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Flue Gas Emission Characterization and Environmental Compliance Assessment of a Pilot-Scale Office Waste Gasification Plant

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Abstract— Based on data collected from a pilot-scale downdraft gasifier operating at 950 °C and an equivalency ratio of 0.30, this study evaluates the flue gas emissions produced by this device. Every one of the pollutants that were measured fell within the limits set by the Nigerian DPR/EGASPIN. This includes carbon monoxide (285 ppm), nitrogen dioxide (142 ppm), sulphur dioxide (9.5 ppm), volatile organic compounds (15.2 mg/Nm3), particulate matter (18.5 mg/Nm3), and heavy metals. The findings point to downdraft gasification as a viable, dispersed, and environmentally friendly waste-to-energy option.

Keywords— Gasification, Flue Gas, Environment, Sustainability, Waste-to-Energy.

I. INTRODUCTION

Greenhouse gas emissions from Nigeria's waste sector account for about 10% of total emissions, with open dumping contributing significantly to methane releases [1, 2]. Transitioning to WTE could reduce these by up to 50% in targeted applications [3]. Policy measures, such as incentives for renewable energy, are essential to overcome adoption barriers [4, 5]. This study aims to bridge these gaps by focusing on the NDDC Headquarters as a case study.

Emission profiles from small-scale WtE units reveal significant variations in flue gas compositions, influenced by operating conditions and waste feedstock characteristics, providing benchmarks for environmental compliance. Particulate matter (PM), CO, NOx, and VOC levels are key pollutants monitored in pilots, with gasification systems typically emitting lower levels than incineration due to controlled oxygen environments. A pilot-scale gasification in China reported PM concentrations of 5-15 mg/Nm^3, CO at 100-200 mg/Nm^3, NOx at 50-100 mg/Nm^3, and VOCs below 20 mg/Nm^3, attributed to optimized air-to-fuel ratios and tar cracking at 800-1000°C [6]. In high-organic MSW feedstocks from developing countries, pyrolysis pilots in Pakistan showed elevated VOCs (30-50 mg/Nm^3) from incomplete decomposition, mitigated by catalytic afterburners reducing them by 60-70% [7]. Operating conditions like temperature and residence time directly affect emissions; lower temperatures (below 700°C) in Ethiopian incineration units increased CO (300-500 mg/Nm^3) and PM (20-40 mg/Nm^3) due to incomplete combustion, while higher excess air reduced NOx but elevated SOx from sulfur-rich waste [8]. Feedstock moisture

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above 40% exacerbates PM and VOC formation, as seen in Nigerian pilots where drying pre-treatment lowered PM2.5 to under 10 mg/Nm^3 [9]. Consolidated data from European small-scale units indicate average emission factors: PM 10-30 mg/Nm^3, CO 150-300 mg/Nm^3, NOx 80-150 mg/Nm^3, and VOCs 10-40 mg/Nm^3, with waste plastics increasing VOCs and organics boosting CO [10]. These profiles underscore the need for integrated controls like scrubbers, aligning with benchmarks for sustainable operation [11, 12].

II. MATERIALS AND METHOD

A. Pilot Plant Configuration and Operating Conditions

The pilot-scale downdraft gasification plant consisted of five integrated subsystems: (1) feedstock preparation and feeding (shredder, dryer, loss-in-weight feeder), (2) downdraft gasifier reactor (1.5 m height, 0.3 m throat diameter, 0.5 m combustion zone, 50 mm alumina-silica refractory lining), (3) gas cleaning train (cyclone separator, shell-and-tube heat exchanger, packed-bed scrubber), (4) power generation unit (spark-ignition internal combustion engine modified for low-BTU syngas, 9 kVA synchronous alternator), and (5) instrumentation and control system (Siemens S7-1200 PLC, National Instruments cDAQ data acquisition).

Emission sampling was conducted during steady-state operation characterized by: feedstock rate = 10.2 ± 0.5 kg/h (as-received, moisture 24.8 ± 1.5%), equivalence ratio = 0.30 ± 0.02, gasifier oxidation zone temperature = 950 ± 25°C (Type K thermocouple, average of 3 probes), specific gasification rate = ~155 kg/(m^2·h), and syngas engine load = ~85% of rated generator capacity (9 kVA).

B. Flue Gas Sampling Protocol

A comprehensive sampling train is employed to extract a representative flue gas sample from the stack under steady-state plant operation. The core apparatus consists of a heated quartz probe maintained at 160°C ± 10°C to prevent condensation of semi-volatile species, followed by a cyclone and a series of glass-fibre filters housed in a heated enclosure for particulate matter collection.

For gaseous species, the sample stream is routed through a condenser to remove moisture and then through a series of impinger trains. Specific impinger solutions are used for targeted capture: diluted hydrogen peroxide for sulphur oxides (SO_x) and ice-chilled methanol for volatile organic compounds. Simultaneously, an adsorbent tube (e.g., Tenax TA or activated carbon) is used for integrated VOC sampling.

Sampling is conducted isokinetically, where the velocity at the probe inlet is matched to the stack gas velocity, measured using an S-type pitot tube and a differential pressure gauge. This is critical for obtaining a representative mass loading of particulate matter. The sampling duration is a minimum of one hour per test run to ensure adequate analyte mass for quantification, with multiple runs conducted to establish reproducibility.

C. Analytical Techniques for Emission Composition

Collected samples are analyzed using a suite of standardized instrumental techniques to quantify pollutant concentrations. The following table summarizes the primary analytical methods, target analytes, and key performance parameters.

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Table 1: Analytical Techniques for Key Pollutants in Flue Gas

Pollutant	Technique	Detection Limit
VOCs	GC-MS (TO-15)	0.01-0.1 ppb
CO	Non-Dispersive Infrared (NDIR) Spectroscopy	0.1-1 ppm
CO_2	Non-Dispersive Infrared (NDIR) Spectroscopy	0.1% vol
NO_x	Chemiluminescence Detection (CLD)	0.5 ppm
SO_x	Ultraviolet Fluorescence (UVF)	0.1 ppm
H_2S	Gas Chromatography with Pulsed Flame Photometric Detection (GC-PFPD)	0.05 ppm
PM (2.5-10)	Gravimetric/Beta Attenuation	0.1 mg/m^3
Metals (Pb, Cd, Zn)	Inductively Coupled Plasma Mass Spectrometry (ICP-MS)	0.1 ng/m^3.

III. RESULTS AND DISCUSSION

Sampling Conditions and Gas Characterization

The average conditions during the sampling campaign were:

Flue Gas Temperature: 285 ± 15 °C, Stack Gas Velocity: 4.2 ± 0.3 m/s, Moisture Content: 12.5 ± 1.8 % (vol, wet basis), Oxygen (O_2) Content: 8.2 ± 0.5 % (dry basis) – used for regulatory concentration corrections.

All pollutant concentrations are reported on a dry basis and are corrected to a standard reference oxygen (O_2) content of 11% for combustion sources, as per common regulatory practice, using the formula:

$$C_{\text{corrected}} = C_{\text{measured}} \times \frac{20.9 - \%O_{2,\text{ref}}}{20.9 - \%O_{2,\text{measured}}}$$

Where %O_2 is by volume, dry basis.

Table 2: Operating Parameters During Flue Gas Emission Sampling Campaign

Parameter	Symbol	Average Value ± Standard Deviation	Units
Sampling Run Details			
Number of Sampling Runs	-	3	-
Duration per Run	-	1.5	hours
Key Process Control Parameters			
Equivalence Ratio (ER)	ER	0.30 ± 0.02	-
Gasifier Oxidation Zone Temp.	T_ox	950 ± 25	°C
Feedstock Rate (as received)	m˙_feed	10.2 ± 0.5	kg/h
Feedstock Moisture Content	M_"feed"	24.8 ± 1.5	% wt.
Specific Gasification Rate	SGR	~155	kg/(m^2·h)
Syngas Engine Load	-	~85	%
Flue Gas Sampling Point Conditions			

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Flue Gas Temperature	T_flue	285 ± 15	°C
Stack Gas Velocity	v_stack	4.2 ± 0.3	m/s
Oxygen Content (dry basis)	O_2	8.2 ± 0.5	% vol.
Moisture Content (wet basis)	H_2 O	12.5 ± 1.8	% vol.

A pilot-scale waste-to-energy plant's flue gas emissions show an equivalency ratio of 0.30 and a gasifier temperature of 950°C. Effective heat management with an average flue gas temperature of 285°C and a stack velocity of 4.2 m/s allows exhaust dispersion at 85% load [13, 14]. High feedstock moisture (24.8%) affects combustion temperatures and syngas quality [15, 16]. With little modifications, isokinetic sampling proves electricity generation stability. Standardization to 11% O_2 assures regulatory compliance and enhanced monitoring mechanisms maintain system resilience to changes [17, 18]. Over classic gasifiers, emissions control is more efficient. Short sample intervals may cause starting spikes to be incorrect [19].

Gaseous Pollutant missions

Table 3: Concentrations of Major Gaseous Pollutants in Flue Gas

Pollutant	Symbol	Average Concentration ± SD	Units	Nigerian DPR Limit	Compliance
Carbon Monoxide	CO	285 ± 32	ppmv	1000 ppm	Yes
Carbon Dioxide	CO_2	7.8 ± 0.4	% vol	-	-
Nitrogen Oxides	NO_x (as NO_2)	142 ± 18	ppmv	350 ppm	Yes
Sulfur Oxides	SO_x (as SO_2)	9.5 ± 2.1	ppmv	200 ppm	Yes
Hydrogen Sulfide	H_2S	0.8 ± 0.3	ppmv	10 ppm	Yes

SD = Standard Deviation

Results show effective steady-state performance in the investigation of gaseous pollutant emissions from a pilot-scale waste-to-energy facility. The average CO concentration was 285 ± 32 ppmv, which indicates that the internal combustion engine was operating at partly optimised combustion, with an equivalency ratio of 0.30 and an oxidation zone temperature of 950 ± 25°C [14]. Over 1.5-hour sample intervals, the engine performance remained constant with little power swings because of this. Enhancing energy output and decreasing engine stress via exhaust gas dilution, the balanced carbon conversion from the biomass feedstock results in a CO2 emission of 7.8 0.4% vol stress [12, 15]. Effective heat regulation in high-temperature zones is shown by the NOx emissions, which were measured at 142 ± 18 ppmv (as NO2), allowing the engine to sustain 85% load without problems [20]. The effective oxidation of sulphur compounds without their accumulation in the exhaust system, together with the low levels of SOx (9.5 ± 2.1 ppmv as SO2) and H2S (0.8 ± 0.3 ppmv), leads to corrosion-free operations and an extended lifetime for components [21, 22]. The research emphasises the capacity to continuously gasify at ~155 kg/(m²·h) with air-feed ratio modifications made in real-time, guaranteeing efficiency and compliance [23, 24, 25, 26]. Using a variety of metrics, operators may efficiently regulate feedstock rates. For CO/CO2, CLD measures NOx, UVF

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measures SOx, and GC-PFPD measures H2S. In comparison to burning biomass or fossil fuels, the downdraft system design produces cleaner syngas and a net output of around 6.37 kW with reduced emissions [27, 28]. The CO levels that were measured under the same circumstances are consistent with those of other downdraft systems, demonstrating the benefits of this waste-to-energy technology compared to more conventional approaches, such as MSW incineration, and bolstering its promise for greener energy recovery [12, 15, 29, 30].

Volatile Organic Compounds (VOCs) and Particulate Matter (PM)

Table 4: VOC and Particulate Matter (PM) Emissions in Flue Gas

Parameter / Compound	Average Concentration ± SD	Units	Detection Limit	Method
Total VOC (as Toluene Equivalent)	15.2 ± 3.8	mg/Nm³	0.01 ppb	GC-MS (TO-15)
Key VOC Species Identified				
Benzene	1.05 ± 0.31	mg/Nm³	0.01 ppb	GC-MS
Toluene	2.18 ± 0.45	mg/Nm³	0.01 ppb	GC-MS
Xylenes	1.89 ± 0.50	mg/Nm³	0.01 ppb	GC-MS
Naphthalene	0.45 ± 0.15	mg/Nm³	0.01 ppb	GC-MS
Particulate Matter (PM_{10})	18.5 ± 4.2	mg/Nm³	0.1 mg/m³	Gravimetric
Particulate Matter ($PM_{2.5}$)	12.1 ± 3.5	mg/Nm³	0.1 mg/m³	Gravimetric
$PM_{2.5}/PM_{10}$ Ratio	0.65	-	-	Calculated

The study on volatile organic compound (VOC) and particulate matter (PM) emissions from a pilot-scale waste-to-energy (WtE) plant highlights the facility's steady-state performance, which is defined by a gasifier oxidation zone temperature of 950°C and an equivalency ratio of 0.30. The successful reduction of tar throughout waste processing and utility production is shown by the reported total VOC concentration of 15.2 ± 3.8 mg/Nm³. Low amounts of benzene, toluene, xylenes, and naphthalene, which are present in the breakdown of plastics and paper, enable secondary reactions to be effective [12, 15].

The amounts of particulate matter were found to be 18.5 ± 4.2 mg/Nm³ and 12.1 ± 3.5 mg/Nm³, respectively, indicating that the particulate matter was well managed, especially when the filters were well-maintained [31, 32]. At 85% engine capacity, a reliable combustion and emissions control system is shown by techniques including GC-MS for volatile organic compound analysis and gravimetric methods for particulate matter monitoring [33, 34].

Based on the study, feedstocks with a moisture content of 24% reduce gasification temperatures, which in turn reduces VOC emissions, helps keep polycyclic aromatic hydrocarbons to a minimum, and increases equipment durability [35].

By obtaining lower benzene levels equivalent to wood gasification, the downdraft gasifier displays fewer VOC emissions than traditional approaches. With downdraft systems demonstrating PM emissions below regulatory levels, compliance with emission requirements is noteworthy [36].

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Heavy Metal Emissions

Table 5: Heavy Metal Concentrations in Flue Gas Particulate Matter

Metal	Average Concentration in PM ± SD	Units	Detection Limit	Method	EGASPIN Limit (2)
Lead (Pb)	0.032 ± 0.008	mg/Nm^3	0.1 ng/m^3	ICP-MS	10 mg/Nm^3
Cadmium (Cd)	0.005 ± 0.002	mg/Nm^3	0.1 ng/m^3	ICP-MS	0.1 mg/Nm^3
Zinc (Zn)	0.215 ± 0.055	mg/Nm^3	0.1 ng/m^3	ICP-MS	-

(2) EGASPIN limit for incineration flue gas.

This study delves into the environmental performance of a pilot-scale waste-to-energy (WtE) plant by studying its heavy metal emissions, specifically during steady-state operation at 950 ± 25°C and an equivalency ratio of 0.30. Exhaust components are kept free from accumulation due to the minimal amounts of lead (Pb) and cadmium (Cd) in office waste feedstock, which are 0.032 ± 0.008 mg/Nm^3 and 0.005 ± 0.002 mg/Nm^3 respectively running [12, 15]. While sampling runs, the facility effectively handles mixed waste without filter clogging. Additionally, the downdraft gasification process preserves most metals in bottom ash, resulting in good syngas quality. The maintenance demands are reduced and operating cycles are extended due to the low sulphur and metal concentration in office waste. Compliance without interruption of energy production is made possible by the study's emphasis on operational stability for decentralised applications [34]. With a detection limit of 0.1 ng/m^3, accurate monitoring is possible, potentially allowing run durations to exceed 4.5 hours. Along with meeting Nigerian legal norms, the metal emission profiles from this WtE facility are lower than those from incineration. The results indicate that better filtering has the potential to lower emissions by 50-70%, which would help with health and regulatory compliance and get us closer to our circular economy aims of recovering resources [33, 31, 36].

Emission Factor for the Process

An important derived result is the Emission Factor (EF), which expresses the mass of pollutant emitted per unit of feedstock processed.

$$\mathrm{EF}_x = \frac{C_x \times Q_{flue}}{\dot{m}_{feed}}$$

Where C_x is pollutant concentration (mg/Nm^3), Q_flue is dry flue gas flow rate (Nm^3/h), and m˙_feed is feedstock rate (kg/h). Based on a measured dry flue gas flow of 31.5 Nm^3/h and a feed rate of 10 kg/h, the emission factor for Carbon Monoxide is:

$$\mathrm{EF}_{CO} = \frac{285\ \text{ppm} \times (28/22.4)\ \text{mg/Nm}^3\ \text{per ppm} \times 31.5\ \text{Nm}^3\text{/h}}{10\ \text{kg/h}} \approx 11.2\ \text{g CO per kg waste}$$

Under steady-state conditions, the pilot-scale waste-to-energy plant achieves an emission factor of 898 mg/kg of carbon monoxide (CO), demonstrating considerable environmental efficiency. Stable operations are achieved by regulated incomplete combustion, which prevents efficiency reductions. Unburned losses are reduced because to

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the plant's design that accounts for feedstock changes and improves energy recovery [21, 22]. Constant vigilance on efficiency and compliance verifies operational resilience. By using downdraft gasification, CO emissions are reduced in comparison to updraft systems. Additionally, by implementing real-time feedback mechanisms, the emission parameters may be further optimised. Minimal environmental effect and compliance with regulatory criteria are ensured by the system's performance, which is in line with low emissions for other pollutants [35, 36].

IV. CONCLUSION

The downdraft gasification system was able to show consistent operation and compliance with regulatory emission limitations while operating under controlled conditions. Its usefulness for environmentally responsible waste treatment is highlighted by its low pollutant levels, notably for volatile organic compounds (VOCs), particulate matter (PM), and heavy metals. Further reduction of emissions and improvement of environmental performance may be achieved via the optimisation of filtering and feedstock preparation.

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