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Exergy Analysis of Waste-to-Energy Technologies for Municipal Solid Waste Management

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ABSTRACT

In recent years, there have been increasing concerns over the detrimental effects of irreversible linear patterns of material and energy consumption, which have led to an enormous generation of municipal solid waste (MSW). Concepts like waste-to-energy (WtE) and recycling have gained increasing recognition and support as responses to these challenges. This study assessed the exergetic potential of four WtE technologies (landfill gas-to-energy, anaerobic digestion, incineration, and plasma gasification) in the context of the MSW characteristics of Maiduguri, Borno State. The population of Maiduguri, waste generation rate, waste composition, and the ultimate and proximate analysis of the MSW were used for the assessment. Exergetic potential in the form of electrical energy generation and three exergy-based indicators (exergy efficiency, exergy defect, and improvement potential) were evaluated for each WtE option. The results reveal that anaerobic digestion and plasma gasification are viable options based on the exergetic potential and the measured exergy performance indicators. These findings offer valuable insights for policymakers and waste management authorities, facilitating informed decisions to address environmental concerns and promote resource-efficient urban development in Maiduguri and similar regions.

1. INTRODUCTION

The global transition of the economy towards more efficient and stable manufacturing processes was marked by unprecedented industrialization, food production, population growth, material use, and waste generation. By the latter part of the 20th century, the dangers of unrestrained environmental pollution and overexploitation of natural resources had become the subject of discourse among researchers and policymakers.

Municipal solid waste (MSW) is an emblematic by-product of industrial society; it is the mixture of solid waste that is disposed daily by both urban and rural populations (Nanda and Berruti, 2021). The composition of MSW varies greatly depending on various factors such as culture, economy, geography, time, etc. Figure 1 shows the composition of MSW for the world, Africa, Nigeria, and Maiduguri. In each of the locations, organic waste which includes food waste and green waste accounts for over 40% of the total waste generated, making it the most prevalent type of MSW.

MSW remains one of the key challenges of the 21st century. For instance, of the 174 million tonnes of waste generated in Sub-Saharan Africa, 69% of the waste is openly dumped and often burned. About 24% of the waste is disposed in some form of a landfill and 7% is recycled or recovered (Kaza et al., 2018). In Nigeria, only 20-30% of the waste generated is being collected and managed properly (Esohe, 2023). This raises a fundamental question: how can MSW be effectively managed to safeguard both public health and the environment? The importance of this question can hardly be overestimated. It bears directly upon the connection between humans, resources and the environment. This is because the characteristic of waste can be likened to a notion of a resource, which can be described as material that possesses value in its

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use and is a reflection of human evaluation (Jones and Hollier, 1997). As awareness of these challenges grows, the traditional perspective of viewing MSW as a burden is slowly being replaced by approaches that seek to derive value from it by converting it into useful products using waste-to-energy (WtE) technologies and other approaches (Hadidi and Omer, 2017; Jadhao et al., 2017; Bakas et al., 2018). Various technological alternatives exist for the disposal and treatment of MSW including recycling, landfill gas-to-energy (LFGTE), composting, anaerobic digestion, gasification, incineration, and pyrolysis.

A 2003 MSW composition analysis in Maiduguri revealed that organic material comprised 25.80%, plastics 18.10%, metals 9.10%, paper and cardboard 7.50%, glass 4.30%, and others 35.20% of the total waste stream (Dauda and Osita, 2003). Compared with Figure 1, organic waste composition increased to 55.21%, and plastic waste increased to 32.56%. These shifts indicate a growing abundance of organic and plastic waste, both of which are viable feedstocks for WtE technologies like anaerobic digestion, incineration, LFGTE and plasma gasification.

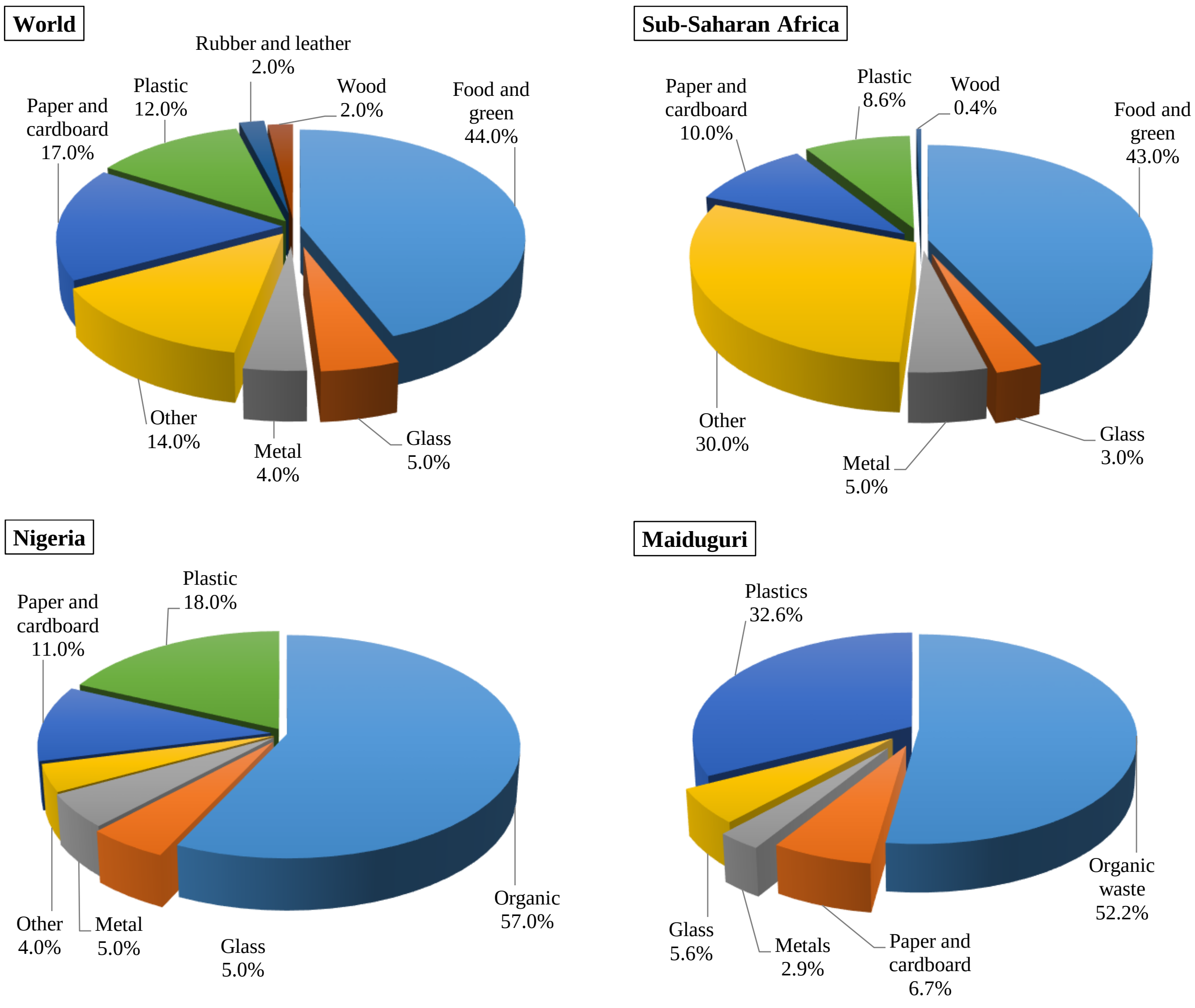

Figure 1. Waste composition for different locations. World and Sub-Sahara's charts were reproduced from Kaza et al. (2018), Nigeria's chart was reproduced from Kofoworola (2016), and Maiduguri's chart was based on data from Oumarou et al. (2017).

From social, economic, and environmental viewpoints, MSW management systems employing these contemporary technologies offer a wide range of benefits. However, the sustainability of these systems is often debated due to the diverse techniques available for weighing them (Soltanian et al., 2022). These techniques include life cycle assessment (LCA), techno-economic analysis, material flow analysis (MFA), and thermodynamic methods.

Among the many sustainability assessment techniques, exergy analysis appears to provide the basis for developing comprehensive methodologies for sustainability. This is attributed to its ability to identify and measure the thermodynamic inefficiencies of the MSW management system (Aghbashlo et al., 2019; Cavalcanti et al., 2019; Chen et al., 2022; Soltanian et al., 2022). Exergy is the maximum possible work that can be obtained from a system through a series of reversible operations that bring it into thermodynamic equilibrium with its surroundings. Exergy makes it possible to account for losses in the quality of resources and to meaningfully compare different types of energy, as well as to compare energy with material resources (Magnanelli et al., 2018), and is only defined with respect to a reference environment (see Gaudreau et al. (2012) for discussion on reference environments and their characteristics). The objective of this study is to evaluate the exergetic potential of converting MSW into useful work through various WtE technologies in Maiduguri, Nigeria. Findings from the study will benefit policymakers, waste management authorities, and communities in Maiduguri by providing insights into the most efficient and sustainable methods for managing MSW and meeting energy needs.

2. METHODOLOGY

2.1 Study area

Maiduguri is the largest city in North-eastern Nigeria and serves as the capital of Borno State, Nigeria. It is located at 11.8311° N, 13.1510° E (see Figure 2). The city has experienced rapid growth in population due to rural-urban migration and the Boko Haram insurgency which has displaced millions of people from the neighbouring villages. The city serves as a commercial centre with links to Niger, Cameroon and Chad. It is composed of two local government areas, namely, Maiduguri Metropolitan Council and Jere Local Government Area.

The waste composition of Maiduguri constitutes the key input in this study. The typical waste composition for Maiduguri is shown in Figure 1, and the ultimate and proximate analysis of MSW utilised in this study is shown in Table 1.

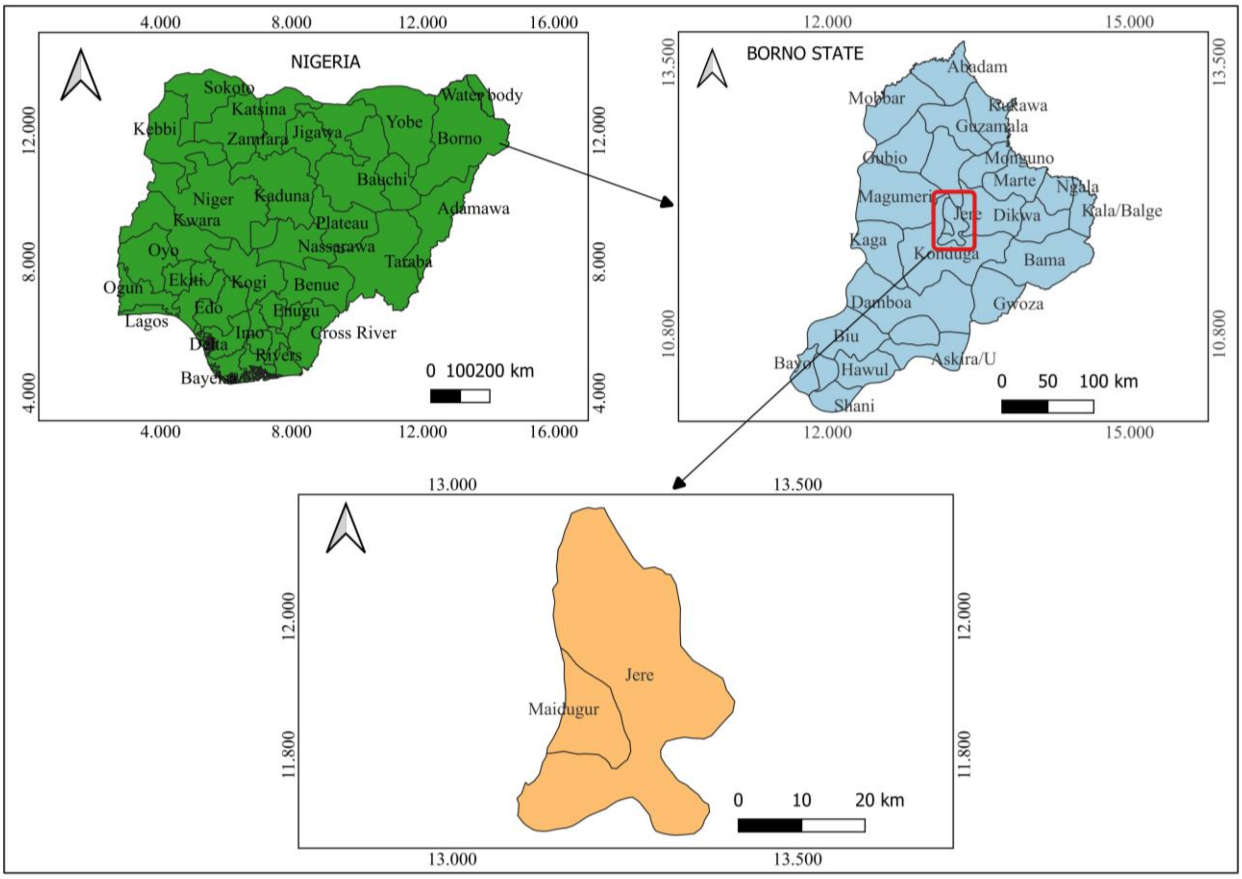

Figure 2. Map of the study area

Table 1. Results of the ultimate and proximate analysis of MSW (dry basis, weight percentage) (Oumarou et al., 2012)

Ultimate analysis	Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen
	20.99	0.490	1.84	0.07	23.95
Proximate analysis	Moisture	Volatile matter	Ash	Fixed carbon	
	21.83	25.12	30.83	22.22	

2.2 Estimation of annual MSW generated

The amount of waste generated in tonnes/year by the population, $P(n)$, is estimated using Equation 1.

$$W = P_0(1+r)^n \times W_{genR} \times \frac{365}{1000} \tag{1}$$

Equation 2 is used to determine the amount of MSW input into each system.

$$W_{in} = W \times W_f \tag{2}$$

Where; P_0 is the base year population, r is the average annual population growth rate, W_{genR} is the waste generation in kg/capita/day and W_f is the fraction of the MSW that is sent to the WtE system.

2.3 Exergy analysis of WtE technologies

The reference state established in this study is characterised by a temperature (T_0) of 298.15 K and a pressure (P_0) of 101.3 kPa. Two components of exergy are considered: physical exergy, which is related to changes in temperature, pressure and concentration; and chemical exergy, which is linked to changes in the chemical composition of substances (Sato, 2004). Physical exergy is expressed as (Jadhao et al., 2017):

$$Ex_{ph} = (h - h_0) - T_0(s - s_0) = \int_{T_0}^{T} c_p dT - T_0 \int_{T_0}^{T} \frac{dT}{T} \tag{3}$$

Where; h is the specific enthalpy (J/kg K), S is the specific entropy (J/kg K), T is temperature (K), h_0, s_0 and T_0 describe the state of the reference environment. The total chemical exergy is determined from the standard chemical exergy values of the elements using Equation 4 (Jadhao et al., 2017).

$$Ex_{ch,i} = \Delta G_i^0 + \sum_i \gamma_i Ex_{q,i}^0 \tag{4}$$

Where; γ_k represents the mole quantities, $Ex_{q,i}^0$ is the standard chemical exergy (kJ/mol) of the i^th reference species and G is the Gibbs free energy (kJ/mol). The chemical exergy of the feed MSW is based on the ultimate analysis data presented in Table 1 and the waste composition shown in Figure 1. The values for the standard exergy of each element are obtained from Rivero and Garfias (2006) (see Table S2 of the supporting information (SI)).

Three exergy-based indicators are used to evaluate the performance of the products of each WtE technology: the total exergy efficiency, which is expressed in Equation 5; the improvement potential (Equation 6), which measures the amount of exergy that can be saved by improving the performance of the process; and the exergy defect (Equation 7), which represents the proportion of exergy lost within a system.

$$\epsilon = \frac{Ex_{out}}{Ex_{in}} = 1 - \frac{Ex_d}{Ex_{in}} \tag{5}$$

$$IP = (1-\epsilon)(Ex_{in} - Ex_{out}) = (1-\epsilon)Ex_d \tag{6}$$

$$\delta = 1 - \epsilon \tag{7}$$

Where; ϵ is the exergy efficiency, Ex_{out} is the exergy of output, Ex_{in} is the exergy of input and Ex_d is the overall exergy lost or dissipated during the process.

2.3.1 Landfill gas-to-energy

The amount of CH_4 (m^3/year) is estimated using the Landfill Gas Emission Model (LandGEM) version 3.02 (Alexander et al., 2005). By this model, CH_4 is formed from decomposable material given by the first-order decomposition rate equation:

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{W_{in}}{10}\right) e^{-kt_{ij}} \tag{8}$$

Where; i is the 1-year time increment, n is [year of the calculation] - [initial year of waste acceptance], j is the 0.1-year time increment, k is the methane generation rate (/year) and L_0 is the methane generation potential (m^3/tonne). The total exergy associated with the collected CH_4 is estimated using Equations 3 and 4. It is assumed that 33% of this exergy gets converted to electricity using an internal combustion engine. The exergy-based performance of this technology is estimated using Equations 5-7.

2.3.2 Anaerobic digestion

The volume of CH_4 obtained (m^3/tonne) from the anaerobic digestion of MSW is estimated using Equation 9 (Huang and Fooladi, 2021):

$$V_{CH_4} = \frac{16\vartheta}{aM_C+bM_H+cM_O+M_N} \times \frac{1000}{\rho_{CH_4}} \qquad (9)$$

Where; ρ_{CH_4} is the density of methane (see Table S1 of the SI). The other parameters are obtained from the Buswell equation which is expressed as:

$$C_aH_bO_cN_dS_e + yH_2O \rightarrow \vartheta CH_4 + (a-x)CO_2 + dNH_3 + eH_2S \qquad (10)$$

Where; $\vartheta = \frac{1}{8}(4a + b - 2c - 3d - 2e)$ and $y = \frac{1}{4}(4a + b - 2c + 3d + 3e)$. The subscripts a, b, c d, e are constants parameters with approximate values given by (Achinas and Euverink, 2016):

$$a = \frac{m_C}{M_C} = \frac{m_C}{12.01} \qquad (11a)$$

$$b = \frac{m_H}{M_H} = \frac{m_H}{1.01} \qquad (11b)$$

$$c = \frac{m_O}{M_O} = \frac{m_O}{16.00} \qquad (11c)$$

$$d = \frac{m_N}{M_N} = \frac{m_N}{14.01} \qquad (11d)$$

Where; m_C, m_H, m_O, and m_N represent the mass of carbon, hydrogen, oxygen and nitrogen, respectively.

The methane production from the digester is lower than the theoretical value because not all of the organic matter decomposes in the digester. Secondly, some of the organic matter in the waste is utilized in the synthesis of cell tissue for microorganisms, which obstructs microbial decomposition (Ogunjuyigbe et al., 2017; Cudjoe et al., 2020). Hence, the actual quantity of methane (m^3) produced from the digester is estimated using:

$$V_{CH_4(act)} = V_{CH_4} \times 0.85 \times W_{in} \qquad (12)$$

The total exergy associated with the electricity generated from collected CH_4 is estimated using a conversion efficiency of 26%.

2.3.3 Incineration

The exergy flow is evaluated across three units of operation which are the dryer, incinerator, and turbine. The schematic of the exergy flow across these units is shown in Figure 3. A detailed description of the exergy analysis of this process is provided in the SI.

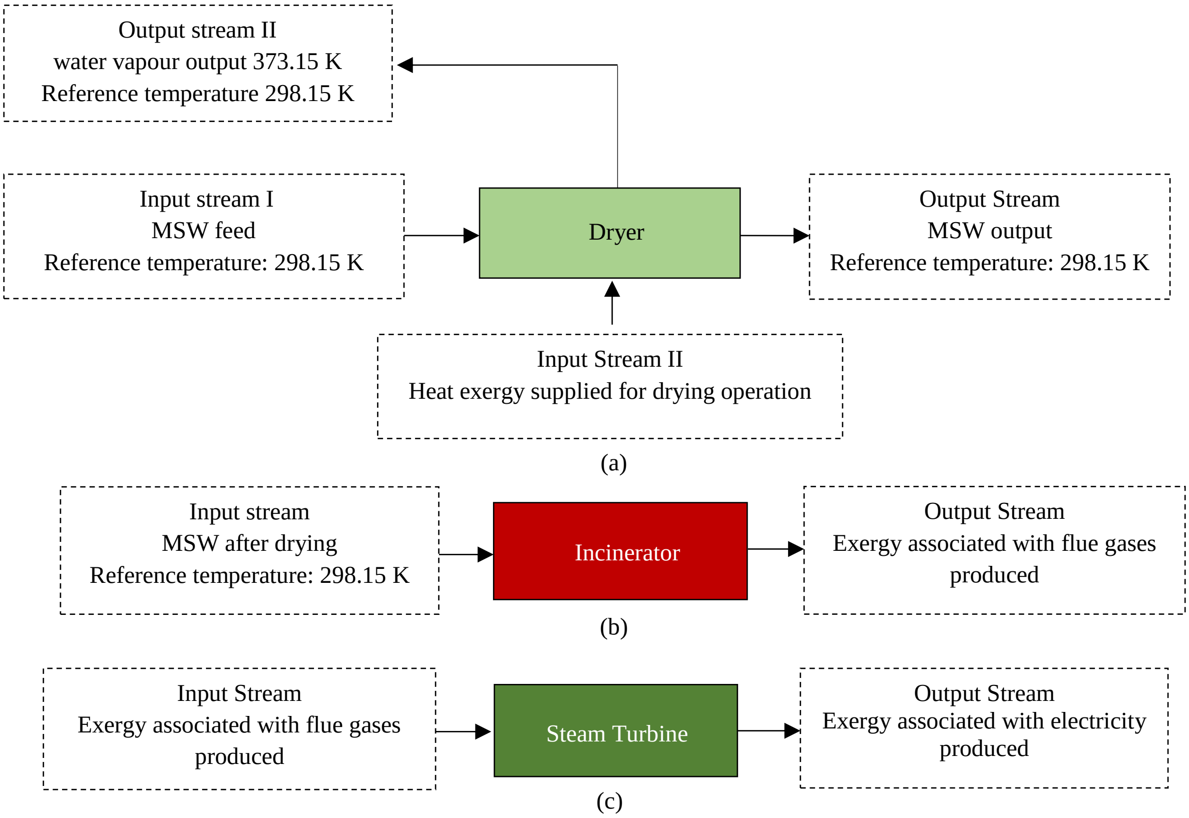

Figure 3. Exergy flow in incineration process

2.3.4 Plasma gasification

The flow of exergy in plasma gasification of MSW is shown in Figure 4. Because the initial moisture content of the Feed MSW and the allowable moisture content post-drying for both incineration and plasma gasification are identical, the exergy flow calculations across the dryer is the same in both processes. The first input stream to the plasma furnace is the chemical exergy associated with the tonnes of MSW. The second input is air at the reference temperature.

For plasma gasification, a plasma torch powered by an electric arc is needed to ionize the gas and catalyse MSW into syngas. The electricity consumption for a plasma torch per tonne of MSW is about 180 kWh (Jadhao et al., 2017). Exergy associated with this electricity is the third input stream to the plasma furnace (see Figure 5).

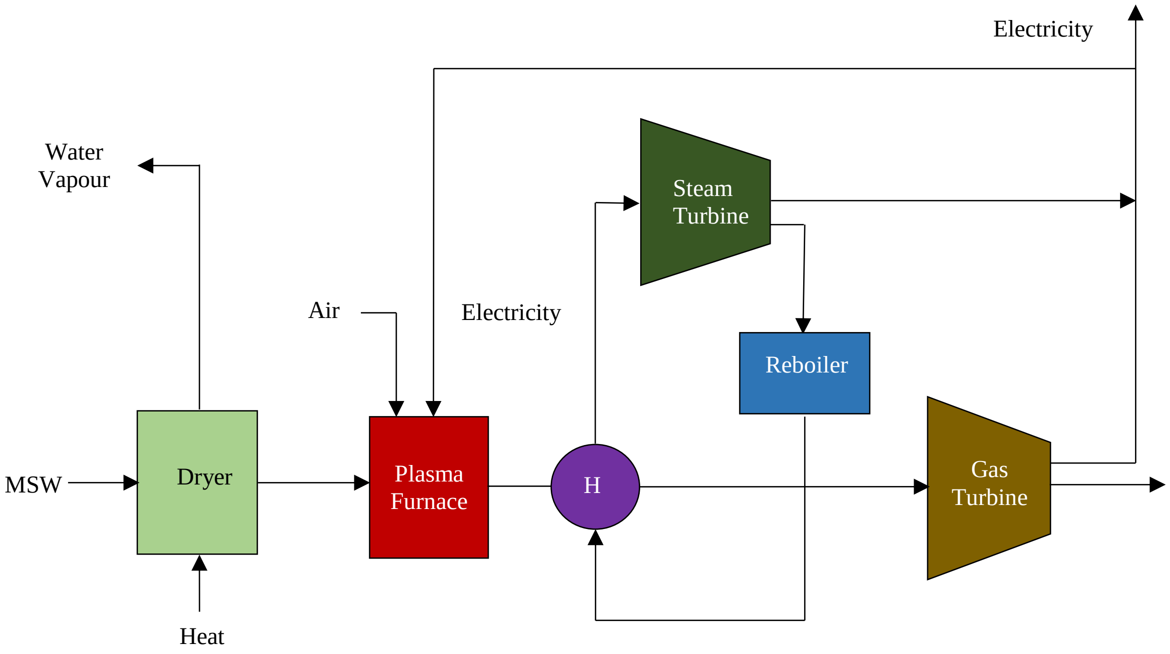

Figure 4. Plasma Gasification of MSW

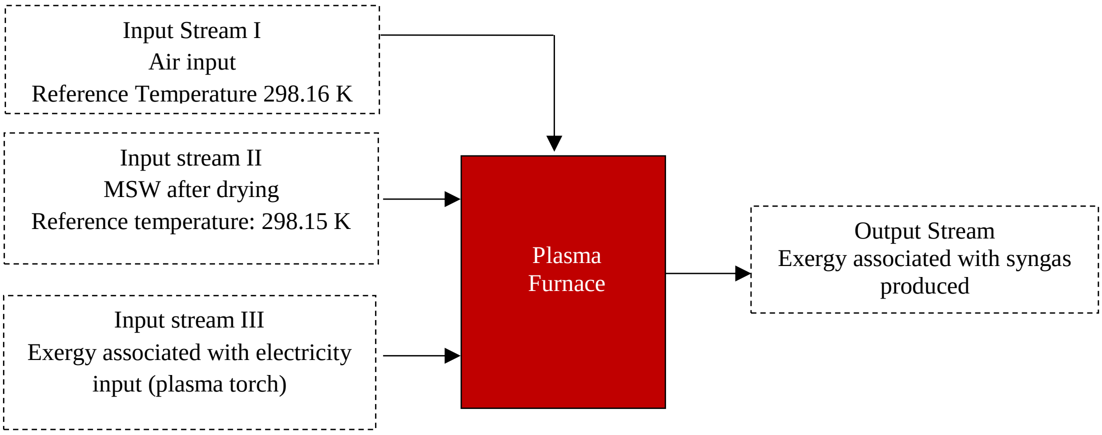

Figure 5. Exergy flow across plasma furnace in plasma gasification of MSW

It is assumed that the plasma gasification products burn and achieve equilibrium before leaving the plasma furnace, therefore, an equilibrium model is utilised in this study. The composition of the syngas produced is predicted based on the equilibrium model established by Zainal et al. (2001) and was slightly adjusted with updated thermodynamic data from Yaws (2003). A detailed description of this process is provided in the SI.

3. RESULTS AND DISCUSSION

3.1 Waste generation

The two primary factors driving MSW generation potential in this study are population size (which depends on the population growth rate) and per capita waste generation rates. The waste generation for the year 2023 was estimated to be 2.63×10^5 tonnes using a waste generation rate of 0.53 kg/capita/day, base-year population of 1,328,100 and an annual growth rate of 2.40%. The MSW generation prediction model is based on the assumption that the type and amount of waste generated will not change over time. However, this is not always the case, as MSW generation is affected by several other factors such as economic development and technological advancements. As a result, there is a lot of uncertainty in MSW generation predictions. This uncertainty is especially pronounced for processes that rely on the composition and quantity of MSW, such as anaerobic digestion and LFG production. Table 2 presents the estimate of the chemical exergy associated with 2.63×10^5 tonnes/year of MSW generated. The total chemical exergy of 1.28×10^{12} kJ serves as the input exergy of feed MSW for each of the WtE technologies.

Table 2. Chemical exergy associated with feed MSW

	Composition %	Molar mass (g/mol)	Mass (Tonnes)	$\mathbf{Ex_q^0}$ (kJ/mol)	$\mathbf{Ex_{ch}^0}$ (kJ)
Carbon	20.99	12.01	32028.74	410.27	1.09×10^{12}
Hydrogen	0.49	1.01	747.69	236.12	1.75×10^{11}
Nitrogen	1.84	14.01	2806.14	0.67	1.34×10^{8}
Sulphur	0.07	32.07	103.76	609.30	1.97×10^{9}
Oxygen	23.95	16.00	36549.99	3.92	8.95×10^{9}
Total					1.28×10^{12}

3.2 Exergy analysis of WtE technologies

Figure 6 illustrates CH_4, CO_2, and total LFG yearly volume rate emissions based on the LandGEM model, and its input parameters are methane generation rate of 0.07/year, methane generation potential of 170 m^3/tonne. According to the model, all of the LFG is made up of CH_4 methane and CO_2 carbon dioxide as well as trace amounts of non-methanogenic organic carbons and other pollutants. It is assumed that the LFG generation starts as soon as it is dumped, and the rate of gas of CH_4 generation reaches its peak within the first 10 years. Figure 6 shows that the production of LFG follows a characteristic trend in which it attains its peak about 10 years after the initial waste acceptance, subsequently entering a phase of decline as the waste undergoes decomposition. CH_4 generation commences from a baseline of zero in the year 2023 and exhibits an incremental trajectory, reaching its peak in 2029 with a volume 8.47×10^6 m^3, after which the rate declines gradually. The average CH_4 collected is 5.86×10^6 m^3/year and the exergy efficiency and other performance indicators associated with the electricity generated from landfilling are given in Table 5. The output exergy for the LFGTE option is 4.94×10^4 GJ, representing only 3.8% of the input exergy.

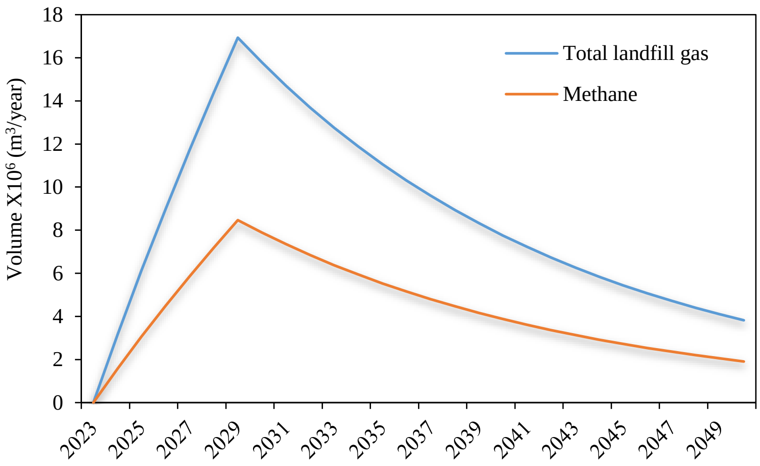

Figure 6. LFG generation from landfill

For anaerobic digestion, the feed MSW into the recovery system is 134,138.43 tonnes representing the organic fraction of MSW. The CH_4 collected as estimated from the Buswell equation, is 2.19×10^7 m^3/year. The exergy flow of the process is shown in Figure 7. The total exergy loss in the digester is 5.36×10^5 GJ, representing 41.88% of the total exergy input. The most substantial exergy loss is observed in the IC engine which accounts for 42.97% of the total exergy input and 73.92% of the exergy of the CH_4 generated by the anaerobic digester.

The exergy content of the flue gases resulting from the incineration of MSW is presented in Table 3. It is worth highlighting an observation: the chemical exergy values of these flue gases are higher when compared to their physical exergy values. This disparity can be attributed to the specific condition of these gas streams, as both their temperature and pressure closely align with those of the reference state. This results in an increase in their chemical exergy, implying the significant role that temperature and pressure conditions play in influencing the exergy content of these gases during the incineration process.

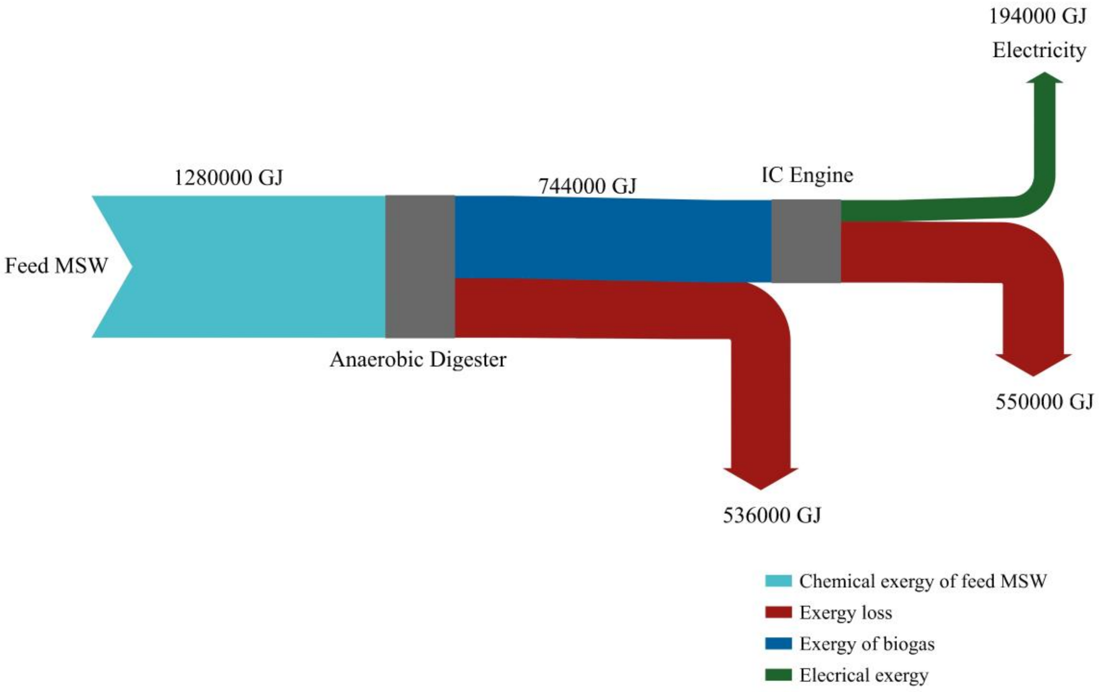

Figure 7. Flow of exergy in anaerobic digestion process

Table 3. Exergy associated with flue gases from incineration

Flue gases	Quantity emitted (kmol)	$\mathbf{Ex_{ph}}$ (kJ)	$\mathbf{Ex_{ch}}$ (kJ)
CO_2	2.67×10^6	5.74×10^{10}	1.97×10^{11}
H_2O	7.40×10^5	1.23×10^{10}	4.45×10^{10}
NO	2.00×10^5	2.80×10^9	2.73×10^{10}
SO_2	3.241×0^3	7.18×10^7	1.14×10^9
HCl	0.00	0.00	0.00
Total		7.26×10^{10}	2.70×10^{11}

In Figure 8, a visual representation is provided for the exergy flow within the incineration process. The most substantial exergy losses occur in the incinerator, as 73.29% of the exergy initially introduced into the incinerator is lost. This phenomenon is due to, firstly, the low carbon composition of the MSW and, secondly, the substantial entropy generation resulting from the inherently highly irreversible combustion process that takes place within the incinerator. Also, approximately 13.86% of the total exergy that is supplied to the drying system is lost.

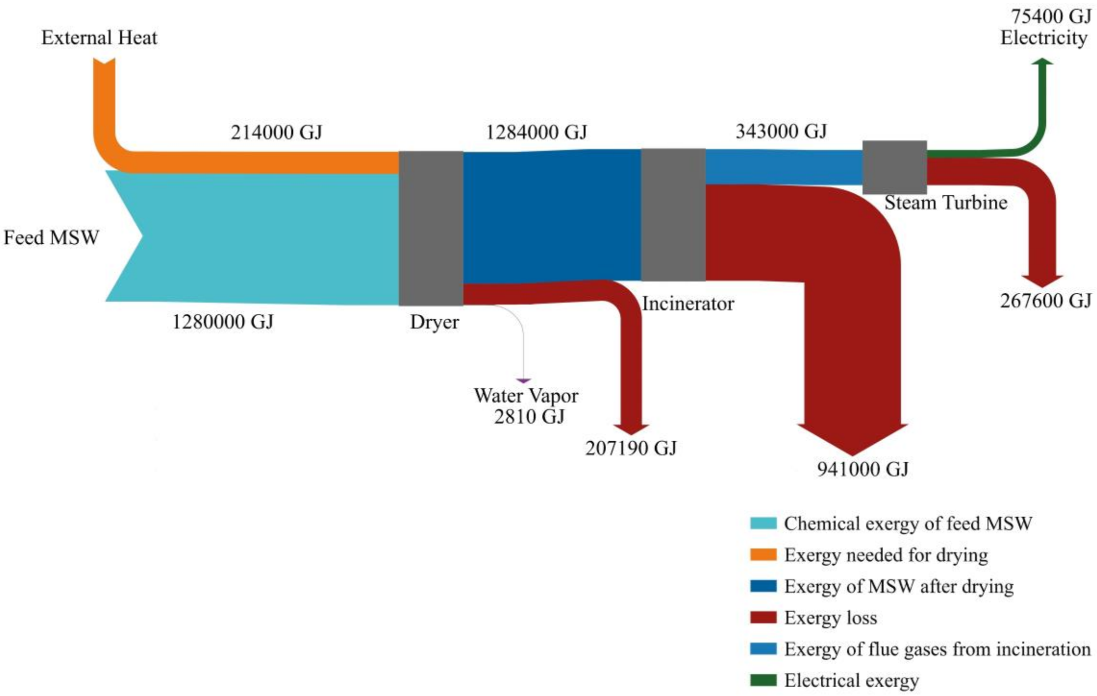

Figure 8. Exergy flow in incineration of MSW

The equilibrium model was employed to predict the products of the plasma gasification process. Initially, the MSW was assumed to have a high moisture content of 42%, which is unsuitable for the plasma process. However, the MSW was dried in the dryer to a permissible moisture content of up to 21.83% based on the results of the proximate analysis. This dried MSW is then introduced into the plasma furnace at ambient temperature and pressure. An electric current is passed through specifically designed electrodes to generate plasma gas. While various gases like oxygen and helium can be used between the electrodes to form plasma, air is assumed as the input gas in this study (see Figure 4) due to its cost-effectiveness. Using the estimated values of the volumetric/molar composition of the syngas and the total moles of syngas from the equilibrium model, the moles of each constituent were estimated. The resulting physical and chemical exergy of each constituent are presented in Table 4.

Analysis of the exergy flows in this process revealed the magnitude and location of exergy losses, as shown in Figure 9. The highest exergy loss was identified to occur within the plasma furnace where 65.49% of the exergy supplied to it is dissipated. This exergy lost within the plasma furnace is notably lower than that observed in the incinerator since the MSW is exposed to higher temperatures in the plasma furnace.

Table 4. Exergy associated with syngas from plasma gasification of MSW

Constituents	Quantity (kmol)	$\mathbf{Ex_{ph}}$(kJ)	$\mathbf{Ex_{ch}}$(kJ)
CO	2.65×10^{6}	4.64×10^{10}	1.44×10^{11}
CO_2	4.73×10^{3}	1.32×10^{8}	1.80×10^{8}
N_2	1.69×10^{6}	2.86×10^{10}	8.90×10^{10}
H_2	3.53×10^{6}	5.74×10^{10}	1.93×10^{11}
CH_4	1.26×10^{4}	4.51×10^{8}	5.20×10^{8}
Total		1.33×10^{11}	4.27×10^{11}

Table 5 provides a comparative analysis of the four technologies using some exergy-based performance metrics. It shows that anaerobic digestion accounts for the highest exergy efficiency. This is due to the high percentage of organic waste in the waste stream. Even though plasma gasification technology requires electricity for its operation, it exhibits the greatest conversion potential as compared to incineration and LFGTE because it generates more net electricity. The low exergy efficiencies of the thermochemical processes are due to the low carbon content in the MSW, as Jadhao et al. (2017) state that the exergy efficiency for such processes is roughly linearly proportional to the carbon content of the feed MSW. Table 5 also shows the inverse relationship between exergy efficiency and exergy defect, i.e., the lower the efficiency, the larger the fraction of exergy that is lost within a system.

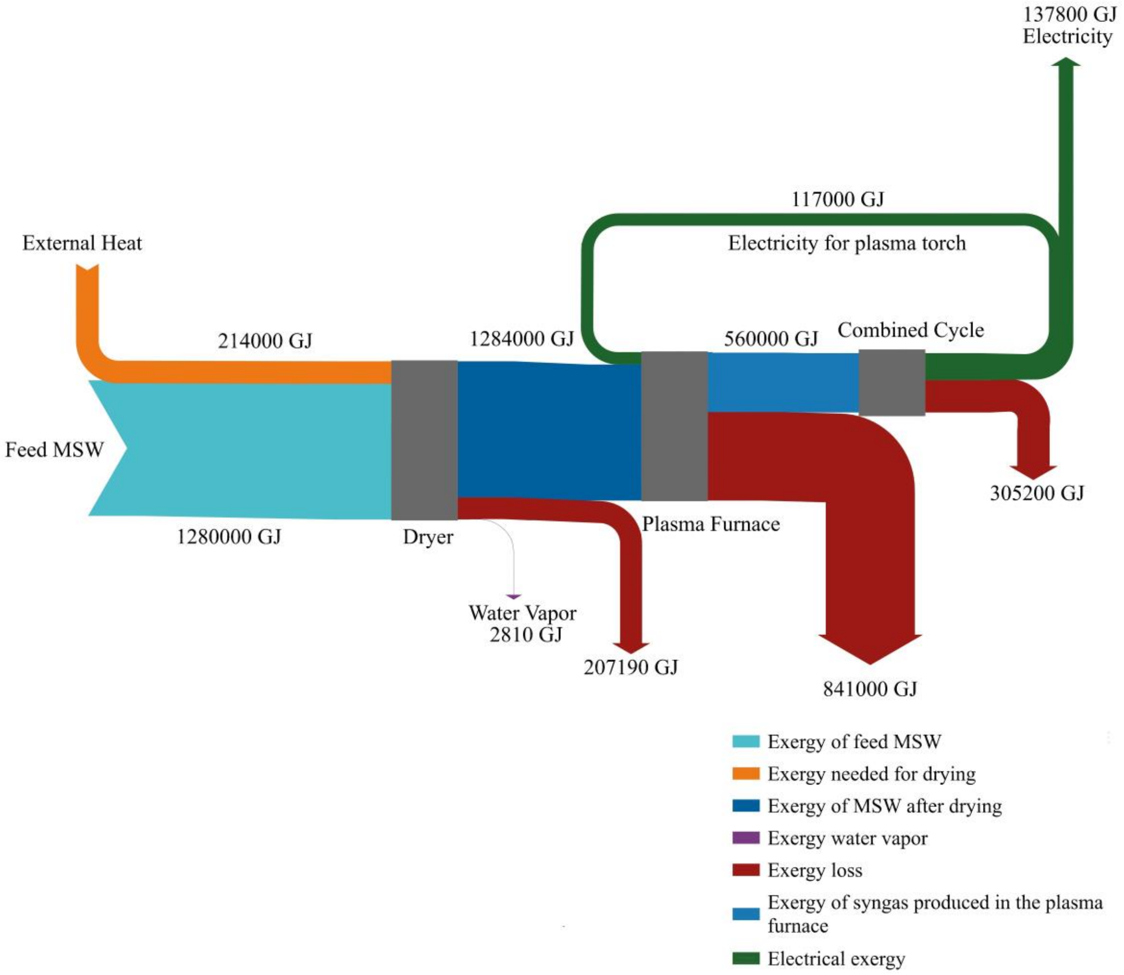

Figure 9. Flow of exergy in plasma gasification of MSW

Table 5. Energy-based performance indicators for WtE options

	ϵ (%)	**IP** (GJ)	**δ**	**Ex_d** (GJ)
LFGTE	3.80	1.96×10^{6}	0.96	1.24×10^{6}
Anaerobic digestion	15.16	9.21×10^{5}	0.85	1.09×10^{6}
Incineration	5.05	1.35×10^{6}	0.95	1.42×10^{6}
Plasma gasification	9.22	1.23×10^{6}	0.91	1.36×10^{6}

The improvement potential values which indicate the possible improvements of each WtE option are also outlined in Table 5. It shows that the LFGTE option has the highest improvement potential and anaerobic digestion has the lowest due to its higher exergy efficiency. Optimizing the waste feedstock with a higher proportion of organic material will help improve the efficiency of these options. For incineration and plasma gasification, it has been noted herein that the incinerator and the plasma furnace account for the highest exergy destruction. Thus, enhancing the performance of this unit can have a significant impact on improving the overall efficiency of the entire process. Fellaou and Bounahmidi (2018) noted that the best way to decrease the irreversibility of a process or system is to decrease the difference between the total exergy output and input values. The irreversibility due to combustion can however, not be avoided completely. Irreversibility due to combustion can be reduced to a minimum value by working with MSW with high carbon content or using better fuel. In this regard, Oumarou et al. (2012) suggest that supplementary fuels such as sugarcane straw or weeds can be added to the MSW.

4. CONCLUSION

This study evaluated the exergy potential of converting MSW into useful energy through four WtE technologies in Maiduguri, Nigeria. The four technologies evaluated were landfill gas-to-energy, anaerobic digestion, incineration, and plasma gasification. The main conclusions are drawn as follows:

1) Anaerobic digestion demonstrated the highest conversion potential, generating more net electricity compared to other options due to the high organic content of the waste stream.

2) Plasma gasification also showed relatively high exergy efficiency due to its operation at elevated temperatures in the plasma furnace.

3) Incineration and landfill gas-to-energy exhibited lower exergy efficiencies.

Analysis of exergy losses identified the incinerator and plasma furnace as the primary sources of exergy losses in the incineration and plasma gasification processes, respectively. Therefore, maximizing the performance of these units through advanced technologies or optimized operating conditions could significantly enhance overall system efficiency. Additionally, incorporating supplementary fuels with high carbon content, as suggested by prior studies, could further improve the performance of thermochemical WtE options.

While anaerobic digestion and plasma gasification emerged as promising options based on different metrics, the optimal choice for Maiduguri will depend on specific local considerations including cost, available infrastructure, and environmental impacts. Further research focusing on improving the performance of critical units, exploring alternative fuels, and conducting techno-economic and environmental impact analysis would be valuable in determining the most sustainable and efficient WtE solution for Maiduguri and similar localities.

SUPPLEMENTARY MATERIAL

Supporting information is provided for this paper. The supporting information includes additional tables of variables used and methodological details that contribute to a comprehensive understanding of the research outcomes.

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