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The Effect of Retention Time on Biogas Yield and the Quality of Effluent Using Cow Dung and Swine Manure

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ABSTRACT

This study investigated the effect of hydraulic retention time on biogas yield and the quality of the resulting effluent using swine manure (S), cow dung (C), and their 50:50 co-digestion (CS) as substrates. A laboratory scale batch anaerobic digestion system was operated at ambient temperature (31 ± 5°C) for 84 days. Substrate temperature and biogas volume were monitored daily, slurry pH measurements weekly, and nutrient contents (nitrogen, carbon, potassium, phosphorus) every two weeks after the initial six weeks. Over 77 days of active gas production, cow dung (C) produced the highest cumulative biogas volume (77,771.50 cm³), followed by swine manure (S) (50,660.33 cm³) and co-digestion (CS) (47,974 cm³). Results confirm that longer retention time significantly enhances cumulative biogas yield. Regarding effluent quality, prolonged retention markedly reduced the nutrient contents particularly nitrogen (N) and Phosphorous (P), in digestates from cow dung and swine manure alone. In contrast, co-digestion (CS) showed relatively stable nutrient levels in the effluent over the same period. These findings demonstrate that while extended retention time increases biogas production across all treatments, it negatively impacts effluent nutrient quality in single substrate digestion (C and S) but preserves and enhances it in co-digestion (CS).

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1.0 Introduction

Rapid population growth, industrialization and urbanization have intensified environmental challenges including improper management of agricultural and industrial wastes, leading to pollution, sanitation issues, and greenhouse gas emissions [1]. Anaerobic Digestion (AD) offers a sustainable solution by converting organic wastes into biogas, a renewable energy source rich in methane while producing nutrient rich effluent suitable as organic fertilizer [2,3].

Animal manures, particularly cow dung and swine manure, serve as common AD feedstocks due to their abundance and inherent microbial consortia [4]. However, mono-digestion often yields low biogas due to suboptimal carbon-to-nitrogen (C/N) ratios and recalcitrant components. Recent studies demonstrate that co-digestion of cow dung and swine manure improves process stability, buffer capacity, and methane yields by balancing nutrients and enhancing biodegradability [5, 6].

For instance, co-digestion with complementary substrates has increased biogas production significantly, as seen in mixtures with food waste or other manures [7], though specific cow dung-swine manure pairings remain underexplored compared to combinations with food waste or crop residues. While extensive research focuses on optimizing hydraulic retention time (HRT) for maximizing biogas yield [8, 9], limited attention addresses its impact on digestate quality, particularly nutrient (N, P, K) retention and availability for agricultural use. Prolonged HRT may enhance degradation and gas production but risks nutrient mineralization and loss in effluents from single-substrate digestion, potentially reducing fertilizer value.

This study addresses this knowledge gap by investigating the effects of extended HRT in batch AD on both biogas yield and effluent nutrient quality using cow dung, swine manure, and their 50:50 co-digestion. The novelty lies in elucidating contrasting HRT impacts on digestate nutrients between mono- and co-digestion systems, providing insights for optimizing dual benefits of energy recovery and high-quality biofertilizer production. The objective is to evaluate how retention time influences cumulative biogas production and changes in nitrogen, phosphorus, and potassium contents in the resulting effluents.

2.0 Materials and Methods

2.1 Substrates and Inoculum

Fresh cow dung (C) and swine manure (S) were collected from the Obafemi Awolowo University Teaching and Research Farm, Ile-Ife, Nigeria (7°31′06″N 4°31′22″E). The substrates were stored at 4 °C prior to use. No external inoculum was added, as the fresh manures contained sufficient indigenous microbial consortia for anaerobic digestion [4].

Initial characteristics of the substrates are presented in Table 1. The total solids (TS) concentration was adjusted to 8% for all treatments, as recommended for optimal anaerobic digestion [8]. Water addition ratios were calculated as follows: 1:1.641 (water:cow dung, w:w wet basis), 1:3.699 (water:swine manure), and 1:2.67 (water:co-digestion mixture).

Table 1: Initial physicochemical characteristics of substrates (mean ± standard deviation, n=3)

Parameter	Cow Dung (C)	Swine Manure (S)	Co-digestion (CS, 50:50)
Ph	7.2 ± 0.2	7.5 ± 0.3	7.3 ± 0.2
Total Solids (TS, %)	18.5 ± 1.2	12.8 ± 0.9	15.6 ± 1.0
Volatile Solids (VS, % of TS)	82.4 ± 2.1	78.6 ± 1.8	80.5 ± 1.9
C/N Ratio	22.5 ± 1.5	14.8 ± 1.2	18.7 ± 1.3
Total Nitrogen (% dry basis)	1.96 ± 0.15	2.31 ± 0.18	2.14 ± 0.16
Total Phosphorus (% dry basis)	0.85 ± 0.08	1.12 ± 0.10	0.98 ± 0.09
Total Potassium (% dry basis)	1.45 ± 0.12	1.68 ± 0.14	1.56 ± 0.13

2.2 Experimental Setup and Procedure

The experiment employed a laboratory-scale batch anaerobic digestion system consisting of 25-L plastic digesters, connected to 10-L water displacement tanks and 5-L collection vessels for biogas measurement. Three treatments were evaluated: 100% cow dung (C), 100% swine manure (S), and 50:50 co-digestion (CS). Each treatment was replicated three times, except cow dung, which had four replicates to account for higher variability observed in preliminary trials and to improve statistical reliability for the substrate yielding the highest biogas volume.

Digesters were loaded to 70% capacity (17.5 L) with substrate mixtures adjusted to 8% TS. Non-degradable materials were manually removed. Digestion was conducted at ambient temperature (31 ± 5°C) for 84 days. Manual agitation was performed twice daily to ensure homogeneity and gas release.

2.3 Analytical Methods

Substrate temperature and biogas volume were monitored daily. Slurry pH was measured weekly using a calibrated pH meter. Nutrient analyses (total nitrogen, phosphorus, potassium) were conducted biweekly after week 6.

Total solids (TS) and volatile solids (VS) were determined gravimetrically according to APHA Standard Methods 2540B and 2540E [10]. Total nitrogen was analyzed using the Kjeldahl method (APHA 4500-Norg). Total phosphorus was quantified spectrophotometrically after acid digestion (APHA 4500-P). Total potassium was measured by flame photometry post-digestion (APHA 3500-K). Carbon content was estimated from VS loss on ignition. Biogas volume was measured via water displacement and reported at standard conditions.

2.4 Statistical Analysis

Data were expressed as means ± standard deviation. Differences in cumulative biogas yield and nutrient contents among treatments and over retention time were assessed using one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test. Pearson correlation was used to evaluate relationships between retention time and measured parameters. Statistical significance was set at $p < 0.05$. All analyses were performed using SPSS version 25.

3.0 Results

The anaerobic digestion process was monitored for 84 days, with active biogas production observed over the first 77 days, after which daily yields dropped below 100 cm³ across all treatments.

3.1 Substrate Temperature and pH

Substrate temperatures closely followed ambient conditions, fluctuating between 28–38°C daily (mean 31 ± 5 °C). No significant differences were observed among treatments (ANOVA, $p > 0.05$). The pH of all treatments decreased initially, reaching a minimum between weeks 5–6, followed by stabilization (Figure 1). Initial pH values were 7.2–7.5 (Table 1). Minimum pH values were 6.4 (C), 5.5 (S), and 5.1 (CS), recovering to 8.0–9.0 by the end of digestion. Co-digestion (CS) exhibited the widest pH fluctuation (5.1–9.7).

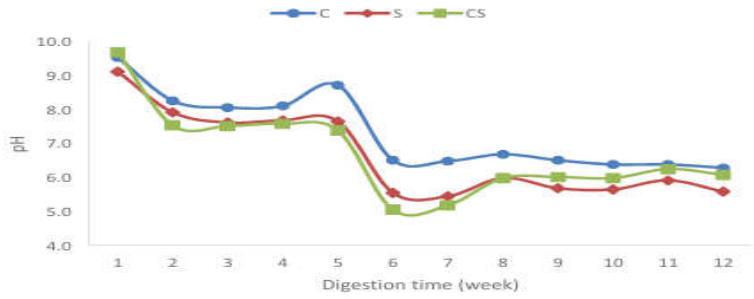


Figure 1: Variation of slurry pH with digestion time (mean ± SD, n=3–4)

3.2 Biogas Yield

Cumulative biogas yields over 77 days of active production differed significantly among treatments (ANOVA, $F = 28.4$, $p < 0.001$). Cow dung (C) produced the highest volume (77,772 ± 4,850 cm³), followed by swine manure (S) (50,660 ± 3,720 cm³) and co-digestion (CS) (47,974 ± 3,510 cm³) (mean ± SD). Tukey's post-hoc test confirmed C > S > CS ($p < 0.05$). Daily biogas production peaked early: day 30 for C (2,690 ± 180 cm³), day 5 for S (2,223 ± 160 cm³), and day 7 for CS (1,498 ± 120 cm³). Production remained sustained in C throughout the period, while S and CS showed greater weekly fluctuations (Figure 2).

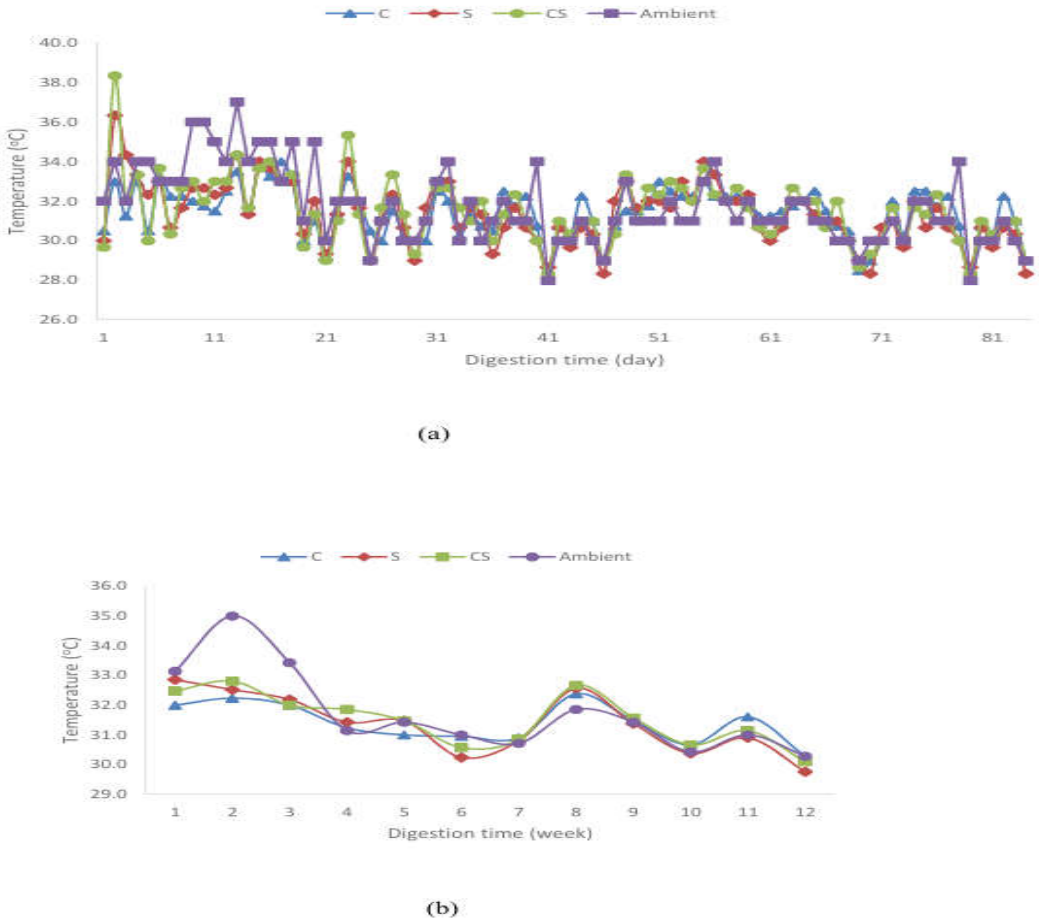


Figure 2: Daily (a) and cumulative (b) biogas yield over digestion time (mean ± SD, n=3–4)

3.3 Effluent Nutrient Content

Nutrient concentrations in the digestate were measured at weeks 6, 8, and 10. Prolonged retention time significantly affected nitrogen and phosphorus levels (ANOVA, $p < 0.01$), with variable effects on potassium.

Nitrogen content declined sharply in mono-digestion treatments from week 6 onward (Figure 3). In C, N decreased from 1.96% (initial) to 0.33 ± 0.05% (week 6), rising slightly to 0.83 ± 0.08% (week 8) before falling to 0.78 ± 0.07% (week 10). In S, N dropped to 0.44 ± 0.06% (week 6) and 0.39 ± 0.05% (week 8), recovering to 0.57 ± 0.07% (week 10). In contrast, CS showed relative stability, increasing from 0.64 ± 0.07% (week 6) to 0.94 ± 0.09% (week 8) and 0.93 ± 0.08% (week 10). Phosphorus decreased steadily in C and S but increased in CS over the same period (Figure 4). Potassium showed a continuous decline in S, a slight increase in C, and a decrease in CS (Figure 5).

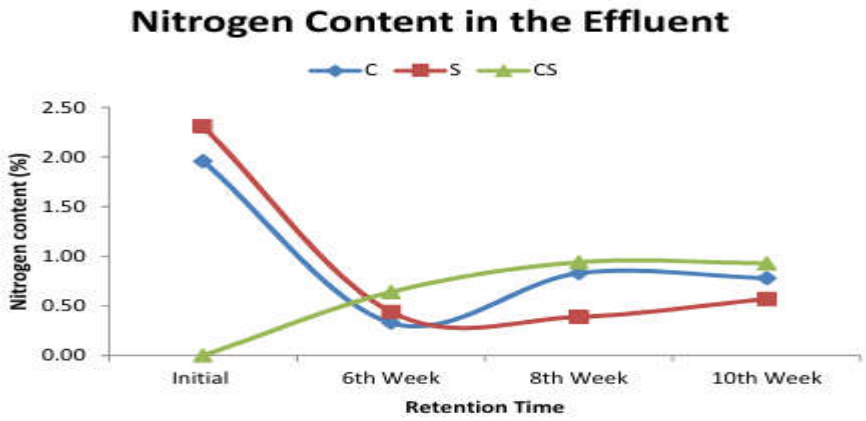


Figure 3: Nitrogen content in digestate at weeks 6, 8, and 10 (mean ± SD, n=3–4)

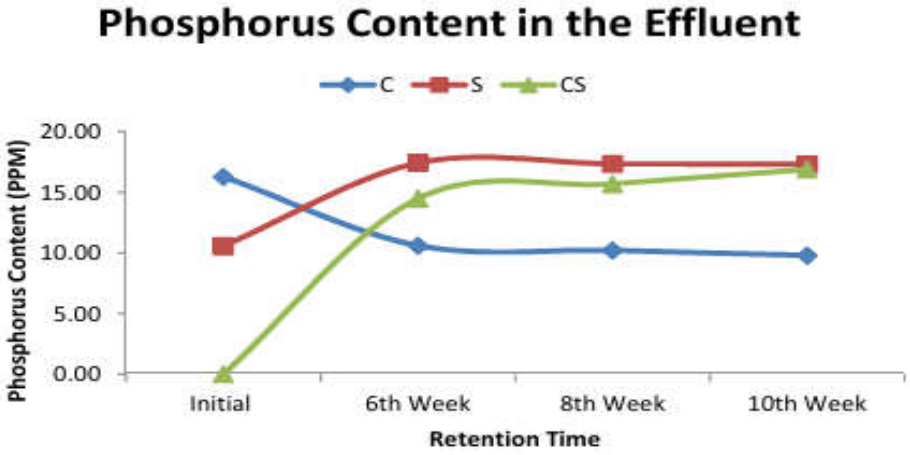


Figure 4: Phosphorus content in digestate at weeks 6, 8, and 10 (mean ± SD, n=3–4)

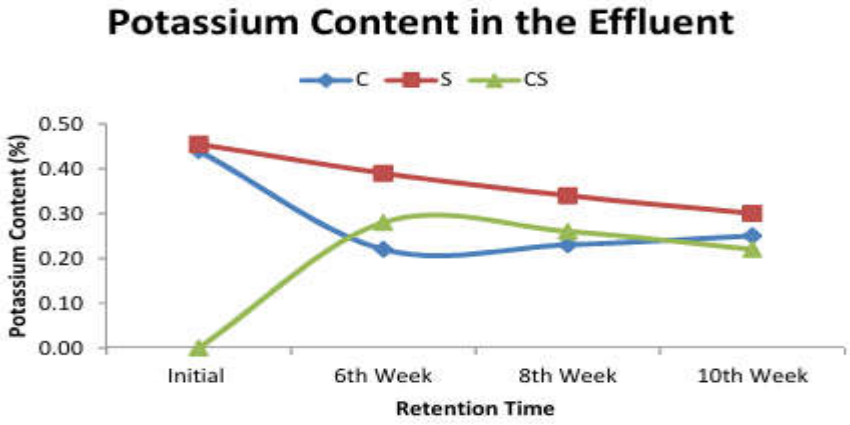


Figure 5: Potassium content in digestate at weeks 6, 8, and 10 (mean ± SD, n=3–4)

4.0 Discussion

The highest biogas yield from cow dung aligns with literature reporting superior methanogenic potential in cattle manure due to its balanced lignocellulosic composition and indigenous microbial community [3,4]. Yields from C (≈310 mL/g VS added, estimated) fall within reported ranges for untreated cow dung (250–350 mL/g VS) under mesophilic/ambient conditions. The lower yield from swine manure reflects its higher protein content and rapid acidification tendency [11], while co-digestion, despite improved C/N ratio (18.7 vs. 14.8 in S), did not enhance biogas production here, contrary to some studies reporting 20–50% synergy in cow dung–swine manure mixtures [5]. This may be attributed to the batch mode and lack of process optimization (e.g., loading rate, mixing).

Initial pH drop and subsequent recovery indicate typical acidification followed by methanogenic stabilization [11]. The wider fluctuation in CS suggests enhanced buffering from synergistic volatile fatty acid consumption and ammonia release, supporting greater process resilience in co-digestion systems [6].

Nutrient dynamics reveal a clear trade-off between energy recovery and fertilizer value. Prolonged retention in mono-digestion promoted excessive mineralization: ammonia volatilization and phosphate precipitation likely drove N and P losses in C and S. In contrast, co-digestion maintained or increased available N and P, possibly due to balanced microbial activity reducing ammonia loss and preventing excessive acidification that immobilizes phosphorus. Similar stabilizing effects of co-digestion on digestate nutrient retention have been reported in cattle–pig manure systems [2].

These findings highlight a key energy–nutrient recovery trade-off: extended HRT maximizes biogas yield but risks diminishing effluent fertilizer quality in mono-digestion, whereas co-digestion mitigates this penalty, enabling longer retention for higher energy output without sacrificing biofertilizer value.

5.0 Conclusion

This study demonstrated that hydraulic retention time (HRT) had negligible effects on digestate temperature but significantly influenced pH dynamics and biogas production in batch anaerobic digestion of cow dung (C), swine manure (S), and their 50:50 co-digestion (CS) at ambient temperature (31 ± 5 °C). The pH exhibited initial declines to minima of 6.4 (C), 5.5 (S), and 5.1 (CS) around weeks 5–6, followed by recovery and stabilization, reflecting typical acidogenic-methanogenic phase transitions. Over 77 days of active production, cumulative biogas yields were highest for C (77,772 ± 4,850 cm^3), followed by S (50,660 ± 3,720 cm^3) and CS (47,974 ± 3,510 cm^3), with significant differences among treatments (ANOVA, $p < 0.001$). These results confirm that extended HRT enhances biogas yield by allowing greater organic matter degradation and methanogenesis.

Regarding effluent quality, prolonged HRT variably affected NPK composition. In mono-digestion (C and S), nutrient levels, particularly nitrogen (N) and phosphorus (P) declined significantly over time ($p < 0.01$), likely due to enhanced mineralization processes: ammonia volatilization under fluctuating pH, phosphate precipitation in acidic conditions, and potassium leaching or microbial uptake. In contrast, co-digestion (CS) preserved or enhanced nutrient retention, with N increasing from 0.64% to ~0.93% and P rising steadily. Mechanistically, this conservation arises from synergistic effects in CS: the balanced C/N ratio (18.7) fosters diverse microbial consortia that optimize volatile fatty acid metabolism, maintain stable pH buffering (reducing acidification-induced P immobilization), and minimize ammonia release/volatilization through efficient nitrogen assimilation. This highlights co-digestion's role in mitigating nutrient losses common in mono-substrate systems.

Overall, while longer HRT universally boosts energy recovery via biogas, it introduces a trade-off in fertilizer value for mono-digestion but synergistically supports dual energy-nutrient benefits in co-digestion systems.

Limitations

The study was conducted in batch mode at uncontrolled ambient temperature, which limits direct comparison to continuous systems. Nutrient analyses measured total NPK rather than plant-available fractions, potentially overestimating fertilizer value. Future work should include bioavailability tests

and continuous reactor trials under controlled conditions.

Recommendations

For systems prioritizing maximum biogas energy production, extended HRT (>77 days) is recommended across all substrates, particularly cow dung for its superior yield potential. However, for applications seeking combined energy and high-quality biofertilizer recovery, co-digestion of cow dung and swine manure is preferable, as it allows prolonged retention without compromising effluent nutrient content, enabling nutrient conservation while sustaining biogas output. In mono-digestion setups (cow dung or swine manure alone), HRT should be limited to ~6–8 weeks to preserve effluent N and P levels for fertilizer use, avoiding excessive degradation that diminishes agronomic value. Future designs should incorporate continuous or semi-continuous reactors to better control HRT and validate these batch-derived insights under operational conditions.

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