MSI Journal of
Multidisciplinary Research (MSIJMR)

Volume: 3, Issue: 8 (August-2026)
Published by *MSI Publishers*
ISSN 3049-0669 (Online)

Received: 23-06-2026
Accepted: 07-08-2026
Published: 12-08-2026

Production of Biogas from Anaerobic Co-digestion of Textile Sludge: Options of Sustainable Sludge Management

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ABSTRACT: Textile industry wastewater treatment generates large quantities of hazardous sludge, posing significant environmental challenges, particularly in developing countries like Ethiopia where open dumping remains common practice. This study investigated anaerobic co-digestion (ACoD) of textile semi-liquid sludge (TSLS) with cow dung (CD) as a sustainable sludge management and renewable energy recovery strategy. Batch experiments were conducted using four TSLS:CD mixing ratios (100:0, 75:25, 50:50, 25:75) under three temperature regimes (ambient ~25°C, 30°C, and 35°C) over a 30-day digestion period. Physicochemical characterization revealed raw TSLS had high organic content (VS: 76.91±0.681 g/L) but suboptimal C/N ratio (13.68) and alkaline pH (8.18), making mono-digestion inefficient. Co-digestion with CD significantly improved substrate properties, with the 50:50 ratio achieving optimal C/N balance (24.99) and near-neutral pH (7.47). This configuration produced maximum biogas yield of 1,533 mL at 35°C with 66.3% methane content, approximately ten times higher than mono-digestion (143 mL). Temperature significantly influenced process kinetics, with 35°C demonstrating fastest biogas initiation (day 3) and highest cumulative yields. The 50:50 ratios

DOI: ***10.5281/zenodo.21902438***

consistently outperformed other mixtures across all temperatures, confirming that substrate balancing is critical for process stability. These findings establish ACoD as a technically viable waste-to-energy pathway for Ethiopia's textile sector, transforming hazardous sludge into valuable renewable energy while promoting circular economy principles and mitigating environmental pollution from open dumping practices.

Keywords: *Anaerobic co-digestion, biogas production, textile sludge, cow dung, methane yield, sustainable waste management*

1. Introduction

The textile industry is vital to global economies, providing essential goods while generating substantial employment and industrial output. However, its manufacturing processes transform fibers into yarn, yarn into fabrics and finishes these materials at various production stages; require extensive use of water, dyes, chemicals, and energy, generating heavily contaminated wastewater. Without proper treatment, these effluents, laden with organic and inorganic pollutants, disrupt aquatic ecosystems and pose environmental risks (Sengupta, 2007; Ghaly et al., 2014). A major byproduct of wastewater treatment is sludge, which contains toxic heavy metals (e.g., Cd, Cr, Pb) and poses disposal challenges due to its non-biodegradable nature and potential for leaching (Islam et al., 2009). In Ethiopia, untreated sludge is often dumped in open landfills, exacerbating soil and water pollution (Delelegn, 2018).

Conventional sludge disposal methods (e.g., land filling, incineration) are unsustainable, prompting the exploration of anaerobic digestion (AD) as a circular economy solution. AD converts organic waste into biogas, a renewable energy source, while reducing sludge volume and toxicity. Recent advances in *anaerobic co-digestion* (ACoD), which combines sludge with nutrient-rich substrates like food waste or cow dung, demonstrate enhanced biogas yields and mitigation of inhibitory pollutants (e.g., dyes, heavy metals) (Kumar et al., 2020). Despite its potential, Ethiopia lacks advanced sludge management practices and research on lab-scale biogas production from textile waste.

This study addresses the existing research gap by exploring the anaerobic co-digestion (AcoD) of semi-liquid textile sludge (TSLS) from MNS Manufacturing PLC, using cow dung (CD) as a co-substrate. The key objectives include optimizing biogas production through substrate mixing ratios, characterizing critical parameters such as pH, total solids

 DOI: ***10.5281/zenodo.21902438***

(TS), volatile solids (VS), and carbon-to-nitrogen (C/N) ratios to evaluate process efficiency, and assessing the environmental impact by proposing a sustainable alternative to open dumping, aligning with Ethiopia’s need for pollution mitigation and energy recovery.

This research, conducted at MNS Manufacturing PLC, a textile facility near Addis Ababa, Ethiopia offers contributions covering multiple domains. At the industrial level, it provides the company with a scalable anaerobic co-digestion (ACoD) model for sludge valorization, reducing disposal costs and greenhouse gas emissions. From a policy perspective, the findings support the development of evidence-based regulations for sludge management in Ethiopia's textile sector. Academically, the study advances understanding of ACoD dynamics for complex industrial wastes, informing future research directions. Environmentally, it promotes circular economy practices by converting hazardous sludge into renewable biogas, thereby protecting soil and water resources. Ultimately, by integrating technical innovation with environmental stewardship, this research contributes to sustainable industrial growth while addressing Ethiopia's urgent waste management challenges.

2. Research Material and Methodology

2.1 Experimental Setup for Anaerobic Co-Digestion

2.1.1 Substrate Preparation and Characterization

The anaerobic co-digestion (ACoD) experiment was designed to evaluate biogas production from textile semi-liquid sludge (TSLS) co-digested with cow dung (CD). Biogas yield was quantified using the standard water displacement method. Prior to digestion, all substrates and co-substrates were subjected to comprehensive physicochemical characterization. Key parameters analyzed included pH, total solids (TS), volatile solids (VS), and carbon-to-nitrogen (C/N) ratio, providing baseline data for assessing degradation efficiency and nutrient recovery potential (summarized in Tables 2 and 3).

2.1.2 Experimental Design and Operating Conditions

The biogas production experiment was conducted using a batch-mode anaerobic co-digestion system consisting of four glass digesters (A, B, C, and D), each with a working

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volume of 1L. The digesters were operated under three temperature regimes: ambient room temperature (~25°C), 30°C, and 35°C, to assess the influence of temperature on methanogenic activity. The total digestion period was 30 days.

Four substrate mixing ratios (TSLS: CD, based on VS content) were evaluated:

- **Digester A:** 100:0 (TSLS mono-digestion, control)
- **Digester B:** 75:25
- **Digester C:** 50:50
- **Digester D:** 25:75

The initial pH of each digester was adjusted within the optimal range of 6.5–8.2, with values of 8.18 (A), 7.52 (B), 7.47 (C), and 7.65 (D). The C/N ratios achieved through substrate blending were 13.68 (A), 15.46 (B), 24.99 (C), and 37.74 (D), representing a gradient from nitrogen-rich to carbon-rich conditions.

Figure 1: Diagram of Experimental Digester Setups

2.1.3 Digester Loading and Biogas Measurement

To ensure substrate homogeneity, each mixture was thoroughly stirred prior to loading into its respective digester. Following loading, each digester was hermetically sealed and connected to a water displacement system for biogas collection. Biogas production was

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measured at 5-day intervals using vertical graduated cylinders, allowing for temporal profiles of cumulative gas yield to be constructed.

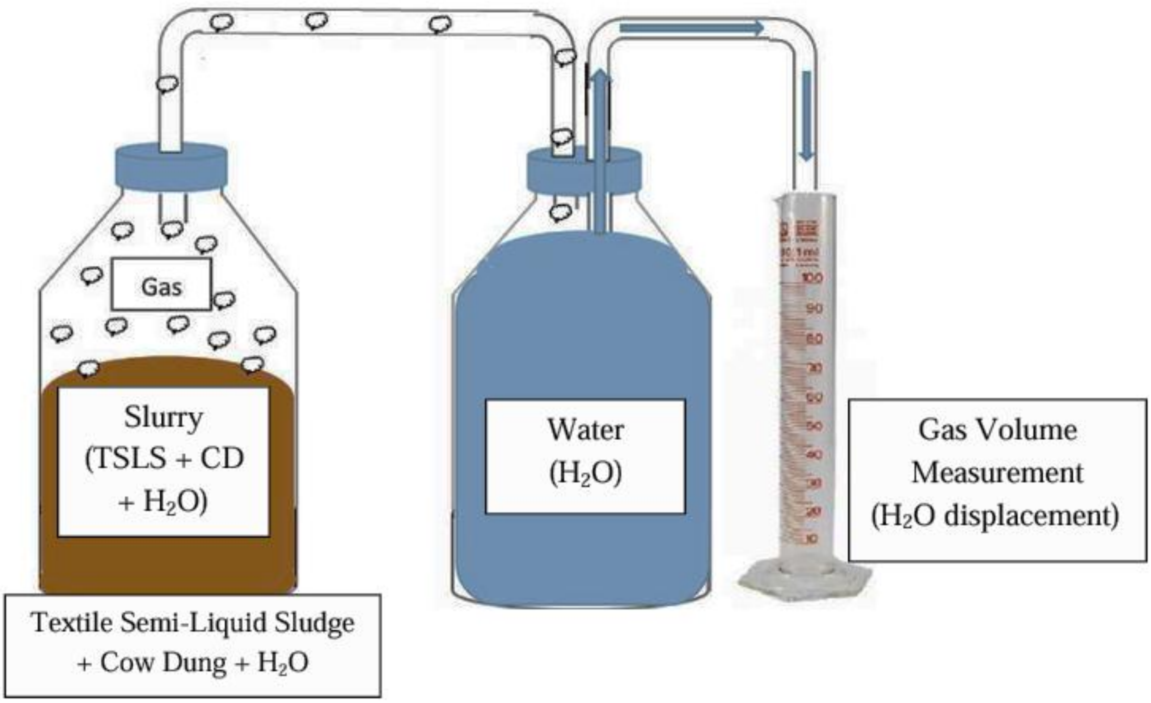

Figure 2: Schematic diagram of water displacement method

The study also examined the effects of pH, temperature, and C/N ratio on AcoD performance. Initial pH levels were set at 8.18 (digester A), 7.52 (B), 7.47 (C), and 7.65 (D), while temperatures varied across the mesophilic range (25–35°C) to optimize microbial activity. The C/N ratios were adjusted through substrate mixing, yielding values of 13.68 (A, nitrogen-rich), 15.46 (B), 24.99 (C, near-optimal), and 37.74 (D, carbon-rich).

The experimental design was adapted from methodologies developed by the Institute of Fuel Research & Development (IFRD), BCSIR, Dhaka (Yousuf et al., 2012), ensuring a robust and replicable system for assessing biogas yield under varying conditions. This setup provided critical insights into the optimal mixing ratios and operational parameters for enhancing biogas production from textile sludge and cow dung co-digestion.

2.2 Sampling Techniques and Procedures

Textile semi-liquid sludge (TSLS) was collected from the effluent treatment plant of MNS Manufacturing PLC. A composite sampling technique was employed, whereby subsamples were gathered from four different locations within the sludge thickening tank and

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homogenized into a single representative sample to minimize bias. Cow dung (CD), used as a co-substrate, was obtained from local livestock farms.

All samples were collected in pre-sterilized containers, with TSLS stored at 4°C to preserve physicochemical properties and CD kept in airtight containers to prevent microbial degradation. Multiple sampling iterations were conducted to ensure reproducibility. This systematic approach ensured that the substrates were representative, uncontaminated, and suitable for subsequent digestion experiments.

2.3 Statistical analysis

Data are reported as mean ± standard deviation. Substrate properties and biogas yields were visualized using histograms and scatter plots. Triplicate sampling minimized experimental error, and findings were cross-referenced with literature (Baquerizo-Crespo et al., 2026) to strengthen analytical robustness. Results were contextualized against meta-analytical evidence on synergistic C/N-balanced co-digestion (Chuenchart et al., 2024; Schultz et al., 2025). This framework enabled systematic assessment of ACoD performance relative to substrate quality.

Table 1: Instruments & Test Methods for Physicochemical Analysis

Parameters	Instrument	Test Methods/standard	Reference
pH	Digital pH meter (calibrated)	EPA Method 9040D	USEPA, 2004
TS	Oven drying (105°C, 24 hrs.)	APHA 2540B	APHA, 2017
VS	Muffle furnace (550°C, 2 hrs.)	APHA 2540E	APHA, 2017
C-content	Elemental analyzer (CHNS/O)	ASTM D5373/ISO 29541	ASTM, 2016; ISO, 2010
N-content	Kjeldahl digestion + Titration	APHA 4500-Norg B/ISO 5663	APHA, 2017; ISO, 1984

3. RESULTS AND DISCUSSIONS

3.1. Anaerobic Co-digestion of Textile Semi-liquid Sludge and Cow dung

3.1.1. Physicochemical Characteristics of Raw TSLS

Physicochemical characterization of raw TSLS (Table 4) revealed properties critical to its anaerobic digestibility. The sludge was slightly alkaline (pH 8.18 ± 0.01), with high total solids (80.66 ± 0.785 g/L) and volatile solids constituting 95.35% of TS (76.91 ± 0.681 g/L). This VS/TS ratio exceeds the 70% threshold for efficient digestion (Li et al., 2019), confirming substantial organic content and high methane potential (Appels et al., 2022).

DOI: 10.5281/zenodo.21902438

Table 1: Characteristics of TSLS before mixing

S/N	Parameters	Units	Semi-liquid sludge value
1	pH	-	8.18±0.01
2	Total Solid (TS)	g/L	80.66±0.785
3	Volatile Solid (VS)	g/L	76.91±0.681
4	Carbon-to-Nitrogen (C/N) ratio	-	13.68±0.652

Note: all the results are average values (mean ± SD).

However, the C/N ratio (13.68 ± 0.652) was suboptimal for anaerobic processes (ideal: 20–30:1), attributable to nitrogen-rich textile dyes (Khan et al., 2021). This limitation necessitates co-digestion with carbon-rich substrates like cow dung (C/N 37.74) to achieve balanced conditions (Wang et al., 2023; Alzate et al., 2023).

These findings confirm that while TSLS offers significant energy recovery potential, successful anaerobic treatment requires C/N adjustment, heavy metal management, and process optimization to prevent inhibition.

3.1.2 Characterization of TSLS and CD Mixtures at Different Ratios

The physicochemical properties of textile semi-liquid sludge (TSLS) and cow dung (CD) mixtures at varying ratios (100:0, 75:25, 50:50, and 25:75) were characterized to assess their suitability for anaerobic digestion (Table 5). The pH values of the mixtures were 8.18 ± 0.01 (100:0), 7.52 (75:25), 7.47 (50:50), and 7.65 (25:75), with the latter three ratios falling within the optimal range (6.5–8.0) for methanogenic activity (Zhang et al., 2020).

Table 2: Characterization of TSLS and CD at different mixing ratios

Parameters	Units	Characteristics of the mixture at different ratios (TSLS: CD)			
		100:0	75:25	50:50	25:75
pH	-	8.18±0.01	7.52±0.00	7.47±0.00	7.65±0.00
TS	g/L	80.66±0.785	79.27±0.975	86.77±0.409	91.1±0.285
VS	g/L	76.91±0.681	73.23±0.93	81.25±0.681	88.42±0.563
C/N ratio	-	13.68±0.652	15.46±0.48	24.99±0.251	37.74±0.387

Note: all the results are average values (mean ± SD).

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Total solids (TS) concentrations increased with higher CD content, measuring 80.66 ± 0.785 g/L (100:0), 79.27 ± 0.975 g/L (75:25), 86.77 ± 0.409 g/L (50:50), and 91.1 ± 0.285 g/L (25:75). Similarly, volatile solids (VS) followed this trend, with values of 76.91 ± 0.681 g/L (100:0), 73.23 ± 0.93 g/L (75:25), 81.25 ± 0.681 g/L (50:50), and 88.42 ± 0.563 g/L (25:75). The consistently high VS/TS ratios (>90%) across all mixtures indicated excellent organic matter biodegradability (Appels et al., 2022). The C/N ratio also improved with increasing CD proportion, addressing the nitrogen-rich limitation of TSLS alone and supporting balanced anaerobic digestion conditions. These results demonstrate that co-digestion with CD enhances substrate properties critical for efficient biogas production.

3.2 Biogas production and Composition at Different Mixing Ratios in lab-scale

3.2.1 Biogas production at Different Mixing Ratios (TSLS: CD) in lab-scale

The 30-day anaerobic co-digestion experiments demonstrated significant improvements in biogas production through optimized TSLS: CD mixing ratios and temperature control (Table 6). The 50:50 mixtures emerged as the most effective formulation, achieving peak biogas yields of 1,533 mL at 35°C, 1,081 mL at 30°C, and 650 mL at room temperature (~25°C). This superior performance resulted from achieving an ideal C/N balance (24.99) and near-neutral pH (7.47), which enhanced microbial synergy and process stability (Li et al., 2019).

Table 3: Total biogas production (mL) under temperature condition over 30 days

Mixing Ratio (TSLS:CD)	Initial pH	Total Biogas Yield (mL/g VS) at different temperature conditions			Peak Production Day
		RT (~25°C)	30°C	35°C	
100:0	8.18	36	80	143	After 30
75:25	7.52	37	92	147	After 30
50:50	7.47	650	1,081	1,533	15-25
25:75	7.65	78	136	336	After 30

Comparative analysis revealed critical limitations in mono-digestion (100:0 TSLS), which produced only 36-143 mL biogas across temperature conditions due to unfavorable alkaline pH (8.18) and nitrogen-rich composition (C/N 13.68) that inhibited

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methanogenesis (Zhang et al., 2020). While the 25:75 ratios showed improvement over mono-digestion, its excessive carbon content (C/N 37.74) likely limited nitrogen-dependent microbial processes (Appels et al., 2022). Temperature significantly influenced reaction kinetics, with 35°C demonstrating the fastest initiation of biogas production (3rd day) compared to 30°C (5th day) and room temperature (15th day) for the 50:50 mixture. These findings align with previous studies showing textile sludge's poor mono-digestion performance while demonstrating the effectiveness of co-digestion strategies reported by Guha and Morshed (2015). The results establish clear operational parameters for maximizing biogas recovery from textile sludge through controlled co-digestion with agricultural waste.

3.2.2 Biogas Composition at different mixing ratios

Gas chromatographic analysis revealed significant variations in methane content across different TSLS: CD ratios (Table 7). The 50:50 mixtures demonstrated optimal performance, achieving 66.3% methane content at 35°C, with progressively lower yields at 30°C (61%) and room temperature (55%). This temperature-dependent enhancement correlates with improved methanogenic activity in mesophilic ranges (Wang et al., 2023), while the balanced C/N ratio (24.99) in this mixture facilitated efficient organic conversion, as evidenced by reduced CO2 emissions (Awe et al., 2023).

Table 4: Biogas composition at different temperature and mixing ratio over 30 days

Mixing Ratio (TSLS:CD)	Total biogas volume (mL)	Temp (°C)	CH_4 (%)	CO_2 (%)	Other Gases (H_2S, N_2) (%)
100:0	36	25	11.87	45.25	20.15
	80	30	11.89	45	19.3
	143	35	12.05	44.2	17.62
50:50	650	~25	55.32	37	8
	1,081	30	60	34	5.5
	1,533	35	66.24	24	3.7
25:75	336	35	57	30	10

Notably, mono-digestion (100:0) and the 75:25 ratio produced minimal methane (11-12%), confirming the inhibitory effects of TSLS's alkaline pH (8.18) and nitrogen-rich

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composition. The 25:75 mixtures showed intermediate performance (57% methane), suggesting carbon saturation may have limited microbial nitrogen utilization. These findings align with Kumar et al. (2020), who reported complete biogas production failure in textile sludge mono-digestion versus 244.1 mL CH_4/g VS in 1:1 co-digestion systems.

The results demonstrate that CD addition achieves dual benefits: (1) mitigating TSLS toxicity through contaminant dilution and (2) enhancing microbial diversity for stable anaerobic digestion (Devi et al., 2023). The 50:50 ratio at 35°C emerged as the optimal configuration, combining thermal advantages with stoichiometrically balanced substrate composition for maximum methane recovery.

3.3 Effect of Operational Parameters on Biogas Productions

3.3.1 Effect of Temperature on Biogas Production and Retention Time

The anaerobic co-digestion of TSLS and CD across various mixing ratios (100:0, 75:25, 50:50, and 25:75) was evaluated over a 30-day digestion period under room temperature (~25°C), 30°C, and 35°C. Operating temperature and substrate proportions significantly influenced microbial activity, degradation kinetics, retention time, and cumulative biogas yields. Over the 30-day incubation period, the highest cumulative yields were consistently recorded at 35°C, followed by 30°C, while ambient room temperature (~25°C) produced the lowest outputs (Figures 3–5). This temperature-dependent trend underscores the critical role of mesophilic conditions in optimizing methanogenic activity, as microbial consortia exhibit peak enzymatic efficiency within the 30–40°C range (Awe et al., 2021; Kumar et al., 2023).

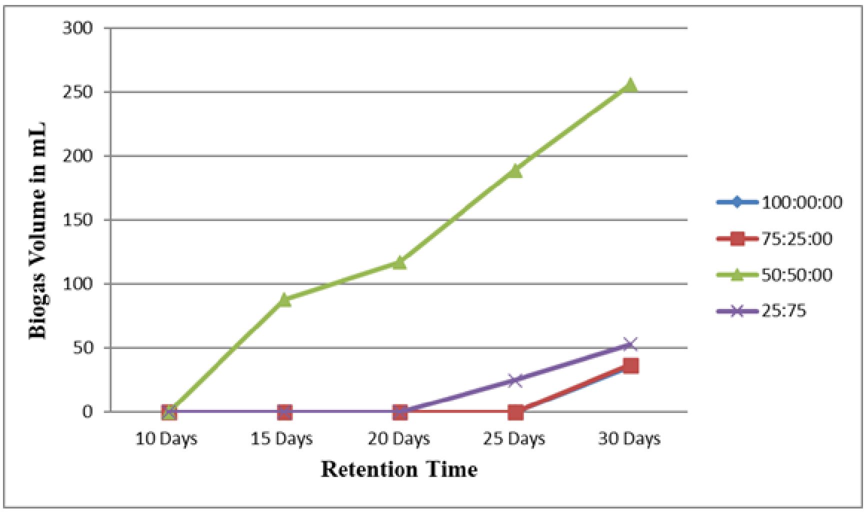

Figure 3: Biogas volume from different mixing ratios kept at room temperature

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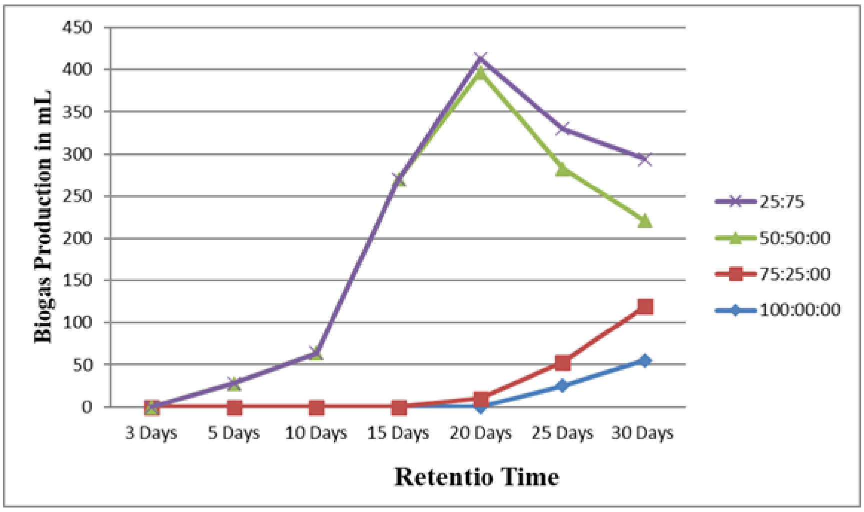

Figure-4: Biogas volume from different mixing ratios kept at 30°C temperature

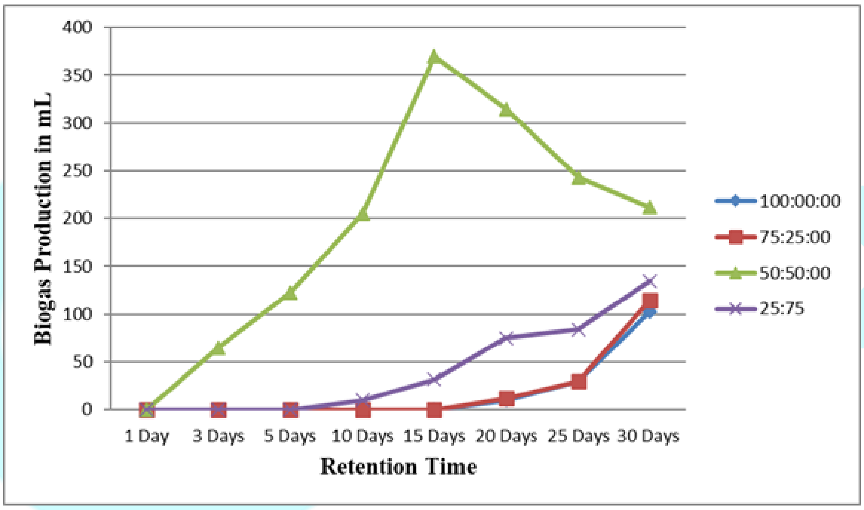

Figure-5: Biogas volume from different mixing ratios kept at 35°C temperature

Across all temperatures, the 50:50 TSLS-to-CD ratios consistently outperformed the other mixtures, confirming that substrate balancing is paramount to process stability. At 35°C, this ratio achieved its peak accumulation rapidly, reaching 370 mL by day 15, before declining to 212 mL by day 30. At 30°C, the 50:50 mixtures peaked later at 387 mL by day 20, with a sharper subsequent drop to 102 mL. In contrast, at room temperature, the same ratio produced a mere 256 mL by day 30, with production not initiating until day 15. This substantial delay at ambient conditions highlights the kinetic limitations imposed by sub-optimal temperatures, which prolong the hydrolysis lag phase and reduce overall substrate conversion rates (Yin et al., 2023).

The sludge-dominated digestates (100:0 and 75:25) exhibited consistently poor performance across all temperature conditions, characterized by prolonged lag phases and

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minimal cumulative yields. Even at the optimal temperature of 35°C, the 100:0 and 75:25 ratios yielded only 103 mL and 115 mL, respectively, by day 30. This inhibition is primarily attributed to the presence of refractory compounds inherent to textile effluent such as azo dyes, heavy metals, and synthetic chemicals which impede microbial acclimatization and enzyme function (Zhang et al., 2020). Conversely, the 25:75 CD dominated mixtures demonstrated delayed but steady production, with yields of 135 mL at 35°C and 73 mL at 30°C by day 30. The slower kinetics in this ratio suggest that excessive cow dung may dilute the organic loading rate or shift the carbon-to-nitrogen (C/N) ratio unfavorably, thereby reducing substrate availability for syntrophic bacteria (Li et al., 2019).

Collectively, these findings establish that while mesophilic temperatures (particularly 35°C) are essential for maximizing methane yield and shortening retention times, the optimal substrate ratio is the primary determinant of overall system resilience. The 50:50 mixtures provide the best compromise, effectively diluting textile sludge toxicity while supplying sufficient buffering capacity from cow dung. However, the observed peak-and-decline pattern at 35°C indicates that strict pH and VFA monitoring is critical for industrial applications to prevent over-acidification. Ultimately, the integration of temperature control with balanced substrate loading offers a viable pathway for scaling up the ACoD of textile sludge, bridging the gap between laboratory efficiency and field-scale wastewater treatment operations (Mishra et al., 2020).

3.3.2 Effect of Carbon-to-Nitrogen Ratio on Biogas Production

The carbon-to-nitrogen (C/N) ratio emerged as a critical determinant of biogas production efficiency in the co-digestion of textile sludge (TSLS) and cow dung (CD). Systematic variation of substrate mixing ratios produced C/N ratios spanning from 13.68 ± 0.652 (100:0 TSLS) to 37.74 ± 0.387 (25:75 TSLS: CD), with the 50:50 mixture achieving the optimal balance of 24.99 ± 0.251. This optimized ratio produced peak biogas yields (1,533mL at 35°C), confirming the established 20-30:1 range for efficient anaerobic digestion (Alzate et al., 2023).

These findings demonstrate that C/N ratio modulation through co-substrate blending effectively addresses two key challenges in textile sludge valorization: mitigating nitrogen

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inhibition while maintaining sufficient carbon availability for balanced microbial metabolism. The 50:50 ratios' superior performance underscores its dual advantage of providing both optimal stoichiometry (C/N ~25) and favorable pH conditions (7.47) for methanogenic activity.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This study demonstrated that anaerobic co-digestion (ACoD) of TSLS with CD is a technically viable strategy for sustainable sludge management and renewable energy recovery. Characterization of raw TSLS confirmed high organic content (VS: 76.91 ± 0.681 g/L) suitable for biogas production; however, its low C/N ratio (13.68) and alkaline pH (8.18) rendered mono-digestion inefficient. Co-digestion with CD effectively addressed these limitations by providing balanced nutrients and buffering capacity.

The 50:50 TSLS:CD ratio emerged as the optimal configuration, achieving a near-ideal C/N ratio (24.99), neutral pH (7.47), and maximum biogas yield of 1,533 mL at 35°C with 66.3% methane content; ten times higher than mono-digestion. Mesophilic temperatures (30–35°C) were confirmed as optimal for process performance. Overall, this research establishes ACoD as a feasible waste-to-energy pathway for Ethiopia's textile sector, transforming hazardous sludge into a valuable resource while promoting circular economy principles and environmental sustainability.

4.2 Recommendations

Based on the findings of this study, the following recommendations are proposed for industrial application, policy development, and future research: .

- **Adopt 50:50 (TSLS: CD) ratio** for optimal C/N balance (24.99) and pH (7.47), as it yielded the highest biogas and methane production.

- **Maintain 35°C** with insulation and heating systems to maximize mesophilic digestion performance.

- **Avoid mono-digestion** of TSLS due to low C/N ratio and alkalinity; co-digestion with cow dung is essential for stability.

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- **Promote ACoD** through financial incentives, subsidies, and stricter enforcement against open dumping.
- **Conduct pilot-scale** trials to validate laboratory findings under real-world conditions.

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