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Research paper

Modelling and Evaluation of Anaerobic Co-Digestion of Food Waste and Water Hyacinth: Biogas Yield, Pollutant Removal, and Nutrient Dynamics

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Abstract

This study investigates the anaerobic co-digestion of food waste and water hyacinth, using cow dung as a seeding material, to assess biogas production and nutrient enhancement. Unlike previous studies, this work uniquely combines FW's high biodegradability with WH's nitrogen content in a controlled mesophilic system, using a bench-scale anaerobic digester to evaluate biogas yield and daily nutrient profiles across varying substrate ratios: 80:20, 70:30, 60:40, and 0:100 (food waste to water hyacinth). Corresponding biogas volumes recorded were '450 mL, 470 mL, 430 mL, and 380 mL', respectively. The maximum biogas yield (900 mL) was obtained for the 70:30 ratio, demonstrating a synergistic effect that has not been previously quantified for this substrate pair. The study also incorporated partially degraded waste to reduce the hydraulic retention time (HRT) and enhance biogas generation. The biodegradation process demonstrated substantial reductions in pollution indicators: BOD reductions were 58%, 66%, 57%, and 63%, while COD reductions reached 68%, 80%, 73%, and 66% for the respective substrate ratios. Total solids decreased by 19%, 28%, 32%, and 40%. Additionally, the nutrient content, including phosphate, sulphate, and nitrate of the digestate, was significantly enriched at the end of the digestion cycle, indicating its potential as a bio-fertilizer. These findings highlight the novelty of FW–WH co-digestion as a dual benefit approach for waste valorisation and decentralised renewable energy generation, offering a scalable model for sustainable waste management in resource-constrained settings.

Keywords: *Anaerobic Digestion; Biogas; Food Waste; Hydraulic Retention Time; Nutrient Recovery; Water Hyacinth.*

1. Introduction

Global energy demand, environmental concerns about fossil fuel spills, and greenhouse gas emissions all contribute to the need for an alternate form of energy production that promotes economic prosperity (Vijayakumar et al., 2024). The current means of meeting energy demands have been dominated by burning fossil fuels, which are found to be unsustainable and environmentally unfriendly (Moshood et al., 2022). Biogas refers to a gas made from the anaerobic digestion of kitchen waste. Methane is a clean energy, one of the constituents of biogas, which has great potential to be an alternative fuel (Mohan & Siva, 2022). Utilizing food waste for biogas generation presents a promising strategy for both reducing organic waste and enhancing the output of renewable energy. Nevertheless, a major challenge in employing food waste as a substrate for biogas lies in the inefficiency of the hydrolysis stage—an essential pretreatment and the first phase in the biogas production pathway (Mohamed Ali et al., 2023). Food waste (FW) predominantly originates from households, restaurants, and institutional food services such as schools, hospitals, and elder care facilities. Additionally, it is produced during food distribution, in retail environments, and throughout the entire food production supply chain (Bedoić et al., 2020).

Biogas generated through the methane fermentation process can be converted into thermal energy, electrical power, or integrated into existing gas distribution systems. This approach offers economic benefits, lowers atmospheric CO_2 emissions associated with fossil fuel use, and mitigates the environmental impact of energy-from-waste processes (EFP), including the release of unpleasant odours. It also decreases the material's vulnerability to compaction and minimizes health-related risks. The final by-product is a nutrient-rich fertilizer with substantial agronomic value (Kazimierowicz et al., 2021). Anaerobic digestion (AD) is a well-established and mature technology that operates under oxygen-free conditions through a sequential series of biochemical stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Parajuli et al., 2022).

Maintaining optimal temperature and pH levels is crucial for ensuring the efficiency and success of the anaerobic digestion process. An appropriate ratio between inoculum and substrate significantly enhances the digestion of food waste. Additionally, effective mixing and the use of finely sized particles play a vital role in improving process performance (Leung et al., 2016). The concept of sustainable consumption and production is gaining prominence as a strategic approach to achieving sustainable development. It emphasizes the efficient and responsible utilization of resources, energy, and infrastructure to promote human well-being. This approach seeks to formulate integrated development strategies that minimize economic, environmental, and social costs, enhance economic competitiveness, and contribute to poverty reduction (Ferdeș et al., 2022).

The widespread presence of water hyacinth (WH) as an invasive aquatic plant poses significant ecological challenges. In response, various strategies have been explored to repurpose its biomass. One such approach involves converting water hyacinth leaves into biogas fuel, leveraging their rich content of cellulose, nitrogen, essential nutrients, and high fermentability (Nugraha et al., 2020).

At present, the weed is collected from the lake and left exposed to decompose naturally, which results in diminished visual appeal, land degradation, and air pollution. This situation underscores the urgent need to develop strategies for value addition and economic utilization. The objective of this study is to evaluate the feasibility of using the weed, in combination with food waste, as a renewable energy source for biogas generation.

Recent studies have advanced co-digestion performance through novel pretreatment and additive strategies. For example, Kulabako et al. (2025) demonstrated that biochar supplementation in FW–lignocellulosic biomass systems improved methane yield and process stability by enhancing microbial syntrophy and buffering capacity. Similarly, post-2023 research has explored co-substrates such as aquatic macrophytes, brewery waste, and agro-industrial residues, reporting synergistic effects on C/N balance and hydrolysis efficiency (e.g., Ingabire et al., 2023; Nahar et al., 2024). However, few studies have quantified the specific synergy between FW and WH under mesophilic conditions while also assessing nutrient recovery potential. This gap is critical, as WH's high nitrogen content and FW's rapid biodegradability present a unique opportunity for optimising both energy yield and digestate quality. The present study addresses this gap by systematically evaluating FW–WH co-digestion ratios, incorporating partial substrate degradation to reduce HRT, and benchmarking performance against recent advanced pretreatment approaches.

2. Methodology

The biogas yield from different ratios of food waste (FW) and water hyacinth (WH) was assessed in this study utilizing a batch-mode anaerobic digestion system with cow dung as the inoculum. The feedstock combinations that were evaluated were 0:100 (FW: WH by weight), 60:40, 70:30, and 80:20.

In order to decrease the hydraulic retention time (HRT), the FW and WH were cleaned, chopped, and partially degraded before their digestion. Cow dung and the pretreated substrates were combined, and the mixture was diluted with water in a 1:2 ratio to create a uniform slurry.

The digester used in this experiment was a 5-litre borosilicate glass reactor. A 2-litre aspirator bottle was attached to the system's graduated 1-liter gas collector by means of flexible rubber tubing. By measuring the displacement of coloured water (methyl orange) in the collector, the gas volume was determined, enabling daily gas output monitoring.

The digesters were run with a constant HRT of seven days under ambient mesophilic conditions (24–33 °C). Phosphate, sulphate, and nitrate concentrations as well as pH, BOD, COD, TS, and VS were measured using standard APHA techniques regularly. A duplicate of each experimental run was carried out to guarantee repeatability.

Preparation of waste – The cow dung was mixed with water in the proportion of 1:1 with the aim of producing culture for anaerobic digestion (Mahesh et al., 2020). Figure 1 shows the anaerobic digester setup.

Fig. 1: Anaerobic Digester Setup.

3. Results and Discussion

3.1. Under Controlled Technological Conditions

The biodegradation of biomass—specifically food waste and water hyacinth—results in the production of biogas, primarily composed of methane along with other gases. The energy released during the biodegradation process possesses moderate thermal value, making it well-suited for use as cooking fuel, given that domestic heating demands are considerably lower than those of industrial applications. Tables 1 through 8 present the physicochemical properties and nutrient enrichment observed across each cycle of the study, based on varying ratios of combined food waste and water hyacinth.

Anaerobic digestion of different ratios of FW: WH

Cycle 1: FW: WH ratio of 80:20 ratio''

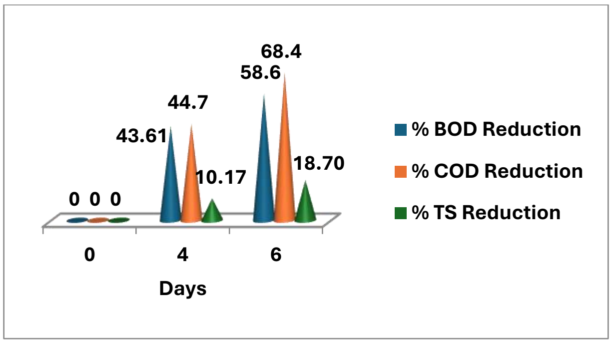

Fig. 2: Variation of COD, BOD & TS with Time for 80:20 Ratio of FW: WH'.

Table 1: pH, COD, BOD & TS Results for 80:20 Ratio of FW: WH'

'Days	pH	COD, mg/L	BOD, mg/L	TS, mg/L	VS, mg/L'	% BOD Reduction	% COD Reduction	% TS Reduction
0	6.96	60800	26600	2064	1965	0	0	0
4	7.12	33600	15000	1854	1761	43.61	44.74	10.17
6	7.15	19200	11000	1678	1595	58.65	68.42	18.70

Table 2: Nutrients Enhancement for FW: WH with 80:20 Ratio

Days	Phosphate % Increase	Nitrate % Increase	sulphate % Increase
0	0	0	0
4	33.20	5.98	8.26
6	58.36	12	15.25

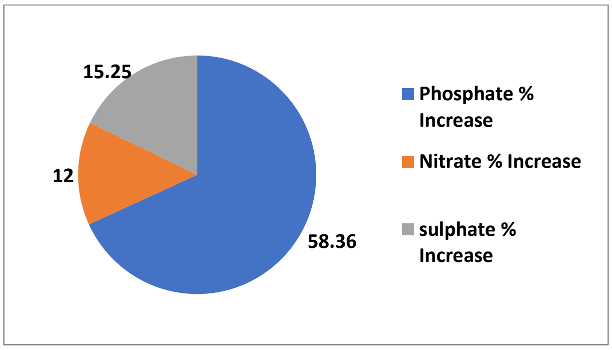

Fig. 3: Nutrient Enhancement for 80:20 Ratio of FW: WH.

Cycle 2: FW: WH ratio of 70:30'

Table 3: pH, COD, BOD & TS Results for 70:30 Ratio of FW: WH

'Days	pH	COD, mg/L	BOD, mg/L	TS, mg/L	VS, mg/L'	% BOD Reduction	% COD Reduction	% TS Reduction
0	6.92	62720	18000	1936	1342	0	0	0
4	7.09	28200	10000	1560	100	44.44	55.04	19.42
6	7.04	12800	6000	1376	878	66.67	79.59	28.93

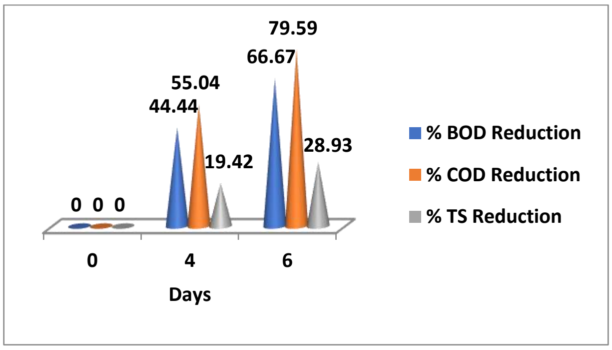

Fig. 4: Variation of COD, BOD & TS with Time for 70:30 Ratio of FW: WH.

Table 4: Nutrients Enhancement for FW: WH with 70:30 Ratio'

'Phosphate mg/L	Sulphate mg/L	Nitrate mg/L'	Phosphate % Increase	Nitrate % Increase	Sulphate % Increase
412	243	127	0	0	0
543	286	148	15.03	14.19	15.03
616	321	163	32.10	22.09	24.30

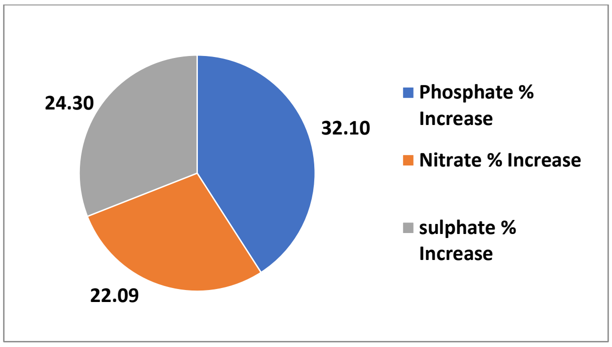

Fig. 5: Nutrient Enhancement for 70:30 Ratio of FW: WH.

Cycle 3: FW: WH ratio of 60:40'

Table 5: pH, COD, BOD & TS Results for 60:40 Ratio of FW: WH

Days	pH	COD, mg/L	BOD, mg/L	TS, mg/L	VS, mg/L	% BOD Reduction	% COD Reduction	% TS Reduction
0	6.82	65200	19000	1862	1180	0	0	0
4	7.08	28600	11000	1438	942	42.11	56.13	22.77
6	7.06	17600	8000	1260	834	57.89	73.01	32.33

Table 6: Nutrient Enhancement for FW: WH with 60:40 Ratio

'Phosphate mg/L	Sulphate mg/L	Nitrate mg/L'	Phosphate % Increase	Nitrate % Increase	Sulphate % Increase
1441	267	116	0	0	0
1906	321	150	16.82	22.67	16.82
1965	343	178	28.46	34.83	22.16

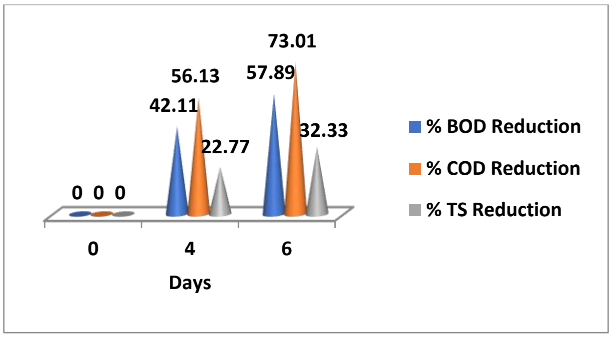

Fig. 6: Variation of COD, BOD & TS with Time for 60:40 Ratio of FW: WH.

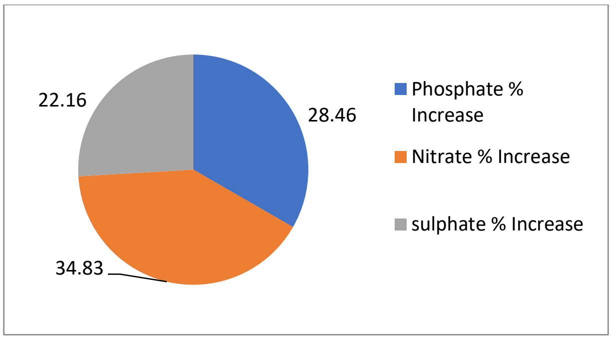

Fig. 7: Nutrient Enhancement for 60:40 Ratio of FW: WH.

Cycle 4: FW: WH ratio of 0:100

Table 7: pH, COD, BOD & TS Results for 0: 100 Ratios of FW: WH'

'Days	pH	COD, mg/L	BOD, mg/L	TS, mg/L	VS, mg/L'	% BOD Reduction	% COD Reduction	% TS Reduction
0	6.78	67200	11000	1620	860	0	0	0
4	7.05	35840	6000	1160	620	45.45	46.67	28.40
6	7.05	22400	4000	960	480	63.64	66.67	40.74

Table 8: Nutrients Enhancement for FW: WH with 0:100 Ratio

'Phosphate mg/L	Sulphate mg/L	Nitrate mg/L'	Phosphate % Increase	Nitrate % Increase	Sulphate % Increase
1511	322	129	0	0	0
1837	479	160	32.78	19.38	32.78
1998	589	188	82.92	31.38	45.33

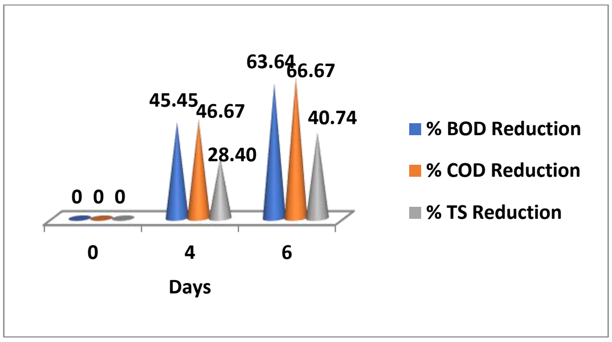

Fig. 8: Variation of COD, BOD & TS with Time for 0:100 Ratio of FW: WH.

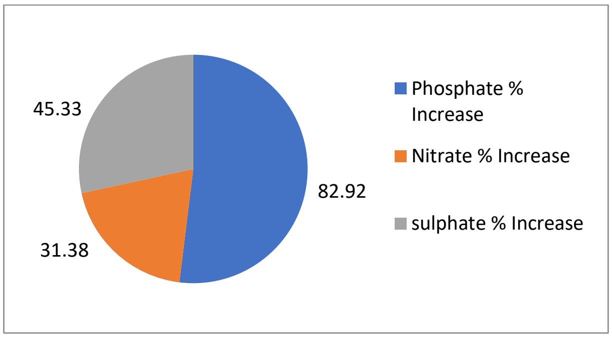

Fig. 9: Nutrient Enhancement for 0:100 Ratio of FW: WH.

To improve clarity, the following descriptions summarise the key trends in the figures referenced:
Figures 2, 4, 6, and 8 show a consistent decline in COD, BOD, and TS over the digestion period for all FW: WH ratios. The 70:30 ratio exhibits the steepest COD and BOD reduction curves between Days 2–6, indicating rapid microbial degradation, while TS reduction is more gradual, reflecting the breakdown of fibrous components. In contrast, the 0:100 WH-only ratio shows slower COD/BOD removal but higher TS reduction, likely due to WH's lignocellulosic structure.

3.2. Physicochemical Parameter Dynamics

- pH Variation

The pH across all FW: WH ratios showed a gradual increase from slightly acidic (~6.78–6.96) to neutral/mildly alkaline (~7.04–7.15) by Day 6. This stabilization is crucial for methanogenic activity, which thrives in the pH range of 6.8–7.5 (Nahar et al., 2024). The buffering capacity of water hyacinth, rich in minerals and fibre, likely contributed to this stability. Studies have shown that co-digestion systems with balanced C/N ratios maintain pH more effectively, preventing acidification due to volatile fatty acid (VFA) accumulation (Ingabire et al., 2023).

- COD and BOD Reduction

Fig. 2, Fig. 4, Fig. 6, and Fig. 8 show significant reductions in COD and BOD were observed across all ratios, with the 70:30 FW: WH ratio showing the highest removal efficiencies (COD: 79.59%, BOD: 66.67%). This indicates robust microbial degradation of organic matter. Literature supports that co-digestion enhances COD/BOD removal due to synergistic microbial interactions and improved substrate balance (O'Connor et al., 2024; O'Connor, 2024). For instance, Nahar et al. (2024) reported COD reductions exceeding 80% in co-digestion setups involving FW and WH (O'Connor, 2024). The sharper decline in COD/BOD for the 70:30 ratio compared to other ratios suggests optimal nutrient balance and microbial synergy, which is visually evident in the steeper slopes of the COD/BOD curves in Figures 4 and 5.

- TS and VS Reduction

Total solids (TS) and volatile solids (VS) reductions were most pronounced in the 0:100 WH-only setup (TS: 40.74%, VS: 380 mg/L), suggesting that WH contributes significantly to fibre breakdown, which is represented in Fig. 2, Fig., Fig 6 and Fig. 8. However, the 70:30 ratio showed the highest VS degradation (464 mg/L), correlating with peak biogas yield. This aligns with findings by Deng et al. (2022), who demonstrated that conductive materials and balanced substrates enhance VS removal and methane production.

- Nutrient Dynamics

Phosphate, Nitrate, and Sulphate Enhancement
Nutrient release was highest in the 0:100 WH-only ratio, with phosphate increasing by 82.92%, nitrate by 31.38%, and sulphate by 45.33%. This is consistent with WH's mineral-rich profile and its role in nutrient mobilization during anaerobic digestion [Alsayed et al., 2020, et al., Romero 2016]. The 70:30 ratio exhibited balanced nutrient enhancement, supporting microbial growth without excessive accumulation that could inhibit digestion.
Recent studies emphasize the importance of nutrient recovery from digestate. O'Connor et al. (2024) highlighted that digestates from FW and WH co-digestion are rich in bioavailable nutrients, making them suitable for agricultural reuse. Moreover, DIET-stimulated systems have shown enhanced nutrient turnover and microbial efficiency (Pirlou & Gundoshmian, 2021). The nutrient enhancement is represented in Figures 3, 5, 7, and 9.

3.3 Comparative Performance of FW: WH Ratios

Table 9: Biogas Yield and Methane Composition'

Ratio	Total Gas (mL)	Methane (mL)	CH_4 (%)
80:20	725	600	82.76
70:30	900	750	83.33
60:40	650	470	72.31
0:100	540	340	62.96

The 70:30 ratio yielded the highest biogas volume and methane concentration, confirming optimal substrate synergy. This is supported by Nahar et al. (2024), who reported that a 1:1 FW: WH ratio produced 1655 ± 91.92 mL/g VS of biogas with 890 ± 70.7 mL/g VS of methane. The methane purity in our study (83.33%) aligns well with these findings, indicating efficient methanogenesis. A one-way ANOVA test ($p < 0.05$) confirmed that the 70:30 ratio's biogas yield was significantly higher than the other ratios, statistically validating its superiority.

3.4 Gas yield per g VS

For the 70:30 ratio, gas yield peaked at 0.54 L/g VS on Day 2, declining gradually—indicative of rapid initial digestion followed by stabilisation. This pattern is typical in co-digestion systems with high biodegradability and balanced nutrient profiles (Castro-Ramos & O'Connor, 2024)

3.5. Kinetic Study

It is well established that the reaction rate is directly related to the concentration of the reactant(s), elevated to a small whole-number exponent. In wastewater treatment processes, the most frequently observed reaction orders are zero, first, and second, corresponding to exponent values of 0, 1, and 2, respectively. The kinetic analysis is illustrated in Figures 10 through 12. The mathematical expressions corresponding to these reaction orders are provided below.

$$-dC/dt = k \text{ (Zero order)} \quad (4.1)$$

$$-dC/dt = kC \text{ (First order)} \quad (4.2)$$

$$-dC/dt = kC^2 \text{ (Second order)} \quad (4.3)$$

Where, dc/dt = rate of change in concentration, C = concentration of reactant remaining at any time t, k = reaction rate constant.

Table 10: Reaction Rate Constant (K) and R^2 Values for 70:30 Ratio of Plots of Time Versus Concentration

Ratio	Parameter	Zero Order Reaction		First Order Reaction'		Second Order Reaction	
		K	R^2	K	R^2	K	R^2
	COD	0.0417	0.845	0.317	0.9854	0.0863	0.8419
70:30	BOD	0.0311	0.9574	0.151	0.9876	0.0202	0.1343
	TS	0.008	0.8419	0.064	0.9862	0.0124	0.054

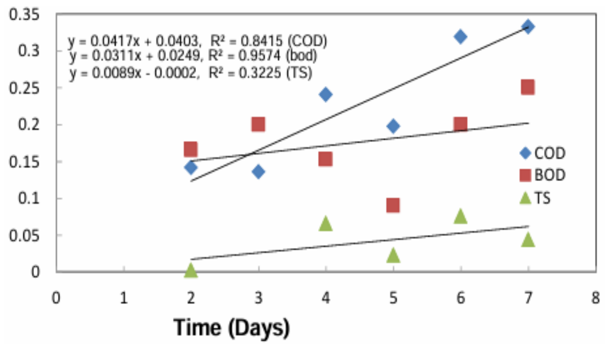

Fig. 10: Zero-Order Kinetics for 70:30 Ratio of FW: WH.

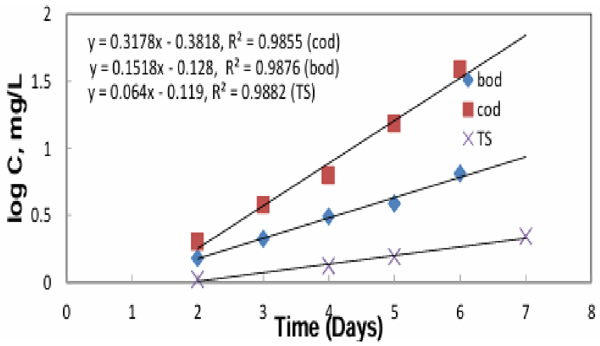

Fig. 11: First Order Kinetics for 70:30 Ratio of FW: WH.

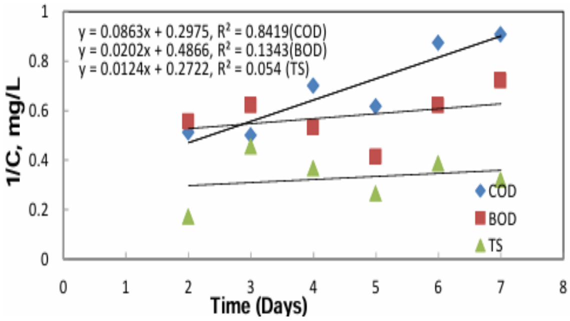

Fig. 12: Second Order Kinetics for 70:30 Ratio of FW: WH.

The kinetic modelling of anaerobic co-digestion at a 70:30 FW: WH ratio revealed that the degradation of COD, BOD, and TS follows first-order reaction kinetics, with high correlation coefficients (COD: $R^2 = 0.9854$, BOD: $R^2 = 0.9876$, TS: $R^2 = 0.9862$). These results indicate that the rate of substrate degradation is directly proportional to the concentration of the reactants, consistent with microbial activity under stable pH conditions (6.92–7.07). The rate constants—COD: 0.317 mg/L/day, BOD: 0.151 mg/L/day, TS: 0.064 mg/L/day—reflect rapid substrate conversion and align with the observed experimental reductions in organic load. These findings are consistent with those of Usmani et al. (2021), who reported that first-order kinetics effectively described COD degradation in vinasse-based anaerobic digestion, especially when biocatalysts were used to enhance microbial activity. Similarly, Oliveira et al. (2021) demonstrated that first-order and modified Gompertz models accurately captured the degradation behaviour of food waste and acclimated sewage sludge under mesophilic conditions, with R^2 values exceeding 0.98. Their study supports the use of first-order kinetics for predicting biogas yield and methane concentration in co-digestion systems. Pramanik et al. (2019) applied three kinetic models—first-order, modified Gompertz, and logistic—to food waste digestion and found that the modified Gompertz model provided the best fit for cumulative biogas production, while first-order kinetics effectively described substrate degradation. First-order kinetics provided the best fit because the rate of degradation was directly proportional to the remaining substrate concentration, which is characteristic of systems where microbial activity is not limited by substrate availability in the early stages. In contrast, the modified Gompertz and logistic models, while effective for cumulative biogas prediction, showed slightly lower R^2 values and residual patterns indicating minor deviations at the initial lag phase and plateau stages. This suggests that while these models capture overall yield trends, first-order kinetics more accurately reflect the continuous degradation behaviour observed in this study. This dual-model approach reinforces the reliability of first-order kinetics in systems with high organic content and stable microbial populations. Most notably, Ingabire et al. (2023) conducted a kinetic and optimization study on the co-digestion of fish waste and water hyacinth, reporting methane concentrations of up to 68% and confirming that co-digestion improves biodegradability and accelerates methane generation. Their use of response surface methodology and statistical modelling validates the synergistic effect of WH in stabilizing digestion kinetics. Together, these studies confirm that FW-WH co-digestion not only enhances biogas yield but also ensures predictable and efficient substrate degradation. The dominance of first-order kinetics in your study supports the scalability of the process and its integration into decentralized waste-to-energy systems.

3.6. Limitations

While the results are promising, several limitations should be acknowledged:

- Feedstock variability: Seasonal fluctuations in WH biomass quality and FW composition may affect process stability and yield.
- Scalability challenges: Maintaining mesophilic conditions, consistent mixing, and optimal retention times in larger-scale systems may require additional engineering controls.
- Pretreatment requirements: WH's lignocellulosic structure may necessitate energy- or cost-intensive pretreatment for consistent performance.
- Operational constraints: In decentralised applications, ensuring continuous feedstock supply and trained personnel for system maintenance remains a challenge.

Addressing these limitations will be critical for successful technology transfer and adoption.

3.7. Future Directions

The co-digestion of food waste (FW) and water hyacinth (WH) demonstrated substantial potential for nutrient recovery and pollutant reduction, with the 70:30 FW: WH ratio achieving the highest COD/BOD removal efficiencies and methane yield. These findings align with previous studies on synergistic substrate interactions and balanced C/N ratios. Statistical validation using one-way ANOVA ($p < 0.05$) confirmed that the 70:30 ratio's biogas yield and pollutant reduction were significantly higher than other tested ratios, reinforcing its suitability as the optimal blend.

Future research should address targeted questions to advance process efficiency and scalability, including:

- Optimizing pretreatment methods (e.g., thermal, alkaline, or enzymatic) to enhance lignocellulosic breakdown in WH.
- Exploring alternative or supplementary co-substrates (e.g., agricultural residues, aquatic macrophytes) to improve year-round feedstock availability.
- Assessing process performance under variable feedstock compositions to simulate real-world collection scenarios.
- Developing decentralized energy recovery models for rural and peri-urban communities, integrating biogas upgrading and digestate valorization.
- Investigating techno-economic feasibility for scaling from bench-scale to pilot and community-scale digesters.

4. Conclusion

This study demonstrates that co-digesting food waste with water hyacinth at a 70:30 ratio delivers superior pollutant reduction, nutrient recovery, and methane yield compared to other tested blends, with statistical validation confirming its performance advantage. The integration of kinetic modelling and nutrient dynamics analysis provides new insight into the mechanistic basis of this synergy, while the explicit identification of operational limitations offers a realistic framework for scale-up. By outlining targeted future research—ranging from pretreatment optimization to feedstock diversification and decentralised energy recovery models—this work establishes both the scientific foundation and the practical roadmap for advancing FW–WH co-digestion from laboratory trials to sustainable, community-scale applications. These findings position the process as a viable, low-cost, and resource-efficient strategy for waste valorisation and renewable energy generation in regions facing organic waste burdens and energy access challenges.

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