Determination of the thermo-physical properties of municipal solid waste from the perspective of its energy utilization

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1. Introduction

In the Republic of North Macedonia, as well as in the entire Western Balkans region, the generation of municipal solid waste (MSW) is continuously increasing [2]. A major concern is North Macedonia's low recycling rate, which remains at less than 1% of total MSW generation [2]. The majority of waste is disposed of in landfills, posing significant environmental risks, primarily due to greenhouse gas (GHG) emissions [4]. The key objective is to shift the perception of waste from being a non-usable material to a valuable energy resource. Achieving sustainable waste management requires integrating energy-consuming and energy-producing sectors through Waste-to-Energy (WtE) technologies. This study focuses on determining the thermo-physical properties of MSW from an energy utilization perspective to support sustainable urban development in Skopje.

2. Materials and Methods

The methodology focuses on identifying the physical and chemical properties of MSW taken from different households in one municipality in Skopje. The parameters analyzed were divided into combustible parameters, such as carbon, hydrogen, nitrogen, sulfur and volatile matter content, and non-combustible parameters, including ash content, moisture content, density and water permeability.

2.1. Sample preparation

The preparation process involved separating inert materials, reducing particle size (shredding), and lowering moisture content (drying). These steps were necessary because some analyses required a particle size of up to 30 mm (MacM30), while others required a finer size of up to 2 mm (MacM2). The density was determined on both waste samples, MacM30 and MacM2. The water permeability was analyzed only on MacM30, whereas all other analyses were done on MacM2.

2.2 Combustible parameters

The analysis of carbon, hydrogen, and nitrogen was conducted using the LECO Truspec CHN 628 analyzer. The samples were combusted at 950 °C in the presence of pure oxygen [7]. Sulfur content was determined using the LECO S832 analyzer, where the sample was burned at 1350 °C [8]. The C, H, N and S content were calculated based on the gasses formed. The gross calorific value (GCV) was measured using a LECO AC500 bomb calorimeter. The sample was combusted in a sealed bomb filled with oxygen at a pressure of 30 bar. The heat released was calculated based on the temperature difference of the surrounding water [9]. Volatile matter content was analyzed using a Neoterm NT 1313 furnace, where the sample was heated to 900 °C for 7 minutes [10].

2.3. Noncombustible parameters

The moisture content was determined by drying the sample in a Zalmed SML 32/250 laboratory oven at 105 °C for 24 hours [11]. The Neoterm NT 1313 furnace was used to determine the ash content. The sample was heated at 800 °C for 1 hour, then cooled to room temperature and weighed (until a constant mass was achieved) [12]. The density was measured using an AccuPyc II 1340 gas pycnometer from Micromeritics operating on the principle of helium displacement [13]. The permeability of the waste was determined using a Proctor apparatus and a Frowag 2.924 triaxial compression system. The sample was compacted in a metal cylinder with a volume of 7850 mm³ and placed in a pressure chamber, where water was passed through under varying pressures (0.2–1.0 bar) [14, 15].

3. Results and Discussion

The content of the components part of the ultimate analysis is calculated using the following equations.

$$C = (\text{mass of } CO_2 \cdot 12.011/44.009)/\text{sample mass} \cdot 100\ [\%]$$

$$H = (\text{mass of } H_2O \cdot 2.016/18.015)/\text{sample mass} \cdot 100\ [\%]$$

$$N = (\text{mass of } N_2 \cdot 14.007/28.014)/\text{sample mass} \cdot 100\ [\%]$$

$$S = (\text{mass of } SO_2 \cdot 32.065/64.066)/\text{sample mass} \cdot 100\ [\%]$$

The GCV was determined using the LECO AC500 bomb calorimeter, which measures the heat released during the complete combustion of a waste sample in a controlled environment. The content of volatile matter (V) in the sample was calculated by determining the ratio of the waste mass before and after heating to the initial waste mass, while accounting for the measured moisture content. The moisture content (ω_{H2O}) of the analyzed sample was determined by calculating the ratio of the mass difference before and after drying the sample to the initial mass of waste. The ash content (A) was determined by calculating the difference between the mass change from the initial drying hour to the n-th hour and the mass change between the initial drying hour and the empty container. The density (ρ) was determined by dividing the sample mass by its volume, where m_{sample} is sample mass [g] and V_{sample} is sample volume [cm³] calculated by the instrument. The water permeability coefficient (k) was determined using the equation below.

$$GCV = [(c_w \cdot \Delta T) + (c_c \cdot m_c)] / m_s\ [MJ/kg]$$

$$V = 100 \cdot [(m_2-m_3)/(m_2-m_1)]-\omega_{H2O}$$

$$\omega_{H2O} = [(M_2-M_3) / (M_2-M_1)] \cdot 100\ [\%]$$

$$A = [1-(m_2-m_3)/(m_2-m_1)] \cdot 100\ [\%]$$

$$\rho = m_{sample}/V_{sample}\ [g/cm^3]$$

$$k = [(a \cdot L)/(A \cdot t)] \cdot \ln(h_1/h_2)\ [m/s]$$

Table 1
Legend

c_w	heat capacity of the calorimeter water [J/°C]
ΔT	temperature change [°C]
c_c	heat capacity of combustion components [J/g]
m_c	mass of combustion components [g]
m_s	mass of the sample [kg]
m_1	mass of the empty crucible and lid [g]
m_2	mass of the crucible and lid and test portion before heating [g]
m_3	mass of the crucible and lid and contents after heating [g]
ω_{H2O}	moisture in the sample as analyzed [% mass fraction]
M_1	mass of empty tray [g]
M_2	mass of the tray plus sample before drying [g]
M_3	mass of the tray plus sample after drying [g]
a	cross-sectional area of the pipe [cm²]
L=10 cm	distance between measuring points 1 and 2 in the flow direction
A=78.54 cm²	cross-sectional area of specimen in the flow direction
t	time interval [s]
h_1, h_2	initial and final water head levels [m]

Table 2
Gross calorific value of MSW in [kJ/kg]

Sample number	GCV
Sample 1	23,269
Sample 2	23,236
Sample 3	23,414
Average	23,306

Table 3
Density of MSW in [g/cm³]

Cycle number	MacM2	MacM30
1	1.408066	1.395
2	1.409094	1.3957
3	1.411167	1.3936
4	1.409378	1.3957
5	1.410359	1.396
6	1.408748	1.396
7	1.41092	1.3953
8	1.411469	1.3958
9	1.41054	1.3987
10	1.411203	1.3983
Average	1.4101	1.3960

The ultimate analysis gives the elemental composition of the MSW. Based on the analyses conducted, technical (proximate) analysis of MSW was done to determine the key physical and chemical properties, such as: moisture content, volatile matter, fixed carbon and ash content.

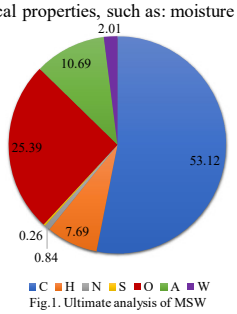


Fig.1. Ultimate analysis of MSW

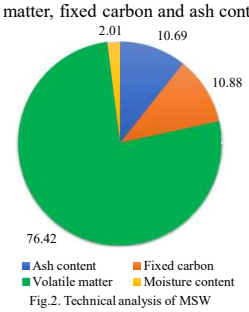
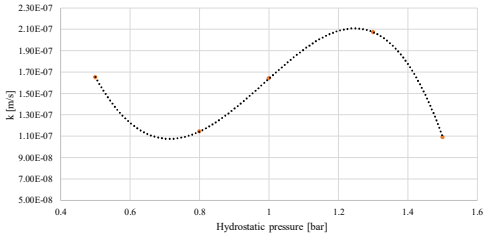


Fig.2. Technical analysis of MSW



The GCV of the MSW is measured to be 23,306 kJ/kg. This is exceptionally high for MSW, significantly exceeding the typical range of 7,000–15,000 kJ/kg. The high C content of 53.12% in MSW enhances its calorific value and combustion efficiency but also increases CO_2 emissions, necessitating proper combustion control to balance energy output and environmental impact. The elevated H content of 7.69% in MSW enhances calorific value and combustion efficiency while reducing soot formation, but it also increases water vapor production, leading to latent heat losses and slightly lower thermal efficiency. The low N content of 0.84% in MSW reduces NO_x formation, lowering air pollution and energy losses while enhancing combustion efficiency and minimizing the need for costly NO_x control technologies. The low S content of 0.26% in MSW reduces SO_x emissions, minimizing acid rain, corrosion, and the need for desulfurization, while enhancing combustion efficiency and fuel quality. The moderate to high O content of 25.39% in MSW enhances combustion efficiency and reduces unburned carbon, but excessive levels may indicate non-combustibles, slightly lowering calorific value. The moderate A content of 10.69% in MSW reduces calorific value and may cause slagging and fouling, but it can aid heat retention and offer reuse potential if non-toxic. The very low moisture content of 2.01% in MSW enhances calorific value, combustion efficiency, and flame stability while reducing energy losses, corrosion, and slag formation. The high density of 1,400 kg/m³ in MSW increases energy output and fuel consistency but may restrict airflow and retain moisture, requiring preprocessing for optimal combustion. A water permeability coefficient of $1.52 \cdot 10^{-7}$ m/s indicates that the MSW has low permeability, minimizing leachate formation but potentially increasing moisture retention, which may require pre-drying before combustion.

4. Conclusion

This study highlights the potential of MSW from large urban areas as a sustainable energy source for WtE systems, with its high GCV of 23,306 kJ/kg and advantageous chemical properties, such as high carbon and hydrogen content, making it a promising alternative to fossil fuels. While the MSW's low nitrogen and sulfur content minimize harmful emissions, proper preprocessing and combustion control are essential to optimize performance and reduce environmental impact, with the low water permeability helping to reduce leachate formation. Overall, MSW is a viable feedstock for energy recovery, but improving pretreatment and combustion processes is key to maximizing efficiency.

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