

Proximate and Ultimate Characterization of Municipal Solid Waste and Sewage Sludge Blends: Implications for Thermal Conversion and Energy Recovery

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DOI: 10.29322/IJSRP.16.07.2026.p17506

<https://dx.doi.org/10.29322/IJSRP.16.07.2026.p17506>

Paper Received Date: 18th May 2026

Paper Acceptance Date: 30th June 2026

Paper Publication Date: 8th July 2026

ABSTRACT

This study evaluates the fuel quality and thermochemical suitability of sewage sludge (SS), municipal solid waste (MSW), and selected SS–MSW blend ratios for co-pyrolysis applications. Proximate and ultimate analyses were used to assess the compositional behavior of the feedstocks, with particular attention to fixed carbon, volatile matter, nitrogen, sulfur, ash, moisture, elemental ratios, and higher heating value (HHV). The results show that MSW possesses superior fuel characteristics relative to SS, with higher volatile matter(83.70%), higher fixed carbon(7.50%), lower ash(0.45%), lower nitrogen(0.64%), and higher HHV(18.91KJ/Kg). In contrast, sewage sludge is characterized by very high ash content(42%) and elevated nitrogen(2.71%), indicating a mineral-rich and heteroatom-laden feedstock with lower thermal efficiency and greater environmental control requirements. The blended feedstocks exhibited a strong non-linear response to increasing SS fraction. Ash content increased sharply with sludge addition, while HHV declined progressively, confirming that even moderate sludge incorporation substantially alters the thermal behavior of the mixture. The observed trends suggest that SS dominates the inorganic residue profile and depresses the energy density of the blend, whereas MSW contributes more favorable volatile and combustible fractions. These findings indicate that co-pyrolysis performance is highly composition-dependent and that feedstock selection must balance energy recovery potential against ash-related operational constraints.

Keywords: Co-pyrolysis, Municipal waste, Solid waste, Ultimate and Proximate

INTRODUCTION

The rapid urbanization and population growth experienced all over the world have led to a significant increase in the generation of municipal solid waste (MSW) and sewage sludge (SS). The management of MSW and SS is a growing challenge worldwide (Siddiqua *et al.*, 2022). According to the World Bank, global MSW generation is expected to increase from 2.01 billion tons in 2016 to 3.4 billion tons in 2022, driven primarily by rapid urbanization, population growth, and economic development in low- and middle-income countries (Adedara *et al.*, 2023). Globally, the generation of SS is equally substantial, with estimates suggesting that over 180 million tons of SS are produced annually. High-income countries, like the US, generate approximately 8 million tons of dry sludge per year, while the European Union collectively produces around 9-10 million tons annually, due to their advanced wastewater treatment systems (Ferrentino *et al.*, 2023). On the other hand, Africa contributes around 125 million tons of MSW annually, accounting for roughly 5% of global waste production, with an average waste generation rate of 0.65 kilograms per capita per day-lower than the global average of 0.74 kilograms per capita per day. However, the region is expected to experience a threefold increase in waste generation by 2050, reaching nearly 400 million tons annually due to its high population growth rate and increasing urbanization

(Kang *et al.*, 2023). Developing nations are expected to account for 40-50% of this increase, highlighting the critical need for sustainable waste management solutions.

Inadequate management of these wastes poses critical environmental, social, and public health challenges, emphasizing the need for innovative and sustainable waste management solutions. The disposal of these wastes has become a pressing global issue, with landfill overflows, greenhouse gas (GHG) emissions, and water pollution among the most notable consequences. Traditional methods of waste disposal, including land filling and incineration, have proven to be inadequate or environmentally damaging (Zhang *et al.*, 2024). While land filling occupies vast areas of land and emits significant quantities of methane, Incineration, reduces waste volume, while generating toxic emissions and ash that require further management. These challenges highlight the urgent need for alternative waste treatment methods that are both environmentally sustainable and economically viable. Sipra *et al.*, 2018 reports that our daily discards, known as municipal solid waste (MSW) or simply trash encompass a wide range of materials, which includes packaging materials, yard waste, furniture, clothes, bottles, food scraps, paper products, appliances, and even paint and batteries. We generate this waste in our homes, schools, hospitals, and even industries. MSW, despite being a waste stream, is actually a type of biomass. It's a mix of organic materials like food scraps and paper, alongside plastics, wood, textiles, metals, and glass. Unfortunately, the most common way to manage MSW is through open dumping. This means piles of trash are left exposed to the environment. This practice poses serious health and environmental risks. Additionally, open dumping struggles with maintenance, labor requirements, and rising transportation costs, especially as populations grow. However, with the hidden benefit of MSW as a potential fuel source, there is a need to access its percentage in a biomass blend that will yield maximum energy product through co- pyrolysis. Pyrolysis, a thermo-chemical process conducted in an oxygen-free environment, has gained attention as a promising solution for converting waste into valuable resources. The process produces three primary outputs: bio-oil, biochar, and syngas (Aboelela *et al.*, 2023). Bio-oil, a liquid fuel, can be further refined into chemicals or energy products alongside syngas can be used as an energy source. Despite its potential, the application of pyrolysis for MSW and SS faces several challenges (Durak, 2023). While the heterogeneity of MSW leads to inconsistent pyrolysis outcomes, the high moisture and ash content of SS negatively impact bio-oil yield and quality (Kasiński and Dębowski, 2024). Co-pyrolysis, a process involving the simultaneous pyrolysis of two or more feedstock, has been proposed as a way to address these limitations. By combining feedstock with complementary properties, to enhance their synergistic interactions, improving energy recovery and product quality (Gusiatin, 2024).

The aim of this study is to investigate the influence of various blends percentages of MSW and SS on the resulting feedstock ultimate and proximate composition, while eliciting the impact of this composition on the resultant fuel profile.

MATERIALS AND METHODOLOGY

Study location

The base of this study is Ibadan, located in Oyo State, in South-West Nigeria, The predominant ethnic group in the state is Yoruba with a rich cultural diversity experienced in their food. The region experiences a tropical climate, with two distinct seasons: a wet season from April to October and a dry season from November to March. Average temperatures in the area range from 25°C to 32°C, with annual rainfall varying between 1500 to 2000 mm. Agriculture in the region thrives, with crops including cassava, yam, maize, and plantain being common. Also, the area is known for its oil palm and coconut plantations. The waste generation in Ibadan, like many other urban and rural areas in Nigeria, includes significant amounts of municipal solid waste (MSW) much of which is often poorly managed. This poses significant challenges to waste management systems and creates opportunities for sustainable waste-to-energy solutions such as co-pyrolysis. The potential for using locally available feedstock like MSW and SS for bioenergy production through pyrolysis remains underexplored in Nigeria at large. This study will contribute to the understanding of how these waste

streams can be efficiently managed and converted into valuable bio-oil, syngas and bio char thereby providing both an environmental and economic solution to waste management issues in Ibadan and similar communities in Oyo State.

Feedstock Collection and Preparation

Municipal Solid Waste (MSW)

Municipal Solid Waste samples were collected from University of Ibadan waste collection centers in Ibadan, Oyo State . The collected waste was segregated to remove non-biodegradable and inorganic materials (e.g., plastics, metals, and glass), while organic components such as food waste, paper, textiles, and agricultural residues were retained. The organic MSW was dried in a muffle furnace for 24 hours at 105°C±5°C to reduce moisture content to 4% and subsequently ground into particles with sizes ranging from 1 mm to 3 mm for uniform thermal treatment.

Sewage Sludge (SS)

Sewage Sludge samples were obtained from Lekki wastewater treatment facility in Lekki, Lagos State. The raw sludge was dewatered using filtration and centrifugation to reduce moisture content to approximately 20% and then dried in a muffle furnace for 24 hours at 105°C±5°C to a moisture content of 4.2%. The dried sludge was further pulverized into a powder form with particle sizes similar to the MSW for consistency in the pyrolysis process.

Preparation of the biomass blends

The dried samples were ground into powder (≤ 3 mm). Sieved ratio of MSW and SS were mixed together using the Box-Behnken design approach of response surface methodology using the factorial equation $2^k + 2k + k$. This experimental design will be run on Design-Expert version 13 Software (Sopyan *et al.*, 2022; Chakraborty *et al.*, 2013) to develop an empirical model that will establish the relationship between process and response variables as shown in Appendix I (Nordiyannah *et al.*, 2013)The experimental design is shown in table 1 below.

TABLE 1: THE BOX BEHNKEN DESIGN TABLE FOR THE THERMO CONVERSION OF MUNICIPAL SOLID WASTE AND SEWAGE SLUDGE

Variables	Symbols	Coded levels (-1, 0,+1)	Variable range
Feed stock ratio (%)	X ₁	10:90 , 50:50, 90:10	0-100
Pyrolysis temperature(°C)	X ₂	400,500,600	400-600
Residence time(Min)	X ₃	120,210,300	120-300

The dried sludge was blended with MSW at the ratios by mass shown in table 1 above. Blending was performed to enhance thermal behaviour, and to reduce emissions during conversion. (Aguiar *et al.*, 2021). The feed stock samples were stored at room temperature in Ziploc bags before characterization.

Characterization of the biomass samples (MSW &SS)

Proximate Analysis of biomass samples

Proximate analysis such as moisture contents, fixed carbon, volatile matter and ash contents was obtained using ASTM E872-82 and ASTM D1102-84.34 standards

Moisture content

Approximately 10g of the specimen was placed inside the dish and reweighed, the dish with the specimen was placed in an oven of partial vacuum (> 100 mmHg) at a temperature of 105°C for about 5 hours, the dish was removed from the oven and gradually allowed to cool and weighed, the process was repeated until a constant weight was obtained (Efetobor *et. al.*, 2022). Moisture content was evaluated using the formula below:

$$\% \text{ moisture} = \frac{\text{weight of sample before drying} - \text{weight of dry sample}}{\text{weight of sample before drying}} \times 100$$

Ash content

Approximately 5g of the prepared sample was placed in a crucible, after which it was placed in an oven at 100°C for 24 hours, it was then removed and transferred to a muffle furnace where the temperature was increased further to $550 \pm 5^{\circ}\text{C}$, this increased temperature was maintained for another 8 hours, the crucible was removed from the furnace and transferred to a desiccator to cool after which it was weighed and recorded (Efetobor *et. al.*, 2022).. The ash content was evaluated in percentage dry basis using the expression below

$$\% \text{ ash content} = \frac{\text{weight of ash}}{\text{weight of sample}} \times 100$$

Volatile matter (VM)

Approximately 10g of the dried specimen were placed inside a pre weighed dish and reweighed, the dish with the specimen was placed in an oven of partial vacuum (> 100 mmHg) at a temperature of 900°C in an inert environment (with N_2) according to fuel-style volatile matter method. The specimen were heated and cooled for 5 hours until a constant was obtained (Chua *et al.*, 2025). The VM was obtained by using the expression below

$$\%, VM = \frac{\text{initial mass of the sample} - \text{final constant mass of the sample}}{\text{initial mass of the sample}} \times 100$$

Fixed carbon

In obtaining the fixed carbon, ASTM D3174 – 76 standard method was used. The crucible cover used in performing the volatile matter last analysis was removed after which the crucible heated over Bunsen burner to allow all the carbon to burn. The difference in

weight of the residue from the previous weight is the fixed carbon (Efetobor *et. al.*, 2022).. The fixed carbon (FC) was therefore obtained by the use of the expression below

$$\% FC = 100 - (\% \text{moisture content} + \% \text{volatile matter} + \% \text{ash content})$$

Ultimate Analysis of feed stock samples

The elemental composition such as carbon, hydrogen, nitrogen, oxygen, and sulphur was determined according to ASTM D5373 and ASTM D4239-11 standard. The ultimate analysis was performed to evaluate the percentage chemical elements of the sample. 2g of the biomass sample was weighed into platinum crucible, then the crucible containing the sample was placed in a leibig - pregle chamber containing sodium hydroxide and magnesium percolate, the sample was ignited and burnt off to yield CO₂ and water, Sodium hydroxide and magnesium percolate is used to absorb the CO₂ and water, respectively.

RESULTS AND DISCUSSION

TABLE 2: PHYSICOCHEMICAL CHARACTERISTICS O VARIABLE MSW: SS FEED STOCKS

S/N	SAMPLES	SEWAGE SLUDGE (0:100)	MUNICIPAL SOLID WASTE (100:0)	FEED STOCK BLEND A (10:90)	FEED STOCK BLEND B (50:50)	FEED STOCK BLEND C (90:10)
1	FIXED CARBON CONTENT	3.50	7.50	7.10	5.47	3.90
2	VOLATILE CARBON CONTENT	46.20	83.70	80.33	64.95	49.95
3	NITROGEN CONTENT	2.71	0.64	0.87	1.68	2.50
4	HYDROGEN CONTENT	3.80	4.30	4.25	4.05	3.85
5	OXYGEN CONTENT	69.69	51.62	53.46	60.66	67.85
6	SILPHUR CONTENT	1.00	3.00	2.80	1.99	1.20
7	ASH	42.00	4.00	7.80	23.10	38.40
8	MOISTURE	0.35	0.45	0.44	0.40	0.36
9	H/C	0.08	0.05	0.05	0.06	0.08
10	O/C	1.40	0.56	0.67	0.98	1.31
11	HHV	14.69	18.91	18.49	16.74	15.12

The proximate analysis results in table 2 above. From table 2, The blend trends are not linear in the way a simple mixing rule might suggest, especially for ash and oxygen-related properties. The volatile matter which is the reactivity indicator shows a strong monotonic decrease across the feed stocks with increasing SS fraction as MSW which is the volatile rich reactive fraction decreases (Singh *et al.*, 2025). Hence blend A and B with 90% and 50% MSW have more ignition speed, flame propagation and gasification yield than blend C. High volatile matter in MSW and its rich blends indicates a strong tendency to devolatilize readily under pyrolytic heating, which is favorable for vapor formation and potentially higher bio-oil production. However, the fixed carbon is relatively modest across all samples, especially in sewage sludge rich blends (B and C), which suggests limited char-forming potential compared with woody biomass feed stocks, hence blends A and B are more suited for bio oil and syngas production, while blend C is more suited for char production. With SS being Nitrogen rich and a strong NO_x precursor, the increasing SS across the blends raises emission risk non-linearly, for this blend C therefore requires; staged combustion, flue gas recirculation, and NO_x control systems. MSW significantly increases SO_x emissions risk, while blending, reduces sulphur proportionally reducing environmental pollution. MSW showed slight higher hydrogen content while SS is highly oxygenated, having low energy density as MSW contributes the calorific value. This shows that blends higher in MSW will yield higher energy value during combustion (Singh *et al.*, 2025). There is a non linear increase in ash content across the 3 blends as SS increases. Higher ash content generally reduces combustibility, slows burning, and can leave more char un burned, this is a limiting factor which MSW synergistically controls. The HHV decreased systemically with increase in SS showing that MSW is the primary energy carrier. The low hydrogen-carbon ratio indicates aromatic or char-dominant structure from SS as well as less hydrogen-rich volatile combustion. Blend A and B with a higher H/C ratio have less dominant structure and more combustibility than blend C.

The ash level is the most severe limitation. Ash does not contribute to heating value, and at elevated levels it lowers net energy density, increases slagging and fouling risk, and raises the frequency of reactor cleaning and residue disposal (Shen *et al.*, 2018). For sewage sludge-based blends, ash is high enough to become an engineering design issue rather than just a compositional detail.

The carbon content from table 2 shows that MSW supports rapid devolatilization and gas/vapor production in pyrolysis, showing that by its composition, it will yield high condensable components than char. (Odzijewicz *et al.*, 2022). In line with recent thermogravimetric studies, Sewage sludge, with lower volatile content and higher ash as above, typically yields more char and less condensable oil under comparable conditions, and its mineral phases can catalyze cracking and gasification reactions that further shift products toward gases and mineral-rich char rather than high-quality bio-oil hence the balance with a volatile rich MSW (Halalshey *et al.*, 2024). Overall, the table confirms and quantifies trends widely reported in recent literature that MSW is a more favorable thermochemical fuel, while sewage sludge is an ash- and nitrogen-rich waste whose co-pyrolysis requires careful control of blend ratio, ash management, emission abatement, and product utilization pathways while showing that blend A with 90% MSW has more oil and gas yielding components than blends B and C. Consequently, engineering design for co-pyrolysis of these feedstocks should prioritize MSW component percentages in blends. This can be achieved using a feed stock design model as follows;

$$0.9 = Y_p + Y_w + Y_f$$

Where,

Y_p = mass fraction of plastic in MSW,

Y_w = mass fraction of woody biomass,

Y_f = mass fraction of food waste

From table 2 above, extracting and applying governing indices the volatile index driver (oil and gas production driver) can be obtained from

$$VI = 0.92\hat{Y}_p + 0.75\hat{Y}_f + 0.60\hat{Y}_w$$

Fixed carbon index (char driver) can be obtained from

$$FC = 0.25\hat{Y}_p + 0.55\hat{Y}_f + 0.80\hat{Y}_w$$

Ash index (penalty term) can be obtained from

$$AI = 0.05\hat{Y}_p + 0.20\hat{Y}_f + 0.50\hat{Y}_w$$

Thus the individual component product yield can be obtained from the models below. The bio oil production model can be given as;

$$Y_{doil} = (VI)^{1.25} (1 - F)(1 - A)$$

The syngas model can be given as;

$$Y_{dgas} = K_2 VI^{0.9} FC^{0.8} (1 - 0.4AI)$$

While the bio char production model can be given as;

$$Y_{dchar} = K_3 F(1 - V + 0.3A)$$

Where K is the empirical proportionality constant, and Y_d is the production yield constant.

CONCLUSION

Overall, the combined proximate–ultimate analyses data indicate that co-pyrolysis of SS and MSW can be positioned as a resource-recovery tool rather than a simple disposal route, but the process window is narrow and strongly composition-dependent. MSW-dominant blends (blend A) exhibit fuel characteristics compatible with efficient, continuous pyrolysis operations and manageable ash loads, whereas sludge-rich blends (Blends, B and C) fall below typical energy-quality thresholds while significantly elevate operational and environmental risks. Consequently, implementation of co pyrolysis should adopt MSW-rich blends as the baseline configuration, integrating advanced ash handling, refractory with Msw materials selection applying the production models above, while incorporating gas utilization technologies to accommodate sludge fractions that are optimized for environmental risk reduction.

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