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# Co-combustion of wood pellet and waste in residential heating boilers – comparison of carbonaceous compound emission

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**Abstract:** Rising carbon dioxide emissions are driving climate change and there is growing pressure to find alternative energy sources. Co-combustion of waste with fuels is still occurring in some regions of the world, and it is important to know the compounds emitted from such combustion. This study investigated the emissions from the combustion of wood pellets with waste. The wood pellet was combusted with different additions of polyethylene terephthalate plastic and medium-density fiberboard (10 and 50%), in a low-power boiler (18W). Phenols, alkylphenols, phthalates, biomass burning markers, and polycyclic aromatic hydrocarbon emissions were determined. Gas chromatography coupled with a mass spectrometry detector was used to analyze these compounds after extraction and derivatization in the particulate matter and gas phase. The emissions of biomass burning markers and phthalates were the highest among all the compounds determined for MDF addition. The total emission of these compounds was 685 mg/h and 408 mg/h for 10% addition and 2401 mg/h and 337 mg/h for 50% addition, respectively. For the co-combustion of biomass with PET, PAHs and phenols had the highest emission; the emission was 197 mg/h and 114.5 mg/h for 10% addition and 268 mg/h and 200 mg/h for 50% addition, respectively. In our opinion, the obtained results are insufficient for the identification of source apportionment from household heating. After further study, tested compounds could be treated as markers for the identification of the fuel type combusted in households.

## Introduction

Rising carbon emissions impact climate change, and there is increasing pressure to find alternative energy sources. Biomass is one of the promising renewable energy sources used in households worldwide, especially in Europe (Poland, Finland, United Kingdom) that can replace fossil fuels [Hardy et al. 2012, Szyszlak-Bargłowicz et al. 2015, Lim et al. 2015]. Biomass absorbs carbon dioxide from the atmosphere during growth through photosynthesis and emits carbon dioxide during combustion, making it an almost CO<sub>2</sub>-neutral fuel [Musialik-Piotrowska et al. 2010, Krugly et al. 2014, Cincinelli et al. 2019]. The fuels used for the combustion of biomass are wood, sawdust, waste paper, wood wastes, grass, short-rotation woody crops, herbaceous species, bagasse industrial residues, municipal solid waste, waste from food processing, aquatic plants and algae animal wastes, and a host of other materials [Demibras 2004, Williams et al. 2012]. The most common forms of solid biomass fuels are straw, logs, pellets, chips, and pulverized fuels mainly composed of straw, wood, and a range of agricultural residues [Williams et al. 2012]. Wood pellets

as fuel are gaining popularity in many European countries in recent years among all forms of biomass [Szyszlak-Bargłowicz et al. 2015, Růžicková et al. 2019]. Wood biomass mainly consists of cellulose (45–55 wt%), hemicellulose (12–20 wt%), and lignins (20–30 wt%). In addition to these three main components, wood contains resins, tannins, fats, proteins, and minerals. The combustion of biomass occurs in 3 stages: drying and preheating fuel, the pyrolytic release of volatile flammable gases, and the combustion of pyrolytic gases and the solid remainder (tar and char). Thermal decomposition of biomass starts above 200°C. Hemicellulose decomposed at 220–320°C, cellulose at 320–370°C, and lignin at 320–500°C. The calorific value of biomass is lower than that of coal (23–28 MJ/kg) and ranges from 14 to 21 MJ/kg and is due to higher moisture content. [Hardy et al. 2012].

Biomass combustion, especially incomplete combustion and co-combustion with coal and wastes, is a source of emissions of particulate matter (PM), carbon monoxide (CO), nitrogen, nitrogen oxides (NO<sub>x</sub>), and volatile organic compounds (VOCs) such as polycyclic aromatic hydrocarbons (PAHs), phenols and aliphatic compounds into the atmosphere [Kistler et al. 2012,

Sun et al. 2018, Czaplicka et al. 2019; Chen et al. 2010]. These compounds are harmful to human health and affect climate change, cloud formation processes, and can scatter or absorb solar radiation. The formation of pollutants (PM, CO, NO<sub>x</sub>, and VOC) depends on the type of fuel, the type of fuel combustion technology, the type and boiler conditions, and individual parameters such as the operator and the condition of the chimney [Chen et al. 2010, Czaplicka et al. 2021].

In poorer countries in the world, including countries in Central and Eastern Europe (for example Poland, the Czech Republic, Romania, and Hungary), co-firing of solid fuels such as coal or biomass with waste such as plastics in domestic stoves is observed. This is often done for economic reasons to reduce the cost of heating households or waste disposal in landfills [Tomsej et al. 2018, Czaplicka et al. 2021]. Tomsej et al. [2018] described that in 2017 in the Czech Republic, there was a 15–25% decrease in the municipal waste collection from villages and suburban areas during the heating season. Another issue is the potential of the utilization of plastics by their co-combustion with solid fuels to reduce landfill waste and environmental contamination. This idea was born after knowing the calorific value of some waste plastics (41.80 MJ/kg for polyethylene, 30.90 MJ/kg for polypropylene, and 21.81 MJ/kg for polyethylene terephthalate plastic) compared to coal (28 MJ/kg) or dry wood (19.2 MJ/kg). Furthermore, through their properties such as excellent flowability, tensile strength, and hydrophobicity, plastics can be ideal candidates for the densification of coal and biomass [Song and Hall 2020; Czaplicka 2021]. Plastic waste comes in various chemical forms that vary in composition and physicochemical properties, these include polypropylene (PP), high-density and low-density polyethylene (HD and LD PE), polyvinyl chloride (PVC), polyacrylic (PA), polystyrene (PS) and polyethylene terephthalate plastic (PET) [Song 2020]. The third most widely used polymer in Europe after PE and LDPE is PET. PET is used in the production of food beverages (for bottle manufacturing) as well as in the production of synthetic fibers in the textile industry, automotive parts, electronics, sheets, films, and houseware [Dhahak 2020]. The main components of PET are carbon, hydrogen, and oxygen. Its calorific value is 21.81 MJ/kg, which is less than PE, PP, or coal, but more than biomass, so it can be used as an additive to the combustion of solid fuels [Oh and Seo 2019, Wasilewski and Siudyga 2013, Ishaq et al. 2006, Kojić et al. 2021]. Another waste used in combustion with biomass in domestic stoves is medium-density fiberboard (MDF). MDF is a type of composite wood product made in sheet form from wood chips and wood particles bonded together with binders and other resins. MDF is mainly used for furniture, flooring, packaging, and construction [Sun et al. 2012, Wang et al. 2018]. Combustion of PET and MDF can

lead to the emission of harmful compounds such as ketones, aldehydes, phenol and its derivatives, carboxylic esters, and their esters, amines, dibenzodioxins, and dibenzofurans and other organic compounds [Zheng et al. 2018]. It is important to know the composition of the emissions of organic compounds from the combustion of wastes in household furnaces and the use of plastics from landfills.

This study aimed to present the effect of the addition of MDF and PET on the emission of PAHs, phthalates, alkylphenols, phenols, and biomass burning markers under conditions of co-combustion with wood pellets in the household boiler.

## Material and methods

### Experimental Section

The experiment for biomass was conducted in the same manner as described in a previous publication for coal [Czaplicka et al. 2021], by use of the 18 kW boiler. Its efficiency was 85% and was equipped with self – contained fuel feeder, an air heater installation, and a measuring system. The entire process was controlled through a system consisting of the Itron CF 55 boiler heat capacity meter and Emiotest analyzer. A detailed description of the measurement system used and the specification of the boiler is presented in the article [Czaplicka et al. 2021]. Because of the type of fuel used in the tests and its additives (waste PET and MDF pellets), the mixtures of it were burned on a fixed grate set above the grate of the hopper.

Table 1 shows the fuel combustion parameters of the boiler.

During the experiment, the amount of dust obtained from the exhaust was also determined, by weighing the filters before and after the combustion process.

### Fuel Characteristics

Softwood pellets were used in the experiment and analyzed to determine their properties (Table 2). The tests were carried out according to standardized methods [Czaplicka et al. 2021].

### Sample Collection

The particulate matter samples were collected according to PZ-Z-2-04030-07:1994 normative procedure. The volume of gas was 1 m<sup>3</sup> with a collection time of 20 minutes. Gas phase samples were collected according to an accredited, author's test procedure by using an ASP3II aspirator [Czaplicka et al. 2021].

### Determination of Particulate Organic Compounds in the Gas and Solid Phase

Samples for analysis of organic compounds were prepared according to the methods more fully described in the previous article [Czaplicka et al. 2021]. The concentrations of PAHs,

**Table 1.** Fuel combustion parameters

| Parameter                                    | Pellet | Pellet + 10%<br>PET | Pellet + 50%<br>PET | Pellet + 10%<br>MDF | Pellet + 50%<br>MDF |
|--|--------|---------------------|---------------------|---------------------|---------------------|
| Amount of fuel burned [kg]                   | 4.0    | 4.0                 | 3.5                 | 6.0                 | 4.73                |
| Exhaust gas temperature [K]                  | 339    | 349                 | 333                 | 396                 | 359                 |
| Share of O <sub>2</sub> in dry flue gas [%]  | 18.2   | 17.7                | 17.0                | 18.7                | 19.3                |
| Share of CO <sub>2</sub> in dry flue gas [%] | 2.4    | 2.8                 | 3.1                 | 1.3                 | 1.7                 |

biomass burning markers, selected esters of phthalic acid, and selected alkylphenols were determined in the dust samples and without esters of phthalic acid also in the gas phase. Those species were analyzed according to the following methods: Janoszka et al. 2020 for biomass burning markers, Czaplicka et al. 2001 for the PAHs, Zubkova et al. 2016 for the phenols, Jaworek and Czaplicka 2013 for the esters of phthalic acid, and Li et al. 2003 for selected alkylphenols.

The limits of detection (LOD), limits of quantification (LOQ), and precision for all analytical procedures used are described in detail in Czaplicka et al. 2021.

## Results and discussion

The results of the study indicated that the quality and composition of the fuel mixture burned to have a significant impact on the emission characteristics of the process. Due to technical reasons, GC-MS analyses were not performed for the combustion of PET and MDF.

### Phenols

Phenol and its derivatives are mainly formed during the thermolysis of macromolecules containing an oxygen atom in their structure at 600–800°C. Authors indicate that phenols can be formed by the reaction of phenolic radicals with free H radicals, or by breaking the aryl ether bonds present in fuels during combustion [Pan et al. 2013, Williams et al. 2012].

The emissions of phenols from pellet co-combustion with additives were from 27.0 to 200.4 mg/h (Table 3). The highest emission was observed for the combustion process with 50% of PET, while the lowest emission was for 50%

of MDF material. Phenol had the highest emissions, ranging from 15.6 to 159.7 mg/h.

Among all phenols, phenol was the highest emitted in all fuels burned. Its emissions increased with the addition of PET, while those of cresols decreased. Whereas emissions differed slightly for MDF.

### Alkylphenols

During the thermolysis of plastic, alkylphenols such as bisphenol and octaphenols among others are produced. These compounds have high water solubility, low Henry's law, and low vapor pressure, so they can be determined in both the solid and gas phases. Alkylphenols, through their estrogenic effects on health, can be harmful to humans and animals [Pan et al. 2013, Uğuz et al. 2009].

The emission of alkylphenols to the solid phase was from 0.41 to 5.1 mg/h for pellet combustion with the additives tested. In the case of the gas phase, the emission was in the range of 0.57 to 4.8 mg/h (Table 4). The highest alkylphenol emissions were obtained in the solid phase for co-combustion with a 10% PET additive. Bisphenol A had the highest emission among all the determined alkylphenols and was in the range of 0.04 to 5.1 mg/h for the PM phase and 0.24 to 4.8 mg/h for the gas phase. Except for 50% PET where the highest emission to the gas phase was 4-tOP and for 10% MDF additive, where the highest emission to the solid phase was 4-nNP. For the co-combustion of the pellet with PET, alkylphenol emissions were highest for the PM phase. In contrast, for the co-combustion of pellets with MDF, the highest emissions were for the gas phase. Salapasidou et al. 2011 also obtained the highest emission of bisphenol A of all the alkylphenols tested.

**Table 2.** Chemical and technical analysis of softwood pellet and co-combustion materials in the dry state

| Assay              | Content/Assigned value |       |       |
|--------------------|------------------------|-------|-------|
|                    | Pellet                 | MDF   | PET   |
|                    | [%weight (%w/w)]       |       |       |
| Ash                | 0.67                   | 0.97  | 14.56 |
| Carbon             | 53.41                  | 51.42 | 60.11 |
| Hydrogen           | 6.13                   | 6.12  | 8.02  |
| Sulfur             | <0.03                  | <0.03 | 0.14  |
| Oxygen (different) | –                      | 42.43 | 31.72 |
|                    | [J/g (MJ/kg)]          |       |       |
| Combustion heat    | 19.71                  | 19.25 | 25.57 |
| Calorific value    | 18.38                  | 17.92 | 23.85 |

**Table 3.** Emission factors of phenols (mg/h)

| Compound   | Pellet | Pellet + 10% PET | Pellet + 50% PET | Pellet + 10% MDF | Pellet + 50% MDF |
|------------|--------|------------------|------------------|------------------|------------------|
| phenol     | 52.7   | 65.7             | 159.7            | 21.5             | 15.6             |
| o-cresol   | 14.8   | 17.5             | 14.4             | 7.0              | 3.0              |
| p,m-cresol | 24.8   | 31.2             | 26.4             | 16.0             | 8.4              |
| total      | 92.3   | 114.5            | 200.4            | 44.6             | 27,0             |

### Phthalates

Studies have shown that one of the groups of compounds formed during carbon thermolysis is phthalates [Zubkova and Czaplicka 2012]. Phthalates are determined in the solid phase due to their low volatility and low solubility in water. Phthalates are produced on a large scale, mainly as plasticizers in polymers and resins, and are used in food packaging, toys, personal care products, pharmaceuticals, varnishes, and paints. Phthalates are not physically bound to polymers, so they can be released from plastics and leached into the environment. Phthalates have negative effects on human health by affecting the immune and endocrine systems. These compounds are suspected of increasing cases of asthma and allergies [Růžičková et al. 2016, Chen et al. 2012].

The obtained results indicate that the phthalates emission factors were from 38.0 to 408.1 mg/h, depending on the composition of the combusted mixture (Table 5). During the combustion of the pellet, DBP had the highest emissions, DMP, DOP, DEP, and DEHA had similar emissions, and DEHP and BBP had negligible emissions. With the addition of PET, DEP and DEHA emissions increased significantly, and DEHP increased slightly, which may indicate that their source is plastic. In contrast, DBP emissions decreased. With the

MDF additive, DEP and DEHP emissions increased slightly. In contrast, DOP emissions decreased significantly, while DMP and DEHA emissions decreased slightly. Other results for waste co-combustion were obtained by Li et al. 2020. They obtained the highest emissions for DEHP, DBP, and BBP while we obtained the highest emissions for DBP, DEP, and DEHP. Salapasidou et al. 2011 also obtained the highest emissions for DEHP.

### Biomass Burning Markers

The emissions factor of the determined monosaccharides in pellet combustion was 661 mg/h (Table 6). The addition of plastics resulted in higher biomass burning markers emissions compared to burning pellets alone. The pellet co-combustion with a 10% addition of PET was characterized by the emission factor 517.7 mg/h. In comparison, the 50% addition of PET resulted in a further decrease in emissions, to 457.3 mg/h compared to pellet combustion.

Levoglucosan had the highest emissions of all the fuels tested. With the addition of PET, the contribution to emissions of the other isomers (mannosan and galactosan) increased slightly. Similar results of biomass burning marker emissions for biomass were obtained by Růžičková et al. 2019.

**Table 4.** Alkylphenol emission factors (mg/h)

| Compound           | Pellet +10% PET |           | Pellet + 50% PET |           | Pellet + 10% MDF |           | Pellet + 50% MDF |           |
|--------------------|-----------------|-----------|------------------|-----------|------------------|-----------|------------------|-----------|
|                    | PM              | Gas Phase | PM               | Gas Phase | PM               | Gas Phase | PM               | Gas Phase |
| <b>4-tOP</b>       | Nd              | 0.86      | 0.03             | 0.57      | 0.14             | 1.24      | 0.15             | 1.0       |
| <b>4-nNP</b>       | Nd              | 0.46      | 0.04             | 0.30      | 0.37             | 0.04      | 0.58             | nd        |
| <b>BPA</b>         | 5.1             | 1.04      | 3.41             | 0.24      | 0.04             | 4.15      | 0.60             | 4.8       |
| <b>total</b>       | 5.1             | 0.86      | 3.44             | 0.57      | 0.41             | 1.24      | 1.18             | 4.8       |
| <b>Grand total</b> |                 | 7.5       |                  | 4.6       |                  | 5.8       |                  | 6.3       |

**Table 5.** Phthalates emission factors (mg/h)

| Compound     | Pellet | Pellet +10% PET | Pellet + 50% PET | Pellet + 10% MDF | Pellet + 50% MDF |
|--------------|--------|-----------------|------------------|------------------|------------------|
| <b>DMP</b>   | 4.3    | 4.8             | 4.6              | 29.6             | 30.2             |
| <b>DEP</b>   | 0.27   | 0.74            | 0.79             | 28.1             | 25.8             |
| <b>DBP</b>   | 30.1   | 17.2            | 23.5             | 277.0            | 203.6            |
| <b>BBP</b>   | 4.2    | 0.74            | 0.31             | 2.2              | 3.3              |
| <b>DEHA</b>  | 0.67   | 0.36            | 0.31             | 3.2              | 2.6              |
| <b>DEHP</b>  | 4.5    | 9.5             | 12.3             | 50.6             | 50.2             |
| <b>DOP</b>   | 4.8    | 4.7             | 9.2              | 17.4             | 21.7             |
| <b>total</b> | 48.9   | 38.0            | 50.9             | 408.1            | 337.4            |

**Table 6.** Biomass burning markers emission factors (mg/h)

| Compound            | Pellet | Pellet +10% PET | Pellet + 50% PET | Pellet + 10% MDF | Pellet + 50% MDF |
|---------------------|--------|-----------------|------------------|------------------|------------------|
| <b>Levoglucosan</b> | 617.3  | 438.4           | 398.5            | 639.2            | 2257.0           |
| <b>Mannosan</b>     | 38.1   | 57.4            | 44.8             | 40.5             | 134.2            |
| <b>Galactosan</b>   | 5.7    | 21.8            | 14.0             | 5.1              | 9.4              |
| <b>total</b>        | 661.1  | 517.7           | 457.3            | 684.8            | 2400.6           |
| <b>LG/MN</b>        | 16.2   | 7.6             | 8.9              | 15.8             | 16.8             |
| <b>LG/(MN+GA)</b>   | 14.1   | 5.5             | 6.8              | 14.0             | 15.7             |

### Polycyclic Aromatic Hydrocarbons

The PAHs emissions varied and depended on the mixture burned. Emission factors were fuel-dependent, ranging from 86.6 to 267.9 mg/h for PAHs (Table 7). The highest emission factors were found for the combustion of pellets with 50% of PET, and the lowest for pellets with 50% of MDF.

The combustion of pellets with plastics was characterized by much higher emissions of PAHs to the gas phase (in the range of 78 to 168.6 mg/h) than to the solid phase (in the range of 8.6 to 66.3 mg/h). The highest emission was obtained for the 50% addition of PET. Phenanthrene had the highest emissions to the gas phase for all fuel types. In contrast, in the solid phase, the highest emission was benzo(a)pyrene for most fuels, except for the 50% PET additive for which the highest emission was indeno(1,2,3-c,d)pyrene.

When pellets were combusted alone, the highest emissions to the gas phase were of 3-ring PAHs. Whereas, when pellets were combusted with both PET and MDF, emissions of light 2-ring PAHs increased, and for MDF emissions of 4-ring PAHs also increased slightly. For the combustion of pellets alone, the highest emissions to the solid phase were characterized by 5-ring PAHs. 4 and 6-ring PAHs also had significant emissions. With the increase of PET addition, the emissions of 5-ring PAHs decreased and those of 4-ring PAHs increased, 6 ring PAHs were almost at the same level. Whereas with the increase of MDF addition, the emission of 4 and 2-ring PAHs increased, and that of 5 and 6-ring PAHs decreased.

PAHs increased significantly at 50% PET and MDF addition versus 10% addition. Similar results of the increase in PAH emissions when burning wood with plastics were obtained by Tomsej et. al 2018.

### Comparison of emission results of selected organic compounds for co-combustion of coal and pellets with PET

Table 8 shows a comparison of results for selected compounds for the combustion of pellets and coal with PET presented in a previous publication by Czaplicka et al. 2021. As can be seen, the results obtained vary depending on the type of basic fuel as well as the amount of PET added to the combustion. Levoglucosan had quite a bit higher emissions for pellets than for coal which is obvious due to its origin. The results may also vary due to the different combustion mechanisms depending on the type of fuel and the addition of waste to combustion as it has. The preliminary results of the analyses may be promising for further studies to determine waste combustion markers and help identify the type of air pollutants.

### Conclusions

The emission factors of gaseous and particulate pollutants from the combustion of biomass with different PET and MDF additives in a low-power boiler were compared. It was estimated that organic compounds' emission factors depend on the biomass-waste mixture. It is well known that burning PET with biomass is illegal, but it still occurs in some regions of the world, and it is therefore important to know the characteristics of air emissions from such processes. The results show that co-combustion with 50% PET is characterized by the highest emissions of PAHs, alkylphenols, and phenols among all tested additives.

Adding 50% of PET to the pellet causes an increase in PAHs emission factor compared to the pellet and pellet with 10% of PET as a fuel. The addition of MDF reduced PAH emissions compared to pellets alone, indicating the origin of PAHs

Table 7. PAHs emission factors (mg/h)

| Compound                | Pellet |       | Pellet +10% PET |       | Pellet + 50% PET |       | Pellet + 10% MDF |       | Pellet + 50% MDF |      |
|-------------------------|--------|-------|-----------------|-------|------------------|-------|------------------|-------|------------------|------|
|                         | PM     | Gas   | PM              | Gas   | PM               | Gas   | PM               | Gas   | PM               | Gas  |
| Naphthalene             | 0.53   | 11.4  | 0.88            | 18.8  | 1.6              | 50,4  | 0.19             | 23.2  | 0.15             | 12.0 |
| Acenaphthylene          | 0.14   | 24.7  | 0.23            | 26.2  | 0.23             | 48,3  | 0.07             | 20.5  | 0.03             | 8.1  |
| Acenaphthene            | 0.14   | 3.3   | 0.34            | 3.0   | 0.40             | 3,3   | 0.08             | 5.7   | 0.08             | 4.0  |
| Fluorene                | 0.30   | 0.7   | 1.4             | 3.4   | 1,3              | 3,0   | 0.44             | 9.1   | 0.41             | 7.6  |
| Phenanthrene            | 1.0    | 50.7  | 1.5             | 55.7  | 4,3              | 64,6  | 0.45             | 63,8  | 0.27             | 23.5 |
| Anthracene              | 0.73   | 30.3  | 1.4             | 32.8  | 2,5              | 19,8  | 0.21             | 27,4  | 0.09             | 11,0 |
| Fluoranthene            | 3.2    | 5.0   | 4.0             | 6.5   | 6.6              | 6,6   | 0.73             | 9.7   | 0.70             | 6.0  |
| Pyrene                  | 3.9    | 4.7   | 4.2             | 5.4   | 6.5              | 5,6   | 0.81             | 9,3   | 0.90             | 5.8  |
| Benzo(a)anthracene      | 4.5    |       | 3.5             |       | 4.6              |       | 0.98             |       | 1.3              |      |
| Chrysene                | 3.1    |       | 2.5             |       | 4.1              |       | 0.71             |       | 0.92             |      |
| Benzo(b)fluoranthene    | 5.8    |       | 4.9             |       | 6.4              |       | 1.2              |       | 0.83             |      |
| Benzo(k)fluoranthene    | 3.6    |       | 3.1             |       | 3.6              |       | 0.36             |       | 0.36             |      |
| Benzo(a)pyrene          | 7.6    |       | 5.7             |       | 6.5              |       | 1.4              |       | 1.1              |      |
| Indeno(1,2,3-c,d)pyrene | 7.4    |       | 6.0             |       | 9.2              |       | 1.1              |       | 0.69             |      |
| Dibenzo(a,h)anthracene  | 1.3    |       | 0.1             |       | 0.35             |       | 0.01             |       | nd               |      |
| Benzo(g,h,i)perylene    | 6.0    |       | 5.2             |       | 7.9              |       | 1.1              |       | 0.64             |      |
| Benzo(j)fluoranthene    | 1.6    |       | 0.27            |       | 0.45             |       | 0.06             |       | 0.10             |      |
| total                   | 50.8   | 130.8 | 45.2            | 151.6 | 66.3             | 201.6 | 10.0             | 168.6 | 8.6              | 78.0 |
| Grand total             |        | 181.6 |                 | 196.9 |                  | 267.9 |                  | 178.6 |                  | 86.6 |

**Table 8.** Emissions for selected organic compounds for co-combustion of coal and pellet with PET [mg/h]

| Compound             | Pellet +10% PET |      | Pellet + 50% PET |       | Coal + 10% PET |       | Coal + 50% PET |       |
|----------------------|-----------------|------|------------------|-------|----------------|-------|----------------|-------|
|                      | PM              | Gas  | PM               | Gas   | PM             | Gas   | PM             | Gas   |
| Phenol               |                 | 65.7 |                  | 159.7 |                | 158.6 |                | 351.5 |
| BPA                  | 5.1             | 1.04 | 3.41             | 0.24  | 9.5            | 21.1  | 10.1           | 234.8 |
| DEP                  | 0.74            |      | 0.79             |       | <0.05          |       | 0.10           |       |
| DOP                  | 4.7             |      | 9.2              |       | 0.5            |       | 2.0            |       |
| DEHA                 | 0.36            |      | 0.31             |       | 0.15           |       | <0.05          |       |
| Levoglucozan         | 438.4           |      | 398.5            |       | 6.2            |       | 10.3           |       |
| Naphthalene          | 0.88            |      | 1.6              | 50,4  | 1.9            | 31.7  | 1.1            | 123.1 |
| Phenanthrene         | 1.5             | 55.7 | 4,3              | 64,6  | 9.4            | 27.2  | 100.4          | 56.9  |
| Anthracene           | 1.4             | 32.8 | 2,5              | 19,8  | 8.2            | 8.3   | 60.6           | 34.8  |
| Benzo(a)pyrene       | 5.7             |      | 6.5              |       | 49.0           |       | 45.1           |       |
| Benzo(g,h,i)perylene | 5.2             |      | 7.9              |       | 25.6           |       | 19.5           |       |

from pellets. Considering the composition of MDF, which is mainly lignin and cellulose, the increase in the concentration of levoglucosan and its isomers relative to PET pellets and pellets is understated. The obtained results for the biomass burning markers confirm the literature data that levoglucosan dominates among the determined monosaccharides anhydride.

Given Poland's current economic and energy situation, the preliminary results described in both articles can help interpret future organic aerosol sample results. After further study, these compounds could be treated as markers for the identification of the fuel combusted in households.

## References

- Chen, L., Zhao, Y., Li, L., Chen, B. & Zhang, Y. (2012), Exposure assessment of phthalates in non-occupational populations in China, *Science of the Total Environment*, 427–428, pp. 60–69, DOI: 10.1016/j.scitotenv.2012.03.090
- Chen, Q., Zhang, X., Bradford, D., Sharifi, V. & Swithenbank, J. (2010). Comparison of emission characteristics of small-scale heating systems using biomass instead of coal, *Energy Fuels*, 24, 8, pp. 4255–4265, DOI: 10.1021/ef100491v
- Cincinelli, A., Guerranti, C., Martellini, T. & Scodellini, R. (2019). Residential wood combustion and its impact on urban air quality in Europe, *Current Opinion In Environmental Science & Health*, 8, pp. 10–14, DOI: 10.1016/j.coesh.2018.12.007
- Czaplicka, M., Cieślak, E., Komosiński, B. & Rachwał, T. (2019). Emission factors for biofuels and coal combustion in a domestic boiler 18kW, *Atmosphere*, 10, 12, DOI: 10.3390/atmos10120771
- Czaplicka, M., Klyta, J., Komosiński, B., Konieczny, T. & Janoszka, K. (2021), Comparison of carbonaceous compounds emission from the co-combustion of coal and waste in boilers used in residential heating in Poland, Central Europe, *Energies*, 14, 5326, pp. 1–15, DOI: 10.3390/en14175326
- Czaplicka, M., Węglarz, A., Klejnowski, K. (2001), Analysis of organic contaminants from motor vehicles adsorbed on the particulate matter for PAHs, *Chemia Analityczna*, 46, pp. 677–689.
- Demibras, A. (2004). Combustion characteristics of different biomass fuels, *Progress in Energy and Combustion Science*, 30, pp. 219–230, DOI: 10.1016/j.peccs.2003.10.004
- Dhahak, A., Grimmer, Ch., Neumann, A., Rüger, Ch., Sklorz, M., Streibel, Th., Zimmermann, R., Mauviel, G. & Burkle-Vitzhum, V. (2020). Real-time monitoring of slow pyrolysis of polyethylene terephthalate (PET) by different mass spectrometric techniques, *Waste Management*, 106, pp. 226–239, DOI: 10.1016/j.wasman.2020.03.028
- Hardy, T., Musialik-Piotrowska, A., Ciołek, J., Mościcki, K. & Kordylewski, W. (2012). Negative Effects of Biomass Combustion and Co-combustion in boilers, *Environment Protection Engineering*, 38, 1, pp. 25–33
- Ishaq, M., Ahmad, I., Shakirullah, M., Arsala Khan, M., ur Rehman, H. & Bahadur, A. (2006), Pyrolysis of some whole plastics and plastics-coal mixtures, *Energy Conversion and Management*, 47, 18–19, pp. 3216–3223, DOI: 10.1016/j.enconman.2006.02.019
- Janoszka, K., Czaplicka, M. & Klejnowski, K. (2020), Comparison of biomass burning tracers concentration between two winter seasons in Krynica Zdrój, *Air Quality, Atmosphere & Health*, 13, pp. 379–385, DOI: 10.1007/s11869-020-00801-1
- Jaworek, K. & Czaplicka, M. (2013), Determination of phthalates in polymer materials – Comparison of GC/MS and GC/ECD methods, *Polimeros*, 23, pp. 718–724, DOI: 10.4322/polimeros.2014.014
- Kistler, M., Schmidl, Ch., Padouvas, E., Giebl, H., Lohninger, J., Ellinger, R., Bauer, H. & Puxbaum, H. (2012). Odor, gaseous and PM<sub>10</sub> emissions from small scale combustion of wood types indigenous to central Europe, *Atmospheric environment*, 51, pp. 86–93, DOI: 10.1016/j.atmosenv.2012.01.044
- Kojić, I., Bechtel, A., Aleksić, N., Životić, D., Trifunović, S., Gajica, G. & Stojanović, K. (2021), Study of the synergetic effect of co-pyrolysis of lignite and high-density polyethylene aiming to improve utilization of low-rank coal, *Polymers*, 13, 5, pp. 1–25, DOI: 10.3390/polym13050759
- Krugly, E., Martuzevicius, D., Puida, E., Buinevicius, K., Stasiulaitiene, I., Radziuniene, I., Minikauskas, A. & Klucininkas, L. (2014), Characterization of gaseous- and particulate-phase emissions from the combustion of biomass-residue-derived fuels in a small residential boiler, *Energy Fuels*, 28, pp. 5057–5066, DOI: 10.1021/ef500420t
- Li, D.H., Oh, J.R. & Park, J. (2003), Direct extraction of alkylphenols, chlorophenols and bisphenol A from acid-digested sediment suspension for simultaneous gas chromatographic-mass spectrometric analysis, *Journal of Chromatography A*, 1012, pp. 207–214, DOI: 10.1016/S0021-9673(03)01174-9
- Li, Zh., Guo, S., Li, Zh., Wang, Y., Hu, Y., Xing, Y., Liu, G., Fang, R. & Zhu, H. (2020), PM<sub>2.5</sub> Associated phenols, phthalates and

- water-soluble ions from five stationary combustion sources, *Aerosol and Air Quality Research*, 20, pp. 61–71, DOI: 10.4209/aaqr.2019.11.0602
- Lim, M.T., Phan, A., Roddy, D. & Harvey, A. (2015). Technologies for measurement and mitigation of particulate emissions from domestic combustion of biomass: A review, *Renewable and Sustainable Energy Reviews*, 49, pp. 574–584, DOI: 10.1016/j.rser.2015.04.090
- Musialik-Piotrowska, A., Kordylewski, W., Ciołek J. & Mościcki, K. (2010). Characteristics of air pollutants emitted from biomass combustion in small retort boiler, *Environment Protection Engineering*, 36, 2, pp. 123–131.
- Oh, S.-Y. & Seo, T.-C. (2019) Upgrading biochar via co-pyrolisation of agricultural biomass and polyethylene terephthalate wastes, *RCS Advances*, 9, pp. 28284–28290, DOI: 10.1039/C9RA05518E
- Pan, Ch.-X., Wei, X.-Y., Shui, H.-F., Wang, Zh.-C., Gao, J., Wei, Ch., Cao, X.-Zh. & Zong, Zh.-M. (2013), Investigation on the macromolecular network structure of Xianfeng lignite by a new two-step depolymerization, *Fuel*, 109, pp. 49–53, DOI: 10.1016/j.fuel.2012.11.059
- Růžičková, J., Kucbel, M., Raclavská, H., Švédová, B., Raclavský, K. & Juchelková, D. (2019). Comparison of organic compounds in char and soot from the combustion of biomass in boilers of various emission classes. *Journal of Environment Management*, 15, pp. 769–783, DOI: 10.1016/j.jenvman.2019.02.038
- Růžičková, J., Raclavská, H., Raclavský, K. & Juchelková, D. (2016), Phthalates in PM<sub>2.5</sub> airborne particles in the Moravian-Silesian Region, Czech Republic, *Perspectives in Science*, 7, pp. 178–183, DOI: 10.1016/j.pisc.2015.11.029
- Salapacidou, M., Samara, C. & Voutsas, D. (2011), Endocrine disrupting compounds in the atmosphere of the urban area of Thessaloniki, Greece, *Atmospheric Environment*, 45, 22, pp. 3720–3729, DOI: 10.1016/j.atmosenv.2011.04.025
- Song, B. & Hall, P. (2020). Densification of biomass and waste plastic blends as a solid fuel: hazards, advantages, and perspectives, *Frontiers in Energy Research*, 8, 58, pp. 1–7, DOI: 10.3389/fenrg.2020.00058
- Sun, J., Shi, G., Jin, W., Chen, Y., Shen, G., Tian, Ch., Zhang, Y., Zong, Zh., Cheng, M., Zhang, X., Zhang, Y., Liu, Ch., Lu, J., Wang, H., Xiang, J., Tong, L. & Zhang, X. (2018). Emissions factors of organic carbon and elemental carbon for residential coal and biomass fuels in China – A new database for 39 fuel-stove combinations, *Atmospheric Environment*, 190, pp. 241–248, DOI: 10.1016/j.atmosenv.2018.07.032
- Sun, L., Wang, F., Xie, Y., Feng, J. & Wang, Q. (2012), The combustion performance of medium density fiberboard treated with fire retardant microspheres, *Bioresources*, 7, pp. 593–601.
- Szyszlak-Bargłowicz, J., Zajac, G. & Słowik, T. (2015). Hydrocarbon emissions during biomass combustion, *Polish Journal of Environmental Studies*, 24, pp. 1349–1354, DOI: 10.15244/pjoes/37550
- Tomsej, T., Horak, J., Tomsejowa, S., Krpec, K., Klanova, J., Dej, M. & Hopan, F. (2018) The impact of co-combustion of polyethylene plastics and wood in the small residential boiler on emissions of gaseous pollutants, particulate matter, PAHs and 1,3,5-triphenylbenzene, *Chemosphere*, 196, pp. 18–24, DOI: 10.1016/j.chemosphere.2017.12.127
- Uğuz, C., Işcan, M. & Togan, I. (2009), Alkylphenols in the environment and their adverse effects on living organisms, *Kocatepe Veterinary Journal*, 2, 1, pp. 49–58.
- Wang, S., Wang, W. & Yang, H. (2018), Comparison of product carbon footprint protocols: Case study on medium-density fiberboard in China, *International Journal of Environmental Research and Public Health*, 15, 10, pp. 1–14, DOI: 10.3390/ijerph15102060
- Wasilewski, R. & Siudyga, T. (2013), Odzysk energetyczny odpadowych tworzyw sztucznych, *Chemik*, 67, 5, pp. 435–445.
- Williams, A., Jones, J.M., Ma, L & Pourkashanian, M. (2012). Pollutants from the combustion of solid biomass fuels, *Progress in Energy and Combustion Science*, 38, pp. 113–137, DOI: 10.1016/j.peccs.2011.10.001
- Zeng, Q., Lu, Q., Zhou, Y., Chen, N., Rao, J. & Fan, M. (2018), Circular development of recycled natural fibers from medium density fiberboard wastes, *Journal of Cleaner Production*, 8, pp. 1–17, DOI: 10.1016/j.jclepro.2018.08.166
- Zubkova, V. & Czaplicka, M. (2012), Changes in the structure of plasticized coals caused by extraction with dichloromethane, *Fuel*, 96, pp. 298–305, DOI: 10.1016/j.fuel.2011.12.067
- Zubkova, V., Czaplicka, M. & Puchala, A. (2016), The influence addition of coal tar pitch (CTP) and expired pharmaceuticals (EP) on properties and composition of pyrolysis products for lower and higher rank coal, *Fuel*, 170, pp. 197–209, DOI: 10.1016/j.fuel.2011.12.067

## Współspalanie drewnianego pelletu i odpadów w kotłach używanych do ogrzewania domostw – porównanie emisji związków węglowych

**Streszczenie:** Rosnąca emisja dwutlenku węgla powoduje zmiany klimatyczne przez co rośnie presja na poszukiwanie alternatywnych źródeł energii. Współspalanie odpadów z paliwami nadal występuje w niektórych regionach świata, dlatego istotna jest wiedza na temat związków emitowanych z takiego spalania. W niniejszej pracy zbadano wpływ dodatku odpadów na emisję ze współspalania z biomasą. Pelet drzewny współspalano z różnymi dodatkami plastiku z politereftalanu etylenu i płyty pilśniowej średniej gęstości (10 i 50%), w kotle małej mocy (18 W). Oznaczono emisję fenoli, alkilofenoli, ftalanów, markerów spalania biomasy oraz wielopierścieniowych węglowodorów aromatycznych. Do analizy tych związków po ekstrakcji i derywatywacji w fazie pyłowej i gazowej zastosowano chromatografię gazową sprzężoną ze spektrometrem mas. Emisja znaczników spalania biomasy oraz ftalanów była najwyższa spośród wszystkich związków oznaczonych dla dodatku MDF. Całkowita emisja tych związków wynosiła odpowiednio 685 mg/h i 408 mg/h dla 10% dodatku oraz 2401 mg/h i 337 mg/h dla 50% dodatku. Dla współspalania biomasy z PET największą emisję miały WWA i fenole; emisja wynosiła odpowiednio 197 mg/h i 114,5 mg/h dla 10% dodatku oraz 268 mg/h i 200 mg/h dla 50% dodatku. Naszym zdaniem uzyskane wyniki są niewystarczające do identyfikacji źródeł zanieczyszczeń z ogrzewania gospodarstw domowych. Po dalszych badaniach, badane związki mogłyby być traktowane jako markery do identyfikacji rodzaju paliwa spalanego w gospodarstwach domowych.