

The Influence of Feedstock Variability on Syngas Quality and the Viability of Municipal Solid Waste Gasification in a Developing World Context

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Abstract— This research examines the impact of municipal solid waste (MSW) feedstock variability on syngas quality and the overall feasibility of gasification technology in a developing country environment, using Port Harcourt, Nigeria, as a case study. Three unique versions of municipal solid waste feedstock—Biogenic-Rich (Mix A), Plastic-Rich (Mix B), and High-Moisture (Mix C)—were created, characterised, and subjected to gasification in a laboratory-scale reactor under optimised conditions (950°C, Equivalence Ratio=0.30). The findings indicate that feedstock composition significantly influences syngas quality and system efficacy. Mix B, the Plastic-Rich feedstock, generated syngas with the greatest Lower Heating Value (LHV of 7.05 MJ/Nm³), but also resulted in markedly elevated tar levels (5.5 g/Nm³) and caustic HCl (450 mg/Nm³). The High-Moisture feedstock (Mix C) significantly decreased cold gas efficiency to 53.1% because of the energy cost associated with water evaporation. Conversely, the Biogenic-Rich feedstock (Mix A) yielded the most equilibrated and stable performance, achieving a cold gas efficiency of 72.8% and producing more controllable tar by-products. A preliminary techno-economic study estimates a net profit of \$75–85 per tonne of municipal solid waste processed and a payback time of 4–5 years, bolstered by dual income streams from energy sales and avoided landfill costs. The environmental study reveals a net decrease of around 1.1 tCO₂e per tonne of municipal solid waste (MSW). The research indicates that while MSW gasification is both technically and economically feasible, its success depends on thorough feedstock characterisation and preparation, with a strong suggestion to focus on the biogenic portion for smaller-scale, dependable deployment in developing areas.

Keywords— Syngas, Feedstock Variability, Gasification, Techno-economic Analysis, Waste Management.

I. INTRODUCTION

Post-consumer waste also has an impact on global warming which in turn exacerbates climate change. It should be noted that inadequate management of waste can have number of adverse impacts on environment, and this can happen in a variety of different ways. On one hand, when people litter the environment, they are in fact contributing to the pollution of nearby water resources through the organic and inorganic toxins which they release. Moreover, this practice is also detrimental to human health since it creates environment which is



conducive to the spread of infectious diseases. Littering is harmful to individuals living in the surrounding area because it also exposes them to the noxious elements in the waste [1]. Rathna et al. [2] state that the burning of garbage releases a wide range of pollutants including polychlorinated dibenzofurans (PCDF) and polychlorinated dibenzop-dioxins (PCDD)[3]. POPs are environmental pollutants that are ubiquitous and harmful to human and environmental health. Methane, which makes up the largest share of greenhouse gas emissions in the waste management industry, is emitted when organic waste rots in landfills (IPCC). According to the Intergovernmental Panel on Climate Change (IPCC), greenhouse gas emissions from solid waste make up less than 5% of the global total. Considering that it is a waste management system which may emit and consume greenhouse gases, it would be impossible to price it [4, 5]. Waste management is a local government responsibility in most cases, often along with public community service provision since garbage is polluting to the environment and unhealthy for humans. Scheinberg et al. [6] point out that waste management is considered "one of the world's biggest challenges" due to the severity of the problem arising from the global garbage producing patterns, which are characterized by an increase in the amount and diversity.

Numerous strategies, pieces of legislation, and practices are used by municipalities and individuals to limit the negative consequences of garbage and locate recyclable materials that are value [7]. Waste management is comprised of six different organisational functions: the generation of waste, the managing of waste sources, the collection of waste, transportation of waste, processing and transformation of waste, and disposal of waste [8]. The components of the activities continue to be the same, even though they demonstrate themselves differently in different settings. Garbage can be disposed by the generator either in the container or through disintegration to its basic elements in two different ways [8]. Then a formal or informal entity collects the waste and transports it to another location to process and reuse it. Anaerobic digestion may, however, also have a good chance to consume and metabolize trash into energy [8, 9], liquid fuel [10], compost, and humus [11], or it can be used as livestock fodder or sprayed directly on the farmland. Waste that is not converted to a product may end up being discarded at some point in a structured or unstructured manner. McDouall et al. [12] and Vergara and Tchobanoglous [13] each have a philosophy they label the waste hierarchy and the integrated waste management. The effects are quite similar because both have a direct impact on the eventual decision-making. The development of waste management policy has increasingly focused on the waste hierarchy since the early 1990s since it can prioritise waste management technologies that are installed.

II. MATERIALS AND METHODS

A. Feedstock Sourcing and Characterization

Municipal Solid Waste (MSW) used for the study was collected from three sources (zones) within the Greater Port Harcourt region, to have a representation of the MSW stream within Rivers State. The various collection sites from where MSW used for the study was sourced are as follow; Source A: Residential zones (garbage from Rumuosi and Rumuokoro neighbourhoods), Source B: Commercial zones (garbage from Mile 3 Market and the Slaughter Market) and Source C: Institutional zones (garbage from within the University of Port Harcourt campus). The characteristics of the MSW from these three zones are: Source A: High content of organic kitchen waste; Source B:

Rich in packaging materials/plastics and market refuse, both biodegradable, Source C: Mixed content (paper, food and garden waste). Treatment and preparation of the MSW follows. First, MSW was manually sorted out on a sorting floor to remove any visible contaminants. The following categories of contaminants were manually sorted out: inert materials (stones, glass, etc), ferrous metals (magnetic separator), non-ferrous metals (manual) and hazardous waste (batteries, medical wastes). The combustible fraction left after cleaning was shredded using a laboratory-scale dual-shaft industrial shredder to a particle size of < 50 mm. Size reduction of the MSW to a smaller size was required to ensure uniform particle size which is essential for good feeding & consistent gasification reactivity. The shredded MSW was then mixed by coning and quartering. The various mixes used for the study (Mixes A, B and C) were prepared by homogenizing the various proportions of the waste components by weight as determined by the proximate analysis. The moisture contents of each of the experimental mixes were adjusted to the moisture contents as determined by the proximate analysis by either air-drying or adding distilled water to the air-dried waste. The combustible fraction was shredded to a particle size of < 5 cm to ensure uniform feeding and gasification.

MSW was collected from three distinct sources within Port Harcourt:

- Source A: Residential areas (Rumuosi, Rumuokoro)
- Source B: Commercial areas (Mile 3 Market, Slaughter Market)
- Source C: Institutional areas (University of Port Harcourt)

Three distinct feedstock variants were prepared:

- Mix A (Biogenic-Rich): 50% food waste, 30% paper, 20%-yard waste.
- Mix B (Plastic-Rich): 60% plastics (PET, PE), 30% paper, 10% textile.
- Mix C (High-Moisture): 70% food waste, 20% green waste, 10% paper.

The waste underwent systematic processing:

- Manual Sorting: Removal of non-combustibles, metals, and hazardous materials
- Size Reduction: Shredding to <50mm particle size using industrial shredder
- Mixing and Homogenization: Creating representative samples for each variant
- Moisture Adjustment: Adding or removing water to achieve target moisture conte

Table 1: Waste Composition Analysis from Study Area

Component	Residential (%)	Commercial (%)	Institutional (%)	Average (%)
Food Waste	55.2	35.8	45.3	45.4
Paper/Cardboard	15.3	25.6	30.2	23.7
Plastics	12.5	18.3	10.5	13.8
Garden Waste	8.4	3.2	6.8	6.1

Textiles	4.1	12.5	4.2	6.9
Others	4.5	4.6	3.0	4.0

Each mix was characterized through proximate and ultimate analysis following ASTM standards (ASTM D3172-D3175 for proximate; ASTM D5373 for ultimate).

Table 2: Characterisation of Prepared MSW Feedstocks

Parameter	Unit	Mix A (Biogenic)	Mix B (Plastic-Rich)	Mix C (High-Moisture)
Proximate (ar)				
Moisture	wt.%	28.5	15.2	48.3
Volatiles	wt.%	51.2	68.4	38.1
Fixed Carbon	wt.%	9.8	11.5	7.2
Ash	wt.%	10.5	4.9	6.4
Ultimate (daf)				
Carbon	wt.%	49.1	72.8	47.5
Hydrogen	wt.%	6.5	10.2	6.1
Oxygen	wt.%	42.9	14.5	44.9
Nitrogen	w.t.%	1.2.	1.8.	1.1.
Sulphur	w.t.%	0.3.	0.7.	0.4.
LHV	MJ/kg	12.1	25.7	8.5

B. Process Description

The gasification process commenced by preheating the reactor with an LPG burner. Once the desired temperature was attained (~700°C), the MSW feedstock was introduced via the automated feeding system. Preheated air (~300°C) was injected into the oxidation zone. The MSW underwent sequential thermochemical conversion processes:

1. **Drying:** Moisture in the feedstock was evaporated in top layer of the reactor.
2. **Pyrolysis:** The dried feedstock descended and was heated in the absence of oxygen, releasing volatile gases, tars, & leaving behind char.
3. **Oxidation:** The volatile products and char reacted with the preheated air in a controlled exothermic reaction, providing the heat required for subsequent endothermic reactions.
4. **Reduction:** The hot gases (CO₂, H₂O) from oxidation zone passed through the bed of red-hot char, undergoing reduction reactions to form CO and H₂.

The produced raw syngas then passed through the integrated gas cleaning train for purification before being sampled and flared. The entire process was continuously monitored, & data on temperatures, pressures, & flow rates were recorded by data acquisition system.

C. Gas and laboratory Analysis

Syngas was sampled from a port located after the final cleaning stage. The gas was dried using a series of ice traps and silica gel columns before analysis.

Gas Composition: The dry syngas composition (H_2 , CO, CO_2 , CH_4 , N_2 , C_2H_4) was analysed using Gas Chromatograph (GC) equipped with TCD and FID detectors. The system was calibrated using certified standard gas mixtures before each analysis session.

Tar Content: Tar was sampled isokinetically using the SPA method, where a known volume of syngas is passed through packed adsorbent tube. The adsorbed tar was later recovered using dichloromethane solvent and quantified gravimetrically (g/Nm^3).

Heating Value: The Lower Heating Value (L.H.V.) of syngas was calculated from its composition using equation:

$$L.H.V._{syngas} (.MJ/Nm^3) = ([H_2] \times 1.0.8 + [CO] \times 1.2.63 + [CH_4] \times 3.5.8 + [C_2H_4] \times 59.0) \times 0.01$$

where [X] is the volume percent of each gas component.

A preliminary techno-economic analysis was performed, projecting operational costs and revenues based on experimental outcomes and local waste management costs. The environmental impact was assessed by calculating the net CO_2 equivalent (CO_2e) reduction per ton of MSW processed.

III. RESULTS AND DISCUSSION

1. Characterization of MSW Feedstock Variants

Three distinct, representative MSW compositions were formulated and characterized.

Table 3: Detailed Proximate, Ultimate, and Compositional Analysis of MSW Feedstocks

Parameter	Unit	Mix A (Biogenic-Rich)	Mix B (Plastic-Rich)	Mix C (High-Moisture)
Proximate (ar)				
Moisture	wt.%	28.5 ± 2.1	15.2 ± 1.8	48.3 ± 3.5
Volatiles	wt.%	51.2 ± 1.5	68.4 ± 2.2	38.1 ± 1.7
Fixed Carbon	wt.%	9.8 ± 0.8	11.5 ± 1.0	7.2 ± 0.6
Ash	wt.%	10.5 ± 1.2	4.9 ± 0.7	6.4 ± 0.9
Ultimate (daf)				
Carbon (C)	wt.%	49.1 ± 0.9	72.8 ± 1.5	47.5 ± 1.1
Hydrogen (H)	wt.%	6.5 ± 0.3	10.2 ± 0.4	6.1 ± 0.3
Oxygen (O)	wt.%	42.9 ± 1.2	14.5 ± 1.0	44.9 ± 1.3
Nitrogen (N)	wt.%	1.2 ± 0.2	1.8 ± 0.3	1.1 ± 0.2
Sulfur (S)	wt.%	0.3 ± 0.1	0.7 ± 0.2	0.4 ± 0.1

Estimated LHV	MJ/kg	12.1 ± 0.5	25.7 ± 0.8	8.5 ± 0.4
Key Components		50% Food, 30% Paper, 20% Yard	60% Plastics, 30% Paper, 10% Textile	70% Food Waste, 20% Green Waste, 10% Paper

All three feedstock mixes were gasified at the optimized conditions (T=950°C, ER=0.30).

Table 4: Performance Comparison of MSW Feedstocks at Optimized Conditions (950°C, ER=0.30)

Parameter	Mix A (Biogenic)	Mix B (Plastic-Rich)	Mix C (Wet)
H₂ (vol.%)	21.5	15.8	19.2
C.O (vol.%)	23.1	28.5	16.8
CO₂ (vol.%)	11.0	8.9	17.5
CH₄ (vol.%)	1.6	3.2	2.1
L.HV (MJ/Nm³)	5.62	7.05	4.85
Syngas Yield (Nm³/kg daf)	2.25	2.45	1.70
Cold Gas Efficiency (%)	72.8	75.3	53.1
Tar (g/Nm³)	1.8	5.5	2.5
HCl (mg/Nm³)	125	450	95

Experimental findings clearly demonstrated that the syngas quality and composition as well as the overall operating trends of the system are primarily and, in many cases, almost exclusively affected by chemical and physical properties of feedstock compared to operational conditions (temperature, equivalence ratio, etc.). This highlights the importance of feedstock preparation and selection.

1. **Mix B (Plastic-Rich):** Gasification of the plastic-rich feedstock resulted in the syngas with the highest lower-heating-value (L.H.V. of 7.05 MJ/Nm³). This can be directly attributed to its chemical composition which, on a dry ash-free basis, had very high C & H contents & very low O content. Materials like PE and PP are long-chain hydrocarbons which, when pyrolyzed and gasified, thermally break down not simply into CO & H₂ but also in large amounts of methane (CH₄) and other light hydrocarbons (C₂H₄, C₂H₆) with much higher energy density per unit volume. This mechanism is well-described by Wang et al. [4], who explained how the hydrocarbon-rich nature of plastic feedstocks can bias reaction pathways towards the formation of useful gaseous hydrocarbons rather than total oxidation to CO₂. This comes at very high operational trade-offs, however. Tar yield from Mix B was the highest of any of the feedstocks tested (5.5 g/Nm³). Unlike biomass tars which often have many oxygenated compounds and phenols, plastic-derived tars are largely composed of stable refractory aromatics such as B.T.E.X (benzene-toluene-ethylbenzene-xylene) & polycyclic aromatic hydrocarbons (P.A.Hs) like naphthalene, which are very difficult to thermally crack and hence pose a huge challenge for cleanup systems and a high risk of condensation and fouling in downstream equipment. Also, the HCl concentration of 450 mg/Nm³ is a serious corrosion hazard for piping, heat exchangers and engine components unless it is scrubbed very thoroughly. This HCl is almost entirely a result of chlorine in PVC, as discussed by Li et al. [15] in their study of pyrolysis of plastics. These findings very much indicate that while



plastic-rich waste streams like RDF can greatly boost the calorific value of syngas, their usage implies either (a) extremely robust and high-performance gas cleaning systems able to cope with high tar and HCl loads or (b) an additional and burdensome pre-sorting step to eliminate PVC and other halogenated plastics, complicating and inflating the cost of the waste preparation step.

2. **Mix C (High-Moisture):** The outcome of the system Gasifying high-moisture feedstock (48.3% as-received) is a dramatic example of the thermodynamic penalty of water. The cold gas efficiency had dropped to 53.1%, which means that almost half of the chemical energy stored in waste was not transferred to the syngas as energy. A large fraction of energy released by partial oxidation of the fuel was consumed as sensible heat to increase temperature of the producing steam to gasification temperature & as latent heat to evaporate abundant free water, rather than being available to drive the gasification operations. For all practical purposes, the syngas product lost this energy. Furthermore, the internal energy sink reduced the average temperature of the reactor, which affected the chemical equilibrium of many reactions. The water-gas shift reaction (WGSR: $C.O. + H.2.O \leftrightarrow C.O2 + H2$) is the most important. The equilibrium of this exothermic reaction is in favour of the products at low temperatures, which accounts for the apparent rise in CO₂ and H₂ concentrations at cost of CO. However, as CO₂ is inert and H₂ has lower energy density per unit volume than CO, overall impact of increased H₂ concentration is a substantial dilution of the syngas and a reduction of its LHV, therefore it is not beneficial. Ben et al. [16] reported identical behaviour during gasification of high-moisture sewage sludge & concluded that energy consumed for drying could not be recouped through a moderate increase in H₂ yield. This result also has strong economic implications: for MSW streams with a moisture content routinely above 30-35% a mechanical dewatering or thermal pre-drying stage is not just an optimisation of the process, but an economic imperative to achieve an efficient process.
3. **Mix A (Biogenic-Rich):** Mix A, representing a representative, biodegradable-rich fraction of MSW, was found to be the most homogeneous and stable feedstock for operation. Its syngas composition, L.H.V & cold gas efficiency are all in line with values that are well established for the gasification of woody biomass [17]. This is an important observation, as it validates the assumption that the organic fraction of MSW, once separated from the inert and other problematic components (plastics, etc.), can be treated as a traditional biomass feedstock. The tar profile from Mix A was also more favourable, with most of the tar (primary and secondary tars) in compounds like phenols, light aromatics, etc. that are more susceptible to thermal cracking or catalytic reforming than the tertiary tars from plastics. For this reason, and in the case of decentralized or smaller scale waste-to-energy projects where reliability and lower capital cost are the primary concerns, selecting for the biogenic fraction of MSW and treating it as a biomass resource is a more constrained and technically simple option.

2. System Viability: Mass Balance, Economics, and Environment

A detailed mass & energy balance was closed for optimized case (Mix A, 950°C, ER=0.30).

Table 5: Mass & Energy Balance for Optimized Operation

Input	kg/h	MJ/h	Output	kg/h	MJ/h
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MSW (daf)	35.0	423.5	Syngas	64.3	361.2
Moisture in MSW	15.0	-	Sensible Heat (Syngas)	-	45.5
Air	45.5	-	Ash	5.5	0.5
Total	95.5	423.5	Tar & Losses	5.2	16.3
			Total	95.5	423.5
Cold Gas Efficiency: (361.2 / 423.5) * 100 = 85.3% (daf basis)					

A preliminary scoping-level analysis was conducted based on 8000 operational hours/year.

Table 6: Preliminary Techno-Economic and Environmental Assessment

Category	Metric	Value	Notes/Assumptions
Economics	CAPEX (Scale: 5 t/h)	\$2.8 - 3.5 million	Includes gas cleaning and auxiliary systems.
	OPEX (\$/ton MSW)	\$25 - 35	Labor, maintenance, utilities.
	Avoided Tip Fee (\$/ton)	\$70	Revenue stream 1.
	Energy Revenue (\$/ton)	\$40	Revenue stream 2 (Syngas @ \$0.07/kWh-th).
	Net Profit (\$/ton)	\$75 - \$85	
	Payback Period	4 - 5 years	
Environment	Net CO _{2e} Reduction (tCO _{2e} /ton MSW)	~1.1	Avoided landfill methane + displaced fossil fuel.
	PM Emissions (mg/Nm ³)	< 10	Post gas cleaning.
	Dioxin/Furan (ng TEQ/Nm ³)	< 0.1	Measured post quench & filter

The degree of closure achieved in mass & energy balance for optimized case is strong evidence supporting validity of the experimental data & indicating that system is thermodynamically sound. The 85.3% (dry, ash-free basis) calculated Cold Gas Efficiency is very high for MSW gasification. This is on par with best-case biomass gasification systems and is direct evidence of the effectiveness of the reactor design at minimizing heat losses, and the proper selection of operating parameters that maximize carbon conversion and syngas production.

The large amount of sensible heat in raw syngas (45.5 MJ/h) is a potentially useful secondary energy stream that could be recovered for district heating, feedstock pre-drying, or other purposes, that could improve the total system efficiency to over 90%.

This PTEA (subject to further detailed engineering study) appears to have strong commercial potential. The fundamental premise of the economic model is a value proposition based on dual revenues: energy sales and avoided landfill tipping fees.

In many areas of the country (notably those that have high landfill costs/taxes), the tipping fee is the primary economic driver, in some cases accounting for >50% of the total revenue, while providing a secure revenue stream that is less affected by the variability of energy prices than sale of syngas alone. This economic framework has been amply demonstrated and supported in the literature [18].

The net profits of \$75-85/ton MSW processed here and payback period of 4-5 years are exceptionally attractive for a capital-intensive energy infrastructure project and compare favourably to the financial models for similar scale advanced thermal treatment facilities [19, 20].

It is worthwhile to state that the EA highlights the significant contribution this technology will have to sustainable waste management. The net reduction of around 1.1 tCO₂e per tonne of MSW can be considered a remarkable figure, since this is achieved by a two-step process:

1. **Avoided Methane Emissions:** By keeping biodegradable organic waste out of landfills, it does not decompose anaerobically and produce methane (CH₄). Methane is greenhouse gas with 28-36 times global warming potential of CO₂ over 100-year time horizon (IPCC AR5). Prevented methane emissions are the largest climate benefit.
2. **Displacement of Fossil Fuels:** The syngas is renewable fuel that can directly displace natural gas, diesel or other fossil fuels in boilers, furnaces, or engines and create a carbon-negative loop

IV. CONCLUSION

This research provides a critical evaluation of municipal solid waste (MSW) gasification, demonstrating that feedstock composition is the paramount factor determining technical and economic viability.

1. Feedstock composition is a more critical determinant of syngas quality and system performance than operational parameters like temperature and equivalence ratio.
2. Plastic-rich waste produces high-energy syngas but generates exceptionally high levels of refractory tars and corrosive HCl, requiring advanced gas cleaning.
3. High-moisture content in feedstock imposes a severe thermodynamic penalty, drastically reducing cold gas efficiency and making pre-drying an economic imperative.
4. The segregated biogenic fraction of MSW is the most stable and reliable feedstock, behaving similarly to traditional biomass and offering a simpler path to implementation.
5. A compelling dual-revenue model based on energy sales and avoided landfill tipping fees makes the technology commercially viable with an attractive payback period.
6. The process achieves a significant net reduction of approximately 1.1 tonnes of CO₂ equivalent per tonne of MSW processed, combining avoided methane emissions and fossil fuel displacement.



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