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Analysis of Municipal Solid Waste in Soweto, Johannesburg Municipality, South Africa: Implications for Sustainable Waste Management Practices

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The generation of municipal solid waste (MSW) has been consistently increasing due to various factors, such as the improvement of living standards, urban migration for employment opportunities, and, most notably, rapid population growth. In South Africa, inadequate collection and transportation methods result in the accumulation of solid waste. The objective of this study is to quantify and analyse the composition of municipal solid waste by type, evaluate proximate and ultimate analysis, and assess the potential effectiveness of energy generation from Johannesburg City in Soweto. According to the proximate analysis findings, the MSW contains a significant amount of moisture and ash. Therefore, it requires additional separation and purification processes before its utilization. The elemental analysis results indicate that the waste material has a decreased concentration of sulfur and nitrogen, which is desirable. The study's findings can help to select and design the thermal waste-to-energy (WTF) process for the composition of the studied waste, thereby expediting the transition to a circular economy in urban regions and reducing pollution.
Keywords: Solid waste; municipal; classification; reuse

1. Introduction

Household, commercial and industrial sources generate municipal solid waste (MSW), also known as garbage (Adhikari et al., 2018). In recent years, municipalities have been generating progressively larger quantities of municipal solid waste (MSW), resulting in environmental contamination, the expansion of landfills and detrimental effects on human health. Nagamori et al. (2023) predict a significant increase in greenhouse gas emissions, soil and groundwater contamination, visual blight, and disease spread due to Africa's population and industrialization. Municipalities in South Africa are responsible for waste management service delivery, as stipulated in the South African Constitution (Nkosi et al., 2013). The Waste Act (Act 59 of 2008) reinforces this directive by requiring towns to comply with national and provincial norms and regulations (DEA, 2011). The Waste Act establishes a waste management hierarchy, prioritizing waste avoidance as the primary objective, followed by waste reduction, reuse, recycling and disposal as the last choice. Recycling, reusing, or converting waste offers benefits like reducing greenhouse gas emissions (Kaur et al., 2021). South Africa currently generates about 12.7 million metric tons of waste annually, with approximately 3.67 million metric tons illegally dumped (Nkosi et al., 2013). Rising living standards and global population growth contribute to the increasing diversity and volume of solid waste. Municipalities are therefore under pressure to implement more efficient technologies and policies to manage MSW and address environmental threats (Young, 2010).
Ma and Hipel (2016) report that the average household size in townships is 3.1 people, with 28% of the community living in overcrowded conditions. Johannesburg, for instance, accommodates over 5 million people in an area of 1 643 km², serving as South Africa's economic hub and representing approximately 8% of the total population. In many townships, inadequate municipal management has resulted in a failure to collect refuse waste, posing a risk of exposure to microorganisms that can cause deadly diseases. A lack of adequate waste management infrastructure makes township settlements vulnerable to airborne and waste-borne diseases. Nagamori et al. (2023) propose that implementing efficient municipal waste management can significantly

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reduce the prevalence of diseases caused by inadequate waste disposal methods. Population growth in Gauteng Province, South Africa, increases garbage production, necessitating effective waste management that is exacerbated by limited landfill space.This has resulted in difficulties in the disposal and management of municipal solid waste (MSW), with unauthorized dumping causing damage to the environment. Municipal waste management has emerged as a prominent engineering field, with a particular emphasis on harnessing the energy potential of trash. Although towns face difficulties managing solid waste systems, research has shed light on how to achieve efficient waste management. Researchers are assessing the potential for South African townships to harness solid waste as a source of electricity. Municipal solid waste (MSW) often goes through thermal conversion methods such as incineration, pyrolysis and gasification. These procedures convert heat energy into electrical energy. MSW offers advantages such as energy recovery, sustainability promotion and greenhouse gas reduction. Additionally, it helps prevent pollution of land and water. Although there has been significant research on the characterization of municipal solid waste (MSW) and its conversion into energy, there is still a need to efficiently apply regulations that might improve the manageability of MSW for municipalities.
The study selected Southwestern townships (Soweto), a municipality in Johannesburg, Gauteng province. The classification of municipal solid waste was based on factors such as economic development, energy sources, seasons, lifestyle and the population size of Soweto, which is 1.3 million. We conducted this classification to identify the types of waste that current available technologies can use for energy generation. The study's objective was to classify municipal solid waste by characterizing its composition, assessing its ultimate and proximate analysis, conducting ash analysis of combustible categories, and evaluating the relevant waste-to-energy technologies relevant to the waste studied.

2. Materials and methods

2.1 Study area

We conducted the research in Soweto, a township within the Johannesburg municipality in the Gauteng province of South Africa. We chose Soweto because of its economic development, energy sources, lifestyle, population size (estimated at 1.3 million), consumption patterns, and frequency of municipal solid waste disposal. It is the largest township in South Africa, with an estimated population of 1.9 million in 2019.

2.2 Waste samples

Samples were manually collected and sorted throughout the year. Each sample, weighing 100 kg, was then sampled and weighed in accordance with the standard (ASTM D5231 – 92, 2008).

2.3 Ultimate analysis and calorific value

The technique employed for determining the chemical composition of the organic fractions in MSW is known as ultimate analysis. This analysis is conducted using a Thermo-Scientific FLASH 2000 CHNS/O Organic Elemental Analyzer. The analyzer measures the weight percentages of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S), while the oxygen content is estimated following ASTM D3176 Standard procedure. The heating value of MSW and legacy waste was determined using a Bomb Calorimeter (LECO, AC 350 LECO model).

2.4 Proximate analysis

The percentage moisture contents were obtained as the weight loss in percentage before and after drying the samples as per ASTM D3173. The volatile matter content was evaluated using standard method per ASTM D3175. Ash content was determined by placing the samples in an oven and were heated to a temperature of about 750 °C for 1 h in agreement with ASTM D3174. Fixed carbon is calculated by summing up % moisture content, % volatile matter and % ash and the total sum is taken away from 100.

2.5 Determination of bulk density

The bulk density of the MSW and legacy waste sample was determined by ASTM D-1895.

3. Results and Discussion

3.1 Municipal solid waste analysis

Table 1 presents the analysis of moisture content in various municipal solid waste categories, including paper, plastics, textiles, food waste and glass, for characterization purposes. Plastics and glass in municipal solid waste have notably low moisture content due to their hydrophobic nature, stemming from the lower surface tension of their components compared to water. The ash content in the studied waste ranged from 0.20% to 19%, falling within the range reported for paper, textiles and organic matter by Yufeng et al. (2021), with the present study showing ash content from 6% to 22%. High ash content is undesirable as it leads to reactor corrosion and affects radiative heat transfer. Additionally, it leads to a decreased rate of heating, which promotes the formation of char but decreases the amount of char produced. In addition, a high ash content hinders the combustion process, resulting in elevated emissions of carbon monoxide (Kaur et al., 2021). Kaur et al. (2021) observed that an increase in ash concentration leads to a reduction in both the calorific value and combustion efficiency of the samples. Hence, MSW is the preferred choice for pyrolysis because of its minimal ash content, which guarantees a significant production of char. The examination of MSW and older waste materials revealed that carbon and oxygen were the primary elements present, although the levels of nitrogen and sulfur were comparatively low. This indicates that the combustion of MSW would result in minimal emissions of nitrogen oxides (NOx) and sulfur oxides (SOx) (Yufeng et al., 2021). On the other hand, the hydrogen content varied from 0.10% for textiles to 11.20% for food waste.

The order of decreasing volatile matter content is as follows: Plastics > Glass > Paper > Textiles > Food waste. Textiles and food waste had volatile matter values exceeding 58%. In contrast, Fixed Carbon (FC) values were lower for food waste and textiles compared to other categories. Carbon and oxygen were the predominant elements in MSW, with food waste and plastics showing the lowest oxygen and carbon and oxygen contents, respectively. These characteristics facilitate efficient pyrolysis and the production of high-quality solid residue char, according to Youn (2010), which may be useful in pyrolysis tests. However, food waste and paper had the highest nitrogen content, suggesting that combustion may result in significant NOx emissions, which is less desirable. This suggests that technologies like catalytic converters or in-situ adsorbents could help reduce the release of harmful gases like SOx and NOx. The bulk density of the different types of waste was between 62.30 kg/m^3 for plastics and 290 kg/m^3 for food waste. Municipal wastes' bulk density also varies based on their water content, composition and distribution patterns. Remember, the density of trash varies depending on its manufacturing process and disposal location. Factors such as storage, handling, decomposition and salvage amount have an impact on density.

Table 1: Details of municipal solid waste analysis (Dry basis)

Analysis	Paper	Plastics	Textiles	Food waste	Glass
Proximate analysis					
Density (kg/m^3)	80.30	62.30	-	290.00	190.00
Moisture content (wt.%)	5.80	2.20	10.00	7.00	2.00
Volatile matter (wt.%)	10.00	0.20	58.00	70.00	2.00
Fixed carbon (wt.%)	77.20	87.60	13.00	22.80	96.00
Ash (wt.%)	7.00	10.00	19.00	0.20	-
Ultimate analysis					
Carbon (wt.%)	42.10	60.00	35.00	73.00	0.00
Hydrogen (wt.%)	6.00	7.10	0.10	11.20	0.00
Oxygen (wt.%)	51.30	32.90	64.70	15.40	0.00
Nitrogen (wt.%)	0.40	-	0.10	0.30	0.00
Sulphur content (wt.%)	0.20	-	0.08	0.10	0.00
Calorific value (kJ/kg)	16710	32505	17520	4650	0.00

The low sulphur content found in textiles, food waste and paper are a result of the combustible fraction present in MSW. The heating value assessment of the collected samples was carried out instrumentally, as detailed in Table 1. The high heating value of plastics, at 32505 kJ/kg, can be attributed to its higher carbon content and lower moisture levels. On the other hand, the lower heating value of MSW is due to its heterogeneous composition, which includes elevated levels of moisture and ash. Legacy waste, although not suitable for recycling, shows potential as a feedstock for pyrolysis, thanks to its low moisture content and high heating value compared to MSW as characterized by other studies (Young, 2010).

3.2 Municipal solid waste characterization

In 2015, the Office of the Auditor General emphasized the importance of understanding the composition of municipal solid waste, noting its varied characteristics and the need for different management strategies. Figure 1 illustrates the waste composition from Soweto in the Johannesburg municipality, with further details provided in Table 2. For the current study, samples were categorized into nine groups after thorough testing and analysis: The study categorized waste into nine groups, including greens, food waste, paper, plastics, textiles, glass, C&D, inerts, metals and other waste. Glass, Construction and Demolition (C&D), inerts, metals, and other wastes account for 9% of total waste. Organic waste constitutes the largest fraction of total waste at 52.5%, followed by paper (around 18%), plastics (approximately 13%), and textiles (7%). Cultural practices, consumer lifestyles and economic conditions all have a significant impact on municipal solid waste composition, which affects its reliability and importance for waste management planning. Factors such as sampling location, time of collection, and sample size could affect the reliability and representativeness of the collected samples. Placing several types of waste, such as food waste, paper, or cardboard, in the same storage container makes recycling difficult due to the high moisture content of food waste. There are few council vehicles for waste collection and transportation, which are unreliable, leading households to use private trucks for waste disposal at a dumping site for a monthly fee (Letshwenyo and Kgetseyamore, 2020). Moreover, private trucks also collect waste from commercial and industrial areas. The dumping site disposes of waste indiscriminately, except in a small area where soil covers it. Vehicle movement at the dumping site lacks proper control, with no security personnel or council staff present to guide vehicles to unloading sites. Poverty, poor governance, urbanization, population growth, a low standard of living, and low environmental awareness are all associated with the indiscriminate disposal of solid waste. Unintegrated into South Africa's municipal waste management policy and institutional framework, waste pickers primarily engage in informal waste recycling. The informal sector plays a significant role in waste management and recycling in Johannesburg, and this affects the reliability of the municipal solid waste data. Municipal solid waste's environmental impacts include scavenging and indiscriminate dumping, which exposes people to environmental hazards, creates breeding grounds for rodents and flies, and contributes to air pollution and climate change. The wind blows plastic waste into nearby areas, making the environment unattractive and posing health risks to animals and humans. The presence of plastic bags indicates a lack of recycling or reuse practices in the local community.

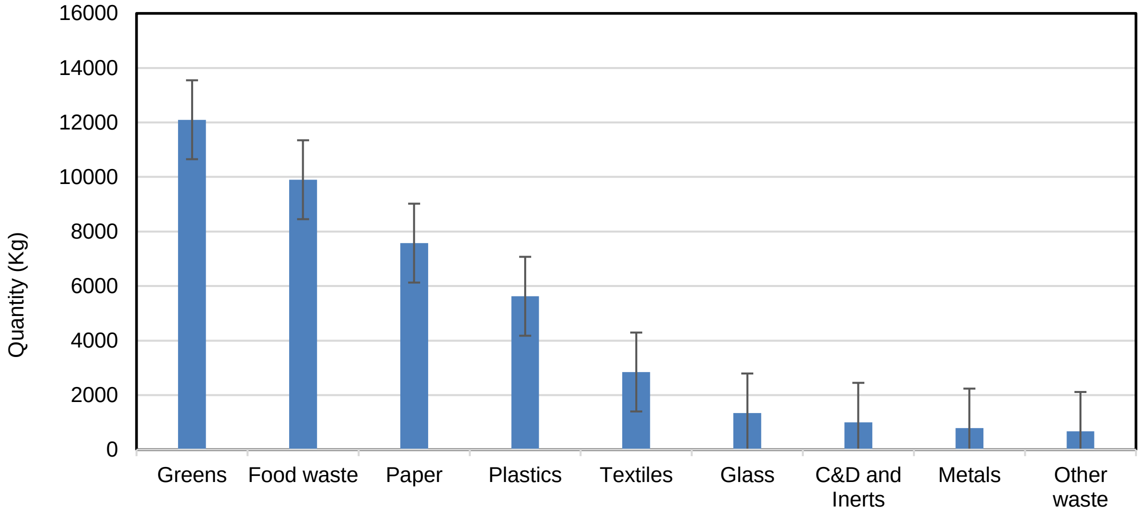

Figure 1: Quantities from waste characterization

Table 2: Characterization of solid municipal waste

Material	Composition
Greens	This includes leaves, weeds, cut flowers, trees, branches and grass cutting.
Food waste	Discarded meat scraps, dairy products, coffee ground, tea bags, eggshells, fruits, vegetables, grains, crisps, bread, rice, etc.
Paper	Newspapers, cardboard, containers (shipping, moving boxes, computer packaging, cartons), magazines, catalogues, brochures, office papers, tissue papers.
Plastics	Polyethylene terephthalate, high density polyethylene, polyvinyl chloride, low density polyethylene, bottles, containers, punnels, milk jugs, water jugs, detergent bottles, empty motor oil bottles, fluids containers, food containers (yogurt, salad vitamin, etc.), plastic bags, other plastics.
Textiles	Items made from thread, yarn, fabric, cloth, draperies, carpets, cushions, cloth fibres.
Glass	Green and amber glass beverage/food containers, liquor bottles, mirrors, light bulbs, window glass, pyrex, corningware, crystal, tableware.
C&D and Inerts	Sand, fine organics, ash
Metals	Tin/steel containers made of steel, bimetal containers, aluminium containers (soda, beer, food containers) ferrous metal, aerosol cans), scraps, cans/tins.
Other waste	Includes miscellaneous items that could not be sorted into any categories and includes such as: tyres from trucks, heavy equipment, street sweepings, ash, condoms, rubber, candles, dog faeces, dead bird, soil, cigarette butts, nappies, medications, filters from automobiles and other automobiles parts, construction waste, batteries, paints.

3.3 Ash analysis of combustible categories

In this study, we conducted an ash analysis in a laboratory setting to better understand the challenges associated with this residue in conversion processes. X-ray fluorescence was used to analyse the major chemical compositions, which are presented in Table 3 as percentages (db) for ten oxides. We assumed, following Zeng et al. (2022), that air exposure under suitable heat conditions converted each element in solid fuels to its highest stable oxide form. The results showed significant variability, as indicated by their standard deviations. We found that the ashes of MSW were rich in CaO and SiO_2, with high values of P2O5 and TiO2 in the plastics category. We strongly linked the levels of SiO_2, K_2O, and Na_2O to the formation of fouling on heat exchange surfaces. Plastics, organic matter, and textiles contained sulfur and chlorine, which, when present in the fuel composition, increased the formation of slag deposits on surfaces in steam generators operating at average temperatures. The highly variable chemical composition of MSW ash is attributed to the presence of various products in the waste stream. The behaviour and properties of ash constituents depend on the form in which the ash-forming matter is present in the solid fuel, as well as the thermal process conditions (Ma and Hipel, 2016). The ash constituents are listed for each category in decreasing order of content: food waste (CaO > SiO_2 > K_2O > Fe_2O_3), paper (CaO > SiO_2 > MgO > Na_2O), plastic (CaO > TiO_2 > SiO_2 > P_2O_5), and textiles (CaO > SiO_2 > Na_2O > TiO_2). The combustible fraction's ash is made up of CaO, SiO_2, TiO_2, and Na_2O, along with lesser amounts of Fe_2O_3, P_2O_5, Cl, and other oxides. Calcium oxide is the major compound detected in both paper and plastic samples, while TiO_2 dominates in textiles. Additionally, SiO_2 and K_2O can affect the ash fusion temperature of MSW (Young, 2010).

Table 3: Ash analysis [wt%]

Category	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	Cao	MgO	P_2O_5	Na_2O	K_2O	Cl
Paper	17.40	15.78	0.88	1.80	52.32	4.10	0.01	2.78	1.51	0.84
Plastics	19.10	-	19..98	8.03	39.67	5.32	18.23	4.66	2.12	2.20
Textiles	23.11	-	8.34	6.61	7.83	7.41	1.19	1.28	4.40	1.80

3.4 Waste to energy technologies

Waste-to-energy (WTE) technologies employ various methods to convert non-recyclable waste materials into useful heat, electricity, or fuel. Thermochemical technologies (e.g., incineration, pyrolysis, gasification, and hydrothermal liquefaction) and biochemical routes (e.g., fermentation, anaerobic digestion, composting, and landfilling) can convert MSW into energy-dense products. These technologies contribute to the decrease in landfill waste, mitigate environmental impacts, and generate sustainable energy. For example, incineration is a prominent waste treatment process that reduces waste bulk volume by 70–90% and is appropriate for wastes with higher calorific values. Pyrolysis, biological conversion, composting, and gasification are methods for converting organic materials from municipal solid waste into biochar, biogas, and other products. Pyrolysis decomposes organic materials, producing biochar. Biological conversion breaks down organic materials in an oxygen-free environment, producing methane and carbon dioxide. Composting generates stable waste and manure, reducing greenhouse gas emissions. The study suggests that municipalities can reduce waste volume by incinerating MSW, which in turn reduces landfill waste and converts generated energy into electricity.

4. Conclusions

The study analyzed municipal solid waste (MSW) as a clean energy source using advanced analytical techniques like proximate and ultimate analysis and ash oxide analysis for alternative energy generation. The volatile matter content decreases in the order of Plastics > Glass > Paper > Textiles > Food waste, with textiles and food waste having values above 58%. Fixed Carbon (FC) values are lower in food waste and textiles. Carbon and oxygen are the primary elements in MSW, with low levels of nitrogen and sulfur, resulting in minimal emissions of NOx and SOx during combustion. Hydrogen content varies widely, from 0.10% in textiles to 11.20% in food waste. Bulk density ranges significantly, from 62.30 kg/m^3 for plastics to 290 kg/m^3 for food waste, influenced by water content, composition, storage, handling, decomposition, and salvage amount. Plastics have a high heating value of 32,505 kJ/kg due to their high carbon content and low moisture. MSW has a lower heating value because of its heterogeneous composition with high moisture and ash levels. The low sulfur content in textiles, food waste, and paper is due to the combustible fraction in MSW. Ash content in the waste samples ranged from 6% to 22%. High ash content is undesirable as it causes reactor corrosion, affects radiative heat transfer, reduces the heating rate, and hinders combustion, leading to elevated carbon monoxide emissions and lower calorific value and combustion efficiency. MSW is suitable for pyrolysis because of its minimal ash content and high levels of carbon and oxygen, which support efficient pyrolysis and high-quality char production.

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