Global Journal of Research in
Engineering and Technology
Journal homepage: https://gsjournals.com/gjret/
ISSN: 2980-4205 (Online)

(RESEARCH ARTICLE)

Performance assessment of an urban solid waste-fired boiler with flue gas heat recovery in some locations in Nigeria

Awua Justin Tarka [1, *], Lucky Esiete [2] and Udeme Victor Akpan [1]

[1] *Department of Mechanical Engineering, Joseph Sarwuan Tarka University, Makurdi, Nigeria.*
[2] *Heritage Energy Operational Services Limited,Block P, Edjeba, Warri Delta State, Nigeria.*

Global Journal of Research in Engineering and Technology, 2026, 04(01), 001–014

Publication history: Received on 13 June 2026; revised on 21 July 2026; accepted on 24 July 2026

Article DOI: https://doi.org/10.58175/gjret.2026.4.1.0013

Abstract

Rapid industrialization and urban growth have intensified waste management and energy supply challenges in developing nations like Nigeria. This study presents the design, characterization, and performance evaluation of an urban solid waste (USW)-fired steam boiler system integrated with a waste-conditioning unit for moisture control. The system aims to enhance combustion efficiency, reduce fuel consumption, and contribute to sustainable waste-to-energy (WtE) conversion. Representative waste samples—including paper, plastics, textiles, and wood residues—were collected from four Nigerian cities (Aba, Akure, Kaduna, and Makurdi) and analysed for proximate, ultimate, and calorific properties following ASTM standards. The results showed significant variations ($p < 0.05$) among waste types, with plastics exhibiting the highest fixed carbon (21.30%) and calorific value, while paper recorded the highest ash content (13.79%). Combustion analysis revealed that lower moisture content and optimized excess air ratios improved furnace temperature, flue gas exergy, and overall boiler efficiency. The integration of the waste-conditioning unit effectively reduced moisture-induced energy losses, enhancing steady-state combustion. Correlation models established between higher heating value (HHV) and fuel parameters such as fixed carbon, ash, and oxygen contents ($R^2 > 0.95$) demonstrated reliable predictive capacity for energy estimation. The findings affirm the feasibility of utilizing heterogeneous urban solid wastes as renewable fuel sources for small- to medium-scale steam generation. This work contributes to advancing circular economy goals and supports the United Nations Sustainable Development Goals 7 and 13 through clean energy generation and climate action.

Keywords: Combustion; Efficiency; Energy Steam-Boiler; Waste**.**

1 Introduction

The rapid pace of industrialization and urbanization over the past century has intensified the global challenge of maintaining a clean and sustainable environment [1]. Growing populations and increasing consumption levels have led to unprecedented waste generation, exerting significant pressure on existing waste management systems and energy supply networks [2]. Solid, liquid, and gaseous wastes are continuously produced from extraction, manufacturing, and consumption activities, and their improper handling has become a major socio-environmental concern, particularly in developing countries [3].

Although fossil fuels have historically met most global energy needs, their limited reserves, rising extraction costs, and associated greenhouse gas (GHG) emissions make them unsustainable in the long term [4]. The resultant global warming and climate instability necessitate the search for cleaner, renewable, and more affordable energy alternatives [5]. In this context, waste-to-energy (WtE) technologies present a promising dual benefit: mitigating solid waste accumulation while simultaneously recovering useful thermal or electrical energy [6]. When integrated with recycling

* Corresponding author: Awua Justin Tarka

and composting systems, WtE facilities can substantially reduce the volume and weight of municipal solid waste (MSW) by up to 90% and 75%, respectively, thereby contributing to circular economy objectives.

Urban Solid Waste (USW)—comprising everyday items such as plastics, paper, textiles, food residues, wood, and metals—varies in composition depending on local lifestyles, consumption patterns, and levels of industrialization [7, 8]. Its heterogeneous nature poses a technical challenge to waste reduction and valorisation efforts. Nevertheless, the organic fraction of USW possesses significant calorific potential suitable for energy generation through thermal conversion processes.

Globally, municipal waste generation is projected to rise from 1.3 billion tonnes in 2012 to 4.2 billion tonnes by 2050 [9]. In Nigeria, the situation is particularly critical due to rapid urban growth, industrial expansion, and inadequate waste management infrastructure. Approximately 20 kg of solid waste is generated per capita annually, amounting to over 2.2 million tonnes nationwide [10]. Most of these wastes are indiscriminately dumped in open spaces, roadsides, or drainage channels, leading to severe environmental degradation, flooding, and public health risks [11, 12].

Despite efforts by federal and state governments to regulate waste management through sanitation agencies, legislation, and awareness campaigns [13], the gap between waste generation and its sustainable utilization persists. The growing waste burden underscores the urgency to develop technologically viable systems that can continuously convert municipal waste into useful energy [14]. Biomass-based thermal conversion technologies, in particular, have gained traction for their ability to utilize renewable feedstocks while significantly reducing CO_2 emissions compared to fossil fuel-based systems [15].

Solid waste, being a form of biomass, is abundantly available in urban environments and offers high potential for energy recovery when properly processed [16]. Through combustion in boilers, this waste can be transformed into heat and steam suitable for domestic and small-scale industrial applications. Moreover, by-products such as fly ash and bottom ash can be repurposed in construction and ceramics industries, adding further economic and environmental value [17].

This study introduces a novel design of an urban solid waste-fired steam boiler system integrated with a waste-conditioning unit connected to the flue gas exit. The conditioning unit functions to remove excess moisture from the waste feedstock, thereby enhancing combustion efficiency, reducing furnace batch time, and minimizing fuel consumption. This innovation not only addresses the challenges of inefficient waste incineration but also improves the overall thermal performance and sustainability of the system.

By aligning with the United Nations Sustainable Development Goals (SDGs) 7 and 13—which advocate for affordable clean energy and climate action—this research aims to provide a locally adaptable solution to Nigeria's twin challenges of waste management and energy insecurity. The system's deployment can support cleaner urban environments, promote renewable energy adoption, and contribute to achieving energy reliability and environmental sustainability in developing economies.

2 Materials and Methods

2.1 Study Locations and Sample Collection

Urban solid waste (USW) samples were collected from four major Nigerian cities representing different geographical zones: Aba (Abia State; 5°07′0″N, 7°22′0″E), Akure (Ondo State; 7°15′9″N, 5°11′35″E), Kaduna (Kaduna State; 10°31′20″N, 7°26′18″E), and Makurdi (Benue State; 7°44′28″N, 8°30′44″E). Sixteen representative samples were collected—four from each site—by manually gathering diverse solid wastes from municipal dumpsites using sterilized collection sacks. The sampling covered four waste categories: paper and paper products, plastics, textiles, and wood residues.

Table 5 List of Equipment and Apparatus used for the Analysis

S/N	Equipment	Model	Source	Purpose Country
1	Balance	Precision analytical	Adam Equipment	To weigh samples Nigeria
2	Ohmmeter	Multi Range	Travotech Agency	Resistance Nigeria

3	Pellets press mold	GHJ Series Rotary	Henan-Olten Machinery	To compress Nigeria samples
4	Electrodes	Cathode/An ode		To ignite Nigeria calorimeter
5	Oxygen tank		Travotech Agency	To hold Oxygen Nigeria
6	Metal bucket	Tin cylindrical	Innopack Co.	To hold Water Nigeria
7	Iron ignition wire			For measuring Nigeria Burnt Materials
8	Thermometer	Streck	Savillex HPX	For temperature Nigeria
9	Volumetric flask	Flat bottom	Duran Group	To hold water Nigeria
10	Steel wool			To check for leakage Nigeria
11	Liquid nitrogen			To ensure effective mix and frozen of the cut samples
12	Bomb calorimeter	XRY-1A oxygen box	Henan-Olten Machinery	For accurate measurement of heat values of the samples

2.2 Sample Preparation

The collected wastes were manually sorted to remove non-combustible and ferrous materials using magnets and handpicking. Each sample was then sun-dried for seven days to reduce moisture to below 25%, ensuring consistent combustion characteristics. Dried samples were further cut into small fragments (0.5–1.0 mm), ground using a hammer mill, and sieved to 250 µm according to ASTM D2013-86 standards. The resulting powders were compressed into uniform pellets using a pellet press mold for calorimetric and proximate analyses.

2.3 Operation of Urban Solid Waste (USW) Steam Boiler

A steam boiler was designed to utilize the characterized urban solid waste as feedstock. The system was designed for a working steam pressure of 10 bar and a fuel feed rate of 500 kg/h. The combustion chamber employed a mass-burn incineration approach with a water-wall furnace. A waste-conditioning unit was integrated into the flue gas exit to utilize waste heat for pre-drying the incoming feedstock, thereby enhancing combustion efficiency, reducing batch time, and minimizing fuel consumption.

For improved performance and emissions control, a circulating fluidized bed **(CFB)** boiler configuration was recommended, offering combustion efficiencies above 90% and nitrogen oxide emissions below 100 mg/Nm^3. Commercially proven CFB-based boiler types such as DZL, SZL, and DHL biomass-fired systems were evaluated as suitable models for scale-up and deployment.

The various operations and steps involved in a mass incineration plant for usw with energy recovery are as follows: The refuse collection vehicles enter into the waste to energy facility and dump the waste collected from the urban solid waste dumps into a pit where an overhead crane removes oversized items and mixes the waste to evenly distribute materials and moisture. The crane feeds the waste (500kg) into three refuse conditioners. The first refuse conditioner closest to the furnace is fed on to a grate, usually by means of a screw conveyor. The grate agitates and transports the wastes across the combustion chamber.

Combustion air is introduced from under the grate (underfire air) and from nozzles located in the furnace above the grate (overfire air). Underfire air initiates combustion and cools the grate. Overfire air helps to mix the combustion gases, ensures more complete combustion and reduces oxides of nitrogen (NOx). Other pollutants are removed in the scrubber and bag filter. Non - combustible (i.e.inert) material and ash are discharged from the end of the grate into a water quench tank. From there they are removed for further treatment, and ultimately, either recovered for use in construction or other applications or disposed of to landfill.

Energy is transferred from the hot flue gases to water in the tubes of a water-wall boiler generating hot water and steam. The steam is used either directly for heating of buildings or for industrial purposes like driving equipment such as pumps, compressors and to generate electricity. The cooled flue gases pass through refuge conditioner to dry the waste before exhaustion to the atmosphere through a chimney. This will increase combustion efficiency and reduce fuel consumption rate. [18]

2.4 Calorific Value Determination

The higher heating value (HHV) of each sample was determined using a bomb calorimeter in accordance with ASTM D5865-04. Each solid pellet was placed in an ignition cup connected to a 12 cm iron ignition wire between the electrode terminals. The bomb chamber was filled with pure oxygen at a pressure of 1000 kN/m^2. After ensuring electrical continuity, the bomb was submerged in a calorimeter bucket containing a known mass of water. The system was thermally insulated, and temperature changes were monitored for 2–3 minutes after ignition. The calorific value was calculated from the measured temperature rise, corrected for heat losses and wire combustion. Each test was conducted in duplicate, and the mean value was recorded for each waste type.

2.5 Proximate Analysis

Proximate analysis was performed following ASTM D2013 procedures to determine moisture content (MC), volatile matter (VM), ash content (AC), and fixed carbon (FC).

Moisture Content (MC):

One gram of each sample was oven-dried at 105 °C for one hour, cooled in a desiccator, and weighed.

$$MC = \frac{(P_i - P_s)}{P_i} \text{ x } 100 \qquad (1)$$

where P_i is the initial weight and P_s is the dried weight.

Volatile Matter (VM):

A 1 g sample was heated in a covered crucible at 950 °C for 7 min.

$$\mathrm{VM} = \left(\frac{\mathrm{P_S} - \mathrm{P_V}}{\mathrm{P_S}}\right) \times 100 \qquad (2)$$

where $\mathrm{P_S}$ is the sample weight after drying and $\mathrm{P_V}$ is the weight after volatile release.

Ash Content (AC): Samples were combusted at 950 °C to constant weight.

$$AC = \left(\frac{P_a}{P_v}\right) \times 100 \qquad (3)$$

where P_a is the ash weight and P_v is the weight after volatile removal.

Fixed Carbon (FC):

$$\mathrm{FC} = 100 - (\mathrm{MC} + \mathrm{VM} + \mathrm{AC}) \qquad (4)$$

2.6 Ultimate Analysis

Ultimate analysis was estimated from proximate results using empirical correlations [19]

$$C = 0.637FC + 0.455VM$$

$$H = 0.052FC + 0.062VM$$

$$O = 0.304FC + 0.476VM$$

where *C*, *H*, and *O* represent the percentages of carbon, hydrogen, and oxygen, respectively.

An analysis of variance (ANOVA) at a 5% significance level was conducted to determine whether the differences among sample categories were statistically significant.

2.7 Density and Specific Gravity Determination

The density and specific gravity of the waste materials were determined using the water displacement method due to their irregular shapes [20]. Samples of 3 cm length were weighed (Ms), then immersed in 500 mL of water. The displaced water volume ($V = M_2 - M_1$) was used to compute density and specific gravity as follows:

$$\rho = \frac{M_s}{V} \quad (5)$$

$$SG = \frac{\rho}{\rho_w} \quad (6)$$

where ρ_w is the density of water.

ρ is density of the sample, SG is specific gravity

3 Results and Discussion

The combustion process of the selected waste samples was investigated to evaluate the influence of major operational parameters and fuel characteristics on furnace performance, heat release rate, and emission tendencies. The analysis focused on the effects of moisture content, excess air ratio, chimney geometry, and flue gas properties, supported by detailed proximate and ultimate analyses of the waste fractions—Paper (A), Plastics (B), Textile (C), and Wood (D). The correlations between the higher heating value (HHV) and key fuel constituents such as ash, fixed carbon, and oxygen contents were also established to provide an integrated understanding of energy conversion efficiency.

3.1 Effect of Moisture Content

The influence of moisture content on combustion performance is illustrated in Figure 1. The wastes were first passed through a refuse conditioner to reduce their moisture before being introduced into the incinerator. It was observed that moisture content played a critical role in determining combustion stability and thermal efficiency. Wastes with higher moisture content required a longer drying duration and absorbed more heat, leading to a noticeable reduction in furnace temperature. When the moisture content exceeded a critical level, the available energy from the waste was insufficient to sustain auto-ignition, necessitating auxiliary fuel input to maintain normal combustion. Numerical simulations conducted for ten different moisture levels revealed that lower moisture contents yielded higher furnace temperatures and larger high-temperature zones. This occurred because drier wastes possessed higher calorific values and contained greater proportions of volatile combustibles, which ignited more readily and burned more completely. Conversely, high-moisture wastes not only reduced the overall furnace temperature but also increased the water vapor concentration in the flue gas, resulting in lower thermal efficiency. Consequently, the pre-drying process in the refuse conditioner proved essential for improving boiler efficiency and maintaining stable combustion conditions.

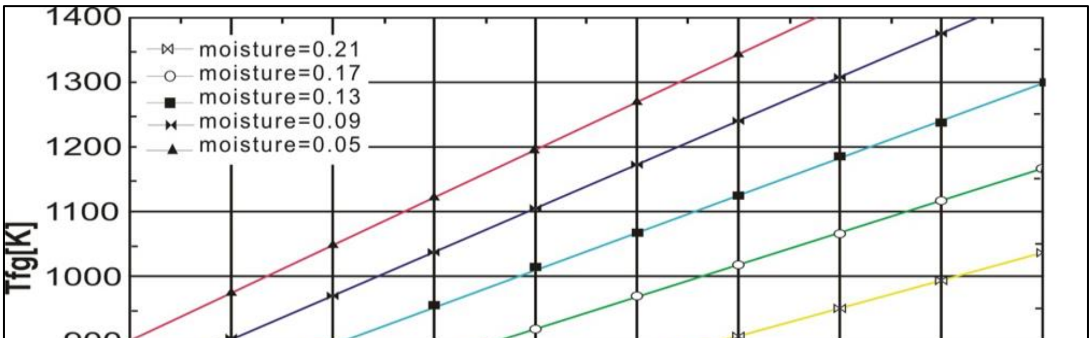

Figure 1 Variation of flue gas temperature with fuel calorific value at different moisture contents.

3.2 Effect of Excess Air on Combustion

Excess air ratio was another key determinant of the combustion process. Adequate excess air ensures complete oxidation of combustible gases and volatile matter, enhancing burning efficiency. As shown in Figure 2, when excess air was increased beyond the stoichiometric requirement, a gradual decline in furnace temperature was observed. This is because excess air introduces a cooling effect—diluting the combustion gases and increasing convective heat losses. While a moderate level of excess air promotes turbulence and uniform flame distribution, excessive amounts reduce the flame temperature and radiation heat transfer within the furnace. The upward shift of the flame centre with higher air ratios leads to less effective heat utilization at the lower furnace zones. Conversely, insufficient air supply caused incomplete combustion, characterized by unburnt carbon and higher CO emissions. Therefore, maintaining an optimum air–fuel ratio is critical for achieving complete combustion, minimizing heat loss, and reducing pollutant emissions. The simulation results confirmed that controlling the excess air can serve as an effective means of regulating furnace temperature and oxygen concentration in the flue gas.

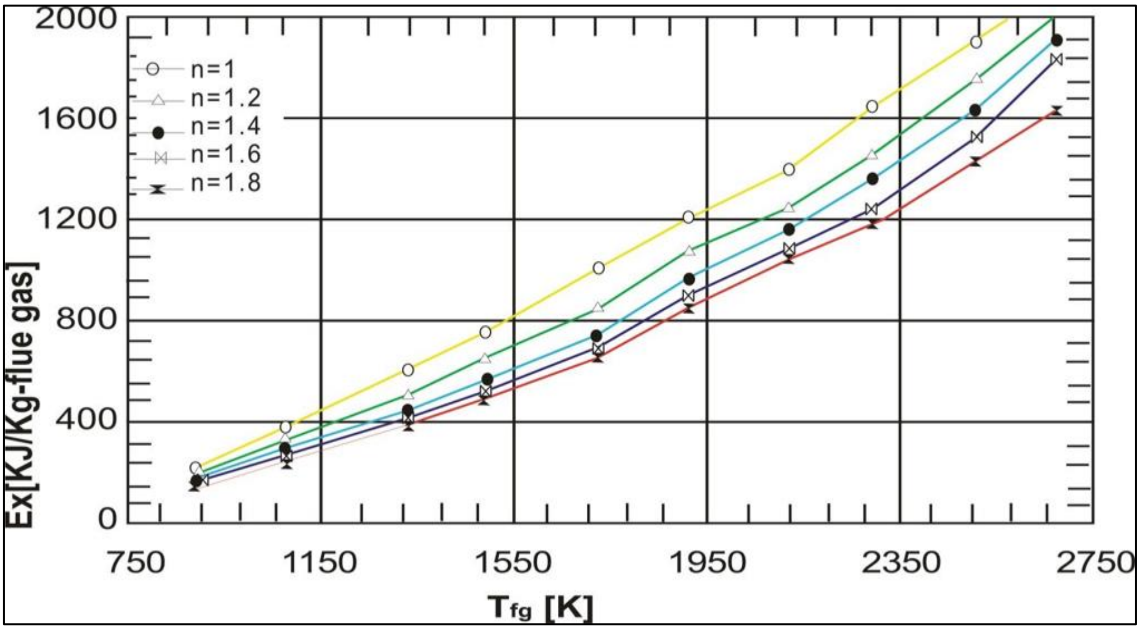

Figure 2 Variation of flue gas temperature with calorific value at different values of excess air

3.3 Interaction between Excess Air and Moisture Content

The combined effect of excess air and waste moisture content on furnace performance is presented in Figure 3. The figure indicates that high-moisture wastes generally exhibited lower furnace temperatures and consumed less oxygen due to their lower calorific value and slower reaction kinetics. This led to higher residual oxygen concentrations at the outlet. In contrast, wastes with lower moisture contents achieved higher temperatures and more complete oxidation, consuming greater amounts of O_2.

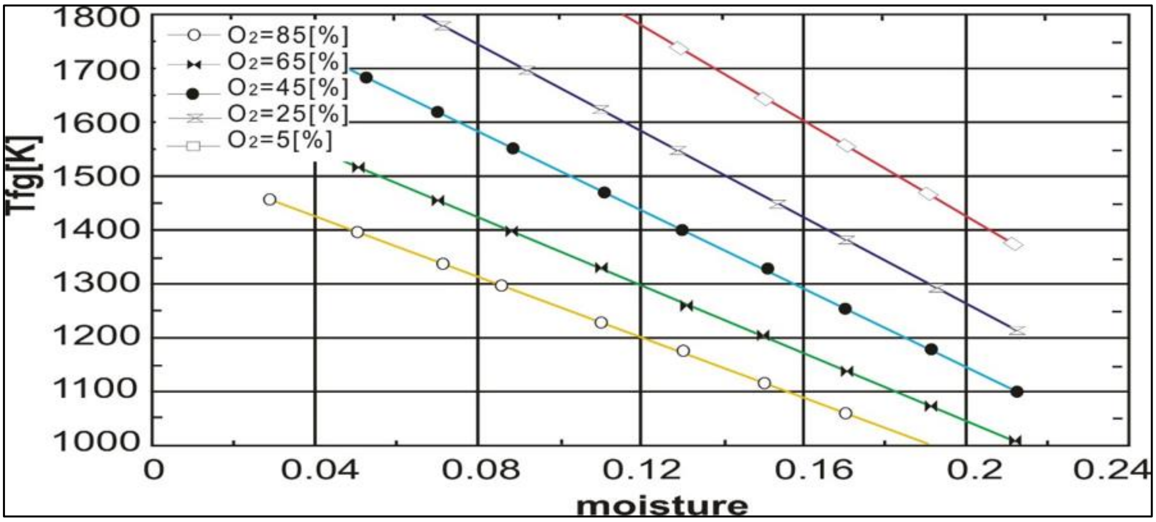

Figure 3 Effect of Moisture Content and Excess Oxygen on Flue Gas Temperature.

These results suggest that the air supply rate, particularly in the primary combustion zone, should be adjusted dynamically based on the moisture content of the feedstock. For drier wastes, the air distribution along the grate should be increased to sustain combustion, while for moist wastes, the air flow should be carefully regulated to avoid quenching effects. Optimizing the air supply relative to waste characteristics is essential for stable combustion and minimal pollutant formation.

3.4 Heat Losses through Boiler Surfaces

Energy losses from the combustion system were also examined by analysing heat flux through the external surface of the steam boiler as a function of its thermal power and operating pressure, as shown in Figure 4. The results indicate that heat flux losses to the atmosphere increased with rising thermal power and steam pressure. The magnitude of this loss depended on the effective heat exchange surface area, the temperature gradient between the steam and the ambient environment, and the heat transmission coefficient.

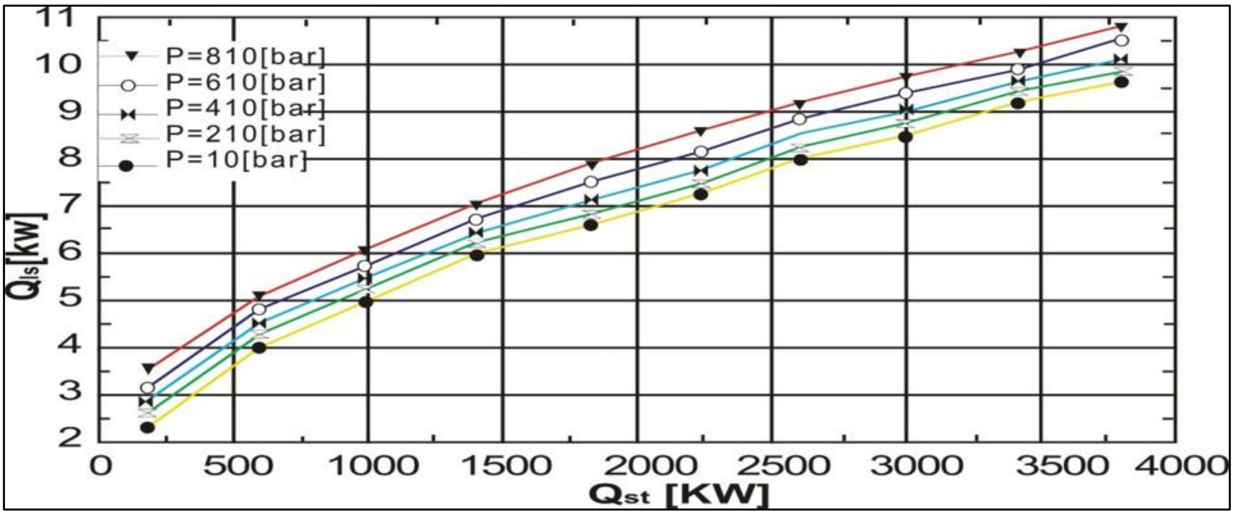

Figure 4 Relationship Between Heat Loss Through the External Wall and Usable Power of the Steam Boiler at Varying Operating Pressures.

For modelling simplicity, this work considered only the effects of steam pressure and boiler thermal power, based on the manufacturer's data [21]. The adopted formulation allowed for an accurate estimation of surface losses without detailed knowledge of insulation thickness or material properties. These losses, though relatively small, become significant in high-capacity boilers and should be minimized through proper insulation and thermal management strategies.

3.5 Influence of Chimney Height

The influence of chimney height on combustion dynamics was evaluated by examining the relationship between flue gas temperature, draught, and gas velocity. As shown in Figure 5a, an increase in flue gas temperature resulted in a higher draught requirement, which further intensified with chimney height. Similarly, Figure 5b shows that higher furnace temperatures corresponded to higher flue gas velocities within the chimney, particularly at greater heights. This relationship reflects the enhanced buoyancy of hot gases, which strengthens natural draught. However, excessively tall chimneys can lead to undesirable pressure differentials, potentially disrupting the stability of the combustion zone. Therefore, optimizing chimney height and temperature gradient is crucial for maintaining efficient gas evacuation and minimizing backflow or incomplete combustion.

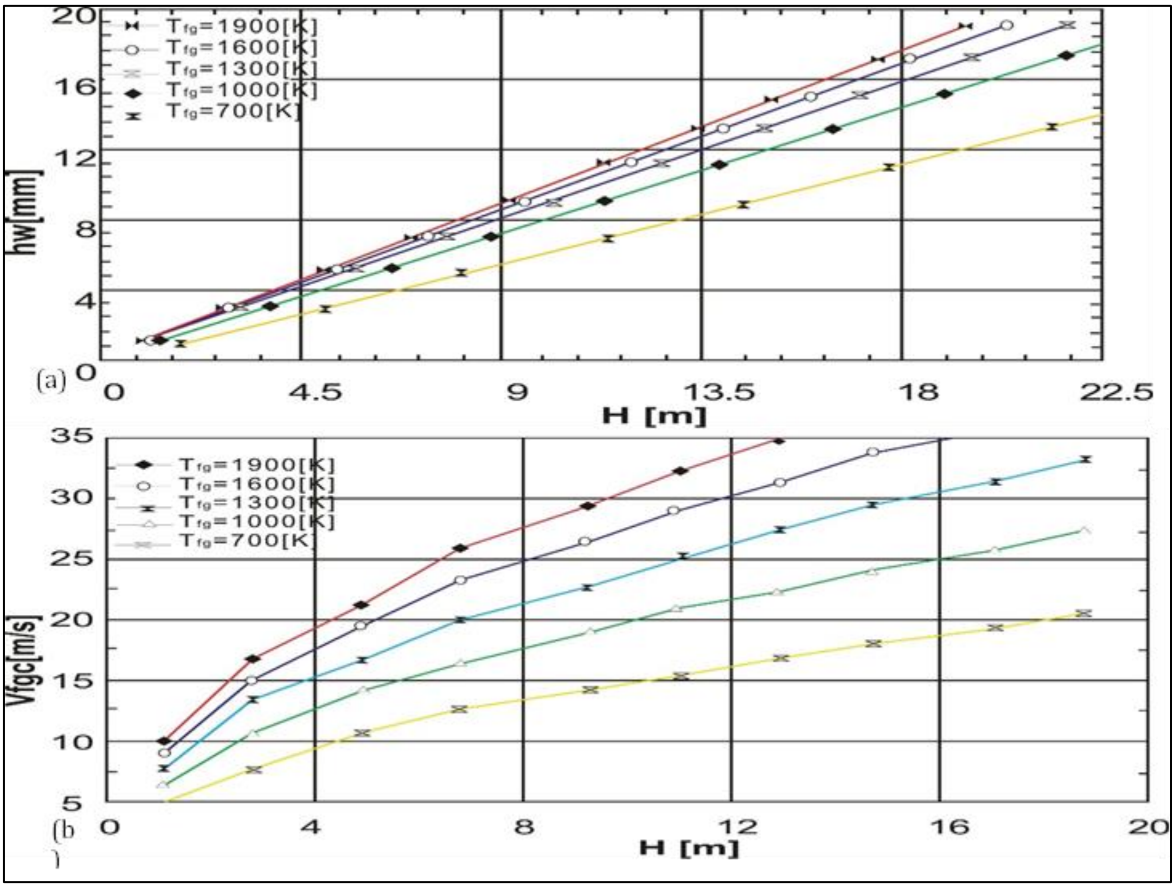

Figure 5 (a) Variation of required draught (mm H_2O) with chimney height above the fire grate (m) at different furnace temperatures; (b) Variation of flue gas velocity within the chimney with chimney height above the fire grate (m) at different furnace temperatures.

3.6 Specific Heat Capacity and Exergy of Flue Gas

The specific heat capacity and specific exergy of flue gases are also important parameters influencing the overall energy balance of the system. The variation of these parameters with furnace temperature under different excess air ratios is shown in Figures 6. It was observed that as the excess air ratio increased, both the specific heat and specific exergy of the flue gas decreased. This can be attributed to the dilution of flue gas composition with inert nitrogen and unreacted oxygen, which reduces the effective thermal capacity and available work potential of the combustion products.

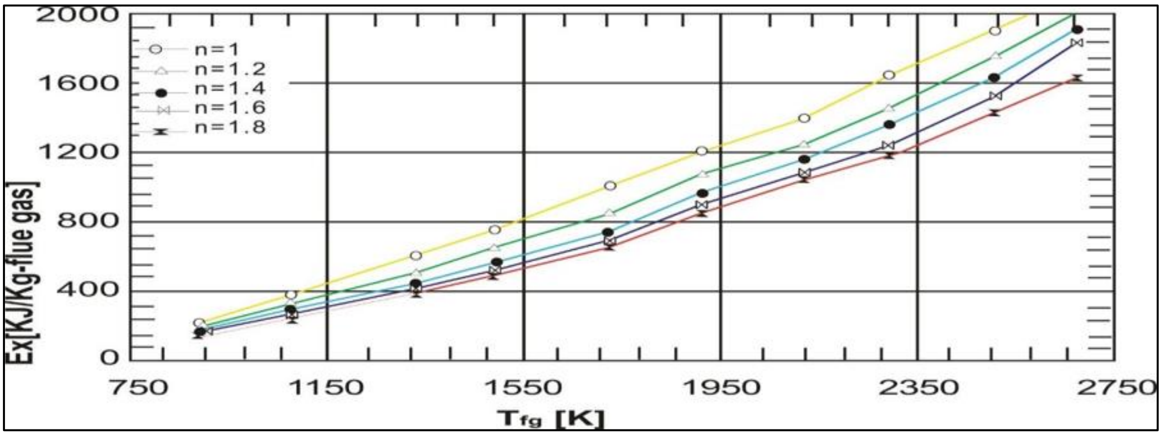

Figure 6 Variation of flue gas specific exergy with furnace temperature at different excess air ratios.

These results align with the observations of [22], who emphasized that flue gas enthalpy and exergy are strongly dependent on excess air level, waste composition, and flue gas temperature. Thus, optimizing excess air not only improves combustion completeness but also maximizes the thermodynamic efficiency of the system.

3.7 Fuel Characterization

3.7.1 Proximate Analysis

The proximate analysis of the waste samples, summarized in Table 1 and Figure 7, revealed statistically significant differences ($p < 0.05$) among Paper (A), Plastics (B), Textile (C), and Wood (D). The ash content varied from 3.82% in Plastics to 13.79% in Paper. The relatively low ash content in Plastics (B) indicates a cleaner combustion with reduced risk of fouling and slagging in heat exchangers, while the high ash content in Paper (A) and Textile (C) suggests potential challenges in maintaining consistent combustion. These values differed from those reported by [23], who observed ash contents below 2% for similar waste types, and also exceeded the range (0.1–0.5%) noted by [24] for typical woody biomass. [25] emphasized that wastes with high ash contents tend to deposit residues on furnace walls, obstructing gas flow and impairing heat transfer. The elevated ash levels observed here, particularly in Textiles, may be due to high mineral content or inorganic additives, consistent with observations by [26] and [27].

Table 1 Analysis of Variance (ANOVA) for Proximate Composition Results

Groups	**Count**	**Sum**	**Average**	**Variance**		
Moisture Content	5	22.7	4.54	0.9475		
Ash Content	5	91.02	18.204	293.9389		
Volatile Matter	5	301.44	60.288	138.9664		
Fixed carbon	5	84.63	16.926	22.60443		
Sulphur Content	5	9.209	1.8418	16.28208		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11019.41	4	2754.853	29.13712	4.33E-08	2.866081
Within Groups	1890.957	20	94.54786			
Total	12910.37	24				
Ho: F ≤ Fcrit				**α = 0.05**		
Ha: F > Fcrit						

3.7.2 Significant Difference

Fixed carbon values ranged from 9.45% (Textile) to 21.30% (Plastics), with Plastics (B) and Wood (D) exhibiting the highest carbon fractions, indicating their strong potential as heat-generating fuels. Fixed carbon serves as the main source of sustained combustion energy and is closely correlated with heating value. As noted by [28], higher carbon content translates into greater fuel calorific value and combustion stability. Volatile matter contents were relatively high across all samples, ranging from 64.23% (Textile) to 66.64% (Wood), consistent with the range of 70–80% reported by [29]. High volatile content facilitates ignition and enhances flame stability but may lead to faster burning, as observed for Wood and Plastics. Conversely, lower volatile content fuels, such as Textiles, burn more slowly, producing steadier heat but potentially incomplete combustion if not adequately aerated.

The moisture contents of the samples varied between 3.01% (Paper) and 5.63% (Textile), which are notably lower than the typical range of 5–20% for dried biomass [28]. Low moisture levels are advantageous for combustion since less energy is expended on water evaporation, improving thermal efficiency and combustion stability. [30] also observed that higher moisture content reduces the HHV due to energy losses in moisture vaporization. The sulphur contents across all samples ranged from 0.029% to 0.06%, well below the emission limits stipulated by Australian and German biomass fuel standards (≤0.08%), implying low potential for SOx formation and associated environmental impacts.

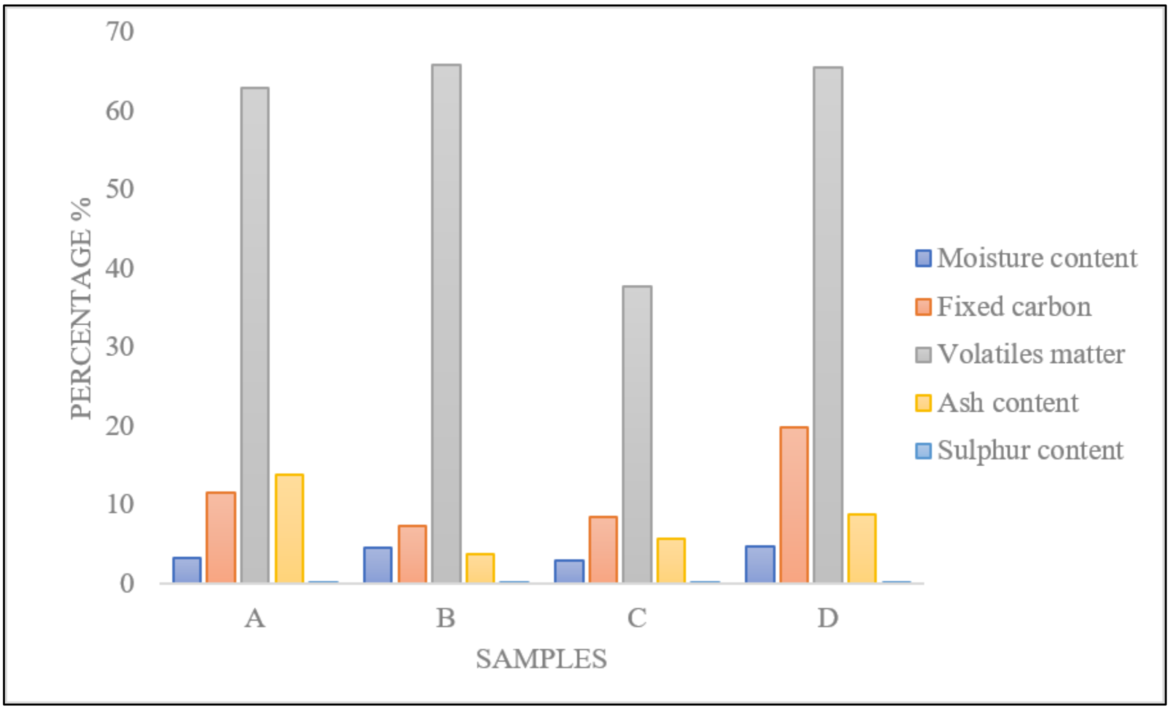

Figure 7 Proximate Composition of the Waste Samples

3.8 Ultimate Analysis

The ultimate analysis revealed significant variations in elemental composition among the samples (Table 2 and Figure 8). Hydrogen content ranged from 3.11% (Textile) to 5.56% (Plastics), aligning with the typical 5–6% range reported [31]. Higher hydrogen content contributes to greater heating value due to hydrogen's high energy-to-weight ratio and clean-burning characteristics. Oxygen content varied between 22.99% (Textile) and 40.69% (Plastics), consistent with the 40–44% range reported by [28]. While oxygen is essential for combustion reactions, excessive oxygen within the fuel reduces the HHV since it contributes to internal oxidation and lowers available energy density. Nitrogen content varied from 0.36% (Textile) to 0.65% (Plastics), exceeding some international standards for biomass fuels (≤0.3%), suggesting that certain samples could produce higher NOx emissions upon combustion. However, the overall nitrogen content remains moderate, indicating manageable emission levels under optimized air supply conditions.

Table 2 Analysis of Variance for Ultimate Analysis Results

SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Carbon	5	201.3931	40.27862	74.47518		
Hydrogen	5	24.4975	4.8995	1.034901		
Oxygen	5	180.0182	36.00364	54.47189		
Nitrogen	5	2.8622	0.57244	0.014299		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6360.124	3	2120.041	65.23391	3.43E-09	3.238872
Within Groups	519.9851	16	32.49907			
Total	6880.109	19				
Ho: F ≤ Fcrit				**α = 0.05**		
Ha: F > Fcrit						

3.8.1 Significant Difference.

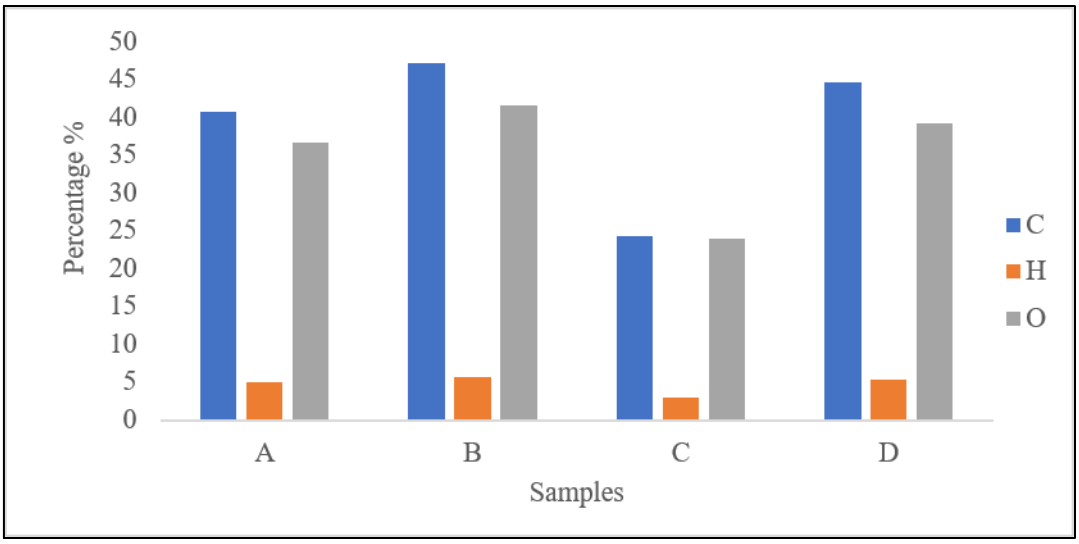

Figure 8 Ultimate Analysis of the Waste Samples

3.9 Correlation between Heating Value and Fuel Properties

The relationship between HHV and key fuel constituents was analysed to develop empirical correlations for energy estimation. As shown in Figure 6, HHV decreased with increasing ash content, with a strong negative correlation (R^2 = 0.9944). This aligns with [32], who reported that each 1% increase in ash reduces the HHV by approximately 0.2 MJ/kg. Since ash is non-combustible, higher ash fractions effectively dilute the energy content of the fuel. In contrast, a positive correlation was observed between HHV and fixed carbon (R^2 = 0.9571), as shown in Figure 7, confirming that carbon is the principal contributor to heat release. The regression model obtained—HHV = 661.44 + 187.34FC—indicates that 95.71% of the variability in HHV is attributable to fixed carbon content. Similarly, Figure 8 shows a strong positive correlation between HHV and oxygen content (R^2 = 0.9887), described by the equation HHV = −494.27 + 119.5OC, though this trend differs from earlier findings by [28], who noted that higher oxygen typically lowers calorific value. The present result suggests that, within certain compositional ranges, oxygen-rich wastes may favour more efficient combustion reactions, improving apparent heating performance.

3.10 Physical Properties

The physical characteristics of the wastes were also considered. As shown in Figure 9, density values ranged from 214 kg/m^3 (Textile) to 256 kg/m^3 (Plastics). Denser materials generally possess higher energy content per unit volume and longer burning durations. This agrees with the observations of [32] and [33], who reported that denser biomass fuels are more energy-dense and provide steady heat output. The specific gravities of the studied samples were within the “light” classification (≤0.36), indicating relatively low bulk densities but favourable ignition properties. Particle size analysis (Figure 10) showed variations between 212 µm (Plastics) and 425 µm (Textile). Smaller particles exhibited higher HHVs due to faster heating rates and more efficient heat transfer, consistent with the findings of [33] and [28]. Fine particles facilitate uniform combustion and reduce char formation, whereas larger particles require longer residence times to achieve complete oxidation.

In summary, the combined experimental and numerical analyses demonstrate that combustion efficiency is highly dependent on waste moisture content, excess air ratio, and fuel composition. The proximate and ultimate analyses highlight the superior combustion characteristics of Plastics (B) and Wood (D), attributed to their low ash and moisture contents, high fixed carbon, and balanced volatile fractions. The established correlations between HHV and compositional parameters provide valuable predictive tools for assessing the energy potential of mixed solid wastes. These findings underscore the necessity of pre-drying, air supply optimization, and particle size control to ensure stable, efficient, and environmentally compliant waste-to-energy conversion processes.

4 Conclusions

This study successfully demonstrated the technical feasibility and environmental relevance of converting urban solid waste (USW) into useful thermal energy through an integrated steam boiler system equipped with a waste-conditioning unit. The proximate and ultimate analyses of representative waste samples from Aba, Akure, Kaduna, and Makurdi revealed that plastics and wood residues possess superior combustion characteristics due to their low ash and moisture contents, high fixed carbon fractions, and favorable heating values. The results further established strong correlations between the higher heating value (HHV) and key fuel constituents such as ash, fixed carbon, and oxygen contents, providing reliable models for predicting the energy potential of mixed solid wastes.

The combustion performance analysis indicated that moisture content and excess air ratio are critical parameters influencing furnace temperature, combustion stability, and thermal efficiency. The integration of a waste-conditioning unit at the flue gas exit significantly enhanced overall system efficiency by utilizing waste heat to pre-dry the feedstock, thereby minimizing fuel losses and reducing drying time. Additionally, optimization of chimney height and air–fuel ratio improved draught, flame stability, and emission control.

Overall, the designed urban solid waste-fired boiler system provides a sustainable, low-cost, and locally adaptable technology for addressing Nigeria’s dual challenges of municipal waste management and energy insecurity which makes it unique. Its deployment can contribute to cleaner urban environments, reduce reliance on fossil fuels, and promote renewable energy generation in alignment with global circular economy initiatives and the United Nations Sustainable Development Goals 7 and 13.

Recommendations

Future research should focus on optimizing the combustion chamber geometry and heat recovery components to further enhance thermal efficiency and emission control. Automation using real-time sensors is also recommended to maintain optimal air–fuel ratios for varying waste compositions. Pilot-scale deployment in urban communities is encouraged to assess long-term performance, economic viability, and environmental impact.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] C. Harper, & Snowden, M. *Environment and society: Human perspectives on* environmental issues. Routledge. (2017).

[2] N. P Hariram, K. B., Mekha, V., Suganthan, and K. Sudhakar. Sustainalism: An integrated socio-economic environmental model to address sustainable development and sustainability. *Sustainability*, *15*(13), 10682. (2023).

[3] Kumari, T., & Raghubanshi, A. S.. Waste management practices in the developing nations: challenges and opportunities. Waste Management and Resource Recycling in the Developing World, 773-797.(2023).

[4] International Energy Agency 2020. World Energy Outlook 2020 – Analysis - IEA

[5] M. Bilgili,, A., Ozbek, , B., Sahin and Kahraman, A.. An overview of renewable electric power capacity and progress in new technologies in the world. Renewable and Sustainable Energy Reviews, 49, 323-334. (2015).

[6] D., Moya, C., Aldás, G., López, and Kaparaju, P. Municipal solid waste as a valuable renewable energy resource: a worldwide opportunity of energy recovery by using Waste-To-Energy Technologies. *Energy Procedia*, *134*, 286-295. (2017).

[7] J. P. Lima,., K. C. D. Lobato,., Leal, F., and Lima, R. D. S.. Urban solid waste management by process mapping and simulation. *Pesquisa Operacional*, *35*, 143-163. (2015).

[8] A., Ebekozien, C., Aigbavboa, F. E., Emuchay, M., Aigbedion, I. F., Ogbaini, and Awo-Osagie, A. I. Urban solid waste challenges and opportunities to promote sustainable developing cities through the fourth industrial revolution technologies. International Journal of Building Pathology and Adaptation, (ahead-of-print). (2022).

[9] C. Ram,. A., Kumar, and P. Rani, Municipal Solid Waste Management: A review of waste to energy (WtE) approaches. *BioResources* 16(2), 4275-4320 (2021).

[10] O.R. Olafusi, Waste Disposal and Management; a case for healthy environment.Unpublished Housing Seminar Report, Department of Architecture, Federal University of Technology, Akure, Nigeria. (2014).

[11] B Fikadu,. Institute of engineering and technology department of urban planning, design and development (Doctoral dissertation, Wollega University). (2018).

[12] NIMET. Agrometeorological Bulletin No.8, Dekad 2, March (11 –20) ISSN: 2315-9790, Nigerian meteorological agency, 8, 10-12. 2018.

[13] Amasuomo, Ebikapade; Baird, Jim Solid waste management trends in Nigeria Journal of Management and Sustainability. DOI: 10.5539/jms.v (2016)..

[14] S., Sharma, Basu, S., Shetti, N. P., Kamali, M., Walvekar, P., and Aminabhavi, T. M. . Waste-toenergy nexus: a sustainable development. Environmental Pollution, 267, 115501. (2020).

[15] K. O., Yoro, and Daramola, M. O. CO2 emission sources, greenhouse gases, and the global warming effect. In *Advances in carbon capture* (pp. 3-28). Woodhead Publishing. (2020).

[16] S. J., Dabe, P. J., Prasad, A. N., Vaidya, and Purohit, H. J.. Technological pathways for bioenergy generation from municipal solid waste: Renewable energy option. *Environmental Progress & Sustainable Energy*, *38*(2), 654-671. (2019).

[17] A. Q., Vilakazi, S., Ndlovu, Chipise, L., and Shemi, A. The recycling of coal fly ash: A review on sustainable developments and economic considerations. *Sustainability*, *14*(4), 1958. (2022).

[18] B.B. Jon Convention of an urban solid waste boiler plant to burn alternate fuels. Thermal Engineering Group, Inc. (2013).

[19] P., Jigisha, S.A., Channiwala, and G.K Ghosal,. A correlation for calculating HHV from proximate analysis of solid fuels. Fuel. Vol. 84, 487-494. (2006).

[20] Usta Mustafa Cem Can Rüstü Yörük Tiina Hain Tiina Hain Peeter Paaverm Ruben Snellings duard Rozov Andre Gregor Rein Kuusik Andres Trikkel and Mai Uib. Evaluation of New Applications of Oil Shale Ashes in Building Materials. https://doi.org/10.3390/min10090765(2020).

[21] Loos International,. An application of production, steam and water boilers. (2012)[22] Coskun Ozlem, Separation techniques: Chromatography. North Clin Istanbul (NCI) 2016;3(2):156–60 doi: 10.14744/nci.2016.32757 (2016).

[22] K Hernandez and. Y.Tello Wood volume production anduse of ten woody species insemiarid zones of northernMexico. International Journal of Forest Research. Vol. 6.1-8 (PDF) Investigation of Combustion Properties of Some Selected Fuel wood Species in Nigeria (2014).

[23] .R.A. Nasser and. M.A Ibrahim. The performance and properties of wood- polypropylene panel as affected by woodaqueous extraction. Forest Products Journal. Vol. 64(5-6),192- 198, (PDF) Investigation of Combustion Properties of Some Selected Fuel wood Species in Nigeria. 2014.

[24] C . Cuvilas,, R.Jirjis, and N.Terziev. Thecharacterization of wood species from Mozambique as fuel.Energy Sources, Part A; Recovery, Utilization and Environmental Effects. Vol. 36(8) 851- 857, 2014

[25] I. M., Aref, R. A., Nasser, Ali, I., Al-Mefarrej, H. A., and Al-Zahrany, S. M. "Effects of aqueous extraction on the performance and properties of polypropylene/ woodcomposites from Phoenix dactylifera and Acacia tortilis wood," Reinf. Plast. Compos.32(7), 476-489. DOI: 10.1177/0731684412454462. (2013).

[26] C.A., Michael, K.. Tanaka T.Akiyama Ozaki T., M. Osakabe, S. Sakakibara, H. Yamaguchi, S. Murakami, M. Yokoyama, M. Shoji. (2018) Role of Helium–Hydrogen ratio on energetic interchange mode behaviour and its effect on ion temperature and micro turbulence in LHD Nuclear Fusion, Volume 58, Number 4

[27] A. Demirbas Hydrogen Production from Biomass by the Gasification Process. Energy Sources Volume 24, 2002 - Issue 1. https://doi.org/10.1080/00908310252712307(2010).

[28] K.W. Raglands and D.J. Aerts. Properties of wood for combustion analysis. Bio- Resources Technology. Vol. 37,161- 168, 1991

[29] N.Y Halim Abd and NIS Muhammad. Investigation of moisture content and higher heating value in refuse derived fuel from agricultural residues using statistical modelling. *AIMS Energy* http://www.aimspress.com/journal/energy Volume 13, Issue 1, 1–12. (2024)

[30] R. Kataki, and D. Konwer, Fuelwood Characteristics of Indigenous Tree Species of North-East India. Biomass and Bioenergy, **Journal of Sustainable Bioenergy Systems**, Vol.6 No.2, May 12, 2016 22, 433-437. http://dx.doi.org/10.1016/S0961-9534(02)00026-0.(2002).

[31] T.U Onuegbu, E. Ekpunobi, I.M Ogbu, M.O Ekeoma and F.O Obumselu. Comparative studies of ignition time and water boiling test of coal and biomass briquettes blend.International Journal of Research & Reviews in Applied Sciences, Vol.7, 5. Bello RS, Adegbulugbe TA, Onilude MA, pp.153–159, 2012.

[32] B.M Jenkins , L.L , Baxter T.R Miles Jr., Miles T.R (1998).. Combustion properties of biomass Volume 54, Issues 1–3, Pages 17-46 https://doi.org/10.1016/S0378-3820(97)00059-3