

Article

Energy Quality of Corn Biomass from Gasoline-Contaminated Soils Remediated with Sorbents

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Abstract: Soil contaminated with petroleum-derived products should be used to cultivate energy crops. One such crop is *Zea mays*. Therefore, a study was performed to determine the suitability of *Zea mays* biomass obtained from gasoline-contaminated soil for energy purposes. The analysis included determining the heat of combustion and calorific value of the biomass, as well as the content of nitrogen, carbon, hydrogen, oxygen, sulfur, and ash in the biomass. Additionally, the suitability of vermiculite, dolomite, perlite, and agrobasalt for the phytostabilization of gasoline-contaminated soil was evaluated. It was found that the application of sorbents to gasoline-contaminated soil significantly reduced the severe negative effects of this petroleum product on the growth and development of *Zea mays*. Gasoline contamination of the soil caused a significant increase in ash, nitrogen, and sulfur, along with a decrease in carbon and oxygen content. However, it had no negative effect on the heat of combustion or calorific value of the biomass, although it did reduce the energy production from *Zea mays* biomass due to a reduction in yield. An important achievement of the study is the demonstration that all the applied sorbents have a positive effect on soil stabilization, which in turn enhances the amount of *Zea mays* biomass harvested and the energy produced from it. The best results were observed after the application of agrobasalt, dolomite, and vermiculite on gasoline-contaminated soil. Therefore, these sorbents can be recommended for the phytostabilization of gasoline-contaminated soil intended for the cultivation of energy crops.



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Keywords: heat of combustion; biomass energy; calorific value; sorbents; gasoline; enzymes

1. Introduction

Biomass as an alternative energy source is becoming increasingly important in the context of efforts to combat global warming and reduce the use of fossil fuels [1–3]. This is justified by the fact that biobased products emit fewer greenhouse gases compared to fossil feedstocks [4,5]. Plant biomass first garnered attention as a sustainable energy source in the 1970s [4–9], and interest in the subject has grown as efforts to mitigate climate change have intensified. Current research on biomass focuses on several primary objectives: reducing greenhouse gas emissions, decreasing fossil fuel exploitation, and increasing energy self-sufficiency [10–12]. Biomass energy production holds significant potential to reduce society's dependence on fossil fuels [2,10].

The calorific value of biomass is a key parameter, particularly when considering its use as an energy source [13]. Biomass derived from agricultural residues has a calorific value of approximately 1.26×10^4 MJ Mg^{−1}, which is half the calorific value of coal and one-third that of diesel [7,14]. The calorific value of petroleum derivatives ranges from 41.5 to 47.0 MJ kg^{−1} [15]. According to Amaral [16], gasoline is composed of a variety of hydrocarbons with different molecular structures. Molecules with a higher number of atoms have higher boiling points, and their calorific value generally increases, with hydrogen having a higher calorific value compared to carbon. According to Zaharin et al. [17], gasoline blends

with ethanol and butanol (E10, E10B5, E10B10, and E10B15) result in lower calorific values, ranging from 41.7 MJ kg^{−1} to 43.1 MJ kg^{−1}.

The calorific value of biomass is significantly lower than that of gasoline [7]. The calorific value of gasoline is almost four times higher than that of biomass, indicating the relatively lower efficiency of biomass as a fuel in terms of the energy released during combustion [13]. Nevertheless, biomass has other advantages, such as a lower impact on greenhouse gas emissions, which can compensate for its lower heating value [18].

One of the main applications of biomass is the production of biofuels such as ethanol and biodiesel [2,19,20]. The European Parliament and other international institutions promote the development of advanced biofuels, which can be produced from agricultural residues, such as straw or crop leftovers [20–24]. The use of such feedstocks minimizes the impact on land use changes and does not compete with food production. In recent years, there has been particular interest in the use of corn residues, which exhibit low resistance to bioconversion processes [9,25]. This means that corn residues, such as stalks, leaves, or cobs, are relatively easy to convert into biofuels or other bioproducts through biochemical processes, such as fermentation or enzymatic decomposition. The chemical structure of plant residues is less complex and more susceptible to degradation, making bioconversion more efficient and leading to higher yields in the production of bioethanol and other forms of renewable energy [26,27]. As a result, maize biomass is one of the most popular feedstocks for biogas production in the energy sector, particularly in countries such as Germany and Austria, where biogas production is well developed [28,29]. Similarly, maize silage, from both whole plant and grain, is highly valued for its energy content, particularly in Poland, where it is used not only for biogas production but also for ethanol [30]. The growing interest in maize biomass, driven by its high biomass yield, makes it an attractive option for biogas plants and contributes to the reduction in greenhouse gas emissions by replacing fossil fuels with renewable energy sources.

One of the challenges associated with the use of biomass for energy is soil degradation [31–33], caused by the over-exploitation of agricultural land and the use of pesticides and herbicides [33–36]. Plants, sorbents, and soil microorganisms can play a crucial role in mitigating these negative effects without reducing crop yields. Finding effective methods to remediate soils contaminated with petroleum-derived products, such as gasoline, remains a major challenge [37,38].

The use of adsorbent materials capable of binding and retaining contaminants on their surface, as noted by Kapoor and Zdarta [39], has proven effective in reducing the bioavailability of toxic compounds in the soil. Petroleum products can lead to soil degradation, reduced fertility, and adverse effects on soil microbiomes and biogeochemical processes occurring in soil formations. Vermiculite, dolomite, perlite, and agrobasalt are four materials that have shown promising properties for improving the quality of soils contaminated with petroleum-derived products. Vermiculite, a natural mineral with high water and nutrient absorption capacity, can support the development of soil microorganisms by improving soil structure and increasing its water-holding capacity [40,41]. Dolomite, a mineral composed mainly of calcium and magnesium carbonate, can neutralize soil acidity [42,43]. Due to its porous structure, perlite increases air circulation in the soil. It has the ability to store water and nutrients. It consists mainly of silica (SiO₂) and oxides of potassium, magnesium, and calcium, which are essential for the development of the plant's root system [44–46]. Agrobasalt, a by-product of the basalt industry, contains numerous micro- and macroelements, such as potassium, magnesium, calcium, and iron, and can stimulate enzymatic activity in the soil, improve soil fertility, and support plant growth [47,48].

Consequently, the search for effective methods of remediating contaminated soils is of paramount importance, as abiotic factors influence the derivatives and end products of petroleum substance degradation. Sorbents can prevent the penetration of contaminants, along with water and oxygen, into deeper soil profiles, thereby affecting permeability, pH levels, and nutrient availability [49–54].

The aim of this study was to determine the suitability of *Zea mays* biomass from gasoline-contaminated soils for energy purposes. The analysis included the determination of the heat of combustion and the calorific value of the biomass, as well as the content of nitrogen, carbon, hydrogen, oxygen, sulfur, and ash in the biomass. Additionally, the effectiveness of vermiculite, dolomite, perlite, and agrobassalt in the phytostabilization of soil subjected to gasoline contamination was also assessed. This research objective prompted us to formulate the following hypotheses: (1) the energy value of *Zea mays* biomass is determined by its content of non-fuel elements; (2) the heat of combustion and calorific value of *Zea mays* biomass are functions of soil contamination with gasoline; (3) the amount of energy extracted from *Zea mays* biomass depends on soil supplementation with sorbents.

2. Materials and Methods

2.1. Research Design

The subject of the study was soil taken from an agricultural field from a depth of 0 to 20 cm. This soil was formed from loamy sand. Such soils take up an area of about 50% of arable land in Poland. Based on the classification by the International Union of Soil Sciences [55], this soil is identified as Eutric Cambisol. Its granulometric composition was as follows: sand—75.68%; silt—23.08%; clay—1.24%. The content of organic carbon (C_{org}) was 9.29 g, total nitrogen (N_{Total})—1.22 g, and pH_{KCl} —4.2. The study was carried out in the vegetation hall in a pot experiment in 4 replicates. Plastic pots were used for the experiment, the volume of which allowed to fill them with soil in the amount of 3.2 kg. The experiment was carried out in two series: uncontaminated soil and soil contaminated with unleaded gasoline 95 at 0 and $24\text{ cm}^3\text{ kg}^{-1}$ of soil. *Zea mays* of the DS1897B variety (producer Pioneer, Warsaw, Poland) and the following sorbents were used for phytostabilization of gasoline-contaminated soil: vermiculite with a fraction of 1–5 mm (producer Sobex, Drezdenko, Poland), dolomite with a fraction of 0.5–1 mm (producer Sobex, Drezdenko, Poland), perlite with a fraction of 3–6 mm (producer Biovita Ltd., Tenczynek, Poland), and agrobassalt with a fraction of 1–7 mm (producer Biovita Sp. z o.o., Tenczynek, Poland). The sorbents used were applied in amounts of 0 and 10 g kg^{-1} d.m. of soil (Figure 1). Unleaded gasoline 95 was purchased at a PKN Orlen (Poland) gas station. Its density varies from 0.720 to 0.775 g cm^{-3} , and its sulfur content is a maximum of 10 mg kg^{-1} . The characteristics of the petroleum substance are available on the PKN Orlen website [56].

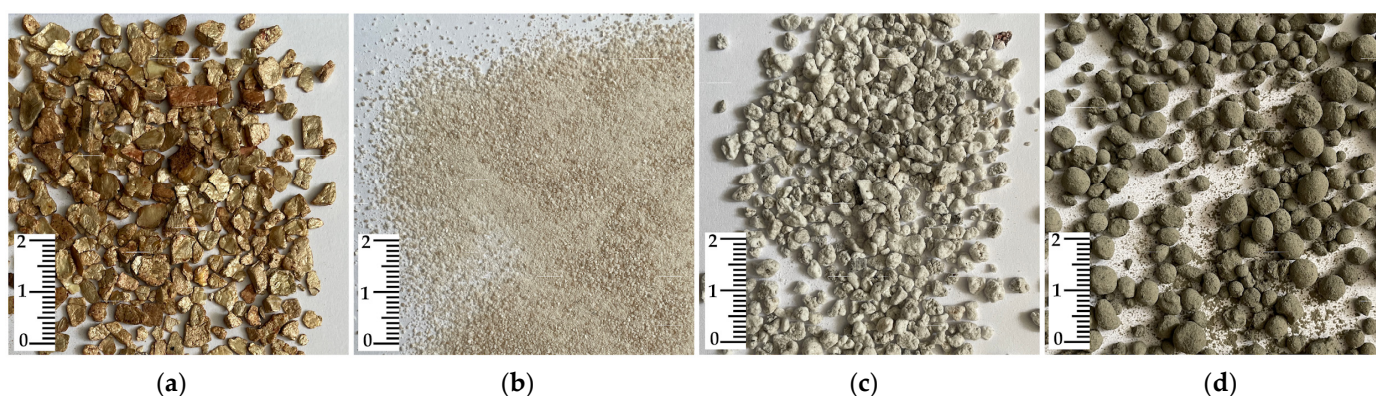


Figure 1. Test sorbents used in the experiment (a) vermiculite; (b) dolomite; (c) perlite; (d) agrobassalt.

In the experiment, homogeneous fertilization with macronutrients was applied in the amount (mg kg^{-1} d.m. of soil): N—225 in the form of $\text{N}_2\text{H}_4\text{CO}$, P—50 in the form of KH_2PO_4 , K—150 in the form of KH_2PO_4 and KCl , and Mg—15 in the form of $\text{MgSO}_4 \times 7\text{H}_2\text{O}$. Three days after packing the soil, eight seeds of *Zea mays* each were sown in pots. When the plants germinated, five plants were left in each pot.

The growing period of the plants was 60 days, but harvesting of the aboveground parts and roots of corn was carried out at stage 51 of the Biological Federal Institute, Bundessortenamt and Chemie (BBCH) (Figure 2).

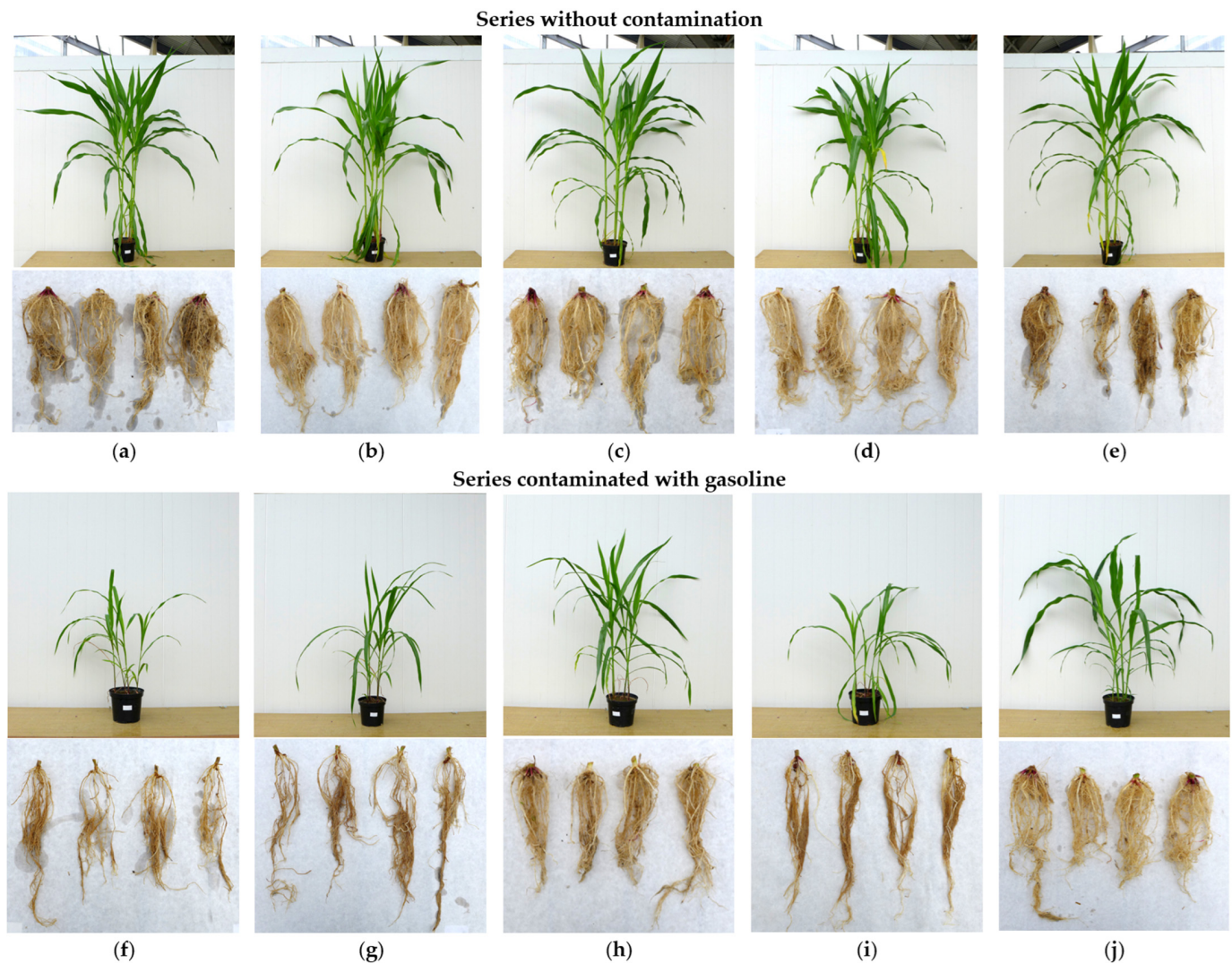


Figure 2. *Zea mays* on the day of harvest. The series without contamination: (a) control; (b) with vermiculite; (c) dolomite; (d) perlite; (e) agrobassalt; and series (f) contaminated with gasoline; (g) vermiculite; (h) dolomite; (i) perlite; (j) agrobassalt.

2.2. Laboratory Analyzes

After harvesting *Zea mays* at BBCH stage 51 and determination of biomass, the plants were ground and dried. The plant samples were then milled using a laboratory grinder (Retsch SM 200, Haan, Germany) and a sieve with a mesh diameter of 0.5 mm. The next step was to determine the heat of combustion (Q), heating value (Hv), and energy production (Yep) of the *Zea mays* biomass (Figure 3). The determination of Q was carried out according to the procedure described in PN-EN ISO 18125:2017 [57], and the calorific value (Hv) of *Zea mays* was calculated according to the formula of Kopetz et al. [58].

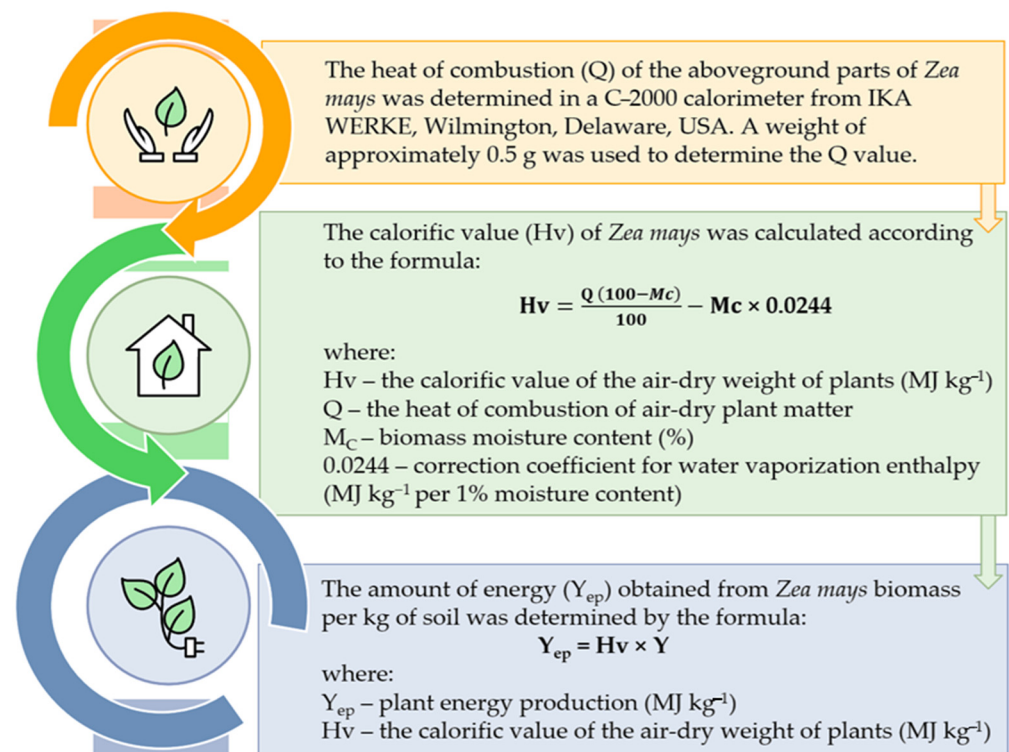


Figure 3. Methods for determining the energetic value of plants.

In order to characterize the biomass of plants for energy purposes, its carbon (C), hydrogen (H), sulfur (S), nitrogen (N), oxygen (O), and ash contents were determined (Figure 4). The contents of C, H, and N were determined according to PN-EN ISO 16948:2015-07 [59], S—PN-G-04584:2021 [60] and PN-EN ISO 16994:2016-10 [61], and ash was determined according to PN-EN ISO 18122:2016-01 [62].

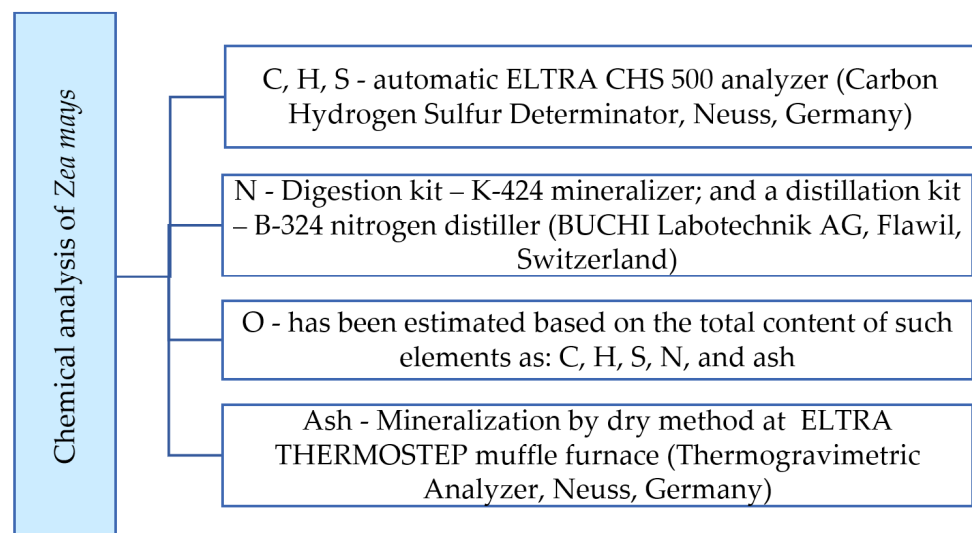


Figure 4. Methods of chemical analysis of plants.

2.3. Statistical Data Processing and Analysis

In order to evaluate the effects of gasoline (G) and vermiculite (V), dolomite (D), perlite (P), and agrobassalt (A) on *Zea mays* biomass, its Q , H_v , and Y_{ep} , as well as the content of N, C, H, S, O, and ash in the biomass, influence indices were calculated using formulae presented in our previous publications [52,63–65]. The data were illustrated on heat maps

using the RStudio 2023.06.0 [66] with the R 4.2.2 addition [67] and the gplots library [68]. Statistical analysis of the results was performed using the Statistica 13.0 package [69].

Tukey's test, principal component analysis (PCA), and Pearson's simple correlation coefficients were used for this purpose. The coefficients of η^2 were also calculated and presented in a pie chart using the Circos 0.68 package [70]. All statistical analyses were performed at a significance level of $p < 0.05$.

3. Results

3.1. *Zea mays* Biomass

Soil contamination with gasoline revealed the sensitivity of *Zea mays* to this xenobiotic (Table 1, Figure 5). Its application to the soil reduced the parameters characterized by the plant (Ya, Yr) by 83% and 84%, respectively. Soil not contaminated with gasoline gave an average yield of 70.26 g d.m. per pot for aerial parts and 7.52 g d.m. per pot for roots, irrespective of the sorbents used (Table 1). The ratio of Ya biomass to Yr biomass was 9.43, and the greenness index (SPAD) was 43.87. On the other hand, the soil contaminated with gasoline yielded Ya at 24.45 g d.m. per pot and Yr at 1.80 g d.m. per pot. The ratio of Ya biomass to Yr biomass was 13.33, and the SPAD index was 45.73. A slight stimulating potential of the sorbents against *Zea mays* was found in the uncontaminated soil. The exception was perlite, which reduced the amount of Ya biomass by 12%.

Table 1. *Zea mays* biomass, SPAD (6th leaf phase).

Objects	Aboveground Parts (Ya)	Roots (Yr)	Ya/Yr	Greenness Index (SPAD)
	Grams of Dry Matter per Pot			
Us	74.145 ^a	7.018 ^a	10.565	44.322 ^{ab}
V	70.961 ^{ab}	8.850 ^a	8.018	43.984 ^{ab}
D	72.325 ^{ab}	7.612 ^a	9.502	44.856 ^{ab}
P	65.447 ^b	7.429 ^a	8.810	42.322 ^b
A	68.428 ^{ab}	6.685 ^a	10.237	43.878 ^{ab}
G	12.679 ^e	1.114 ^b	11.384	45.372 ^{ab}
V_G	26.448 ^{cd}	1.749 ^b	15.119	45.256 ^{ab}
D_G	30.099 ^c	2.025 ^b	14.862	45.753 ^{ab}
P_G	20.080 ^d	1.874 ^b	10.713	44.278 ^{ab}
A_G	32.946 ^c	2.258 ^b	14.589	48.013 ^a

Explanations of the abbreviations of the sorbents tested (objects) are given in the abbreviations section. Homogeneous groups denoted with letters (a–e) were calculated separately for each part of the plant and greenness index.

On the other hand, in a series of experiments where the soil was contaminated with gasoline, all the sorbents (vermiculite, dolomite, perlite, and agrobasalt) had a positive effect and significantly reduced the toxic effects of this contaminant on *Zea mays*. For example, the use of agrobasalt in gasoline-contaminated soil increased the amount of Ya biomass by 2.6 times, dolomite by 2.4 times, vermiculite by 2.1 times, and perlite by 1.6 times. The application of sorbents to uncontaminated soil had no significant effect on root biomass, whereas it increased the size of *Zea mays* biomass in gasoline-contaminated soil. Thus, the sorbents used in the study were very effective in reducing the negative effects of gasoline on the growth and development of the plant under study. The above-mentioned relationships were also reflected in the yield ratio of aboveground parts to plant roots, which, in the gasoline-contaminated series, was highest in the sites supplemented with vermiculite, dolomite, agrobasalt, and perlite, respectively. The above statements are confirmed by the results shown in Figure 5. The positive indices of the effect of sorbents on the yield of *Zea mays* grown on gasoline-contaminated soil clearly demonstrate that they can be used to mitigate the effects of this contaminant on this plant. Their values for Ya biomass ranged from 0.584 (perlite) to 1.599 (agrobasalt), and for Yr biomass from 0.571 (vermiculite) to 1.028 (agrobasalt).

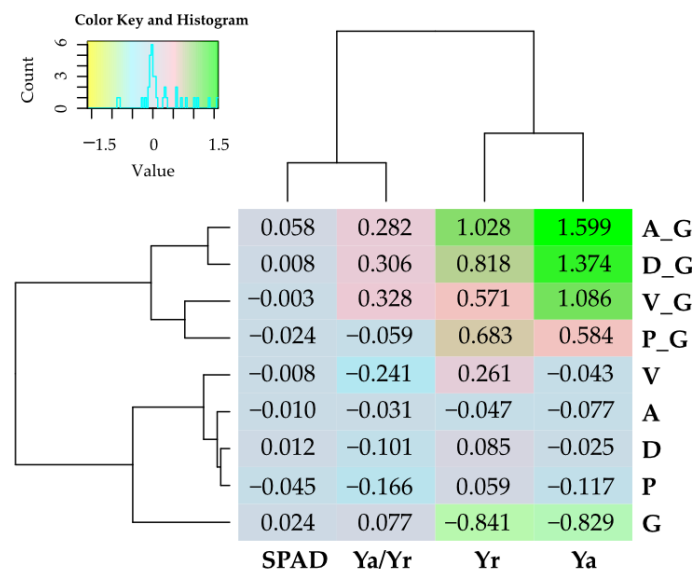


Figure 5. Indexes of the influence of gasoline (G) and sorbents on the yield of aboveground parts (Ya), roots (Yr), the ratio of yield of aboveground parts to plant roots (Ya/Yr) and the greenness index (SPAD). Explanations of the abbreviations of the sorbents tested (objects) are given in the abbreviations section.

3.2. Contents of Ash, Nitrogen, Carbon, Hydrogen, Sulfur and Oxygen in Aboveground Parts of *Zea mays*

Both gasoline soil contamination and sorbent application had an effect on the ash content and non-ash elements in the aboveground biomass of *Zea mays* (Table 2). Soil contamination with gasoline caused a significant increase in sulfur, nitrogen, and ash and a decrease in carbon and oxygen. For maize grown on uncontaminated soil, soil supplementation with dolomite and agrobassalt resulted in a significant increase in ash content, dolomite and perlite in nitrogen content, and perlite and agrobassalt in oxygen content. Dolomite and perlite contributed to a significant reduction in hydrogen content, while these sorbents had no statistically significant effect on sulfur content. The effect of sorbents on the content of ash and non-ash elements in maize biomass extracted from gasoline-contaminated soil was slightly different. Namely, vermiculite caused an increase in ash content, dolomite, perlite, and agrobassalt—nitrogen, perlite—sulfur and all sorbents—oxygen. In turn, all sorbents contributed to a decrease in carbon content: vermiculite, dolomite and perlite—hydrogen, dolomite and perlite—ash, and dolomite—sulfur.

Table 2. Ash content and elements determining the energy value of aboveground biomass of *Zea mays* (%).

Objects *	Ash	Nitrogen (N)	Carbon (C)	Hydrogen (H)	Sulfur (S)	Oxygen (O)
Us	4.971 ^f	2.044 ^g	51.124 ^{ab}	5.730 ^{ab}	0.092 ^{de}	36.039 ^b
V	4.970 ^f	1.940 ^h	51.319 ^a	5.788 ^a	0.082 ^e	35.901 ^b
D	5.710 ^d	2.683 ^e	50.865 ^b	5.538 ^{cd}	0.098 ^d	35.105 ^c
P	5.097 ^f	2.347 ^f	49.163 ^c	5.488 ^d	0.101 ^d	37.804 ^a
A	5.328 ^e	2.035 ^g	49.212 ^c	5.739 ^a	0.083 ^e	37.604 ^a
G	9.636 ^b	4.158 ^c	49.244 ^c	5.746 ^a	0.215 ^b	31.000 ^g
V_G	10.594 ^a	3.962 ^d	47.998 ^d	5.584 ^{bcd}	0.206 ^{bc}	31.657 ^f
D_G	9.150 ^c	4.615 ^a	47.434 ^e	5.459 ^d	0.195 ^c	33.146 ^e
P_G	9.130 ^c	4.316 ^b	47.162 ^{ef}	5.503 ^d	0.247 ^a	33.642 ^d
A_G	9.547 ^b	4.294 ^b	47.030 ^f	5.676 ^{abc}	0.212 ^b	33.240 ^{de}

* Explanations of the abbreviations of the sorbents tested (objects) are given in the abbreviations section. Homogeneous groups indicated by letters (a–h) were calculated separately for each parameter tested.

The described changes in the chemical composition of maize biomass extracted from soil supplemented and unsupplemented with sorbents and contaminated and uncontaminated with gasoline are well represented by the indexes of influence of gasoline (G) and sorbents on the content of ash and elements determining the energy value of the above-ground biomass of *Zea mays* presented in Figure 6. These indices show that the chemical composition of the biomass was more strongly influenced by gasoline than by sorbents. In the case of petroleum substances, the influence index for ash was 0.939, N—1.035, and S—1.322, while for C and O it was negative, respectively: −0.037 and −0.140. These indexes were significantly higher than the sorbent influence indices. The exception was the sorbent influence indices for C. Their values were low and almost always negative.

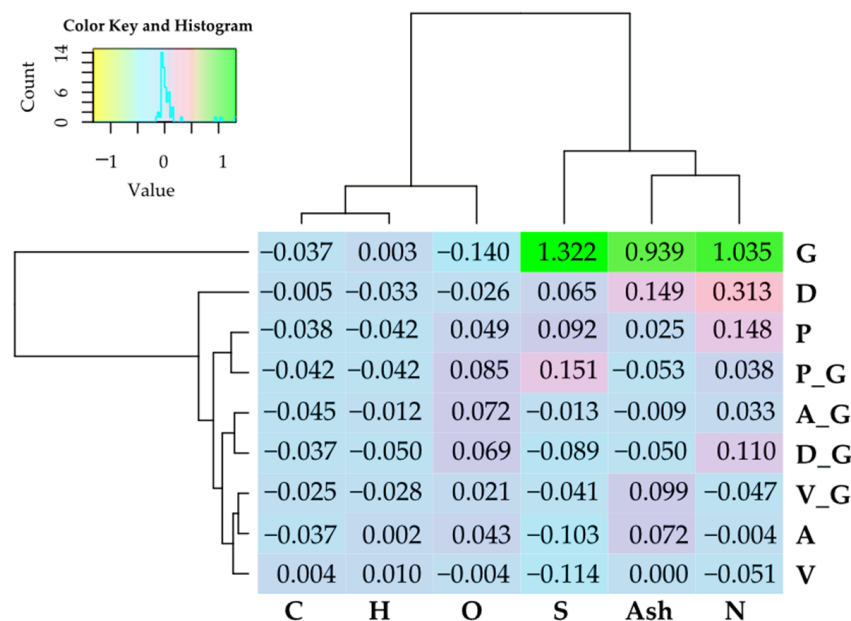


Figure 6. Indexes of the influence of gasoline (G) and sorbents on the content of ash and elements determining the energy value of aboveground biomass of *Zea mays*. Explanations of the abbreviations of the sorbents tested (objects) are given in the abbreviations section.

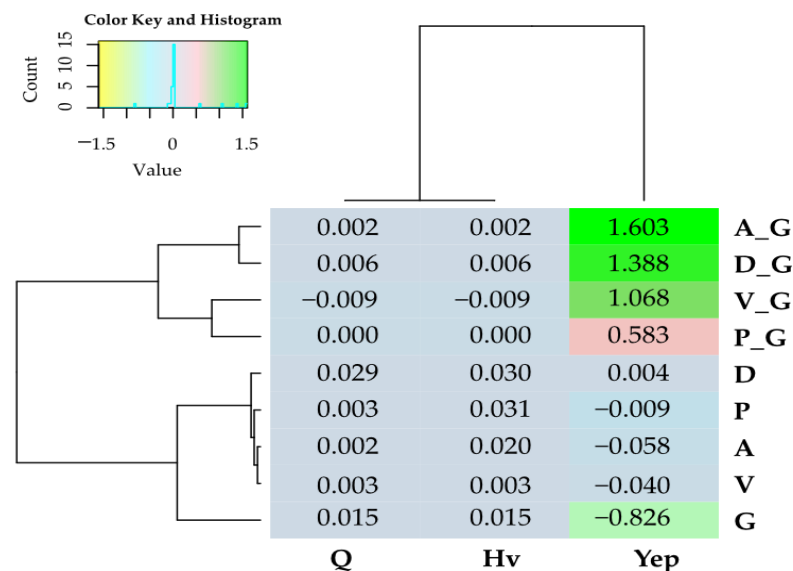
3.3. Energy Value of Aboveground Parts of *Zea mays*

All sorbents contributed to increasing the calorific value (Hv) and heat of combustion (Q) of the biomass of aboveground parts of maize grown on soil not contaminated with gasoline (Table 3). The highest Hv value was found under perlite (15.578 MJ kg^{−1}) and dolomite (15.563 MJ kg^{−1}). The heat of combustion was also highest in plant biomass extracted from soil supplemented with the mentioned sorbents. Perlite increased Q from 18.710 MJ to 19.268 MJ, while dolomite increased Q from 18.710 MJ to 19.250 MJ. The Hv and Q values of maize grown on gasoline-contaminated soil were increased only by the effect of dolomite, whereas they were decreased by the effect of vermiculite. In this series of experiments, both perlite and agrobassalt did not change the Hv and Q values. Since gasoline greatly reduced the growth and development of *Zea mays*, the amount of energy extracted (Yep) from maize on contaminated soil was reduced by 0.927 MJ per pot. This was a 5.8-fold reduction. The introduction of sorbents into gasoline-contaminated soil significantly increased Yep yields, with agrobassalt and dolomite increasing Yep production the most. The impact index for the former sorbent was 1.603, and the latter 1.388 (Figure 7). Such a spectacular effect of sorbents was not observed for maize biomass produced on uncontaminated soil.

Table 3. Heat of combustion (Q), calorific value (Hv), and amount of energy obtained (Yep) from *Zea mays* biomass.

Objects *	Heat of Combustion (Q)	Heating Value (Hv)	Energy yield of Plant Biomass (Yep), MJ pot ⁻¹
	MJ kg ⁻¹ Air-Dry Matter Plants		
Us	18.710 ^f	15.115 ^f	1.121 ^b
V	18.769 ^e	15.163 ^e	1.076 ^c
D	19.250 ^a	15.563 ^a	1.126 ^a
P	19.268 ^a	15.578 ^a	1.020 ^e
A	19.080 ^b	15.422 ^b	1.055 ^d
G	18.982 ^c	15.340 ^c	0.194 ^j
V_G	18.820 ^d	15.206 ^d	0.402 ^h
D_G	19.093 ^b	15.432 ^b	0.465 ^g
P_G	18.979 ^c	15.337 ^c	0.308 ⁱ
A_G	19.015 ^c	15.368 ^c	0.506 ^f

* Explanations of the abbreviations of the sorbents tested (objects) are given in the abbreviations section. Homogeneous groups denoted with letters (a–j) were calculated separately for Q, Hv, and Yep.

**Figure 7.** Indexes of the influence of gasoline (G) and sorbents on the heat of combustion (Q), calorific value (Hv), and amount of energy produced (Yep) from *Zea mays* biomass. Explanations of the abbreviations of the sorbents tested (objects) are given in the abbreviations section.

3.4. Interactions Between *Zea mays* Yield and Its Energy Value

Gasoline (G) had a significantly greater effect on the dependent variable than the sorbents used (Figure 8). This petroleum-based substance influenced up to 96% of the yield of the underground parts of the plants, 93% of the carbon content of the plant biomass, and the ash content. It affected the energy yield of the biomass (Yep) by 72%, the calorific value of the biomass (Hv) by 68%, the yield of the aboveground parts of the plant (Ya) by 65%, the sulfur content (S) by 58%, and the oxygen content (O) by 55%. Sorbents, on the other hand, reduced the hydrogen content (H) by 85%, the heat of combustion (Q) by 74%, and the nitrogen content of *Zea mays* biomass by 52%. Only the leaf greenness index was more dependent on the combined use of sorbents and gasoline ($S \times G$).

Calculated Pearson's simple correlation coefficients (Figure 9) and principal component analysis (PCA) (Figure 10) allowed us to determine the strength of the interaction between the parameters studied. Thus, the amount of energy produced (Yep) was significantly positively correlated with *Zea mays* biomass, C and O content, and significantly negatively with N, S, and ash content. The heat of combustion (Q) and the calorific value (Hv) of plant biomass were negatively correlated with the H content, while they did not

form significant correlations with the other parameters studied. There was a significant positive correlation between N content and ash and S content and C, O, and H content, and a negative correlation between C and O and ash, S, and N content.

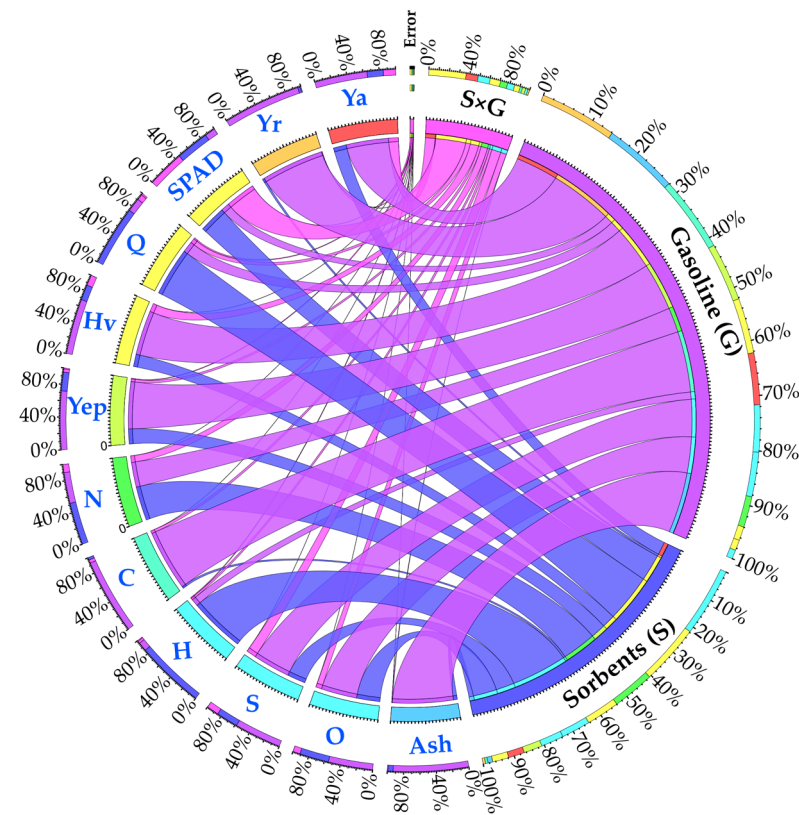


Figure 8. Share of independent variables (η^2) in determining dependent variables in *Zea mays* biomass, %. Explanations of the abbreviations of the sorbents tested (objects) are given in the abbreviations section.

Variable	Ya	Yr	Ya/Yr	SPAD	Q	Hv	Yep	N	C	H	S	O	Ash
Ya	1.000												
Yr	0.861	1.000											
Ya/Yr	0.011	−0.355	1.000										
SPAD	−0.327	−0.387	−0.006	1.000									
Q	0.064	0.055	0.047	−0.064	1.000								
Hv	0.064	0.055	0.047	−0.064	1.000	1.000							
Yep	0.994	0.862	0.021	−0.336	0.091	0.091	1.000						
N	−0.930	−0.843	−0.037	0.430	0.076	0.076	−0.932	1.000					
C	0.768	0.725	−0.105	−0.282	−0.206	−0.206	0.764	−0.829	1.000				
H	0.210	0.234	0.103	−0.072	−0.545	−0.545	0.198	−0.385	0.446	1.000			
S	−0.963	−0.854	−0.047	0.381	−0.061	−0.061	−0.968	0.957	−0.820	−0.303	1.000		
O	0.867	0.763	0.087	−0.446	0.240	0.240	0.877	−0.848	0.482	0.057	−0.842	1.000	
Ash	−0.946	−0.858	−0.001	0.432	−0.098	−0.098	−0.952	0.947	−0.789	−0.234	0.949	−0.913	1.000

Figure 9. Pearson's simple correlation coefficients. Significant at $p = 0.05$, $n = 24$. Red color—statistically significant, black color—statistically insignificant. Explanations of the abbreviations of the sorbents tested (objects) are given in the abbreviations section.

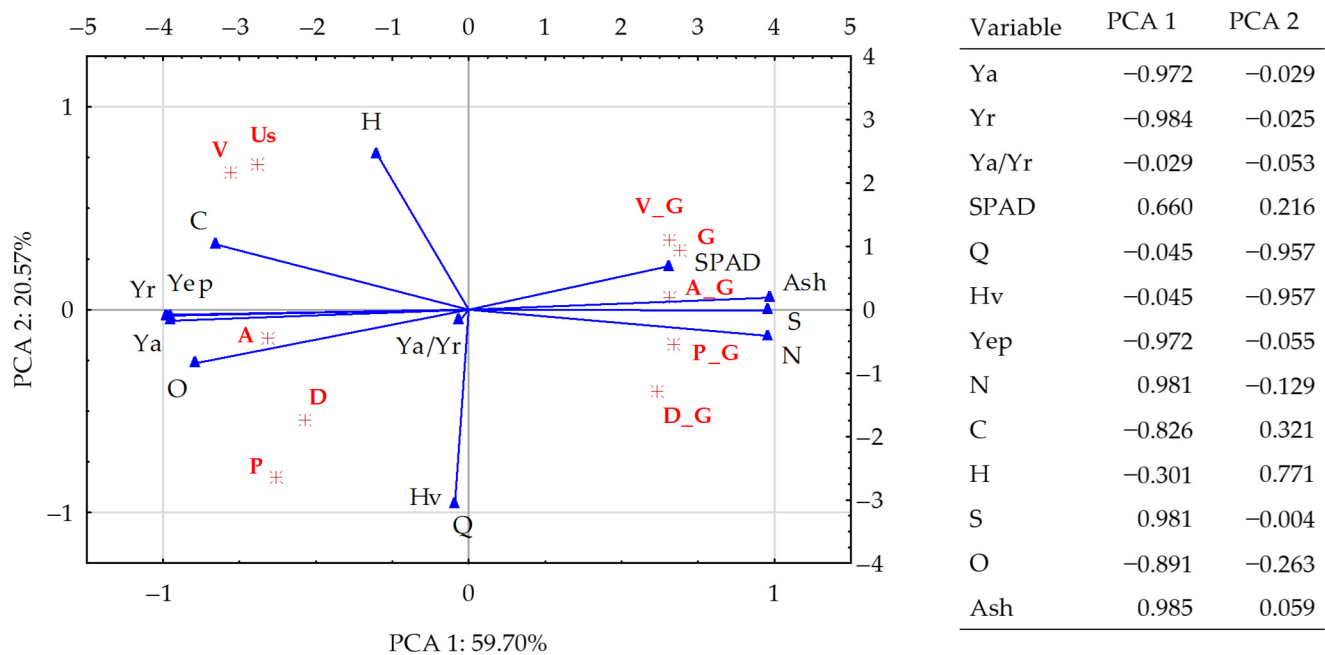


Figure 10. The interaction between the studied parameters using (PCA). Explanations of the abbreviations of the sorbents tested (objects) are given in the abbreviations section.

4. Discussion

Petroleum-derived products are toxic to all soil organisms [71,72] and plants [54,73–75]. Therefore, rapid and effective detoxification of these soils is important [37,76,77]. Our research shows that *Zea mays* is highly susceptible to the destructive effects of gasoline. Under the influence of this pollutant, plant biomass decreased by 83%. The negative effect of gasoline on maize growth and development was significantly reduced by all the sorbents used in the study, i.e., vermiculite, agrobassalt, perlite, and dolomite. This is probably due to the adsorption of gasoline by these sorbents, which limited the direct contact of gasoline with the plant roots. According to the literature [52,70,78–81], their effectiveness in revitalizing soils depends on the type of sorbent. In our study, despite the positive effectiveness of all sorbents, agrobassalt and dolomite were the most effective. The effect coefficients of these sorbents on *Zea mays* biomass were very high, being 1.599 for the first sorbent and 1.374 for the second, respectively. The effectiveness of agrobassalt and dolomite may be due to their ability to neutralize contaminants and improve soil properties by providing both calcium and magnesium, which may benefit plant growth and pH regulation [82]. According to Huang et al. [83], the particle size of the sorbent is also one of the main factors affecting its effectiveness in neutralizing soil acidity, as the reaction rate between calcium material and H^+ in the soil depends on the specific surface area. Cai et al. [84] also observed that dolomite accelerates the mineralization of nitrogenous organic compounds, thereby improving the respiration of acidic soils. On the other hand, Wu et al. [82] observed that smaller dolomite particles have a larger specific surface area, which may increase their ability to adsorb pollutants and improve soil structure; larger agrobassalt particles have a greater ability to adsorb pollutants [85,86]. These factors clearly influence interactions with the soil microbiome by promoting the growth of microorganisms that stimulate *Zea mays* growth. This is due to the different sorption capacity and chemical composition of these sorbents [87–93].

The negative effect of gasoline on *Zea mays* was not only limited to biomass production but also caused changes in its chemical composition. Under its influence, the content of N, S, and ash in the biomass increased, and the content of C and O decreased. The increase in the content of N, S, and ash was much greater than the decrease in the content of C and O. The index of the effect of gasoline on the content of S, N, and ash was 1.322, 1.035, and

0.939, respectively. Changes in the chemical composition of the biomass of gasoline-treated plants may result from the direct toxic effect of this substance on the plant, disturbances in the uptake of ions by the plants, and dysfunctions in the ion balance [94,95]. The above considerations are only appropriate for this research. However, it should be taken into account that in environmental research other issues come into play that are extremely important for the existence of ecosystems and consequently for human and animal health. These include the contamination of groundwater with benzene, toluene, ethylbenzene, and xylene (BTEX), which stresses all organisms that use the resource [96,97]. The significant amounts of carbon, hydrogen, and oxygen, as well as nitrogen and sulfur, in *Zea mays* biomass are also important for energy production. Through combustion, fermentation, or gasification, these components can be converted into heat, electricity, or biofuels such as bioethanol [98,99].

In our study, despite the variable effects of gasoline on the chemical composition of the plant, we found a positive effect of this substance on the heat of combustion and the calorific value of the biomass. Of course, this did not bridge the differences between the energy production of maize grown on uncontaminated and contaminated soil, due to the negative effect of this pollutant on the yield of corn, and thus on the amount of biomass and energy obtained [100,101].

Energy production (Yep) was positively affected by all sorbents. It was increased most by agrobasalt (influence factor of 1.603) and least by perlite (influence factor of 0.583). Thus, they can play an important role in the cultivation of plants on soils degraded with organic compounds for energy purposes. Also, Zahed et al. [102]; Vasilyeva et al. [50]; Wyszowski and Kordala [103]; Sabitov et al. [104]; Wyszowski et al. [105]; and Wyszowska et al. [106] demonstrated the usefulness of sorbents (biocarbon, zeolite, kaolinite, vermiculite, diatomite, bentonite, activated carbon, molecular sieve, halloysite, sepiolite, expanded clay, biochar, and alginite) in the phytostabilization of soil contaminated with petroleum-derived products. According to Zhang and Liang [107], Qu et al. [108], and Vociante et al. [109], the amount of energy extracted from *Zea mays* biomass depends on the soil properties, so sorbents introduced into the soil may help to modify the soil structure, increasing its capacity to retain water and nutrients, thus influencing higher biomass production. According to Ho et al. [110]; Atero-Calvo et al. [111]; Wyszowski and Kordala [112]; and Kamenchuk et al. [113], sorbents can influence the availability of elements that are key to the intensity of the photosynthetic process, thereby increasing biomass and energy while offsetting the stress caused by soil contamination [114].

Both our results and those of other authors [100,115,116] indicate the significant potential of *Zea mays* to replace fossil fuels. Maize grown on contaminated soils has a high energy potential as an alternative energy source. A study by Morales-Máximo et al. [115] also demonstrates that *Zea mays* biomass has a high energy potential as an alternative energy source. The average calorific value determined by these authors in samples of plant material was 17.6 MJ kg^{-1} , and in our study, it ranged from 18.7 MJ kg^{-1} to 19.3 MJ kg^{-1} , which is at a comparable level compared to other biofuels [117–119]. Replacing fossil fuels with *Zea mays* biomass has numerous environmental benefits. Biomass combustion is carbon dioxide-neutral, as the CO_2 released during combustion is offset by the CO_2 absorbed by the plant during photosynthesis [4,98,99]. Additionally, biomass production can help reduce emissions of other harmful gases, such as nitrogen and sulfur oxides, which are typical of fossil fuel combustion [115,118,120].

Despite its many benefits, biomass production from *Zea mays* also poses several challenges. One of the main problems is competition for land and water resources with food production [121,122]. Therefore, it is important to develop technologies and practices that minimize these conflicts, for example by using marginal soils that are not suitable for food production. Further research into the genetic improvement of maize may in the future lead to varieties with higher energy yields and better resistance to environmental stresses [123]. Summarizing the results of our study, it can be concluded that *Zea mays* biomass has great potential as a sustainable energy source that can contribute to reducing

fossil fuel consumption. However, it is crucial that biomass production be carried out in a sustainable manner, taking into account both environmental and social aspects.

5. Conclusions

Gasoline creates unfavorable conditions for the growth and development of *Zea mays*. Growing maize on non-remediated soil limits its use for energy purposes. On the other hand, the application of agrobassalt, dolomite, vermiculite, and perlite to contaminated soil enhances both biomass production and the amount of energy obtained from it. The amount of energy obtained from *Zea mays* was significantly positively correlated with carbon and oxygen content and negatively correlated with nitrogen, sulfur, and ash content. Our research shows that all the sorbents tested represent a promising strategy for managing sites contaminated with petroleum-derived products.

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Abbreviations

Us—uncontaminated soil, V—uncontaminated soil with the addition of vermiculite, D—uncontaminated soil with the addition of dolomite, P—uncontaminated soil with the addition of perlite, A—uncontaminated soil with the addition of agrobassalt, G—soil contaminated with gasoline, V_G—soil contaminated with gasoline with the addition of vermiculite, D_G—soil contaminated with gasoline with the addition of dolomite, P_G—soil contaminated with gasoline with the addition of perlite, A_G—soil contaminated with gasoline with the addition of agrobassalt. Ya—yield of aerial parts, Yr—yield of roots, Ya/Yr—the ratio of aboveground parts yield to plant roots, SPAD—greenness index, Q—heat of combustion, Hv—calorific value, Yep—energy yield, C—carbon, H—hydrogen, S—sulfur, N—nitrogen, O—oxygen.

References

1. Jåstad, E.O.; Bolkesjø, T.F.; Trømborg, E.; Rørstad, P.K. The Role of Woody Biomass for Reduction of Fossil GHG Emissions in the Future North European Energy Sector. *Appl. Energy* **2020**, *274*, 115360. [\[CrossRef\]](#)
2. Saez de Bikuña, K.; Garcia, R.; Dias, A.C.; Freire, F. Global Warming Implications from Increased Forest Biomass Utilization for Bioenergy in a Supply-Constrained Context. *J. Environ. Manag.* **2020**, *263*, 110292. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Günel, A.Ç.; Tunca, S.K.; Arslan, P.; Gül, G.; Dinçel, A.S. How Does Sublethal Permethrin Effect Non-Target Aquatic Organisms? *Environ. Sci. Pollut. Res.* **2021**, *28*, 52405–52417. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Ahmed, S.F.; Rafa, N.; Mofijur, M.; Badruddin, I.A.; Inayat, A.; Ali, M.S.; Farrok, O.; Yunus Khan, T.M. Biohydrogen Production from Biomass Sources: Metabolic Pathways and Economic Analysis. *Front. Energy Res.* **2021**, *9*, 753878. [\[CrossRef\]](#)
5. Anwar, M.N.; Fayyaz, A.; Sohail, N.F.; Khokhar, M.F.; Baqar, M.; Yasar, A.; Rasool, K.; Nazir, A.; Raja, M.U.F.; Rehan, M.; et al. CO₂ Utilization: Turning Greenhouse Gas into Fuels and Valuable Products. *J. Environ. Manag.* **2020**, *260*, 110059. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Sahoo, G.; Sharma, A.; Chandra Dash, A. Biomass from Trees for Bioenergy and Biofuels—A Briefing Paper. *Mater. Today Proc.* **2022**, *65*, 461–467. [\[CrossRef\]](#)
7. Antar, M.; Lyu, D.; Nazari, M.; Shah, A.; Zhou, X.; Smith, D.L. Biomass for a Sustainable Bioeconomy: An Overview of World Biomass Production and Utilization. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110691. [\[CrossRef\]](#)

8. Gyamfi, B.A.; Ozturk, I.; Bein, M.A.; Bekun, F.V. An Investigation into the Anthropogenic Effect of Biomass Energy Utilization and Economic Sustainability on Environmental Degradation in E7 Economies. *Biofuels Bioprod. Biorefining* **2021**, *15*, 840–851. [CrossRef]
9. Cadillo-Benalcazar, J.J.; Bukkens, S.G.F.; Ripa, M.; Giampietro, M. Why Does the European Union Produce Biofuels? Examining Consistency and Plausibility in Prevailing Narratives with Quantitative Storytelling. *Energy Res. Soc. Sci.* **2021**, *71*, 101810. [CrossRef]
10. Yang, L.; Wang, X.-C.; Dai, M.; Chen, B.; Qiao, Y.; Deng, H.; Zhang, D.; Zhang, Y.; Villas Bôas de Almeida, C.M.; Chiu, A.S.F.; et al. Shifting from Fossil-Based Economy to Bio-Based Economy: Status Quo, Challenges, and Prospects. *Energy* **2021**, *228*, 120533. [CrossRef]
11. Vijay, V.; Chandra, R.; Subbarao, P.M.V. Biomass as a Means of Achieving Rural Energy Self-Sufficiency: A Concept. *Built Environ. Proj. Asset Manag.* **2022**, *12*, 382–400. [CrossRef]
12. Noorollahi, Y.; Janalizadeh, H.; Yousefi, H.; Jahangir, M.H. Biofuel for Energy Self-Sufficiency in Agricultural Sector of Iran. *Sustain. Energy Technol. Assess.* **2021**, *44*, 101069. [CrossRef]
13. Huang, Y.-F.; Lo, S.-L. Predicting Heating Value of Lignocellulosic Biomass Based on Elemental Analysis. *Energy* **2020**, *191*, 116501. [CrossRef]
14. Mao, G.; Huang, N.; Chen, L.; Wang, H. Research on Biomass Energy and Environment from the Past to the Future: A Bibliometric Analysis. *Sci. Total Environ.* **2018**, *635*, 1081–1090. [CrossRef] [PubMed]
15. de Paulo, E.H.; dos Santos, F.D.; Folli, G.S.; Santos, L.P.; Nascimento, M.H.C.; Moro, M.K.; da Cunha, P.H.P.; Castro, E.V.R.; Cunha Neto, A.; Filgueiras, P.R. Determination of Gross Calorific Value in Crude Oil by Variable Selection Methods Applied to ¹³C NMR Spectroscopy. *Fuel* **2022**, *311*, 122527. [CrossRef]
16. Amaral, L.V.; Santos, N.D.S.A.; Roso, V.R.; de Oliveira Sebastião, R.d.C.; Pujatti, F.J.P. Effects of Gasoline Composition on Engine Performance, Exhaust Gases and Operational Costs. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110196. [CrossRef]
17. Zaharin, M.S.M.; Abdullah, N.R.; Masjuki, H.H.; Ali, O.M.; Najafi, G.; Yusaf, T. Evaluation on Physicochemical Properties of Iso-Butanol Additives in Ethanol-Gasoline Blend on Performance and Emission Characteristics of a Spark-Ignition Engine. *Appl. Therm. Eng.* **2018**, *144*, 960–971. [CrossRef]
18. Stöcker, M. Biofuels and Biomass-To-Liquid Fuels in the Biorefinery: Catalytic Conversion of Lignocellulosic Biomass Using Porous Materials. *Angew. Chem. Int. Ed.* **2008**, *47*, 9200–9211. [CrossRef]
19. Zahed, M.A.; Movahed, E.; Khodayari, A.; Zanganeh, S.; Badamaki, M. Biotechnology for Carbon Capture and Fixation: Critical Review and Future Directions. *J. Environ. Manag.* **2021**, *293*, 112830. [CrossRef]
20. Lee, J.-Y.; Lee, S.-E.; Lee, D.-W. Current Status and Future Prospects of Biological Routes to Bio-Based Products Using Raw Materials, Wastes, and Residues as Renewable Resources. *Crit. Rev. Environ. Sci. Technol.* **2022**, *52*, 2453–2509. [CrossRef]
21. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast). 2018. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001> (accessed on 25 September 2024).
22. The Paris Agreement | UNFCCC. Available online: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed on 25 September 2024).
23. National Energy and Climate Plan for the Years 2021–2030—Ministerstwo Klimatu i Środowiska—Portal Gov.Pl. Available online: <https://www.gov.pl/web/klimat/national-energy-and-climate-plan-for-the-years-2021-2030> (accessed on 25 September 2024).
24. Energy Policy of Poland Until 2040—Portal Gov.Pl. Available online: <https://www.gov.pl/web/klimat/polityka-energetyczna-polski> (accessed on 25 September 2024).
25. Malacara-Becerra, A.; Melchor-Martínez, E.M.; Sosa-Hernández, J.E.; Riquelme-Jiménez, L.M.; Mansouri, S.S.; Iqbal, H.M.N.; Parra-Saldívar, R. Bioconversion of Corn Crop Residues: Lactic Acid Production through Simultaneous Saccharification and Fermentation. *Sustainability* **2022**, *14*, 11799. [CrossRef]
26. Mosier, N.; Wyman, C.; Dale, B.; Elander, R.; Lee, Y.Y.; Holtzapple, M.; Ladisch, M. Features of Promising Technologies for Pretreatment of Lignocellulosic Biomass. *Bioresour. Technol.* **2005**, *96*, 673–686. [CrossRef] [PubMed]
27. Ashokkumar, V.; Venkatkarthick, R.; Jayashree, S.; Chuetor, S.; Dharmaraj, S.; Kumar, G.; Chen, W.-H.; Ngamcharussrivichai, C. Recent Advances in Lignocellulosic Biomass for Biofuels and Value-Added Bioproducts—A Critical Review. *Bioresour. Technol.* **2022**, *344*, 126195. [CrossRef] [PubMed]
28. Bielik, P.; Belinska, S.; Bajusová, Z.; Adamičková, I.; Bullová, T.; Belinska, Y.; Husárová, P. Economic Impact of Using Biomass for Biogas Production in the Context of Sustainable Development. *WSEAS Trans. Bus. Econ.* **2024**, *21*, 1684–1697. [CrossRef]
29. Bórawski, P.; Będycka-Bórawska, A.; Kapsdorferová, Z.; Rokicki, T.; Parzonko, A.; Holden, L. Perspectives of Electricity Production from Biogas in the European Union. *Energies* **2024**, *17*, 1169. [CrossRef]
30. Czekala, W.; Pulka, J.; Jasiński, T.; Szewczyk, P.; Bojarski, W.; Jasiński, J. Waste as Substrates for Agricultural Biogas Plants: A Case Study from Poland. *J. Water Land Dev.* **2023**, *56*, 45–50. [CrossRef]
31. Kumar, A.; Ramamoorthy, D.; Kumar, N.; Verma, R.; Kumar, A.; Verma, D.K.; Jayabalan, I.; Marwein, B.M.; Jaiswal, K.K. Investigation on the Potential of Eco-Friendly Bio-Char for Amendment in Serpentine Soils and Immobilization of Heavy Metals Contaminants: A Review. *Biomass Convers. Biorefinery* **2023**, *13*, 16585–16605. [CrossRef]

32. Ekka, P.; Patra, S.; Upreti, M.; Kumar, G.; Kumar, A.; Saikia, P. Land Degradation and Its Impacts on Biodiversity and Ecosystem Services. In *Land and Environmental Management Through Forestry*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2023; pp. 77–101, ISBN 978-1-119-91052-7.
33. Gonçalves, J.; Freitas, J.; Fernandes, I.; Silva, P. Microalgae as Biofertilizers: A Sustainable Way to Improve Soil Fertility and Plant Growth. *Sustainability* **2023**, *15*, 12413. [\[CrossRef\]](#)
34. Wyszowska, J.; Kucharski, J.; Kucharski, M.; Borowik, A. Applicability of Biochemical Indices to Quality Assessment of Soil Polluted with Heavy Metals. *J. Elem.* **2014**, *18*, 733–756. [\[CrossRef\]](#)
35. Wyszowska, J.; Boros-Lajszner, E.; Kucharski, J. The Impact of Soil Contamination with Lead on the Biomass of Maize Intended for Energy Purposes, and the Biochemical and Physicochemical Properties of the Soil. *Energies* **2024**, *17*, 1156. [\[CrossRef\]](#)
36. Baćmaga, M.; Wyszowska, J.; Borowik, A.; Kucharski, J. Effect of Sulcotrione and Terbutylazine on Biological Characteristics of Soil. *Appl. Soil Ecol.* **2024**, *195*, 105232. [\[CrossRef\]](#)
37. Gertsen, M.M.; Arlyapov, V.A.; Perelomov, L.V.; Kharkova, A.S.; Golyseva, A.N.; Atroshchenko, Y.M.; Cardinale, A.M.; Reverberi, A.P. Environmental Implications of Energy Sources: A Review on Technologies for Cleaning Oil-Contaminated Ecosystems. *Energies* **2024**, *17*, 3561. [\[CrossRef\]](#)
38. Ambaye, T.G.; Chebbi, A.; Formicola, F.; Prasad, S.; Gomez, F.H.; Franzetti, A.; Vaccari, M. Remediation of Soil Polluted with Petroleum Hydrocarbons and Its Reuse for Agriculture: Recent Progress, Challenges, and Perspectives. *Chemosphere* **2022**, *293*, 133572. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Kapoor, R.T.; Zdarta, J. Fabrication of Engineered Biochar for Remediation of Toxic Contaminants in Soil Matrices and Soil Valorization. *Chemosphere* **2024**, *358*, 142101. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Yu, M.; Tariq, S.M.; Yang, H. Engineering Clay Minerals to Manage the Functions of Soils. *Clay Miner.* **2022**, *57*, 51–69. [\[CrossRef\]](#)
41. Garbowski, T.; Bar-Michalczyk, D.; Charazińska, S.; Grabowska-Polanowska, B.; Kowalczyk, A.; Lochyński, P. An Overview of Natural Soil Amendments in Agriculture. *Soil Tillage Res.* **2023**, *225*, 105462. [\[CrossRef\]](#)
42. Mota, J.; Merlo, E.; Martínez-Hernández, F.; Mendoza-Fernández, A.J.; Pérez-García, F.J.; Salmerón-Sánchez, E. Plants on Rich-Magnesium Dolomite Barrens: A Global Phenomenon. *Biology* **2021**, *10*, 38. [\[CrossRef\]](#)
43. Bolan, N.; Sarmah, A.K.; Bordoloi, S.; Bolan, S.; Padhye, L.P.; Van Zwieten, L.; Sooriyakumar, P.; Khan, B.A.; Ahmad, M.; Solaiman, Z.M.; et al. Soil Acidification and the Liming Potential of Biochar. *Environ. Pollut.* **2023**, *317*, 120632. [\[CrossRef\]](#)
44. Abdul-Sahib, A.M.; Golbashy, M.; Abbass, J. Effect of Date Palm Wastes, Perlite and Magnesium on Growth and Flowering in Gerbera Plants (*Gerbera jamesonii* L.). *Int. J. Hortic. Sci. Technol.* **2023**, *10*, 375–386. [\[CrossRef\]](#)
45. Wyszowska, J.; Borowik, A.; Zaborowska, M.; Kucharski, J. The Potential for Restoring the Activity of Oxidoreductases and Hydrolases in Soil Contaminated with Petroleum Products Using Perlite and Dolomite. *Appl. Sci.* **2024**, *14*, 3591. [\[CrossRef\]](#)
46. Cedeño, J.M.; Magán, J.-J.; Thompson, R.B.; Fernández, M.-D.; Gallardo, M. Comparison of Methods to Determine Nutrient Uptake of Tomato Grown in Free-Draining Perlite Substrate—Key Information for Optimal Fertigation Management. *Horticulturae* **2024**, *10*, 232. [\[CrossRef\]](#)
47. Ramos, C.G.; dos Santos de Medeiros, D.; Gomez, L.; Oliveira, L.F.S.; Schneider, I.A.H.; Kautzmann, R.M. Evaluation of Soil Re-Mineralizer from By-Product of Volcanic Rock Mining: Experimental Proof Using Black Oats and Maize Crops. *Nat. Resour. Res.* **2020**, *29*, 1583–1600. [\[CrossRef\]](#)
48. Luchese, A.V.; Leite, I.J.G.d.C.; Giarretta, A.P.d.S.; Alves, M.L.; Pivetta, L.A.; Missio, R.F. Use of Quarry Waste Basalt Rock Powder as a Soil Remineralizer to Grow Soybean and Maize. *Heliyon* **2023**, *9*, e14050. [\[CrossRef\]](#)
49. Bandura, L.; Woszek, A.; Kołodyńska, D.; Franus, W. Application of Mineral Sorbents for Removal of Petroleum Substances: A Review. *Minerals* **2017**, *7*, 37. [\[CrossRef\]](#)
50. Vasilyeva, G.; Mikhedova, E.; Zinnatshina, L.; Strijakova, E.; Akhmetov, L.; Sushkova, S.; Ortega-Calvo, J.-J. Use of Natural Sorbents for Accelerated Bioremediation of Grey Forest Soil Contaminated with Crude Oil. *Sci. Total Environ.* **2022**, *850*, 157952. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Aspectos Ecológicos Del Uso de Sorbentes Para Mejorar La Eficiencia de Bioremediación de Suelos Contaminados Por Petróleo | Fuentes, El Reventón Energético. Available online: <https://revistas.uis.edu.co/index.php/revistafuentes/article/view/12501> (accessed on 27 September 2024).
52. Wyszowska, J.; Borowik, A.; Zaborowska, M.; Kucharski, J. The Usability of Sorbents in Restoring Enzymatic Activity in Soils Polluted with Petroleum-Derived Products. *Materials* **2023**, *16*, 3738. [\[CrossRef\]](#)
53. Islam, T.; Li, Y.; Cheng, H. Biochars and Engineered Biochars for Water and Soil Remediation: A Review. *Sustainability* **2021**, *13*, 9932. [\[CrossRef\]](#)
54. Mohanta, S.; Pradhan, B.; Behera, I.D. Impact and Remediation of Petroleum Hydrocarbon Pollutants on Agricultural Land: A Review. *Geomicrobiol. J.* **2024**, *41*, 345–359. [\[CrossRef\]](#)
55. IUSS Working Group. World Reference Base for Soil Resources 2014, Update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. *World Soil Resour. Rep.* **2015**, *106*, 192.
56. EuroSuper 95—Unleaded Gasoline—ORLEN. Available online: <https://www.orklen.pl/pl/dla-biznesu/produkty/paliwa/benzyna/benzyna-bezolowiowa-95> (accessed on 8 July 2024).
57. PN-EN ISO 18125:2017-07; Solid Biofuels—Determination of Calorific Value. Polish Standardization Committee: Warsaw, Poland, 2017.

58. Kopetz, H.; Jossart, J.; Ragossnig, H.; Metschina, C. *European Biomass Statistics 2007*; European Biomass Association: Brussels, Belgium, 2007.
59. PN-EN ISO 16948:2015-07; Solid Biofuels—Determination of Total Content of Carbon, Hydrogen and Nitrogen. Polish Standardization Committee: Warsaw, Poland, 2015.
60. PN-G-04584:2001; Solid Fuels—Determination of Total and Ash Sulfur Content with Automatic Analyzers. Polish Standardization Committee: Warsaw, Poland, 2006.
61. PN-EN ISO 16994:2016-10; Solid Biofuels—Determination of Total Content of Sulfur and Chlorine. Polish Standardization Committee: Warsaw, Poland, 2016.
62. PN-EN ISO 18122:2016-01; Solid Biofuels—Determination of Ash Content. Polish Standardization Committee: Warsaw, Poland, 2016.
63. Wyszowska, J.; Borowik, A.; Zaborowska, M.; Kucharski, J. Calorific Value of Zea Mays Biomass Derived from Soil Contaminated with Chromium (VI) Disrupting the Soil's Biochemical Properties. *Energies* **2023**, *16*, 3788. [\[CrossRef\]](#)
64. Wyszowska, J.; Borowik, A.; Kucharski, J. The Role of Grass Compost and Zea Mays in Alleviating Toxic Effects of Tetracycline on the Soil Bacteria Community. *Int. J. Environ. Res. Public Health* **2022**, *19*, 7357. [\[CrossRef\]](#) [\[PubMed\]](#)
65. Wyszowska, J.; Borowik, A.; Zaborowska, M.; Kucharski, J. Mitigation of the Adverse Impact of Copper, Nickel, and Zinc on Soil Microorganisms and Enzymes by Mineral Sorbents. *Materials* **2022**, *15*, 5198. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Citing RStudio. Available online: <https://www.posit.co/> (accessed on 8 July 2024).
67. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2019. Available online: <https://www.r-project.org> (accessed on 8 July 2024).
68. Warnes, G.R.; Bolker, B.; Bonebakker, L.; Gentleman, R.; Huber, W.; Liaw, A.; Lumley, T.; Maechler, M.; Magnusson, A.; Moeller, S.; et al. Gplots: Various R Programming Tools for Plotting Data. R Package Version 2.17.0. 2020. Available online: <https://CRAN.R-Project.org/package=gplots> (accessed on 8 July 2024).
69. Tibco Software Inc. *Statistica*, version 13 Data Analysis Software System; Tibco Software Inc.: Palo Alto, CA, USA, 2021. Available online: <https://www.tibco.com/> (accessed on 8 July 2024).
70. Krzywiński, M.; Schein, J.; Birol, İ.; Connors, J.; Gascoyne, R.; Horsman, D.; Jones, S.J.; Marra, M.A. Circos: An Information Aesthetic for Comparative Genomics. *Genome Res.* **2009**, *19*, 1639–1645. [\[CrossRef\]](#) [\[PubMed\]](#)
71. Udume, O.A.; Abu, G.O.; Stanley, H.O.; Vincent-Akpu, I.F.; Momoh, Y.; Eze, M.O. Biostimulation of Petroleum-Contaminated Soil Using Organic and Inorganic Amendments. *Plants* **2023**, *12*, 431. [\[CrossRef\]](#)
72. Mishra, P.; Kiran, N.S.; Romanholo Ferreira, L.F.; Yadav, K.K.; Mulla, S.I. New Insights into the Bioremediation of Petroleum Contaminants: A Systematic Review. *Chemosphere* **2023**, *326*, 138391. [\[CrossRef\]](#)
73. Aziz, Z.S.; Jazza, S.H.; Dageem, H.N.; Banoon, S.R.; Balboul, B.A.; Abdelzaher, M.A. Bacterial Biodegradation of Oil-Contaminated Soil for Pollutant Abatement Contributing to Achieve Sustainable Development Goals: A Comprehensive Review. *Results Eng.* **2024**, *22*, 102083. [\[CrossRef\]](#)
74. Wei, Z.; Wei, Y.; Liu, Y.; Niu, S.; Xu, Y.; Park, J.-H.; Wang, J.J. Biochar-Based Materials as Remediation Strategy in Petroleum Hydrocarbon-Contaminated Soil and Water: Performances, Mechanisms, and Environmental Impact. *J. Environ. Sci.* **2024**, *138*, 350–372. [\[CrossRef\]](#)
75. Abbaspour, A.; Zohrabi, F.; Dorostkar, V.; Faz, A.; Acosta, J.A. Remediation of an Oil-Contaminated Soil by Two Native Plants Treated with Biochar and Mycorrhizae. *J. Environ. Manag.* **2020**, *254*, 109755. [\[CrossRef\]](#)
76. Dahiya, P.; Behl, M.; Kumari, D.; Arya, E.; Rathour, R.K.; Kumar, V.; Bhatia, R.K. Detoxification of Contaminated Soil to Restore Its Health for Sustainable Agriculture. In *Advancements in Microbial Biotechnology for Soil Health*; Bhatia, R.K., Walia, A., Eds.; Springer Nature: Singapore, 2024; pp. 295–322, ISBN 978-981-9994-82-3.
77. Vasilyeva, G.K.; Strijakova, E.R.; Ortega-Calvo, J.J. Remediation of Soils Polluted by Oil Industries. In *Soil Remediation Science and Technology*; Ortega-Calvo, J.J., Coulon, F., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 191–234, ISBN 978-3-031-60192-7.
78. Wyszowski, M.; Kordala, N. Trace Element Contents in Petrol-Contaminated Soil Following the Application of Compost and Mineral Materials. *Materials* **2022**, *15*, 5233. [\[CrossRef\]](#)
79. Murtaza, G.; Ahmed, Z.; Eldin, S.M.; Ali, I.; Usman, M.; Iqbal, R.; Rizwan, M.; Abdel-Hameed, U.K.; Haider, A.A.; Tariq, A. Biochar as a Green Sorbent for Remediation of Polluted Soils and Associated Toxicity Risks: A Critical Review. *Separations* **2023**, *10*, 197. [\[CrossRef\]](#)
80. Van Nguyen, T.T.; Phan, A.N.; Nguyen, T.-A.; Nguyen, T.K.; Nguyen, S.T.; Pugazhendhi, A.; Ky Phuong, H.H. Valorization of Agriculture Waste Biomass as Biochar: As First-Rate Biosorbent for Remediation of Contaminated Soil. *Chemosphere* **2022**, *307*, 135834. [\[CrossRef\]](#) [\[PubMed\]](#)
81. Borowik, A.; Wyszowska, J.; Zaborowska, M.; Kucharski, J. Soil Enzyme Response and Calorific Value of Zea Mays Used for the Phytoremediation of Soils Contaminated with Diesel Oil. *Energies* **2024**, *17*, 2552. [\[CrossRef\]](#)
82. Wu, H.; Hu, J.; Shaaban, M.; Xu, P.; Zhao, J.; Hu, R. The Effect of Dolomite Amendment on Soil Organic Carbon Mineralization Is Determined by the Dolomite Size. *Ecol. Process.* **2021**, *10*, 8. [\[CrossRef\]](#)
83. Huang, J.; Fisher, P.R.; Argo, W.R. Container Substrate-pH Response to Differing Limestone Type and Particle Size. *HortScience* **2007**, *42*, 1268–1273. [\[CrossRef\]](#)
84. Cai, W.K.; Liu, J.H.; Zhou, C.H.; Keeling, J.; Glasmacher, U.A. Structure, Genesis and Resources Efficiency of Dolomite: New Insights and Remaining Enigmas. *Chem. Geol.* **2021**, *573*, 120191. [\[CrossRef\]](#)

85. Qi, S.; Xue, Q.; Niu, Z.; Zhang, Y.; Liu, F.; Chen, H. Investigation of Zn²⁺ and Cd²⁺ Adsorption Performance by Different Weathering Basalts. *Water. Air. Soil Pollut.* **2016**, *227*, 126. [\[CrossRef\]](#)
86. Ai, H.; Li, X.; Chen, C.; Xu, L.; Fu, M.-L.; Sun, W.; Yuan, B. Immobilization of β -FeOOH Nanomaterials on the Basalt Fiber as a Novel Porous Composite to Effectively Remove Phosphate from Aqueous Solution. *Colloids Surf. Physicochem. Eng. Asp.* **2022**, *632*, 127815. [\[CrossRef\]](#)
87. Marková, I.; Kubás, J.; Buganová, K.; Ristvej, J. Usage of Sorbents for Diminishing the Negative Impact of Substances Leaking into the Environment in Car Accidents. *Front. Public Health* **2022**, *10*, 957090. [\[CrossRef\]](#)
88. Sabadash, V. Adsorption of Oil Products by Natural Sorbents. In *Modern Technologies in Energy and Transport*; Boichenko, S., Zaporozhets, A., Yakovlieva, A., Shkilniuk, I., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 137–158, ISBN 978-3-031-44351-0.
89. Balidakis, A.; Matsi, T.; Karagianni, A.-G.; Ipsilantis, I. Sewage Sludge Treated with Bentonite, Vermiculite or Biochar Can Improve Soil Properties and Enhance Growth of Grasses. *Soil Use Manag.* **2023**, *39*, 1403–1421. [\[CrossRef\]](#)
90. Faleh, S.T.; Fahmi, A.H.; Abood, M.A. The Role of Biochar and Perlite in Improving Some Chemical Properties of Clay Loam Soil and Sandy Loam Soil. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1262*, 082011. [\[CrossRef\]](#)
91. Ansari, S.; Bahmaninia, H.; Mohammadi, M.-R.; Ostadhassan, M.; Norouzi-Apourvari, S.; Schaffie, M.; Ranjbar, M.; Hemmati-Sarapardeh, A. On the Evaluation of Asphaltene Adsorption onto Dolomite Surface: The Roles of Flow Condition, Composition of Asphaltene, and Dolomite Size. *Alex. Eng. J.* **2022**, *61*, 9411–9425. [\[CrossRef\]](#)
92. Yuan, X.; Xia, W.; An, J.; Yin, J.; Zhou, X.; Yang, W. Kinetic and Thermodynamic Studies on the Phosphate Adsorption Removal by Dolomite Mineral. *J. Chem.* **2015**, *2015*, 853105. [\[CrossRef\]](#)
93. Tuchowska, M.; Wołowicz, M.; Solińska, A.; Kościelniak, A.; Bajda, T. Organo-Modified Vermiculite: Preparation, Characterization, and Sorption of Arsenic Compounds. *Minerals* **2019**, *9*, 483. [\[CrossRef\]](#)
94. Wojcieszak, D.; Przybył, J.; Czajkowski, L.; Majka, J.; Pawłowski, A. Effects of Harvest Maturity on the Chemical and Energetic Properties of Corn Stover Biomass Combustion. *Materials* **2022**, *15*, 2831. [\[CrossRef\]](#)
95. Wojcieszak, D.; Przybył, J.; Ratajczak, I.; Goliński, P.; Janczak, D.; Waśkiewicz, A.; Szentner, K.; Woźniak, M. Chemical Composition of Maize Stover Fraction versus Methane Yield and Energy Value in Fermentation Process. *Energy* **2020**, *198*, 117258. [\[CrossRef\]](#)
96. Mendes, M.P.; Cunha, D.L.; dos Santos, V.M.L.; Vianna, M.T.G.; Marques, M. Ecological Risk Assessment (ERA) Based on Contaminated Groundwater to Predict Potential Impacts to a Wetland Ecosystem. *Environ. Sci. Pollut. Res.* **2020**, *27*, 26332–26349. [\[CrossRef\]](#)
97. Fali, K.T.; Mohd Razali, S.F.; Abdul Maulud, K.N.; Abd Rahman, N.; Abba, S.I.; Yaseen, Z.M. Assessment of Petroleum Contamination in Soil, Water, and Atmosphere: A Comprehensive Review. *Int. J. Environ. Sci. Technol.* **2024**, *21*, 8803–8832. [\[CrossRef\]](#)
98. Saxena, R.C.; Adhikari, D.K.; Goyal, H.B. Biomass-Based Energy Fuel through Biochemical Routes: A Review. *Renew. Sustain. Energy Rev.* **2009**, *13*, 167–178. [\[CrossRef\]](#)
99. Srivastava, R.K.; Shetti, N.P.; Reddy, K.R.; Kwon, E.E.; Nadagouda, M.N.; Aminabhavi, T.M. Biomass Utilization and Production of Biofuels from Carbon Neutral Materials. *Environ. Pollut.* **2021**, *276*, 116731. [\[CrossRef\]](#)
100. Saleem, M. Possibility of Utilizing Agriculture Biomass as a Renewable and Sustainable Future Energy Source. *Heliyon* **2022**, *8*, e08905. [\[CrossRef\]](#)
101. Gao, C.; El-Sawah, A.M.; Ali, D.F.I.; Alhaj Hamoud, Y.; Shaghaleh, H.; Sheteiwy, M.S. The Integration of Bio and Organic Fertilizers Improve Plant Growth, Grain Yield, Quality and Metabolism of Hybrid Maize (*Zea mays* L.). *Agronomy* **2020**, *10*, 319. [\[CrossRef\]](#)
102. Zahed, M.A.; Salehi, S.; Madadi, R.; Hejabi, F. Biochar as a Sustainable Product for Remediation of Petroleum Contaminated Soil. *Curr. Res. Green Sustain. Chem.* **2021**, *4*, 100055. [\[CrossRef\]](#)
103. Wyszowski, M.; Kordala, N. Role of Different Material Amendments in Shaping the Content of Heavy Metals in Maize (*Zea mays* L.) on Soil Polluted with Petrol. *Materials* **2022**, *15*, 2623. [\[CrossRef\]](#) [\[PubMed\]](#)
104. Sabitov, A.; Atamanov, M.; Doszhanov, O.; Saurykova, K.; Tazhu, K.; Kerimkulova, A.; Orazbayev, A.; Doszhanov, Y. Surface Characteristics of Activated Carbon Sorbents Obtained from Biomass for Cleaning Oil-Contaminated Soils. *Molecules* **2024**, *29*, 3786. [\[CrossRef\]](#) [\[PubMed\]](#)
105. Wyszowska, M.; Wyszowska, J.; Kordala, N.; Zaborowska, M. Molecular Sieve, Halloysite, Sepiolite and Expanded Clay as a Tool in Reducing the Content of Trace Elements in *Helianthus annuus* L. on Copper-Contaminated Soil. *Materials* **2023**, *16*, 1827. [\[CrossRef\]](#)
106. Wyszowska, J.; Borowik, A.; Zaborowska, M.; Kucharski, J. Biochar, Halloysite, and Alginite Improve the Quality of Soil Contaminated with Petroleum Products. *Agriculture* **2023**, *13*, 1669. [\[CrossRef\]](#)
107. Zhang, W.; Liang, Y. Performance of Different Sorbents toward Stabilizing Per- and Polyfluoroalkyl Substances (PFAS) in Soil. *Environ. Adv.* **2022**, *8*, 100217. [\[CrossRef\]](#)
108. Qu, J.; Zhang, X.; Guan, Q.; Kong, L.; Yang, R.; Ma, X. Effects of Biochar Underwent Different Aging Processes on Soil Properties and Cd Passivation. *Environ. Sci. Pollut. Res.* **2022**, *29*, 57885–57895. [\[CrossRef\]](#)
109. Voccianti, M.; Franchi, E.; Fusini, D.; Pedron, F.; Barbafieri, M.; Petruzzelli, G.; Reverberi, A.P. Sustainable Recovery of an Agricultural Area Impacted by an Oil Spill Using Enhanced Phytoremediation. *Appl. Sci.* **2024**, *14*, 582. [\[CrossRef\]](#)
110. Nguyen Ho, Q.; Hidaka, T.; Rahman, M.A.; Yoshida, N. Application of Natural Zeolite Adsorption in Cooperation with Photosynthesis for the Post-Treatment of Microbial Fuel Cells. *RSC Adv.* **2024**, *14*, 26484–26493. [\[CrossRef\]](#)

111. Atero-Calvo, S.; Magro, F.; Masetti, G.; Navarro-León, E.; Rios, J.J.; Blasco, B.; Ruiz, J.M. Comparative Effects of Root and Foliar Leonardite-Suspension Concentrate Application on Plant Growth and Photosynthetic Efficiency of Lettuce Plants (*Lactuca sativa* L.). *J. Plant Growth Regul.* **2024**. [\[CrossRef\]](#)
112. Wyszowski, M.; Kordala, N. Applicability of Compost and Mineral Materials for Reducing the Effect of Diesel Oil on Trace Element Content in Soil. *Materials* **2023**, *16*, 3655. [\[CrossRef\]](#) [\[PubMed\]](#)
113. Kamenchuk, V.; Rumiantsev, B.; Dzhatdueva, S.; Sadykhov, E.; Kochkarov, A. Analysis of Cross-Influence of Microclimate, Lighting, and Soil Parameters in the Vertical Farm. *Agronomy* **2023**, *13*, 2174. [\[CrossRef\]](#)
114. Głab, T.; Gondek, K.; Mierzwa-Hersztek, M. Biological Effects of Biochar and Zeolite Used for Remediation of Soil Contaminated with Toxic Heavy Metals. *Sci. Rep.* **2021**, *11*, 6998. [\[CrossRef\]](#)
115. Morales-Máximo, C.N.; López-Sosa, L.B.; Rutiaga-Quñones, J.G.; Corral-Huacuz, J.C.; Aguilera-Mandujano, A.; Pintor-Ibarra, L.F.; López-Miranda, A.; Delgado-Domínguez, S.N.; Rodríguez-Magallón, M.d.C.; Morales-Máximo, M. Characterization of Agricultural Residues of Zea Mays for Their Application as Solid Biofuel: Case Study in San Francisco Pichátaro, Michoacán, Mexico. *Energies* **2022**, *15*, 6870. [\[CrossRef\]](#)
116. Priya; Deora, P.S.; Verma, Y.; Muhal, R.A.; Goswami, C.; Singh, T. Biofuels: An Alternative to Conventional Fuel and Energy Source. *Mater. Today Proc.* **2022**, *48*, 1178–1184. [\[CrossRef\]](#)
117. Havrland, B.; Ivanova, T.; Lapczynska-Kordon, B.; Kolaříková, M. Comparative Analysis of Bio-Raw Materials and Biofuels. *Eng. Rural. Dev.* **2013**, 541–544.
118. Gerssen-Gondelach, S.J.; Saygin, D.; Wicke, B.; Patel, M.K.; Faaij, A.P.C. Competing Uses of Biomass: Assessment and Comparison of the Performance of Bio-Based Heat, Power, Fuels and Materials. *Renew. Sustain. Energy Rev.* **2014**, *40*, 964–998. [\[CrossRef\]](#)
119. Zihare, L.; Soloha, R.; Blumberg, D. The Potential Use of Invasive Plant Species as Solid Biofuel by Using Binders. *Agron. Res.* **2018**, *16*, 923–935. [\[CrossRef\]](#)
120. Kalt, G.; Lauk, C.; Mayer, A.; Theurl, M.C.; Kaltenegger, K.; Winiwarter, W.; Erb, K.-H.; Matej, S.; Haberl, H. Greenhouse Gas Implications of Mobilizing Agricultural Biomass for Energy: A Reassessment of Global Potentials in 2050 under Different Food-System Pathways. *Environ. Res. Lett.* **2020**, *15*, 034066. [\[CrossRef\]](#)
121. Rocha-Meneses, L.; Luna-delRisco, M.; González, C.A.; Moncada, S.V.; Moreno, A.; Sierra-Del Rio, J.; Castillo-Meza, L.E. An Overview of the Socio-Economic, Technological, and Environmental Opportunities and Challenges for Renewable Energy Generation from Residual Biomass: A Case Study of Biogas Production in Colombia. *Energies* **2023**, *16*, 5901. [\[CrossRef\]](#)
122. Raza, A.; Zunaira-Tu-Zehra; Khurram, M.; Khan, M.A.P.; Durez, A.; Khan, L.A.; Raza, A.; Zunaira-Tu-Zehra; Khurram, M.; Khan, M.A.P.; et al. Comparison of Evaporation in Conventional Diesel and Bio-Fuel Droplets in Engine Cylinder. In *Exergy—New Technologies and Applications*; IntechOpen: London, UK, 2023; ISBN 978-1-83768-545-5.
123. Rocha-Meneses, L.; Ferreira, J.A.; Mushtaq, M.; Karimi, S.; Orupöld, K.; Kikas, T. Genetic Modification of Cereal Plants: A Strategy to Enhance Bioethanol Yields from Agricultural Waste. *Ind. Crops Prod.* **2020**, *150*, 112408. [\[CrossRef\]](#)

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