced substantial amounts of biogas with a high energy potential (up to 3.29 kWh/day), while simultaneously reducing pollutant loads (COD and BOD_5) and eliminating key pathogens. Although some resistant spore-forming bacteria persisted, the hygienic quality of the digestate improved significantly, supporting its reuse in agriculture. Furthermore, the conservation of essential nutrients and the absence of heavy metal mobilization reinforce the agronomic value of the final product.

These findings validate the integration of small-scale anaerobic digesters into urban waste management strategies, providing a circular, climate-resilient approach to sustainable

agriculture and renewable energy generation in sub-Saharan Africa. Future research should focus on optimizing operational parameters, evaluating long-term system performance, and conducting economic feasibility studies to facilitate wider adoption of this technology in the region.

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Abbreviations

The following abbreviations are used in this manuscript:

Ab	Abobo Dokui
BOD_5	5-Day Biological Oxygen Demand
$Ca(OH)_2$	Calcium Hydroxide
CH_4	Methane
CFU	Colony Forming Unit
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
EP	Energy Potential
H_2S	Hydrogen Sulfide
HNO_3	Nitric Acid
LCV	Lower Calorific Value
MAB	Mesophilic Aerobic Bacteria
PBk	Port Bouët Kamboukro

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