Characterization and Comparative Assessment of Flue Gas Emissions from Municipal Solid Waste Incineration

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1. INTRODUCTION

In this paper, the emissions of pollutants from the incineration process of municipal solid waste (MSW) are calculated and compared with those from more common fuel types, such as lignite and biomass. The main harmful substances released into the atmosphere through gaseous combustion products include sulphur oxides (SO_2 and SO_3), nitrogen oxides (NO and NO_2), carbon compounds (CO and CO_2), and solid particles originating from fly ash and residues of unburned fuel [1]. Two types of MSW were analysed: one from Skopje, North Macedonia (MacM2), sampled at the Drisla landfill, and another from Kraków, Poland (Pl2), collected at the intake of the Ekospalarnia incineration plant. Sampling followed Standard CEN/TR 15310-1, using a composite method that combines multiple sub-samples to ensure representativeness [2]. Both samples were prepared by removing inert material, reducing particle size (shredding), and lowering moisture content (drying). The particle size of the MSW samples did not exceed 2 mm. The ultimate analyses of both MSW types are presented in Tables 1 and 2.

Table 1. Ultimate analysis of MSW MacM2 [in mass %]

N	C	H	S	O	A	W
0.84	53.12	7.69	0.26	27.57	7.76	2.76

Table 2. Ultimate analysis of MSW Pl2 [in mass %]

N	C	H	S	O	A	W
0.52	46.39	6.80	0.26	33.90	8.90	3.23

2. MATERIALS AND METHODS

The emissions calculations were performed using established and verified equations from reputable academic sources, including faculty textbooks [3]. To perform a quantitative analysis of the fuel combustion process material balance of all substances involved was carried out, determining: O_{min}, V_{Lmin}, V_L, V_{RSt}, V_{RS}, $V_{H_2O}^t$, V_{H_2O}, V_{RWt} and V_{RW} in [m³/kg]. The equations used for calculating the emissions from the combustion process are the following:

Emissions of fly ash
$$M_{lp} = 10B\left(A + \frac{q_A H_d}{32{,}65}\right) a_{lp}(1-\eta_0) \quad \text{[g/s]} \quad (1)$$

Emissions of sulphur oxides
$$M_{SO_2} = B g_{SO_2}(1-\eta_{SO_2'})(1-\eta_{SO_2''}) \quad \text{[g/s]} \quad (2)$$

Emissions of nitrogen oxides expressed as NO_2
$$M_{NO_2} = B V_{RS} C_{NO_2} \frac{\lambda_s}{\lambda_{ig}} \quad \text{[g/s]} \quad (3)$$

Where: B - consumption of solid fuel [kg/s]; A - ash content in the fuel [mass %]; q_A - heat loss due to fuel incomplete mechanical combustion [%]; H_d - lower heating value [MJ/kg]; a_{lp} - portion of total ash introduced with the fuel carried away as fly ash [-]; η_0 - ash removal efficiency of the flue gas [-]; g_{SO_2} - mass of SO_2 per unit mass of fuel in the flue gases [g/kg]; $\eta_{SO_2'}$ - fraction of sulfur oxides bound to fly ash in the boiler flue gas ducts [-]; $\eta_{SO_2''}$ - portion of sulphur oxides removed from the flue gases in the ash collector [-]; C_{NO_2} - total maximum concentration of nitrogen oxides in the gases in the combustion zone for λ_s [g/m³]; $C_{NO_2}^T$ - total maximum concentration of thermal nitrogen oxides [g/m³]; $C_{NO_2}^G$ - total maximum concentration of fuel nitrogen oxides [g/m³]; $C_{NO_2}^B$ - total maximum concentration of prompt nitrogen oxides [g/m³]; λ_s - excess air coefficient in the combustion zone [-]; λ_{ig} - excess air coefficient in the flue gases at the chimney outlet [-].

3. RESULTS

Figures 1–3 present the annual emissions of harmful pollutants from the combustion of the examined waste materials, compared with those from a conventional fossil fuel (hard coal) and a renewable organic fuel (biomass). The x-axis indicates the percentage share of fuel in the combustion process: 25% corresponds to 39,799 t/year, 50% to 79,598 t/year, 75% to 119,397 t/year, and 100% to 159,196 t/year. The bars represent the emissions of different pollutants at varying fuel shares, while the dashed lines indicate the maximum emissions at 100% fuel share for lignite and biomass, used here as reference values.

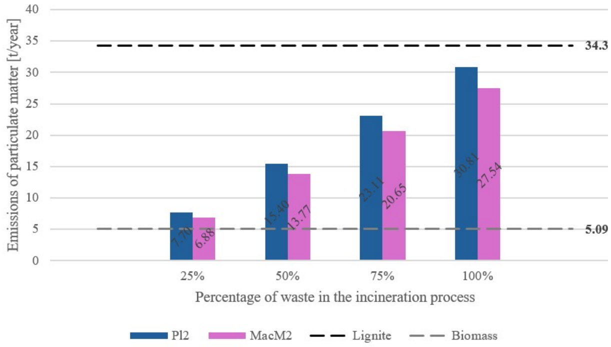

Figure 1. Annual emissions of particulate matter

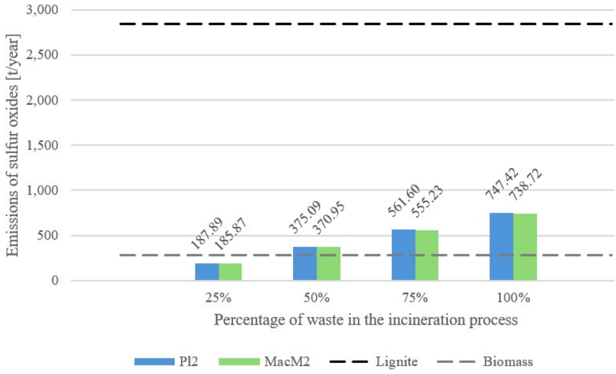

Figure 2. Annual emissions of sulphur oxides

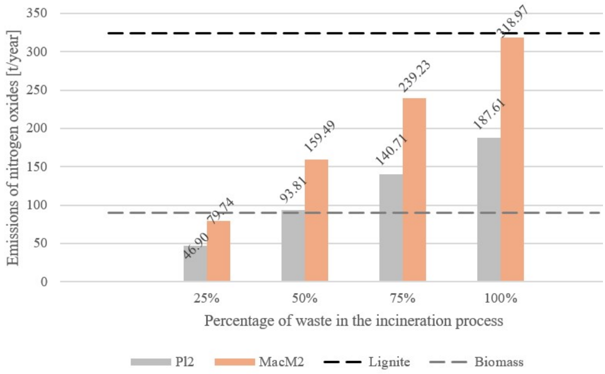

Figure 3. Annual emissions of nitrogen oxides

Across all fuels, the highest annual emissions of particulate matter (0.229 t/year), sulphur oxides (19 t/year), and nitrogen oxides (2.163 t/year) were recorded for lignite. The two waste types showed intermediate values, with Pl2 emitting 0.205 t/year PM, ~5 t/year SO_x, and 1.251 t/year NO_x, and MacM2 emitting 0.184 t/year PM, ~5 t/year SO_x, and 2.126 t/year NO_x, while biomass consistently exhibited the lowest emissions (0.034 t/year PM, 2 t/year SO_x, and 0.598 t/year NO_x).

4. CONCLUSIONS AND RECOMMENDATIONS

Lignite combustion generates the highest emissions among the fuels studied. At full fuel share, particulate matter reaches 0.229 t/year, followed by MSW types Pl2 (0.205 t/year) and MacM2 (0.184 t/year). Biomass has the lowest particulate matter emissions at 0.034 t/year, due to its low ash content. Sulphur oxides (SO_x) are the most significant pollutants. Lignite produces nearly 19 t/year, MSW around 5 t/year, and biomass only 2 t/year. These differences reflect fuel composition: lignite contains high sulphur, while biomass and MSW have 0.1% and 0.26% sulphur, respectively. Nitrogen oxides (NO_x) show a similar trend. Lignite emits 2.163 t/year, closely followed by MacM2 at 2.126 t/year. Pl2 emits 1.251 t/year, and biomass the lowest at 0.598 t/year. High NO_x from lignite is due to elevated combustion temperatures that promote thermal NO_x, while MacM2's high nitrogen content (0.84%) is a key contributor. Replacing lignite with biomass or selected MSW types could significantly cut emissions. However, waste incineration still produces notable NO_x and particulates, requiring advanced flue gas cleaning. Biomass is the most sustainable option, while MSW can support circular economy goals if paired with proper emission controls.

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