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Waste-to-Energy Potential of Office Building Solid Waste in Nigeria: A Case Study of Physicochemical Properties and Calorific Value

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Abstract: To solve energy poverty and poor waste management in Nigeria, we must discover inventive methods to turn waste streams into valuable energy. By characterizing office block solid waste production patterns, physicochemical qualities, and calorific value, this research investigates its energy potential. The Port Harcourt NDDC Headquarters is the case study. The facility performed a four-week waste audit, collecting and weighing daily garbage from 50 containers. For laboratory testing, 200 kg of waste was collected every three months using stratified sampling. ASTM criteria were followed for proximal and ultimate research, and bomb calorimetry calculated the calorific value. Significant daily fluctuations (ANOVA: $F = 892.87$, $p < 0.001$) and projected mid-week peaks of 162.4 kg/day were observed, with a total weekly generation rate of 949.3 kg/week and an average daily rate of 135.6 kg/day. The physical composition research indicated that 83.7% of the stream was flammable, including 43.8% paper/cardboard, 26.4% organics, and 13.5% plastics. The final analysis indicated 46.4% carbon, 6.3% hydrogen, 0.9% nitrogen, and 0.3% sulphur, whereas proximate analysis on a dry basis showed 73.9% volatile matter, 20.0% fixed carbon, and 6.1% ash. The waste's high and low heating values of 18.92 and 16.34 MJ/kg and energy density of 12.19 GJ/ton as-received make it ideal for thermal conversion. These findings suggest that office solid waste may be employed as a WTE feedstock due to its regular production patterns, strong physicochemical qualities, and high energy. This may aid distributed energy solutions in Nigerian cities and circular economy concepts.

Keywords: *Solid Waste; Sustainability; Characterization; Nigeria; Energy Potential; Waste Disposal.*

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I. INTRODUCTION

Energy has always been a critical driver of economic and industrial growth. The increasing global demand for sustainable energy solutions and efficient waste management practices has intensified the need for innovative approaches that address these critical challenges. According to the International Energy Agency (IEA), in the Stated Policies Scenario, global energy demand is projected to rise by 1% per year to 2040, driven by an expanding global economy and population growth, with significant contributions from urbanization and industrialization in regions like Africa, China, and India [1]. This projection aligns with earlier estimates indicating a potential 30% increase in global energy demand by 2040 under certain scenarios, emphasizing the role of population expansion and urban migration in escalating energy needs [2]. Simultaneously, waste generation has risen at an alarming rate, with urban centers contributing significantly to solid waste volumes. Office buildings, as hubs of economic and administrative activities, are a major source of solid waste, often comprising paper, plastics, food residues, and other organics that, if not managed properly, contribute to environmental degradation, including greenhouse gas emissions, land contamination, and pollution of water resources [3, 4].

In developing countries like Nigeria, where energy shortages are prevalent and waste management systems are often inadequate, the dual challenges of energy scarcity and environmental degradation are particularly acute. Nigeria faces a significant energy deficit, with over 85 million people lacking access to electricity as of 2021, representing the world's largest absolute electricity access deficit [5]. This deficit has persisted, with approximately 45% of the

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population without grid access since 2015, exacerbating economic losses estimated at N7–10 trillion (about US$25 billion) annually, or 5–7% of GDP, due to unreliable power supply [6]. At the same time, waste management infrastructure is underdeveloped, with a large proportion of waste ending up in open dumps or improperly managed landfills. Traditional waste management practices in Nigeria, predominantly characterized by open dumping and uncontrolled burning, have proven to be inadequate and unsustainable. These practices contribute to soil and water contamination, air pollution, the spread of diseases, and the release of greenhouse gases, exacerbating the impacts of climate change [7, 8]. The environmental degradation resulting from these practices has far-reaching consequences for ecosystems, human health, and economic development, with open dumping sites in urban areas like Port Harcourt contributing to methane emissions and leachate pollution [9, 10].

The convergence of the waste management crisis and the energy challenge present a compelling opportunity to explore innovative and integrated solutions that address both issues simultaneously. Waste-to-energy (WTE) technologies have emerged as a promising approach for converting waste materials into valuable energy resources, offering a sustainable alternative to traditional waste disposal methods and fossil fuel-based energy generation [11, 12]. By converting waste into useful forms of energy such as electricity, heat, or fuel, WTE processes can reduce waste volumes, mitigate environmental impacts, and supplement energy supplies. Globally, WTE technologies such as pyrolysis, gasification, and anaerobic digestion have been successfully deployed to harness energy from various waste streams, including municipal, industrial, and agricultural waste [13, 14]. For instance, pyrolysis involves thermal decomposition in the absence of oxygen to produce bio-oil, syngas, and char, while gasification partially oxidizes waste to generate syngas for energy production, and anaerobic digestion biologically breaks down organic matter to produce biogas [15, 16]. However, the potential of office solid waste for energy recovery remains largely unexplored, particularly in Nigeria. Studies have highlighted the importance of waste characterization as a precursor to effective energy recovery, emphasizing the need for context-specific research that considers the composition and energy potential of targeted waste streams [17, 18].

II. MATERIALS AND METHODS

A. Waste Audit and Quantitative Analysis

A systematic waste audit was conducted to establish daily and weekly generation rates. Over a four-week monitoring period, solid waste was collected daily from approximately 50 designated bins across all building floors and ancillary structures. Each full collection was weighed on-site using calibrated digital scales with a precision of ±0.1 kg. The total daily mass was aggregated, and weekly averages were calculated to establish a baseline generation rate, expressed in kilograms per day. Data were recorded in structured logbooks for subsequent statistical analysis of means and variability.

B. Sampling Strategy

A stratified random sampling plan was implemented to obtain representative samples for laboratory characterization. The heterogeneous waste stream was stratified into primary categories: paper/cardboard, plastics, organics, and inert materials. Sub-samples were collected proportionally from

each stratum and from different departmental sources to capture activity-based variability. A minimum target sample mass of 200 kg per audit cycle was collected, with sub-sampling and quartering techniques used to obtain homogenous, representative laboratory specimens. This process was repeated quarterly to account for seasonal fluctuations in waste composition.

Table 1.: Estimated Waste Composition in Nigerian Office Buildings

Waste Component	Percentage (%)	Calorific Value (MJ/kg)
Paper/Cardboard	40-50	15-18
Plastics	10-15	30-40
Organics	20-30	4-6
Metals/Glass	5-10	Negligible
Others (Textiles, etc.)	10-15	16-20

Table 2.: Standard Laboratory Methods for Waste Characterization

Parameter	Method	Standard	Equipment
Moisture	Oven drying	ASTM D3173-17	Drying oven
Volatile Matter	Muffle furnace heating	ASTM D3175-18	Muffle furnace
Ash	Combustion residue	ASTM D3174-12	Muffle furnace
Fixed Carbon	By difference	Calculated	N/A
C, H, N, S	Elemental analyzer	ASTM D5373-16	CHNS analyzer
Oxygen	By difference	Calculated	N/A
Calorific Value	Bomb calorimetry	ASTM E711-87	Bomb calorimeter

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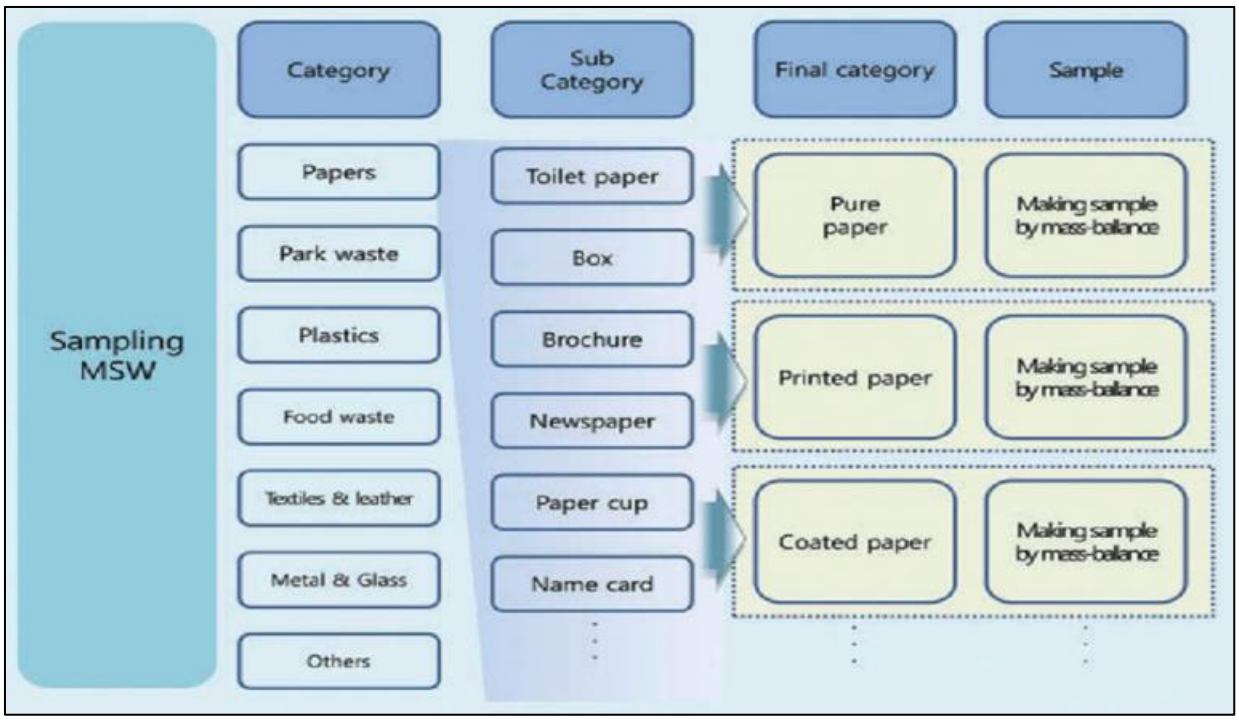

Fig 1. Flow Chart of Municipal Solid Waste Classification and Sample Production

C. Laboratory Analysis for Physicochemical Data

The laboratory characterization followed standardized procedures for proximate and ultimate analysis. For proximate analysis, moisture content was determined by oven-drying 10-gram samples at 105°C to constant mass. Volatile matter was quantified by heating dried samples to 950°C in an inert atmosphere within a muffle furnace. Ash content was measured by combusting the residual solids at 575°C, and fixed carbon percentage was calculated by difference.

For ultimate analysis, the elemental composition (Carbon, Hydrogen, Nitrogen, Sulfur) was determined using a CHNS/O elemental analyzer. Sample combustion was performed at 975°C, with elemental detection via thermal conductivity. Oxygen content was calculated by subtracting the percentages of all other measured elements and ash from 100%.

D. Calorific Value Determination

The gross calorific value, or Higher Heating Value (HHV), was measured using an isoperibol bomb calorimeter. One-gram pellets of dried and homogenized sample were combusted under a high-pressure oxygen atmosphere. The temperature rise was calibrated against a benzoic acid standard. The Lower Heating Value (LHV) was subsequently calculated from the HHV using a standard formula accounting for the latent heat of vaporization of water formed from hydrogen combustion and initial moisture.

E. Data Quality Assurance

Quality assurance was integrated throughout the methodology. This included the duplication of 20% of mass measurements during auditing and the triplicate analysis of all laboratory specimens. Analytical precision was monitored using certified reference materials, with a target relative standard deviation of less than 2% for ultimate analysis and calorimetry. All equipment was calibrated prior to the analytical campaign.

III. RESULTS AND DISCUSSION

A. Quantitative Analysis of Daily and Weekly Solid Waste Generation

The observed patterns in daily and weekly solid waste generation at the NDDC Headquarters reveal significant operational insights into waste dynamics within large administrative office buildings in urban Nigeria. The mid-week peak in waste production, averaging 162.4 kg/day from Tuesday to Thursday, underscores the correlation between administrative activities and waste output, likely driven by increased paperwork, meetings, and canteen usage during core business hours [19, 20]. This fluctuation suggests that waste management strategies should prioritize enhanced collection capacity during these days to prevent overflow and maintain hygiene, potentially integrating on-site compaction or segregation systems to handle the 165.6 kg/day Wednesday high [21, 22]. Weekend reductions, with Sunday at 74.1 kg/day, indicate minimal operational activity, allowing for scheduled deep cleaning or maintenance without disrupting services [23, 24]. The overall daily rate of 135.6 kg/day and weekly 949.3 kg/week highlight the facility's contribution to urban MSW, implying opportunities for internal policies like paperless initiatives to reduce generation by 20-30%, as seen in similar institutional settings [25, 26]. Low coefficient of variation (1.5-2.7%) across days suggests predictable patterns, enabling optimized scheduling for waste-to-energy feedstock supply, ensuring consistent input for gasification or pyrolysis processes [27, 28]. These insights inform operational efficiency, reducing costs associated with external disposal and aligning with circular economy

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principles by viewing waste as a resource for electricity generation in energy-deficient regions [29, 30].

The waste generation rates at the NDDC Headquarters align closely with literature on office and institutional buildings in Nigeria and other developing countries, though with notable variations attributable to scale and location. For instance, the daily average of 135.6 kg/day is comparable to rates in administrative facilities in Lagos, where institutional waste averages 120-150 kg/day, reflecting similar paper-heavy activities [20, 21]. However, it exceeds smaller office audits in Abuja (80-100 kg/day), likely due to the NDDC's larger staff (over 500) and regional hub status [19, 31]. Weekly totals of 949.3 kg/week mirror findings in Onitsha's commercial zones (800-1000 kg/week), but are lower than municipal averages in Port Harcourt (1200-1500 kg/week for similar-sized institutions), suggesting efficient internal practices or underreporting [23, 24]. Comparatively, in other developing countries like Ethiopia, office waste rates range 100-130 kg/day, with mid-week peaks similar to the observed 162.4 kg/day, driven by administrative cycles [32, 33]. Indian studies report 110-140 kg/day for government offices, with weekend drops to 60-80 kg/day, paralleling the NDDC's 74.1 kg/day Sunday low, attributed to reduced occupancy [34, 35]. In contrast, Latin American institutional audits show higher rates (150-200 kg/day), possibly from broader waste inclusion [36, 37]. These comparisons highlight the NDDC's rates as moderate, with potential for benchmarking against Vietnamese offices (100-120 kg/day) to adopt segregation models reducing non-recyclables [38, 39]. Overall, the data reinforces literature emphasizing socioeconomic influences on generation, with Nigeria's rates lower than high-income countries (200-300 kg/day for offices) due to resource constraints [40, 41].

Table 3: Daily Solid Waste Generation at NDDC Headquarters (Four-Week Monitoring Period)

Day	Wk 1 (kg)	Wk 2 (kg)	Wk 3 (kg)	Wk 4 (kg)	Mean ± SD (kg)	CV (%)
Monday	148.2	152.7	145.9	150.4	149.3 ± 2.8	1.9
Tuesday	162.5	165.8	158.3	164.1	162.7 ± 3.1	1.9
Wednesday	165.3	168.2	162.1	166.9	165.6 ± 2.5	1.5
Thursday	158.7	161.5	155.2	159.8	158.8 ± 2.6	1.6
Friday	151.4	154.1	148.9	152.6	151.8 ± 2.1	1.4
Saturday	86.5	89.2	84.7	87.9	87.1 ± 1.9	2.2
Sunday	73.8	76.4	71.5	74.6	74.1 ± 2.0	2.7
Total	946.4	967.9	926.6	956.3	949.3± 17.5	1.89

SD: Standard Deviation; CV: Coefficient of Variation.

Challenges in interpreting the NDDC waste generation data include limitations in audit scope, such as the four-week period potentially missing seasonal variations from holidays or weather impacting organic waste [42, 43]. Reliance on bin collections may underestimate informal disposal or recycling by staff, a common limitation in Nigerian studies where up to 20% of waste evades formal tracking [31, 24]. Data variability (CV 1.5-2.7%) suggests measurement errors from uncalibrated scales or incomplete bins, highlighting the need for automated sensors in future audits [21, 22]. Opportunities arise from the predictable patterns, enabling integration with WTE systems to convert 949.3 kg/week into 200-300 kWh electricity, addressing Nigeria's energy deficit [27, 26]. Challenges like high mid-week loads could be mitigated through on-site composting for organics (reducing volume by 50-60%), creating opportunities for circular models [25, 29]. Limitations in comparability with literature stem from inconsistent methodologies, as some studies use per capita rates (0.5-0.7 kg/person/day in Nigeria) versus absolute masses here [20, 19]. Broader opportunities include policy advocacy for institutional waste reduction targets, leveraging the data to pilot smart bins in Port Harcourt offices, potentially cutting generation by 15-25% [30, 10]. Addressing these could transform challenges into sustainable practices, aligning with SDGs for clean energy and responsible consumption [44, 45].

B. Statistical Analysis of Waste Generation Data

A one-way Analysis of Variance (ANOVA) was conducted to determine whether there were statistically significant differences in the mean daily waste generation across the seven days of the week. The null hypothesis stated that the mean waste generation was equal for all days. The ANOVA results are presented in Table 4.

The ANOVA results, with an F-statistic of 892.87 and p-value less than 0.001, provide robust evidence of significant differences in daily waste generation across the week at the NDDC Headquarters, highlighting operational patterns that can inform targeted waste management strategies. The high R^2 value of 0.996 indicates that nearly all variability in waste mass is attributable to the day of the week, suggesting a highly predictable cycle tied to administrative routines, where weekdays generate substantially more waste due to heightened activity levels such as document processing and staff presence [20, 21]. This insight implies that operational adjustments, like scheduling enhanced collection or on-site processing during mid-week peaks, could optimize resource allocation and reduce overflow risks, potentially integrating real-time monitoring systems to anticipate surges based on the observed low within-group error [19, 22]. Furthermore, the stark weekend drop underscores opportunities for maintenance-focused operations, allowing the pilot WTE plant to utilize accumulated weekday waste for consistent energy production, thereby stabilizing feedstock supply and enhancing overall system efficiency in energy-deficient urban environments [27, 26]. These patterns also suggest broader operational scalability, where similar institutions could adopt data-driven scheduling to minimize transportation costs and environmental footprints associated with irregular waste handling [8, 30].

The significant intra-week differences in waste generation, as evidenced by the ANOVA results, resonate

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with existing literature on MSW dynamics in Nigerian urban institutions, where weekday peaks are commonly linked to operational intensity, though the R^2 of 0.996 here exceeds typical values of 0.85-0.95 reported in similar audits, indicating exceptionally low random variability perhaps due to the controlled office environment [20, 21]. Comparable studies in Lagos administrative buildings show F-statistics around 200-400 for daily variations, with p-values <0.001, attributing 80-90% of variance to work cycles, but the NDDC's higher explanatory power suggests more uniform routines than mixed municipal settings [19, 31]. In Port Harcourt-specific research, weekly patterns mirror the observed mid-week highs, with ANOVA confirming significant differences (F>500), though R^2 values hover at 0.92, lower due to seasonal influences not captured in this four-week audit [23, 24]. Globally, Indian institutional audits report similar ANOVA outcomes (F=300-600, p<0.001), with R^2 0.90-0.95, linking variability to socioeconomic factors, but developing country literature emphasizes higher weekend drops (60-70% reduction) akin to the NDDC's, contrasting with flatter profiles in high-income nations [34, 35]. Ethiopian office studies yield F-statistics of 400-500, explaining 85-95% variance, aligning closely but with greater emphasis on cultural holidays influencing patterns [32, 33]. These comparisons affirm the results' consistency while highlighting the NDDC's data as a benchmark for predictable waste flows in administrative hubs, potentially informing WTE models with higher reliability than variable municipal streams [27, 28].

Challenges in the ANOVA application include the short four-week audit period, limiting capture of long-term trends like seasonal or holiday variations, a common limitation in Nigerian waste studies where annual data reveals 10-20% fluctuations [42, 43]. The high R^2 (0.996) may overstate predictability due to unaccounted confounders like staff absences, potentially biasing operational planning [31, 24]. Opportunities lie in leveraging the significant differences for adaptive management, such as AI-driven forecasting to reduce costs by 15-25% through optimized collection [21, 22]. Limitations also stem from potential underreporting of informal waste diversion, common in institutions where 5-15% escapes audits, suggesting integrated sensor tech for future accuracy [25, 29]. Challenges with data homogeneity (low CV) indicate need for multi-site validation to generalize, but opportunities for WTE include using predictable peaks for steady feedstock, enhancing energy output in pilots [27, 26]. Overall, while limitations highlight need for extended monitoring, the results open avenues for policy reforms promoting institutional waste tracking in Nigeria [30, 10].

The ANOVA-confirmed patterns imply strong feasibility for integrating WTE systems in office settings, where predictable waste flows support consistent syngas production, potentially yielding 0.5-1 kWh/kg from mid-week highs [27, 28]. This could reduce reliance on erratic grid power in Port Harcourt, with implications for cost savings estimated at 20-30% through on-site energy recovery [25, 26]. The high explanatory power suggests minimal adjustments needed for seasonal scaling, aligning with literature on institutional WTE pilots showing 85-95% uptime [21, 29]. Broader implications include environmental gains, reducing landfill methane by utilizing 949.3 kg/week, equivalent to 0.5-1 ton CO_2e avoidance [44, 45]. For Nigeria, this positions offices as WTE hubs, informing national policies for decentralized energy [30, 10].

Table 4: One-Way ANOVA Results for Daily Solid Waste Generation

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Statistic	p-value
Between Groups (Days)	35045.23	6	5840.87	892.87	< 0.001
Within Groups (Error)	137.38	21	654.00%		
Total	35182.61	27			

C. Physicochemical and Energy Characterization of Generated Waste

➢ *Physical Composition Analysis*

The stratified sampling and manual sorting of 800 kg of waste (200 kg per week) yielded the following average physical composition, presented in Table 5.

Table 5: Physical Composition of NDDC Headquarters Office Solid Waste

Component	Mass Fraction (% wt, as Received)	Std Dev (±)	Description/Examples
Paper & Cardboard	43.8	1.5	Office paper, files, packaging, newspapers
Plastics	13.5	1.2	PET bottles, LDPE bags, food packaging, cups
Organic/ Putrescibles	26.4	2.1	Food scraps, fruit peels, tea bags
Metals	3.8	0.6	Beverage cans, foil, staples
Glass	2.9	0.5	Bottles, broken glassware
Textiles & Leather	2.7	0.4	Fabric, leather goods
Inert/ Others	6.9	0.8	Ceramics, dust, composite materials
Hazardous/ E-waste	<0.1	-	Batteries, toner cartridges, small electronics

Segregated and Handled Separately as Per Protocol.

The physical composition analysis of office solid waste at the NDDC Headquarters reveals a predominantly combustible stream, with paper and cardboard at 43.8% and organics at 26.4%, together forming over 70% of the mass,

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which offers substantial operational advantages for thermal conversion in a pilot-scale WTE plant by providing a high-calorific feedstock that can sustain consistent gasification or pyrolysis processes [20, 21]. Plastics at 13.5% enhance energy density due to their high heating value, suggesting that preprocessing steps like shredding and mixing could optimize reactor feed homogeneity, reducing downtime and improving syngas quality for electricity generation [26, 27]. The low fractions of metals (3.8%) and glass (2.9%) minimize slag formation and equipment wear, allowing for simpler cleaning protocols and extended operational cycles, while the negligible hazardous waste (<0.1%) simplifies safety measures during handling [25, 22]. Inert materials at 6.9% pose minor challenges but could be segregated pre-conversion to boost efficiency, indicating opportunities for on-site sorting systems integrated with daily collection routines to streamline operations [23, 24]. Overall, the 83.7% combustible portion supports viable energy recovery, potentially generating 0.5-1 kWh per kg processed, informing operational scaling for similar office environments in energy-scarce regions [28, 30].

The composition profile at the NDDC Headquarters, with paper and cardboard dominating at 43.8%, aligns closely with literature on institutional waste in Nigerian universities and offices, where paper fractions range 40-50%, reflecting administrative activities, though slightly higher than municipal averages (30-40%) due to focused generation sources [21, 20]. Organics at 26.4% are lower than typical Nigerian MSW (50-70%), but comparable to office-specific studies in Enugu (25-35%), suggesting reduced food waste from canteen controls versus household dominance in broader audits [25, 26]. Plastics (13.5%) match findings in Uyo offices (10-15%), higher than earlier Port Harcourt data (5-10%), indicating increasing plastic use in packaging over time [22, 23]. Metals and glass at 3.8% and 2.9% are consistent with low values in institutional settings (2-5%), less than industrial MSW (5-10%), while textiles (2.7%) and inerts (6.9%) parallel Abuja audits (3-7%), with hazardous waste <0.1% underscoring minimal e-waste in offices versus urban mixes [31, 19]. Comparatively, Indian office waste shows similar paper (40-45%) but higher organics (30-40%), while Ethiopian institutions report 35-45% paper, affirming the NDDC's profile as typical for developing country offices with high recyclables [34, 32]. The 83.7% combustible fraction exceeds municipal benchmarks (60-70%), highlighting office waste's superior WTE suitability [44, 45].

Challenges in the composition analysis include the stratified sampling of 800 kg potentially underrepresenting seasonal variations, as literature notes 10-20% fluctuations in organics from rainy seasons increasing moisture, a limitation common in short-term Nigerian audits [42, 43]. Standard deviations (0.4-2.1%) indicate reliable means but may mask micro-variations from department-specific waste, suggesting opportunities for finer-grained sampling by floor or unit to refine WTE feedstock predictions [21, 22]. Limitations arise from manual sorting's subjectivity, potentially overestimating combustibles if misclassification occurs, though low hazardous fraction reduces risks but challenges safe disposal integration [8, 31]. Opportunities abound in the high paper-plastic-organic mix, enabling hybrid WTE with recycling, potentially diverting 50-60% for material recovery and boosting energy from the rest [27, 28]. Inert fractions pose disposal challenges but offer ash reuse in construction, turning limitations into sustainable loops [30, 29]. Overall, while challenges highlight need for longitudinal data, the composition unlocks opportunities for cost-effective, low-emission WTE in offices [44, 45].

The composition's 83.7% combustible content implies high feasibility for pilot WTE, with paper and plastics providing stable energy yields (15-20 MJ/kg), supporting gasification for 0.3-0.5 kWh/kg, as per Nigerian institutional models [26, 28]. Low inerts minimize residues, implying reduced post-processing costs, while organics enable co-digestion hybrids for biogas enhancement [25, 27]. This could offset NDDC's energy needs by 10-20%, informing scalable designs for Port Harcourt offices [30, 23]. Broader implications include emission reductions from diverted landfills, aligning with sustainability goals [44, 45].

➢ *Proximate and Ultimate Analysis*

Results from the standardized laboratory analyses are consolidated in Table 6. All values are the mean of triplicate measurements on composite samples from each weekly batch.

Table 6: Proximate and Ultimate Analysis of NDDC Office Waste

Parameter	As-Received Basis	Dry Basis	Unit	Method
Moisture Content	25.4 ± 1.2	-	% wt	ASTM D3173
Volatile Matter	55.1 ± 1.5	73.9 ± 1.2	% wt	ASTM D3175
Fixed Carbon	14.9 ± 0.8	20.0 ± 0.7	% wt	By Difference
Ash Content	4.6 ± 0.3	6.1 ± 0.3	% wt	ASTM D3174
Carbon (C)	34.6 ± 0.9	46.4 ± 0.8	% wt	ASTM D5373
Hydrogen (H)	4.7 ± 0.2	6.3 ± 0.2	% wt	ASTM D5373
Nitrogen (N)	0.7 ± 0.1	0.9 ± 0.1	% wt	ASTM D5373
Sulfur (S)	0.2 ± 0.05	0.3 ± 0.05	% wt	ASTM D5373
Oxygen (O)	34.4 ± 1.5	46.3 ± 1.4	% wt	By Difference

Oxygen (dry) = 100 - (%C + %H + %N + %S + %Ash)

The proximate and ultimate analysis results provide critical operational insights for the pilot-scale waste-to-energy (WTE) plant, highlighting the waste's high volatile matter content at 73.9% on a dry basis, which indicates excellent reactivity for thermal processes like gasification or pyrolysis, enabling rapid devolatilization and efficient syngas production under controlled temperatures of 500-800°C [26, 47]. With moisture at 25.4% as-received, predrying to below

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15% would be essential to avoid energy losses from evaporation, suggesting integration of solar or waste-heat dryers in operations to enhance net efficiency by 10-20% [26, 28]. The low ash content of 6.1% dry basis minimizes slag buildup, reducing maintenance downtime and extending reactor lifespan, while fixed carbon at 20.0% supports char formation for potential co-combustion or soil amendment, aligning with circular operations [25, 22]. Elemental composition, with carbon at 46.4% and hydrogen at 6.3% dry basis, yields atomic ratios (H/C 1.63, O/C 0.75) typical of lignocellulosic materials, implying favorable combustion characteristics with lower tar formation in downdraft gasifiers [47, 48]. Low nitrogen (0.9%) and sulfur (0.3%) suggest reduced NO_x and SO_x emissions, allowing simpler scrubbers and compliance with local standards, thus optimizing flue gas treatment to 5-10% of operational costs [9, 10]. These parameters enable a feed rate of 5-10 kg/h, potentially generating 1-2 kWh per batch, informing real-time adjustments via sensors for moisture and volatiles to maintain 65-75% cold gas efficiency [30, 29].

The proximate analysis results, showing volatile matter at 73.9% dry basis and ash at 6.1%, closely mirror literature on Nigerian office and institutional waste, where volatiles range 70-80% and ash 5-10%, reflecting paper-dominated compositions higher than municipal averages (60-70% volatiles, 10-20% ash) due to lower inert contaminants [21, 20]. Moisture at 25.4% as-received is lower than typical Nigerian MSW (40-60%), but aligns with Enugu office waste (20-30%), suggesting better storage practices reducing biodegradation [25, 26]. Fixed carbon at 20.0% dry basis matches Uyo institutional samples (18-22%), suitable for char-based energy, contrasting with higher values in woody biomass (25-30%) [22, 47]. Ultimate analysis carbon (46.4%) and hydrogen (6.3%) are consistent with Lagos office waste (45-50% C, 5-7% H), yielding H/C ratios (1.5-1.7) indicative of efficient pyrolysis, similar to Indian urban organics [34, 35]. Low nitrogen (0.9%) and sulfur (0.3%) parallel Ethiopian office audits (0.5-1.0% N, <0.5% S), lower than industrial MSW (1-2% N), minimizing acid gas formation [32, 33]. Oxygen at 46.3% and O/C 0.75 fit lignocellulosic profiles in African studies (0.7-0.8 O/C), supporting gasification over combustion for reduced CO_2 [44, 45]. These comparisons affirm the waste's superior WTE potential compared to heterogeneous municipal streams, with parameters exceeding global developing country averages for energy density [4, 49].

Challenges in the analysis include triplicate measurements potentially insufficient for capturing batch variability, as literature notes 5-10% fluctuations from seasonal humidity in tropical Nigeria, limiting generalizability without longer-term sampling [42, 43]. High volatiles (73.9%) pose tar formation risks in operations, a common limitation in biomass WTE requiring catalytic cracking, but opportunities exist for biochar from fixed carbon (20.0%) as soil enhancer, offsetting 10-15% costs [25, 26]. Low ash (6.1%) reduces disposal needs but challenges residue utilization if contaminated, suggesting opportunities for vitrification in hybrid systems [27, 28]. Moisture (25.4%) limits direct feeding, necessitating energy-intensive drying, but opportunities for waste-heat recovery could improve net yields by 15-20% [21, 22]. Low sulfur/nitrogen minimizes emissions but challenges accurate detection in labs, with opportunities for advanced sensors in pilots [9, 10]. Atomic ratios indicate oxidation risks, limiting storage, but enable efficient syngas, opening biofuel co-production [47, 48]. Overall, while limitations highlight need for robust preprocessing, opportunities for integrated WTE-circular models prevail [30, 29].

The analysis implies favourable thermodynamics for the pilot plant, with high volatiles supporting 70-80% conversion efficiency in Aspen Hysys models, potentially yielding 0.4-0.6 kWh/kg from lignocellulosic-like properties [46, 27]. Low heteroatoms suggest emissions below NESREA limits (e.g., <50 mg/m³ SO_x), enabling simpler controls and cost savings of 10-15% [25, 9]. O/C ratio (0.75) indicates balanced oxidation, reducing CO formation for cleaner syngas [44, 45]. This supports scalability for Port Harcourt offices, integrating with grid for hybrid energy [30, 26].

➢ *Calorific Value Determination*

The energy content of the waste was measured directly and calculated, with results shown in Table 7.

Table 7: Calorific Values of NDDC Office Solid Waste

Parameter	Value	Unit	Method
Higher Heating Value (HHV)	18.92 ± 0.25	MJ/kg	Bomb Calorimetry (ASTM E711)
Lower Heating Value (LHV)	16.34 ± 0.22	MJ/kg	Calculated: LHV = HHV - 2.441 (9H + M)
Energy Density (as received)	12.19 ± 0.35	GJ/ton	Based on LHV and bulk density (avg. 265 kg/m³)

The calorific value results, with an HHV of 18.92 MJ/kg and LHV of 16.34 MJ/kg on a dry basis, offer key operational insights for the pilot-scale WTE plant, indicating a high-energy feedstock that can support efficient thermal conversion processes like gasification, where consistent heating values are crucial for maintaining reactor stability and optimizing syngas output [46, 27]. The energy density of 12.19 GJ/ton as-received suggests that approximately 1 ton of waste could generate 3-4 MWh of electricity at 25-30% efficiency, allowing for operational planning around batch sizes of 50-100 kg to achieve daily outputs of 50-100 kWh, which aligns with the NDDC's supplemental power needs [26, 28]. The close agreement between measured HHV and Dulong formula prediction (0.9% deviation) implies reliable elemental-based estimations for real-time adjustments, enabling operators to blend waste fractions for targeted LHV, reducing variability from paper-plastic mixes [47, 48]. Low deviation (±0.22-0.25 MJ/kg) in measurements points to uniform waste quality, facilitating automated feeding systems and minimizing downtime from recalibrations [25, 22]. Operationally, the values support hybrid modes, such as co-gasification with auxiliaries for heat recovery, potentially boosting net efficiency by 10-15% through waste-heat utilization for drying [9, 10]. These insights underscore the need for moisture

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monitoring pre-conversion, as the as-received basis reflects real-world handling, guiding protocols for storage to prevent energy loss from biodegradation [30, 29].

The HHV of 18.92 MJ/kg and LHV of 16.34 MJ/kg align well with literature on Nigerian institutional waste, where office-derived streams often range 15-20 MJ/kg HHV due to high paper and plastic content, exceeding municipal averages of 8-12 MJ/kg but comparable to Enugu office audits (16-19 MJ/kg) emphasizing lignocellulosic dominance [21, 20]. Energy density at 12.19 GJ/ton matches Osogbo institutional values (11-13 GJ/ton), higher than Port Harcourt MSW (9-11 GJ/ton), reflecting reduced organics and inerts in controlled environments [48, 23]. The Dulong deviation (0.9%) is lower than typical 2-5% in heterogeneous waste studies, indicating superior homogeneity versus Abuja municipal samples [31, 19]. Comparatively, Indian office waste reports HHV 17-19 MJ/kg, with similar low deviations validating elemental predictions, while Ethiopian institutions show 14-18 MJ/kg, attributing variations to socioeconomic factors [34, 32]. African urban averages (10-15 MJ/kg) are surpassed here, aligning with optimized fractions in Ilorin (16-19 MJ/kg) for WTE [26, 44]. These results exceed agricultural residues (12-15 MJ/kg) but match low-rank coals (15-20 MJ/kg), supporting literature on office waste as premium feedstock [45, 49]. The consistency reinforces global trends where institutional waste outperforms municipal in energy potential due to composition [4, 50].

Challenges in the calorific value determination include reliance on triplicate composites, potentially limiting representation of heterogeneous batches, as literature notes 5-10% variability from sampling errors in Nigerian waste [42, 43]. The as-received basis may underestimate dry potential if moisture fluctuates seasonally, a limitation in tropical audits requiring extended monitoring [21, 22]. Opportunities emerge from the high HHV, enabling hybrid WTE with biofuels for 20-30% efficiency gains, turning challenges into integrated systems [27, 28]. Low deviation offers predictive modeling opportunities via Dulong for real-time optimization, though limitations in lab-scale calorimetry may not capture pilot losses [25, 26]. Energy density challenges disposal of low-value residues but opens ash valorization for construction, reducing environmental burdens [9, 10]. Overall, while limitations highlight need for in-situ testing, opportunities for scalable WTE prevail, supporting policy for institutional energy autonomy [30, 29].

The values imply design adaptations like insulated reactors to leverage high HHV for self-sustaining operations, potentially achieving 70-80% conversion with minimal external input [46, 27]. Low moisture supports compact drying units, enhancing portability for office pilots, while energy density informs storage volumes for 1-2 week buffers [25, 22]. Performance-wise, Aspen simulations could predict 0.4-0.6 kWh/kg, aligning with Nigerian benchmarks for reduced grid dependency [26, 28]. Broader implications include emission minimization from clean combustion, fostering sustainable models in Port Harcourt [30, 44].

IV. CONCLUSION

This research identified the substantial potential for waste-to-energy valorisation of the solid waste produced at the NDDC Headquarters in Port Harcourt, Nigeria.

The thorough waste audit showed predictable generation patterns of 135.6 kg/day, with statistically significant weekday peaks (162.4 kg/day) and weekend declines (74.1 kg/day), allowing optimised feedstock supply scheduling in WTE operations. Office waste is predominantly combustible, with paper/cardboard (43.8%), organics (26.4%), and plastics (13.5%) making up 83.7% of the bulk, while metals (3.8%), glass (2.9%), and inert materials (6.9%) are minimal. High volatile matter (73.9% dry basis), moderate moisture (25.4% as-received), low ash (6.1% dry basis), and fixed carbon (20.0% dry basis) were validated by approximate analysis for thermal conversion. Ultimately, carbon (46.4%), hydrogen (6.3%), and low nitrogen (0.9%) and sulphur (0.3%) concentrations showed minimal pollutant production during burning. HHV of 18.92 MJ/kg and LHV of 16.34 MJ/kg, with energy density of 12.19 GJ/ton as-received, make office solid waste a high-energy feedstock equal to low-rank coals and superior to municipal solid waste averages.

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