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Predictive Analysis of Waste Co-Combustion with Fossil Fuels Using the Life Cycle Assessment (LCA) Methodology

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Abstract: The use of waste for energy purposes could become widespread and the radical lowering of the costs associated with that process could occur, if the resulting fuel did not have the status of waste. The key issue in removing the status of waste for a given substance is to eliminate the environmental impact of its use. Currently, there are no known fuels whose combustion does not lead to a negative impact on the environment, even to a minimum extent. It is therefore necessary to set a threshold of environmental impact at which we "recognize" a fuel to be harmless to the environment. The ecological impact of lignite was assumed in this text to be such a threshold. This paper proposes a methodology for determining the limit of environmental impact of fuel from waste. It also presents the results of our own research on the morphological and elemental composition of a waste mixture created by the separation of the over-screen fraction of municipal waste undesirable for a fuel, namely, chlorine carriers (PVC), multi-material waste, ferrous and non-ferrous metals, and non-combustible fractions (ash). The results obtained were used to assess the relative environmental impact of a waste mixture used as fuel.

Keywords: waste-based fuel; chemical composition of fuel; environmental footprint analyses; CML 2001 methodology

1. Introduction

The problem of using waste for energy purposes is a current and extremely important issue necessary to introduce a sustainable development policy [1]. The environmental impact of different waste management scenarios shows that the recycling process provides growing environmental savings, as well as for energy recycling processes. The savings are higher if the energy recovery shows higher yields for the energy recovery process [2]. Fast-growing environmental legislation can promote the development of innovative technologies and equipment. Each process has to achieve the economic, technological, and environmental balance in advanced waste management, especially the ones linked with emission limits [3].

The process of exerting environmental impact can be a rather complex issue and has been examined in different studies [4]. The location in the system under analysis can play a significant role in the assessment process. For instance, the results of assessing different fuel scenarios regarding development in the power generation industry may be highly influenced by the market reality [5]. Similarly, the method of waste thermal utilization technology may affect the final result of the evaluation [6].

Of key importance are the conditions that must be met in order for the waste to lose its waste status and thus become a fuel. In the legislation [7,8], in addition to a number of conditions of a technical, economic, and technological nature, there is an environmental nature requirement stating that the re-use of a waste item or substance should not result in any negative consequences for the life or health of people or the environment [9]. To satisfy this condition, it is necessary to use an appropriate methodology for assessing environmental effects. An example of a universal indicator model is the CML 2001 methodology [10]. In some studies, an exergy-based evaluation (thermo-ecological cost) is used [11]. It finds its wide application in the analysis of the impact on the environment and is often cited in the literature as an appropriate methodology to assess such subjects. It has the most accurate environmental impact indicators necessary to determine the environmental impact of burning coal or other fuels. In SimaPro programs used for Life Cycle Assessment (LCA) calculations, the Intergovernmental Panel on Climate Change (IPCC) Global Warming Potential (GWP) 100a, ReCiPe, and Eco-Indicator methodology, based on the ecoinvent database and others, are also frequently applied. CML 2001 methodology is based on six basic categories of impact, namely, depletion of mineral resources (AD), climate change (CC), toxicity to humans (HT), photo-oxidant formation (POF), acidification (AC), and eutrophication (EU) [12,13]. Each impact category (IC) is calculated using the equivalent unit (i.e., the equivalent substance representing the category) and is based on methodology. In this article, we took into account three basic impact categories—HT, CC, and AC.

The human toxicity (HT) category takes into account the effects of toxic substances on the human environment. The category uses the method based on the Uniform System for the Evaluation of Substances (USES-LCA) model, describing fate, exposure, and effects of toxic substances in the infinite time horizon. The equivalent unit of this category is expressed as 1,4-dichlorobenzene equivalents/kg emission. The geographic scope of this category takes into account the fate of a substance, and it is different for the local and global scales [14].

The climate change (CC) category is linked to the emissions of greenhouse gases into the air. The characterization model used in the CML method was developed by the Intergovernmental Panel on Climate Change (IPCC) and was chosen in this study for developing the characterization factors. Factors are shown as global warming potential for a time horizon of 100 years (GWP100) and the equivalent unit is kg carbon dioxide/kg emission [14].

Acidifying substances produce a wide range of impacts on groundwater, soil, organisms, surface water, ecosystems, and materials (buildings). The acidification (AC) category is based on the adapted RAINS 10 model, describing acidifying substances and their path in the environment. AC is calculated in the equivalent unit as kg SO_2 equivalents/kg emission [14].

Many interpretation disputes have arisen concerning the issue of the requirement stated above. It is impossible to treat it literally. At present, in fact, there are no known substances whose combustion "does not lead to negative effects on the life or health of people or the environment" [14], even to a minimum extent. It should be emphasized that this concerns not only waste fuels, but also any other fuel currently used. This becomes even more evident if we adopt an approach based on the full fuel life cycle. It is therefore necessary to set a threshold for environmental impact at which we "recognize" a fuel to be harmless to the environment. The ecological impact of lignite was assumed in this text to be such a threshold. In other words, it was assumed that to remove the waste status from a fuel, it must meet the environmental criteria, including the indicators of environmental impact on the health and life of people, designated by lignite, which is still allowed to be burnt as a fuel. It is essential to select averaged compositions of this fuel [15].

The European Union (EU) level provisions concerning alternative fuels include the CEN/TS 15359:2011 technical specification. Its objective is to establish clear and transparent classification rules and a specification of the parameters concerning solid recovered fuels (SRFs). The specification was conceived as a tool to promote the acceptance of this product and facilitate trading in SRFs.

The basic assumption is that SRFs can be generated from non-hazardous waste. SRFs constitute a group of heterogeneous waste, as they can be composed of different groups of waste. However, it should be stressed that they are still regarded as waste.

In the standard, the classification is based on only three parameters—the net calorific value (NCV), chlorine content (Cl), and mercury content (Hg). Fuels are divided into five classes, depending on the calorific value. Each class defines the requirements concerning the content of chlorine and mercury [15].

In the European Union, apart from the general CEN standard, there are also country-specific requirements applicable in particular countries, associated with the admissible content of substances from waste in the fuel to allow this fuel to lose its status of waste. These additional requirements apply in general to the maximum content of trace elements, which extends the requirements beyond chlorine and mercury included in the CEN standard. An example is Austria, a country that is very accurate in determining the share of several trace elements in waste fuels and that additionally determines the maximum percentage share of waste fuel that can be burnt together with coal in power boilers [16].

This paper proposes a methodology for determining the limit of environmental impact of waste. It also presents the results of our own research on the morphological and elemental composition of a mixture of waste created by the separation of the over-screen fraction of municipal waste undesirable for a fuel, namely, chlorine carriers (PVC), multi-material waste, ferrous and non-ferrous metals, and non-combustible fractions (ash). Waste samples subject to marking were prepared on a typical municipal waste sorting line equipped with, among others, three optical sorters. The sorting line used is located in one of the Polish cities. The results obtained were used to assess the relative environmental impact of a waste mixture used as a fuel.

2. Methodology to Determine the Environmental Impact of Waste Fuel

In order to determine the limit values of element concentrations in the substitute fuel, indicators of the relative unit emission potential X were proposed. They were developed for each element of the elemental composition and each impact category. It is an aggregate indicator containing information about the following [17]:

- the type of compounds arising from a given element in the combustion chamber;
- the formation of the aforementioned compounds;
- the harmfulness of the aforementioned compounds in a given impact category;
- the effectiveness of the node of flue gas purification assumed in the calculations, in relation to the aforementioned compounds.

The X indicators are expressed in kg of the equivalent substance defined in the CML 2001 methods and related to 1 kg of the component under analysis (kg e.s./kg comp.).

The environmental impact of fuel combustion process depends also on the emissions of substances formed in the combustion chamber, whose emissions depend on the technology used, not directly on the fuel content. The sum of such compounds is represented by the additional intermediate compound (AIC) indicator that is also determined for each impact category. Similarly to the X indicator, it includes information on the generation of individual compounds, the mechanism of its removal from flue gases, and its effectiveness and impact on the environment within a particular impact category. The values of this indicator are calculated on the basis of the data available in the literature [18].

The general division of the indicators are identified in [19] and [20] as follows:

- The AIC includes environmental impact—CO, aldehydes, dioxins, benzene, toluene, pentachlorobenzene, hexachlorobenzene, methane, pentachlorophenol, hydrocarbons and derivatives, and NOx.
- The X indicator is determined for other compounds of substances that are closely related to the fuel composition. It is the product of environmental impact, creation indicators, emission indicators, and removal effectiveness. Depending on the substance nature, the product is determined in various ways, depending on the type of element and its conversion into a compound.

The final environmental impact indicator (II) within a given impact category (IC) can be expressed by the following general equation:

$$II_{IC} = \sum_{i=1}^{n} X_{IC,i} \cdot \varepsilon_i + AIC_{IC}, \tag{1}$$

where II_{IC} is the environmental impact indicator of a fuel in the IC (kg of eq. subst./kg of i); $X_{IC,i}$ are indicators of the relative unit emission potential in the impact category (IC) for the i element (kg of eq. subst./kg of i); ε_i is the content of the i element in fuel (kg of i/Mg of fuel); and AIC_{IC} is the indicator of the environmental impact of additional intermediate compounds for the IC impact [kg of eq. subst./Mg of fuel].

The limit state for two fuels in terms of their environmental impact is described by the following situation:

$$II_{IC,\text{ fuel 1}} = II_{IC,\text{ fuel 2}}. \tag{2}$$

The fulfillment of this condition in all the impact categories results in recognizing both fuels as having an equal impact on the environment. X_{IC} is a constant for each element contained in the fuel. By modifying the ε_i, it is possible to obtain the same state necessary to fulfill the condition expressed by Equation (2).

In the case of some impact categories (e.g., HT), the number of elements that must be considered is large enough for the existence of many combinations of concentrations that will allow the fuel to satisfy the aforementioned boundary condition.

The environmental impact of lignite combustion calculated in such a way is presented in Table 1. The indicators for lignite were determined in accordance with the assumptions made in [21].

Table 1. Indicators of environmental impact calculated for lignite related to the functional units Mg of fuel and MJ of chemical energy in the fuel.

Impact Category	Value of Environmental Impact Indicator (II)	
	(kg of eq. subst./Mg of fuel)	(kg of eq. subst./MJ)
CC—Climate change	8.92×10^{2}	1.23×10^{-1}
HT—Human toxicity	3.34×10^{1}	4.59×10^{-3}
AC—Acidification	3.22	4.43×10^{-4}
EU—Eutrophication	1.64×10^{-1}	2.25×10^{-5}
POF—Photo-oxidant formation	4.23×10^{-2}	5.81×10^{-6}
AD—Depletion of mineral resources	6.71	9.22×10^{-4}

Limiting the Environmental Impact of Fuel from Waste

The limit concentrations of individual elements in the fuel were determined for particular impact categories, taking into consideration the environmental impact of the reference fuel. Because the same level of environmental impact can occur at different concentrations of individual elements in the fuel, comparative formulas were created to allow the evaluation of different solutions in line with the emergence of new requirements limiting the content of certain elements in the fuel.

In the eutrophication impact category, the level of negative impact depends on the emissions of AICs, including NO_x. Only a portion of them is formed from nitrogen contained in the fuel. The formation of toxic compounds is therefore highly dependent on how the combustion process is conducted. The negative environmental impact in this category thus depends on the technology and not on the fuel composition. Hence, in the EU category it is impossible to indicate the limiting values of the fuel composition.

In the photo-oxidant formation category of impact (similarly to the EU category), the amount of the negative impact depends on the emission of compounds (AICs), whose formation is not directly related to the fuel composition. Hence, in the POF category it is impossible to indicate the limiting values of the fuel composition.

In the AD category, the substitute fuel demonstrates each time a lower environmental impact in relation to lignite. Assuming that all the emitted trace elements are treated as depleting mineral resources, the II_{AD} indicator for lignite amounted to 6.71 kg of eq. substance/Mg of fuel or 9.22×10^{-4} kg of eq. substance/MJ. This is due to the significant impact of using only coal in this category and the damage associated with it in mineral resources.

It should be emphasized that for a substitute fuel, the total environmental impact in the AD category can be assumed to be zero. This occurs based on the assumption that all the minerals used to produce it have been extracted earlier due to the functionality of objects as a source for waste materials. Therefore, by using the substitute fuel, we do not have to face any further depletion of the Earth's mineral resources.

In the impact category of acidification, the environmental impact depends on the emissions of several compounds generated from the elements present in the fuel. These elements include chlorine (Cl), fluorine (F), and sulfur (S). In addition, the environmental impact in the acidification category depends on the additional intermediate compound (AIC) emissions.

The boundary formula of equilibrium in this category takes the following form based on the assumptions specified above:

$$(\varepsilon_{Cl} \cdot 0.271 + \varepsilon_F \cdot 0.99 + \varepsilon_S \cdot 0.275 + 0.63)/W_{d,alternativce\,fuel} = II_{lignite,Acid}, \tag{3}$$

where $W_{d,alternativce\ fuel}$ is the calorific value of the alternative fuel (MJ/kg); $II_{lignite,Acid}$ is the value of the environmental impact of lignite in the AC category, expressed in kg of eq. SO_2/MJ of chem. en. in lignite; and ε represents the contents of the individual elements in the fuel, expressed in kg/Mg of fuel.

The numerical values of the coefficients in the equations of equilibrium include the formation of harmful substances from the elements and the efficiency of removal from flue gases as well as the harmfulness of substances emitted into the atmosphere.

The human toxicity (HT) category of impact is associated with the fuel composition to the largest extent. The following are of importance: ash, chlorine, fluorine, sulfur, and heavy metals such as arsenic, cadmium, cobalt, chromium, nickel, lead, antimony, vanadium, thallium, and mercury.

The limiting equilibrium formula has the following form:

$$\begin{gathered}(\varepsilon_A \cdot 0.264 + \varepsilon_{Cl} \cdot 0.154 + \varepsilon_F \cdot 49.5 + \varepsilon_S \cdot 0.275 + \varepsilon_{As} \cdot 0.00355 + \varepsilon_{Cd} \cdot 7.9914 + \varepsilon_{Co} \cdot 0.0006 \\ + \varepsilon_{Cr} \cdot 0.2535 + \varepsilon_{Cu} \cdot 0.0317 + \varepsilon_{Hg} \cdot 0.0002 + \varepsilon_{Ni} \cdot 0.0015 + \varepsilon_{Pb} \cdot 0.0173 + \varepsilon_{Sb} \cdot 0.00003 \quad , \\ + \varepsilon_V \cdot 0.6239 + \varepsilon_{Tl} \cdot 432 + 6.87/W_{d,alternativce\,fuel} = II_{lignite,HT}\end{gathered} \tag{4}$$

where $II_{lignite,HT}$ is the value of the environmental impact of lignite in the HT category, expressed in kg 1,4-DB (dichlorobenzene)/MJ of chem. en. in lignite and ε represents the contents of the individual elements in the fuel, expressed in kg/Mg of fuel.

The environmental impact of dust also includes the harmful effects of metals deposited on dust particles and emitted along with them into the atmosphere. It was assumed that the harmful effect of manganese is entirely included in the emitted dust. The environmental impact indicators of manganese are negligible compared to other elements.

Indicators in the climate change (CC) category of impact for lignite were determined based on the assumption that the entire CO_2 emission is attributed to the long carbon cycle. For the substitute fuel, the waste fraction is associated with a short cycle of lignite (e.g., biodegradable fraction), so a portion of the emission associated with its combustion can be assumed to be zero. This reduces the environmental impact of the substitute fuel in the CC impact category. The biodegradable fraction share in the substitute fuel must be defined separately for each fuel type.

The limiting equilibrium formula has the following form:

$$(\varepsilon_C \cdot 3.67 + 0.166)/W_{d,alternativce\ fuel} = II_{lignite,CC} \tag{5}$$

where $II_{lignite,CC}$ is the value of the environmental impact of lignite in the CC category, expressed in kg of CO_2/MJ of chem. en. in lignite; ε_C represents the content of carbon in the substitute fuel expressed in kg/Mg of fuel; and W_d is the fuel calorific value of the substitute fuel.

In the case of the CC category, in fact, only the content of the C element (of which CO_2 is composed of) has an impact. It is obviously very important to limit carbon dioxide emissions, but this cannot be stated in the case of the limiting content of carbon in the fuel, since the larger the carbon content, the more energetic the fuel. Therefore, comparing the calculations of the environmental impact of lignite and of the substitute fuel, it is necessary to consider the values calculated per unit of energy MJ. This is the only way to state whether the fuel exerts a similar environmental impact.

3. Characteristics of Waste Fuel Obtained during the Tests

In order to assess the suitability of the above theoretical considerations, our own research was conducted on the elemental and morphological composition of the over-screen fraction formed as a result of municipal waste sorting. The plant from which the test samples were taken was equipped with an automatic sorting machine allowing for the segregation of undesirable elements from the mixture of waste, namely, chlorine carriers (PVC), multi-material waste, ferrous and non-ferrous metals, and non-combustible fractions (ash). The process equipment of the plant included three optical-pneumatic sorters for eliminating the aforementioned undesirable elements [22,23]. Material recovery from the stream of waste was not conducted during the plant's operation. Two samples of waste were taken for tests.

Two measurement series were carried out for each waste mixture under analysis. Studies of the morphological composition were conducted at an accredited laboratory, using a gravimetric method described in the internal laboratory procedure. The test results obtained for the mixture of waste showed the following:

- the material fractions constituting the largest share in the waste under analysis included plastics, paper, textiles, and composite materials;
- there was a very large fraction of plastics and textiles (in total, reaching even 70%).

Subsequently, the chemical compositions of the waste mixtures obtained when conducting the tests were analyzed covering the range of components responsible for or contributing to the formation of environmentally harmful substances in the combustion process [24].

Two measurement series were performed. The test material for both measurement series included mixtures of waste separated during a test run of the sorting machine, that is, the over-screen fraction subjected to the process of separation of undesirable substances, namely, chlorine carriers (PVC), multi-material waste, ferrous and non-ferrous metals, and non-combustible fractions (ash), using regular sorting equipment.

For the prepared material, the content analyses of the following elements were performed:

- sulfur (S), chlorine (Cl), and fluorine (F), in the analytical state;
- arsenic, lead, manganese, copper, chromium, nickel, vanadium, antimony, cobalt, cadmium, and thallium, in the ash formed after ashing the sample; this was followed by the conversion of the heavy metal content into ash in the dry matter of the waste fraction;
- mercury (Hg), based on the dry weight of a given waste fraction.

The study on the elemental composition of the selected waste fractions was conducted in an accredited laboratory. Analyses were performed:

- using an in-house laboratory method for sulfur (S);
- in accordance with PN—ISO 587:2000 for the chlorine (Cl) content;
- using an in-house laboratory method for the content of arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), manganese (Mn), nickel (Ni), lead (Pb), antimony (Sb), and vanadium (V);
- using an in-house laboratory method for the mercury (Hg) content;
- in accordance with PN-EN 12457—4:2006 for the fluorine (F) content.

The content of the selected elemental composition items for waste mixtures under analysis is given in the Table 2.

Table 2. Content of the selected elemental composition items for waste mixtures under analysis.

Parameter	Symbol	Unit	First Measurement Series	Second Measurement Series
Total sulfur content	S	%	0.74	0.33
Content of chlorine	Cl	%	0.62	0.48
Content of fluorides	F	mg/kg of dry mass	11.20	2.13
Arsenic	As		20.10	0.10
Lead	Pb		28.70	39.00
Manganese	Mn		46.80	88.00
Copper	Cu		27.00	42.00
Chromium	Cr		43.40	147.00
Nickel	Ni		4.50	58.00
Vanadium	V		2.80	5.90
Antimony	Sb		14.40	11.00
Cobalt	Co		2.40	7.30
The total of 9 heavy metals			190.10	398.30
Thallium	Tl		12.00	1.00
Cadmium	Cd		1.15	1.58
Mercury	Hg		2.40	6.36

4. Discussion

In accordance with the methodology proposed in this paper, the analysis of environmental impacts of using fuel produced from waste was conducted in the following three environmental impact categories:

- Acidification—AC;
- Human toxicity—HT;
- Climate change—CC.

Tables 3 and 4 below summarize the calculation results of the environmental harmful effects in the three aforementioned impact categories for the waste mixtures under analysis.

The tables also include information on the total environmental harmful effects in each of the categories depending on the functional unit of Mg and MJ. The obtained values were additionally compared with the values determined for the lignite reference fuel.

The analysis of the data obtained allows us to state that in the case of the MJ functional unit, the total harmful effects (impact) of fuel from waste obtained when the tests were conducted demonstrated a lower value than the value for the reference fuel (lignite). This observation applies to all the categories of impact under analysis and the results obtained in both measurement series.

Table 3. Environmental harmful effects of the waste mixture obtained during the first measurement series.

Component	**Content**	**X_{AC}**	**X_{HT}**	**X_{CC}**	**$II_{fuel\ AC}$**	**$II_{fuel\ HT}$**	**$II_{fuel\ CC}$**
	kg/Mg	(kg of eq. SO_2/kg of *i*)	(kg of eq. 1,4-DB/kg of *i*)	(kg of eq. CO_2/kg of E)	(kg of eq. SO_2/Mg of fuel)	(kg of eq. 1,4-DB/Mg of fuel)	(kg of eq. CO_2/Mg of fuel)
Dust	1.40×10^{2}	-	2.64×10^{-1}	-	0	3.70×10^{1}	0
Sulfur	7.40	2.75×10^{-1}	2.75×10^{-1}	-	2.04	2/04 × 100	0
Chlorine	6/20	2.71×10^{-1}	1.54×10^{-1}	-	1.68	9.55×10^{-1}	0
Fluorine	1.12×10^{-2}	9.90×10^{-1}	4.95×10^{1}	-	1.11×10^{-2}	5.54×10^{-1}	0
Arsenic	2.01×10^{-2}	-	3.55×10^{-3}	-	0	7.14×10^{-5}	0
Cadmium	1.15×10^{-3}	-	7.99	-	0	9.19×10^{-3}	0
Cobalt	2.40×10^{-3}	-	5.56×10^{-4}	-	0	1.33×10^{-6}	0
Chromium	4.34×10^{-2}	-	2.54×10^{-1}	-	0	1.10×10^{-2}	0
Copper	2.70×10^{-2}	-	3.17×10^{-2}	-	0	8.56×10^{-4}	0
Mercury	2.40×10^{-3}	-	2.07×10^{-4}	-	0	4.97×10^{-7}	0
Nickel	4.50×10^{-3}	-	1.51×10^{-3}	-	0	6.80×10^{-6}	0
Lead	2.87×10^{-2}	-	1.73×10^{-2}	-	0	4.97×10^{-4}	0
Antimony	1.44×10^{-2}	-	2.61×10^{-5}	-	0	3.76×10^{-7}	0
Vanadium	2.80×10^{-3}	-	6.24×10^{-1}	-	0	1.75×10^{-3}	0
Thallium	1.00×10^{-3}	-	4.32×10^{2}	-	0	4.32×10^{-1}	0
AIC	-	-	-	-	6.30×10^{-1}	6.87	1.66×10^{-1}
Carbon	4.06×10^{2}	-	-	3/67	0	0	1.49×10^{3}
II fuel (kg/Mg)	-	-	-	-	4.36	4.78×10^{1}	1.49×10^{3}
II coal (kg/Mg)	-	-	-	-	3.22	3.34×10^{1}	$8/92 \times 10^{2}$
II fuel (kg/MJ)	-	-	-	-	1.84×10^{-4}	2.02×10^{-3}	6.30×10^{-2}
II coal (kg/MJ)	-	-	-	-	4.43×10^{-4}	4.59×10^{-3}	1.23×10^{-1}
II fuel (kg/MJ)/II coal (kg/MJ)	-	-	-	-	4.16×10^{-1}	4.41×10^{-1}	5.13×10^{-1}

Table 4. Environmental harmful effects of the waste mixture obtained during the second measurement series.

Component	**Content**	**X_{AC}**	**X_{HT}**	**X_{CC}**	**II $_{\text{fuel AC}}$**	**II $_{\text{fuel HT}}$**	**II $_{\text{fuel CC}}$**
	kg/Mg	(kg of eq. SO_2/kg of *i*)	(kg of eq. 1,4-DB/kg of *i*)	(kg of eq. CO_2/kg of E)	(kg of eq. SO_2/Mg of fuel)	(kg of eq. 1,4-DB/Mg of fuel)	(kg of eq. CO_2/Mg of fuel)
Dust	2.00×10^{2}	-	2.64×10^{-1}	-	0	5.28×10^{1}	0
Sulfur	3.30	2.75×10^{-1}	2.75×10^{-1}	-	9.08×10^{-1}	9.08×10^{-1}	0
Chlorine	4.80	2.71×10^{-1}	1.54×10^{-1}	-	1.30	7.39×10^{-1}	0
Fluorine	2.13×10^{-3}	9.90×10^{-1}	4.95×10^{1}	-	2.11×10^{-3}	1.05×10^{-1}	0
Arsenic	1.00×10^{-4}	-	3.55×10^{-3}	-	0	3.55×10^{-7}	0
Cadmium	1.58×10^{-3}	-	7.99×10^{0}	-	0	1.26×10^{-2}	0
Cobalt	7.30×10^{-3}	-	5.56×10^{-4}	-	0	4.06×10^{-6}	0
Chromium	1.47×10^{-1}	-	2.54×10^{-1}	-	0	3.73×10^{-2}	0
Copper	4.20×10^{-2}	-	3.17×10^{-2}	-	0	1.33×10^{-3}	0
Mercury	6.36×10^{-3}	-	2.07×10^{-4}	-	0	1.32×10^{-6}	0
Nickel	5.80×10^{-2}	-	1.51×10^{-3}	-	0	8.76×10^{-5}	0
Lead	3.90×10^{-2}	-	1.73×10^{-2}	-	0	6.75×10^{-4}	0
Antimony	1.10×10^{-2}	-	2.61×10^{-5}	-	0	2.87×10^{-7}	0
Vanadium	5.90×10^{-3}	-	6.24×10^{-1}	-	0	3.68×10^{-3}	0
Thallium	1.00×10^{-3}	-	4.32×10^{2}	-	0	4.32×10^{-1}	0
AIC	-	-	-	-	6.30×10^{-1}	6.87	1.66×10^{-1}
Carbon	540	-	-	3.67	0	0	1.98×10^{3}
II fuel (kg/Mg)	-	-	-	-	2.84	6.19×10^{1}	1.98×10^{3}
II coal (kg/Mg)	-	-	-	-	3.22	3.34×10^{1}	8.92×10^{2}
II fuel (kg/MJ)	-	-	-	-	1.27×10^{-4}	2.77×10^{-3}	8.88×10^{-2}
II coal (kg/MJ)	-	-	-	-	4.43×10^{-4}	4.59×10^{-3}	1.23×10^{-1}
II fuel (kg/MJ)/II coal (kg/MJ)	-	-	-	-	2.87×10^{-1}	6.04×10^{-1}	7.22×10^{-1}

The results of the presented harmful effect analysis of the use of waste fuel show that it is less harmful (burdensome) to the environment than lignite, assuming the use of both fuels in the same way (the same combustion conditions, the same efficiency of the flue gas cleaning system). The differences between the fuel generated from waste (waste mixtures under analysis) and lignite in certain impact categories are even up to several dozen percent (in favor of the fuel from waste). The presented analyses show that this fuel, in order to maintain the total environmental impact at a lower level than lignite, should show a possibly high calorific value and a low content of ash, chlorine, and heavy metals.

5. Conclusions

This paper presents a methodology for determining the limit of environmental impact of waste fuel and the results of our own research on the morphological and elemental composition of fuel produced under real conditions. The methodology presented in this paper was then used to assess the environmental impact of the fuel obtained from waste. The value of this parameter was compared with the value of the environmental impact for the reference fuel (i.e., lignite). The scope of the proposed methodology for waste fuel environmental impact assessment allowed us to note the following:

- The environmental impact in the eutrophication (EU) and photo-oxidant formation (POF) categories does not depend on the elemental composition of fuel. Therefore, no limiting values were determined for these categories. In both categories, the environmental impact of the waste fuel is not greater than for lignite.
- In the depletion of mineral resources (AD) category, the fuel from waste shows each time a lower environmental impact than lignite, since the raw materials used to produce this fuel have already been used to manufacture products for other purposes.
- The environmental impact in the categories of acidification (AC) and human toxicity (HT), to the greatest extent, depends on the composition and waste fuel parameters. The elements that determine the environmental impact in these categories, to the greatest extent, include the content of chlorine, ash, and heavy metals and the calorific value.

Using the proposed methodology for assessing the environmental harmful effects of the waste fuel, the values of this parameter were determined in three impact categories, based on the results of our own research on the elemental composition of fuel from waste. It turned out that the environmental impact of the fuel obtained from waste is lower in all the impact categories than the environmental impact of lignite. This is due in part to a much higher calorific value of the fuel from waste.

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