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Energy Treatment of Solid Municipal Waste in Combination with Biomass by Decentralized Method with the Respect to the Negative Effects on the Environment

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Abstract: Waste is a product of society and one of the biggest challenges for future generations is to understand how to sustainably dispose of large amounts of waste. The main objective of this study was to determine the possibility and conditions of the decentralized combustion of non-hazardous municipal waste. The analysis of the combustion properties of a mixture of wood chips and 20–30% of municipal solid waste showed an improvement in the operating parameters of the combustion process. Analysis also confirmed that the co-combustion of dirty fuels and biomass reduced the risk of releasing minerals and heavy metals from fuel into the natural environment. Approximately 55% of the heavy metals passed into the ash. The analysis of municipal solid waste and fuel mixtures containing municipal solid waste for polycyclic aromatic hydrocarbons showed the risk of increasing polycyclic aromatic hydrocarbon concentrations in flue gases.

Keywords: biomass; municipal solid waste; combustion

1. Introduction

In recent years, two important issues have been actively discussed in Slovakia and around the world. The first is the protection of the air and reduction of negative effects on the environment from different types of fuels. An integral part of these discussions and ongoing research is the European Parliament’s call for pollution reduction without loss of effectiveness. Directive 2009/28/EC of the European Parliament and of the Council about the promotion of the use of energy from renewable sources refers to the use of energy efficient technologies [1]. The second problem is municipal waste treatment. Waste is an inevitable product of society and one of the biggest challenges for future generations is to understand how to sustainably dispose of large amounts of waste. One approach is to minimize the amount of waste produced and recycle larger fractions of waste material. However, there is still a significant proportion of unwanted end products that need to be taken care of, and a more appropriate solution than landfilled needs to be found [2].

Thus, the main aim of this study was to determine the possibility and conditions required for decentralized combustion of non-hazardous municipal waste.

In the last few months, due to the discovery of a new type of virus, the problem of municipal solid waste (MSW) has become a topical issue [3]. Most face masks and medical waste are produced from non-renewable petroleum-based polymers that are not biodegradable, environmentally damaging, and cause health problems [4,5]. According to the 11 March 2021 press release of the State Council’s joint prevention and control mechanism in China, the amount of MSW in large- and medium-sized cities increased by 30% during the disease outbreak.

The proportion of noninfectious waste, which accounts for more than 80% of the total quantity of healthcare waste generated, needs to be collected and disposed as a municipal
This type of waste cannot be stored so a resolution for this problem must be found. Such waste is currently not only an undesirable product of society but also a source of energy. Energy recovery from waste can solve two problems at once: The treatment of a non-recyclable and reusable amount of waste, and the production of a significant amount of energy that can be included in the energy production mix to meet consumer needs.

Directive 2008/98/EC of the European Parliament and of the Council outlines the measures for the protection of the environment and human health by preventing or reducing the adverse effects of waste generation and management, reducing the overall impact of resource use, and increasing the efficiency of such use [7].

Municipal solid waste is classified and defined in different ways depending on the country and the waste management practices. Eurostat identifies MSW as produced by households or from other sources, such as trade, authorities, and public institutions [8]. Waste is collected by or on behalf of local authorities and disposed of through a waste management system. The Environmental Protection Agency (EPA) defines MSW even more precisely as everyday items such as product packaging, yard decorations, furniture, clothing, bottles and cans, food, newspapers, appliances, electronics, and batteries [9,10]. In this study, MSW includes packaging material, paper, and textiles (including working aids from the food and healthcare industries) from mechanical waste treatment such as sorting, crushing, pressing, compaction, and pelletizing.

The legislative framework is constantly pushing the energy sector to replace primary fuels with new types of alternative fuels that are both safe and energy efficient. This study focuses primarily on the possibilities of sharing energy from MSW and biomass. During the experiments, samples of fuels with different ratios of non-hazardous municipal waste and ordinary wood chips were studied to achieve the best energy result while meeting the standards for emissions of harmful substances into the atmosphere.

2. Materials and Methods

The main objective of this study was to determine the possibility and conditions of decentralized combustion of non-hazardous municipal waste.

We used MSW during the experiments, which belongs to the category of non-hazardous and other combustible waste, according to Decree of the Ministry of the Environment No. 365/2015 Coll. of the Slovak Republic, which is responsible for establishing the Waste Catalogue [11].

A series of experimental measurements performed in the study were divided into the following categories:

1. Energy properties of municipal solid waste (biofuels and non-hazardous municipal textile waste).
2. The migration of heavy metals (HM).
3. The formation and migration of polycyclic aromatic hydrocarbons (PAH).

This study was primarily based on previously approved European standards and laws, which have made it possible to formulate a methodology for studying the composition of alternative fuels and to demonstrate their suitability as fuels. According to Decree 410/2012 of the Ministry of the Environment of the Slovak Republic, which is based on Directive (EU) 2015/2193/EU of the European Parliament and of the Council, MSW storage is limited by HM emission limit values during its combustion, namely, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V, Cd, Tl, Hg [12]. Experimental measurements were performed using a biomass boiler with a stepped sliding grate with a nominal output of 83 kW. The boiler characteristics are in Table 1.

| Year of Manufacture | Fuel                | Minimum Power (kW) | Nominal Power (kW) | Heat Output in Fuel at Rated Heat Output (kW) | Boiler Class * |
|---------------------|---------------------|--------------------|--------------------|---------------------------------------------|----------------|
| 2011                | Wood chips, pellets | 24.9               | 83.0               | 90.1                                        | 3              |

* According to EU boiler classification.
The flue gases generated during combustion of the experimental samples were also analyzed. Flue gas analysis was performed using a Testo 360 measuring device, the characteristics of which are in Table 2.

### Table 2. Characteristics of measuring device Testo 360.

| Parameters                  | Measuring Range                  |
|-----------------------------|----------------------------------|
| \( \text{O}_2 \)           | 0–21 Vol.% \( \text{O}_2 \)      |
| \( \text{NO} \)            | 0–3000 ppm \( \text{NO} \)       |
|                             | 0–6160 mg/m\(^3\) \( \text{NO} \) |
| \( \text{NO}_2 \)          | 0–500 ppm \( \text{NO}_2 \)      |
|                             | 0–1030 mg/m\(^3\) \( \text{NO}_2 \) |
| \( \text{NO}_x (\text{NO}+\text{NO}_2) \) | 0–3500 ppm \( \text{NO}_x \) |
|                             | 0–7190 mg/m\(^3\) \( \text{NO}_x \) |
| \( \text{SO}_2 \)          | 0–5000 ppm \( \text{SO}_2 \)     |
|                             | 0–14,650 mg/m\(^3\) \( \text{SO}_2 \) |
| \( \text{CO}_2 \)          | 0–25 Vol.% \( \text{CO}_2 \)     |
| \( \text{CO} \)            | 0–10,000 ppm \( \text{CO} \)     |
|                             | 0–12,560 mg/m\(^3\) \( \text{CO} \) |
| Absolute pressure           | 40–1200 hPa                      |
| Flue gas moisture           | 2–31% \( \text{H}_2\text{O} \)   |
|                             | 15–70 °C \( \text{td} \)        |
| Temperature (flue gas temperature) | –40 to +1200 °C             |
| Flow speed                  | 5–40 m/s                         |
|                             | 0–50% hPa                        |

Experimental samples were prepared according to STN EN ISO 18135, which is the Slovak equivalent of European standard EN 14778: 2011 [13]. During sampling, great attention was paid to the correct method of sampling so that the sample, as far as was possible, represented the unit of fuel measured. In the samples, the grain sizes were maintained in the same ratio as in the investigated fuel. It was ensured that there was no change in the properties of the samples taken, such as oxidation or drying.

#### 2.1. Energy Properties

The basis for the energy evaluation of materials is the analysis of the energy properties of fuel, which includes the following properties:

- Elemental composition of fuel (C, H, N, O, S)
- Calorific values or combustion heat
- Humidity
- Ash and biomass content
- Emission factor
- Density

Analysis of the energy properties of the samples was conducted according to the following EU and Slovak norms and standards:

- Analysis of the elemental composition of the fuel was carried out according to EN 15,407 “Solid recovered fuels. Methods for determining the carbon (C), hydrogen (H) and nitrogen (N) content” [14].
- Analysis of the calorific value and combustion heat of the fuel was performed according to the standard EN 15,400 “Solid recovered fuels. Determination of fuel calorific value” [15].
- Fuel moisture content analysis was performed based on EN 15,414 “Solid recovered fuels. Determination of the moisture content using the oven drying method” [16].
The ash content analysis of the fuel was performed according to standard EN 15,403 “Solid recovered fuels. Determination of ash content” [17].

Analysis of the biomass content determination of the fuel was performed based on standard EN 15,440: “Solid recovered fuels. Methods for determining the biomass content” [18].

We analyzed four weight ratios of the fuel mixture in this study: 50/50, 70/30, 75/25, and 80/20. These ratios were evaluated using the boiler parameters, emission limits, and MSW production capacities.

The solid fuel in this study was not homogeneous and, therefore, great attention was paid to the correct method of sampling so that the sample represented the unit of fuel measured. The analytical samples were taken from different parts of the fuel. Every fuel sample was made from 10 separately mixed smaller samples. The weight of each small sample was 2–4 kg. The samples of the biomass and MSW were first separately mixed and then, after the necessary weight ratio of the small sample was obtained, it was mixed again. Each experimental fuel mixture was divided into batches. In each sample, the grain sizes were maintained in the same ratio as in the investigated fuel. For each ratio, the weight required for analysis was calculated. After sampling, conditions were provided to ensure that there was no change in the properties of the samples taken, such as oxidation or drying [13].

Fuel samples were taken according to the European standard STN EN ISO 18135. Figure 1 shows the sampling plan and procedure.

![Division of solid fuel into batches and preparation of mixture ratios](image)

**Figure 1.** Sampling procedure plan.

In a case of the removal of large amounts of samples in the repeated dose of the biofuel, each sample was prepared and analyzed separately, and the identity of the individual measurement $P$ was calculated by the following equation:

$$ P = 2s = 2\sqrt{V_{\text{SPT}}}, $$

(1)

where $s$ is the estimated standard deviation of the baseline for the sample and $V_{\text{SPT}}$ is the total variance of results for repeated samples.
The variance $V_{SPT}$ was calculated as

$$V_{SPT} = \frac{V_I}{N_{SL} \cdot n} + \frac{V_{PT}}{N_{SL}}$$  \hspace{1cm} (2)

The $P_L$ for the whole amount of the biofuel is calculated by

$$P_L = 2\sqrt{\frac{V_I}{N_{SL} \cdot n} + \frac{V_{PT}}{N_{SL}}}$$  \hspace{1cm} (3)

where $P_L$ is overall consistency for sampling, sample preparation and testing for the entire batch of biofuel at a confidence level of 95%; $V_I$ is the scattering of the primary sub-samples; $N_{SL}$ is the number of parts of the sub-dose in the dose; $n$ is the number of incremental samples per dose/sub-dose; and $V_{PT}$ is the variance of the sample preparation and testing.

2.2. The Migration of Heavy Metals

To obtain objective data on the determination of HM migration, our method was based on STN EN 15,309, which states the “characterization of waste and soil. Determination of elemental composition by X-ray fluorescence” [19]. Decree 410 of the Ministry of the Environment of the Slovak Republic, which was prepared based on standards and requirements of the European Union on emission reductions and environmental protection, sets precise emission limits for all sources of environmental pollution [12]. Based on this decree, the following list of pollutants was determined and they were monitored in this study:

1. Antimony, arsenic, lead, chromium, cobalt, copper, manganese, nickel, and vanadium: Maximum content in a flue gas 0.5 mg/m$^3$;
2. Cadmium and thallium: Maximum content in a flue gas 0.05 mg/m$^3$;
3. Mercury: Maximum content in a flue gas 0.05 mg/m$^3$.

X-ray fluorescence spectrometry was used for semi-quantitative determination of elements in a sample with high sensitivity, especially heavier elements. The technical parameters of the device are as follows:

1. Focusing with polycapillary optics on a beam with a diameter of 25 µm and interaction depth of 10–1000 µm;
2. A wide-angle camera and two coaxial digital microscopes, 10× and 100×, to search the test site in the sample;
3. Mosaic scanning when measuring large objects;
4. An X-ray tube with a Rh target, excitation maximum of 50 kV/600 µA, and 5 filters;
5. An SDD (Silicon Drift Detector) with a resolution of 145 eV and active area of 30 mm$^2$.

The concentrations of all the pollutants during the processing of the results were converted to normal conditions and reference oxygen content.

2.3. Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons (PAH) are organic compounds characterized by the presence of three or more fused benzene nuclei in a chemical structure. Almost all PAH sources are based on thermal processes associated with the combustion and processing of organic raw materials: Petroleum products, coal, wood, waste, food, tobacco, etc.

Decree 382/2018 of the Ministry of the Environment of the Slovak Republic, which was prepared based on the standards and requirements of the European Union on waste storage, sets a precise list and emission limits for all hazardous substances in waste storage, including PAHs and HMs [20]. Polycyclic aromatic hydrocarbons are defined as the sum of naphthalene, acenaphthene, acenaphthylene, fluorene, anthracene, phenanthrene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indene(1,2,3-cd)pyrene, dibenzo(ah)anthracene, and benzo(ghi)perylene.
According to Decree 382/2018, the emission limit for PHCs at a landfill for inert waste is 80 mg/kg.

To determine the concentration of PAHs in fuel and waste, a series of measurements was performed based on the standard EN 15,527: “Characterization of waste. Determination of polycyclic aromatic hydrocarbons (PAHs) in waste by gas chromatography-mass spectrometry (GC-MS)” [21].

3. Results

The main objective of this study was to determine the possibility and the conditions of the combustion of MSW as a secondary fuel in decentralized energy production. Based on the standards and procedures described in the Section 2, a series of measurements and analyses of mixtures of pure biomass and MSW were performed.

3.1. Energy Properties

The results of the analysis of the elemental composition of wood chips and its mixtures with MSW are shown in Table 3.

| Element | Wood Chips | MSW 50/50 | 70/30 | 75/25 | 80/20 |
|---------|------------|-----------|-------|-------|-------|
| C (%)   | 53.55      | 64.27     | 53.82 | 55.31 | 56.74 | 54.21 |
| H (%)   | 6.4        | 9.0       | 7.05  | 7.17  | 7.23  | 6.9   |
| N (%)   | 0.28       | 0.49      | 0.48  | 0.46  | 0.42  | -     |
| O (%)   | 39.64      | 26.21     | 38.54 | 36.87 | 35.37 | 38.42 |
| S (%)   | 0.13       | 0.026     | 0.11  | 0.19  | 0.24  | -     |

Compared to wood chips, MSW contains a higher concentration of carbon but a lower concentration of oxygen at almost the same concentrations of other components. The N and S concentration of the fuel mixture 80/20 were rated as uncertain, even after strictly following the method.

The results of laboratory measurements of calorific value, biomass/volatile matter content, humidity/ash content, and emission factors are shown in Table 4.

| Element                          | Wood Chips | MSW 50/50 | 70/30 | 75/25 | 80/20 |
|----------------------------------|------------|-----------|-------|-------|-------|
| Calorific value, MJ/kg          | 22.53      | 27.09     | 15.82 | 22.02 | 20.67 | 19.32 |
| Humidity, %                     | 27.46      | 6.59      | 9.27  | 6.96  | 6.63  | 6.30  |
| Ash content, %                  | 0.83       | 7.47      | 4.54  | 4.02  | 3.65  | 3.28  |
| Biomass content, %              | 93.28      | 21.82     | 72.33 | 84.25 | 83.16 | 82.07 |
| Volatiles, %                    | 80.87      | 86.6      | 79.2  | 82.63 | 78.3  | 73.97 |
| Emission factor tCO₂/TJ         | 88.66      | 86.99     | 124.7 | 91.34 | 100.6 | 82.64 |
| Density, kg/m³                  | 222.1      | 80.0      | 104.8 | 107.8 | 103.8 | 99.8  |

Based on the EU norms and the working parameters of the equipment, the uncertainty of the energy parameter analysis was 5–10%. The smallest values of the fuel mixtures of the calorific value, humidity and density are a result of the nonhomogeneous and stable structure of the fuel. The MSW sample analyzed represents the real waste mass. It can be concluded that even after mixing, the fuel mixtures remain nonhomogeneous.

The next stage of assessing the possibility and conditions of the fuel was a series of measurements during the combustion of the wood chips and its mixture with MSW. The main monitored parameters were the temperature in the combustion chamber, the temperature of the flue gas, and the concentration of CO, CO₂, NO, and O₂.
3.2. Combustion

The results of the measurements of the temperature in the combustion chamber during the combustion of fuel mixtures with different concentrations of MSW and wood chips are shown in Figure 2, while the temperatures of the flue gases are shown in Figure 3.

The reference measurement for combustion was the combustion of wood chips. During the first 10 min of the intensive operation phase, the temperature in the chamber increased slowly until reaching a temperature of approximately 475 °C. During further operation, the average temperature of the combustion chamber was stable, with the extremes of the graphs correlating with the periods of fuel supply to the combustion chamber.

The combustion of fuel with 50% wood chips and 50% MSW had a different character compared to the combustion of only wood chips. The temperature in the chamber increased...
more rapidly (6 min compared to 10 min) but the average temperature in the chamber was around 420 °C. Combustion under such conditions has a more stable temperature curve, as the mean deviation between the extremes decreased by 22%.

Combustion of fuels with ratios of 70/30 to 80/20 had a similar character. Due to the MSW content in the fuel mixture, they had a faster increase of temperature and the high content of wood chips had a stabilizing effect on the combustion process.

The flue gas temperature (Figure 3) during the combustion process of different fuels correlates with the temperature in the chamber. The higher flue gas temperature is the reason for the higher temperature in the combustion chamber. This is shown by the technical parameters of the exchanger.

The concentrations of CO in the flue gases during the combustion of wood chips and its mixture with MSW are shown in Figure 4. The concentration of CO in the combustion of wood chips was about 50% higher than the combustion when in a mixture. However, even in this case, the concentration of CO in the flue gas did not exceed the emission limit of 250 mg/m³.

![Figure 4. CO concentration in flue gases.](image)

The concentration of CO₂ in the flue gases during the combustion of wood chips and its mixture with MSW are shown in Figure 5. The concentration of CO₂ during the combustion of wood chips was about 7% higher than combustion in mixture with MSW. The reasons for this are the higher oxygen concentration in the fuel and lower temperature in the combustion chamber for the formation of nitrogen oxides.

The concentration of O₂ in the flue gases from the combustion of wood chips and its mixture with MSW are shown in Figure 6. The lower concentration of O₂ in the flue gases during the combustion of clean wood chips (about 5% lower compared to the combustion of mixtures) is a result of improved binding to organic carbon. In the case of fuel mixtures, the higher O₂ concentration is a result of the presence of longer hydrocarbon chains that take a longer time to fully oxidate.
The concentration of CO in the flue gases during the combustion of wood chips and its mixture with MSW are shown in Figure 5. The concentration of CO during the combustion of wood chips was about 7% higher than combustion in mixture with MSW. The reasons for this are the higher oxygen concentration in the fuel and lower temperature in the combustion chamber for the formation of nitrogen oxides.

Figure 5. CO concentration in flue gases.

The concentration of O2 in the flue gases from the combustion of wood chips and its mixture with MSW are shown in Figure 6. The lower concentration of O2 in the flue gases during the combustion of clean wood chips (about 5% lower compared to the combustion of mixtures) is a result of improved binding to organic carbon. In the case of fuel mixtures, the higher O2 concentration is a result of the presence of longer hydrocarbon chains that take a longer time to fully oxidate.

Figure 6. O2 concentration in flue gases.

The concentration of NO in the flue gases during the combustion of wood chips and its mixture with MSW are shown in Figure 7. The reason for the higher concentration of nitrogen oxides in the flue gas is the higher concentration of nitrogen in fuel mixtures compared to wood chips. The concentration of NO in the flue gases during the combustion of all types of fuel did not exceed the emission limit of 250 mg/m³.

Figure 7. NO concentration in flue gases.

After combustion of experimental fuel samples, we carried out a CHNS/O ash analysis, the results of which are shown in Table 5.

According to the CHNS/O analysis of the ash, it is possible to determine that the addition of 20–30% of the amount of MSW to the wood chips improves the combustion of combustible fuel components by 2–18%.
the higher O₂ concentration is a result of the presence of longer hydrocarbon chains that take a longer time to fully oxidate.

Figure 6. O₂ concentration in flue gases.

The concentration of NO in the flue gases during the combustion of wood chips and its mixture with MSW are shown in Figure 7. The reason for the higher concentration of nitrogen oxides in the flue gas is the higher concentration of nitrogen in fuel mixtures compared to wood chips. The concentration of NO in the flue gases during the combustion of all types of fuel did not exceed the emission limit of 250 mg/m³.

Figure 7. NO concentration in flue gases.

After combustion of experimental fuel samples, we carried out a CHNS/O ash analysis, the results of which are shown in Table 5.

Table 5. Elemental analysis of ash.

| Element | Wood Chips | MSW | 50/50 | 70/30 | 75/25 | 80/20 |
|---------|------------|-----|-------|-------|-------|-------|
| C (%)   | 5.31       | -   | 7.53  | 4.25  | 3.91  | 4.91  |
| H (%)   | 0.47       | -   | 0.87  | 0.42  | 0.3   | 0.45  |
| N (%)   | 0.37       | -   | 0.38  | 0.36  | 0.36  | 0.37  |
| O (%)   | -          | -   | -     | -     | -     | -     |
| S (%)   | 0.08       | -   | 0.05  | 0.07  | 0.09  | 0.07  |

3.3. The Migration of Heavy Metals

The results of the analysis of wood chips, MSW and mixtures for heavy metal and metalloid content are shown in Table 6.

Table 6. Heavy metal (HM) and metalloids concentration in the fuel. Values are mg/kg.

| Element         | Wood Chips | MSW | 50/50 | 70/30 | 75/25 | 80/20 |
|-----------------|------------|-----|-------|-------|-------|-------|
| Cd + Tl         | 0.1        | 7.92| 3.98  | 2.44  | 2.09  | 1.65  |
| Hg              | 0.6904     | 0.265| 0.512 | 0.6836| 0.7135| 0.5947|
| Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V | 41.9856 | 111.03| 48.697 | 67.63 | 64.53 | 61.48 |
| Zn              | 3.49       | 135 | 114.4 | 42.943| 36.3675| 29.792|

The content of heavy metals in wood chips was within the permitted limits according to Decree 410. However, the concentration of HM and metalloids can vary significantly depending on the species and origin [22].

Based on the EU norms and the working parameters of the equipment, the uncertainty of the HM analysis was 12–30%. The analysis of HM concentrations in MSW indicated the possibility of contamination of a given type of fuel with cadmium, chromium, lead, zinc, and copper. However, analysis of the concentration of HM in the ash (Table 7) showed that about 55% of HM was set in the ash. The concentration of HM in the flue gases, even in the case of average contamination, was in the range of 0.4 mg/m³, which is 20% below the permitted limits.
Table 7. HM and metalloids concentration in ash. Values are mg/kg.

| Element | Wood Chips | MSW 50/50 | 70/30 | 75/25 | 80/20 |
|---------|------------|-----------|-------|-------|-------|
| Cd + Tl | 0.00415    | -         | 2.437 | 1.801 | 1.301 |
| Hg      | 0.00083    | -         | -     | 0.0005| 0.001 |
| Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V | 52.79846 | -         | 20.8753 | 57.868725 | 110.18024 |
| Zn      | 1.24417    | -         | 110.856 | 21.23812 | 41.318 |

3.4. Polycyclic Aromatic Hydrocarbons

Based on the information regarding fuel composition, an analysis of PAH in fuel and ash was performed, and the results are presented in Table 8. This analysis was carried out to determine the content of PAHs captured and released into the atmosphere.

Table 8. The concentration of polycyclic aromatic hydrocarbons (PAH) in the fuel.

| Element | Wood Chips | MSW 50/50 | 70/30 |
|---------|------------|-----------|-------|
| acenaften | -         | -         | -     |
| acenaftylen | -         | -         | -     |
| benzo(a)antracen | -         | -         | -     |
| benzo(a)pyren | -         | -         | -     |
| benzo(b)fluoranten | -         | -         | -     |
| benzo(ghi)perylen | -         | -         | -     |
| benzo(k)fluoranten | -         | -         | -     |
| fenantren | 0.000564 | 0.064 | 0.00876 |
| fluoranten | -         | -         | -     |
| fluoren | -         | -         | -     |
| chryzen | -         | -         | -     |
| indeno (123cd)pyren | -         | -         | -     |
| naftalen | 0.000432 | 0.03423       | 0.03423 |
| pyren | -         | -         | -     |
| antracen | -         | -         | -     |
| dibenz(a)anthracen | -         | -         | -     |
| Sum PAU | 0.000996 | 0.064 | 0.04689 |

Based on the EU norms and the working parameters of the equipment, the uncertainty of the PAH analysis was 20–30%. Analysis of wood chips showed that, depending on the origin of their origin, they could contain phenanthrene and naphthalene, but their concentrations were almost 100 times below the permitted limits [23].

MSW analysis indicated a phenentrene content of 0.06 mg/m$^3$. However, ash analysis of fuels containing MSW indicated the possibility of fuel contamination by the following PAHs: acenaphthene, benzo (a) anthracene, benzo (b) fluoranthene, phenanthrene, fluorene, chrysene, naphthalene, pyrene, and anthracene. The total concentration of PAHs in the ash was about 0.12 mg/kg, which is 85% lower than the permitted limit of 0.8 mg/kg.

4. Discussion

The main aim of the study was to analyze the possibility of using energy from MSW in co-combustion with wood chips. Biomass fuels have significantly lower heating values than other fuels because of their higher moisture and oxygen contents. Furthermore, the global energy biomass production is still lower than consumption.

The combustion of MSW and biomass requires special combustion and filtering equipment. Another problem is its composition and structure. Even good mixing of the MSW does not mean that its composition will be the same even during one combustion
cycle. In this article, the scheme proposed for co-combustion of MSW and wood chips had the aim of reducing or even eliminating the negative aspects of separate combustion [24].

When co-combustion of dirty fuels with biomass is implemented, it reduces the total emissions per unit energy produced compared with separate combustion [25]. The approach proposed in this article produced stable fuel composition results of combustion during the whole cycle. The flammable compounds of the MSW were faster to react from a cold start, which helps the boiler to achieve its optimum working parameters faster. When the working parameters are achieved, the dominant concentration of the wood chips helps reach stable combustion and reduces the concentration of pollutants in the exhaust gases [24].

Our results for the co-combustion of MSW with wood chips were somewhat similar to the results for the co-combustion of dirty fuels and biomass, that is, reducing the risk of the release of minerals and HM, especially arsenic, from ash into the natural environment [26]. According to our results, approximately 55% of the HMs in the fuel mix are passed into ash, which made the exhaust gases of such combustion appropriate even for decentralized use. A report by the New York State Energy Research and Development Authority confirmed that such types of co-combustion may take place with special control of the HM concentration of the fuel and coupled with regular revisions of the combustion and exhaust equipment [27].

A previous study showed that the main source of PAH concentrated in the air of residential areas within cities is solid fuel burning [28]. According to our results, the co-combustion of MSW and wood chips increases the PAH concentration in the exhaust gases to approximately 0.77 mg/m$^3$, which is 3.75% under the limits. This increase is possibly attributable to the polymer compounds in the MSW. Filtration systems may not effectively arrest the gas phase pollutants, which needs to be addressed by specific air cleaning technological measures [29,30]. The exhaust system of the boiler should appropriately distribute the PAH outdoors.

5. Conclusions

The main objective of this study was to determine the possibility and conditions of the combustion of non-hazardous municipal waste in a decentralized manner. Based on our findings, we can draw the following conclusions:

1. An addition of 20–30% of MSW to the fuel mixture showed an improvement in the operating parameters of the combustion process. The addition of 50% of MSW will lead to undesirable effects during the combustion process due to the different physics of the combustion of MSW and wood chips. With concentrations of MSW in the fuel of more than 30%, the emission limits cannot be met.

2. During the combustion of the fuel mixtures, approximately 55% of the HM from the biomass and MSW passed into the ash. Analysis confirmed that the co-combustion of dirty fuels and biomass reduces the risk of releasing minerals and HM from the fuel into the natural environment. The HM concentration in the flue gases was in the range of 0.4 mg/m$^3$, which is 20% lower than emission limits.

3. Analysis of PAHs in MSW and fuel mixtures containing MSW showed a risk of increasing PAH concentrations in flue gases. Although the concentration of PAHs in the flue gas was within the appropriate limits, it is necessary to thoroughly control the chimney system of the combustion equipment in order to eliminate the increase in PAH content in the outdoor environment, especially in residential areas.

It can be concluded that combustion of biomass/MSW mixtures is a possible alternative for MSW treatment. Nevertheless, it should be appropriately controlled to meet legal environmental standards. Furthermore, even good mixing of MSW does not guarantee a homogenous structure.
Author Contributions: Conceptualization, M.R. and O.K.; methodology, O.K.; software, A.K.; validation, A.K., O.K. and M.R.; formal analysis, M.F.; data curation, M.R.; writing—original draft preparation, O.K.; writing—review and editing, M.R. and A.K.; visualization, M.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Slovak Research and Development Agency under the contract No. APVV-16-0192.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. European Parliament. Council of the European Union. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC. Off. J. Eur. Union 2009. Available online: http://data.europa.eu/eli/dir/2009/28/oj (accessed on 24 January 2021).
2. Taskin, A.; Demir, N. Life cycle environmental and energy impact assessment of sustainable urban municipal solid waste collection and transportation strategies. Sustain. Cities Soc. 2020, 61, 102339. [CrossRef]
3. Calma, J. The COVID-19 pandemic is generating tons of medical waste. Verge 2020. Available online: https://www.theverge.com/2020/3/26/21194647/the-covid-19-pandemic-is-generating-tons-of-medical-waste (accessed on 12 February 2021).
4. Dharmaraj, S.; Ashokkumar, V.; Harirhan, S.; Manibharathi, A.; Show, P.L.; Chong, C.T.; Ngamcharussrivichat, C. The COVID-19 pandemic face mask waste: A blooming threat to the marine environment. Chemosphere 2021, 272, 129601. [CrossRef] [PubMed]
5. Kulkarni, B.N.; Anantharama, V. Repercussions of COVID-19 pandemic on municipal solid waste management: Challenges and opportunities. Sci. Total Environ. 2020, 743, 140693. [CrossRef] [PubMed]
6. World Health Organization. Water, Sanitation, Hygiene, and Waste Management for SARS-CoV-2, the Virus that Causes COVID-19. Available online: https://www.who.int/publications/i/item/water-sanitation-hygiene-and-waste-management-for-the-covid-19-virus-interim-guidance (accessed on 3 March 2021).
7. European Parliament; Council of the European Union. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives. Off. J. Eur. Union 2008. Available online: http://data.europa.eu/eli/dir/2008/98/oj (accessed on 2 February 2021).
8. European Commission. Guidance on Municipal Waste Data Collection. Unit E2–Environmental Statistics and Accounts; Sustainable Development; Eurostat: Luxembourg, 2017.
9. Environmental Protection Agency. Advancing Sustainable Materials Management. 2019. Available online: https://www.epa.gov/sites/production/files/2019-11/documents/2017_facts_and_figures_fact_sheet_final.pdf (accessed on 3 March 2021).
10. Ncube, L.K.; Ude, A.U.; Ogunmuyiwa, E.N.; Zulkifli, R.; Beas, I.N. An Overview of Plastic Waste Generation and Management in Food Packaging Industries. Recycling 2021, 6, 12. [CrossRef]
11. Ministry of the Environment of the Slovak Republic. Decree of the Ministry of the Environment of the Slovak Republic No. 365/2015 Coll. 2015. Available online: https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2015/365/20160101 (accessed on 1 March 2021).
12. Ministry of the Environment of the Slovak Republic. Decree of the Ministry of the Environment of the Slovak Republic No 410/2012 Implementing Certain Provisions of the Clean Air Act, As Amended; Ministry of the Environment of the Slovak Republic: Bratislava, Slovakia, 2012.
13. Slovak Technical Standard. STN EN ISO 18135. Solid Biofuels-Sampling (ISO 18135:2017); Slovak Technical Standard: Bratislava, Slovakia, 2017.
14. European Committee for Standardization. EN 15407:2011. Solid Recovered Fuels. Methods for the Determination of Carbon (C), Hydrogen (H) and Nitrogen (N) Content; European Committee for Standardization: Brussels, Belgium, 2011.
15. European Committee for Standardization. EN 15400:2011. Solid Recovered Fuels. Determination of Fuel Calorific Value; European Committee for Standardization: Brussels, Belgium, 2011.
16. European Committee for Standardization. EN 15414-3:2011. Solid Recovered Fuels. Determination of Moisture Content Using the Oven Dry Method. Moisture in General Analysis Sample; European Committee for Standardization: Brussels, Belgium, 2011.
17. European Committee for Standardization. EN 15403:2011. Solid Recovered Fuels. Determination of Ash Content; European Committee for Standardization: Brussels, Belgium, 2011.
18. European Committee for Standardization. EN 15440:2011. Solid Recovered Fuels. Methods for the Determination of Biomass Content; European Committee for Standardization: Brussels, Belgium, 2011.
19. Slovak Technical Standard. STN EN 15309. Characterization of Waste and Soil-Determination of Elemental Composition by X-Ray Fluorescence; Slovak Technical Standard: Bratislava, Slovakia, 2011.
20. European Parliament; Council of the European Union. Decree of Ministry of the Environment of the Slovak Republic no. 382/2018 Coll. about landfill and storage of waste mercury. Off. J. Eur. Union 2019.

21. Slovak Technical Standard. STN EN 15527. Characterization of Waste. Determination of Polycyclic Aromatic Hydrocarbons (PAH) in Waste Using Gas Chromatography Mass Spectrometry (GC/MS); Slovak Technical Standard: Bratislava, Slovakia, 2009.

22. Pastircková, K. Determination of trace metal concentrations in ashes from various biomass materials. Energy Educ. Sci. Technol. 2004, 13, 97–104.

23. Löser, C.; Ulbricht, H.; Hoffmann, P.; Seidel, H. Composting of Wood Containing Polycyclic Aromatic Hydrocarbons (PAHs). Compost Sci. Util. 2013, 7, 16–32. [CrossRef]

24. Glushkov, D.; Paushkina, K.; Shabardin, D.; Strizhak, P.; Gutareva, N. Municipal solid waste recycling by burning it as part of composite fuel with energy generation. J. Environ. Manag. 2019, 231, 896–904. [CrossRef] [PubMed]

25. Demirbas, A. Combustion characteristics of different biomass fuels. Prog. Energy Combust. Sci. 2004, 30, 219–230. [CrossRef]

26. Wang, T.; Wang, Y.; Wang, Y.; Wang, J.; Zhang, Y.; Pan, W.-P. Arsenic release and transformation in co-combustion of biomass and coal: Effect of mineral elements and volatile matter in biomass. Bioresour. Technol. 2020, 297, 122388. [CrossRef] [PubMed]

27. New York State Energy Research and Development Authority. Elemental Analysis of Wood Fuels, Northeast States for Coordinated Air Use Management (NESCAUM); New York State Energy Research and Development Authority: Boston, MA, USA, 2013.

28. Kliucininkas, L.; Krugly, E.; Stasiulaitiene, I.; Radziuniene, I.; Prasauskas, T.; Jonusas, A.; Kauneliene, V.; Martuzevicius, D. Indooreoutdoor levels of size segregated particulate matter and mono/polycyclic aromatic hydrocarbons among urban areas using solid fuels for heating. Atmos. Environ. 2014, 97, 83–93. [CrossRef]

29. Bari, M.A.; Kindzierski, W.B.; Wheeler, A.J.; Héroux, M.E.; Wallace, L.A. Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada. Build. Environ. 2015, 90, 114–124. [CrossRef]

30. Stasiulaitiene, I.; Krugly, E.; Prasauskas, T.; Ciuzas, D.; Kliucininkas, L.; Kauneliene, V.; Martuzevicius, D. Infiltration of outdoor combustion-generated pollutants to indoors due to various ventilation regimes: A case of a single-family energy efficient building. Build. Environ. 2019, 157, 235–241. [CrossRef]