Determination of the Possibilities of Using Woody Biomass Ash from Thermal Power Plants in Corn Cultivation

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Abstract: Combustion of woody biomass in professional bioheating plants to generate heat and reduce the dust emissions from this process results in the formation of a huge mass of woody biomass ash (WBA). Due to WBA’s rich chemical composition and the assumptions of the circular economy, this mineral material should be used for environmental purposes to recover valuable macronutrients and micronutrients. The basis of the research was a pot experiment designed to assess the effect of six doses of WBA (15, 30, 45, 60, 75, and 90 g pot⁻¹) on the growth, development, yield, and chemical composition of corn. Each pot contained 9 kg of soil. Observations show that the use of increasing doses of WBA had a positive effect on the height of corn plants, increasing its yield by 7 to 10% but reducing the dry matter content by 0.47 to 1.37% and the leaf greenness index (SPAD). Moreover, WBA application (T1–T5 treatments) had a positive effect on the content of macronutrients (N, K, Mg, Ca, and Na) in corn biomass. A significant increase in the content of K (54%), Mg (38%), Ca (43%), and Na (19%) was observed. However, at the same time, a significant increase in the content of heavy metals—Ni, Cd, and Pb—was observed. Different results were obtained for P, Zn, Cu, Cr, and Co, whose content in corn decreased after WBA application to soil. The obtained results indicate the possibility of using WBA in an environmentally friendly way. However, due to the great diversity of this material in terms of the content of undesirable heavy metals, it is necessary to optimize its dosage and monitor its chemical composition. Considering the growing number of bioheating plants in our country in recent years and the resulting increase in the amount of WBA produced, it is necessary to develop a rational and environmentally friendly method for managing them in the future. The results of our research may provide partial indications of such solutions.

Keywords: woody biomass ash; corn; yield; leaf greenness index (SPAD); macronutrients; trace elements

1. Introduction

The development of society on a global scale results in an increase in industrial production and energy demand. Most of this energy is derived from processed fossil raw materials. Recently, however, a significant increase in the share of renewable energy sources in the total energy produced has been observed. This is particularly visible in Europe, where biomass combustion is the dominant renewable energy source [1]. The most commonly used biomass is wood itself, wood chips, and pellets, as well as wood waste. Additionally, agricultural products and the waste generated from their processing into food are a rich source of biomass. The mentioned sources, as well as animal waste, food processing waste, algae and aquatic plants, and municipal solid waste from energy production are also used [2]. Biomass in the form of wood chips is very popular among the combusted biomass in many countries. Its share in the energy production process will increase in the coming years as a result of ecological programs adopted by individual European countries. After the combustion of biomass for energy purposes, woody biomass ash (WBA), a waste product, is destined for landfills [3]. Due to the increase in the mass of
woody ash from biomass combustion in the coming years, problems with its management will increase. One of the possibilities for its use seems to be natural management [4].

WBA is a by-product produced during the energy production process. This material can be incorporated into the soil to recover nutrients and prevent acidification [5]. The significant presence of basic metals in the composition of WBA makes it possible to use this material as an improver with a liming and neutralizing effect [1]. According to Mayer et al. [6], WBA reuse in agriculture and forestry is the basis of a circular economy. Moreover, this method of WBA management reduces the amount of waste deposited in landfills [7,8]. WBA produced during the combustion of wood for energy purposes contains many valuable components (macro- and microelements) necessary for plant development [6,9–11], and their content is most often correlated with the tree species [7,12]. WBA contains nutrients that are easily available to plants, allowing it to be used as a fertilizer [13]. WBA can be used as a rich source of phosphorus fertilizer on light, clayey sand soils [4]. Soil application of WBA improves the sorption properties of soils [11] and increases the pH, the total carbon, and available forms of macro- and micronutrient content [11,14]. According to Basu et al. [15] and Gill et al. [16], WBA improves soil properties. This contributes to an increase in the yield of cultivated plants [5,10], and the observed effects may persist in subsequent years [5,14]. WBA application can stimulate the uptake of N by plants as a result of increasing the soil organic matter mineralization and releasing this macroelement into the soil. However, the potential positive effect of WBA on plant growth and development may be reduced by low nitrogen (N) concentrations in this material [5]. In order to fully use the fertilizing potential of WBA, it should be remembered that it acts as a fertilizer with an insufficient N content in relation to the other P:K components—1:10:50, respectively [9]. To counteract this, some researchers recommend supplementing the deficiency of nitrogen in WBA with mineral fertilizers. According to Adekayode and Olojugba [17], a mixture of mineral fertilizer and WBA is an appropriate agronomic solution for profitable corn production. Moreover, according to Romdhane et al. [10], soil application of WBA reduces the sensitivity of corn to drought and improves shoot and root growth. These effects can be intensified in combination with other mentioned earlier amendments [10]. One of the proposed solutions is to combine WBA with sewage sludge, which results in effective sludge dewatering and a significant reduction in the total number of bacteria. Such mixtures may be a good alternative to synthetic or mineral fertilizers, which are used for the fertilization of perennial plantations [18]. According to Mayer et al. [6], an assessment of the potential for macronutrient recovery from biomass using power plants in southwestern Germany indicated that approximately 3.1, 7.5, and 22.8% of N, P, and Ca from fertilizers, respectively, could be replaced by WBA. Moreover, ash from biomass combustion containing chipped wood willow, varieties of energetic willow, corn, and straw is more effective in terms of yield than traditional mineral fertilization [19].

The beneficial impact of WBA on plant development, growth, and yield [5,13,14,16,17,19–21] usually depends on the dose of WBA and the plant species [9,20]. Plant development is often assessed by the measuring of the degree of greenness of the leaves, which may be an appropriate indication for assessing the impact of applied fertilization on the growing conditions of a crop [22,23]. The degree of greenness, which indicates the chlorophyll content in plants, is quite often expressed as the SPAD index [22–25]. Some studies show that WBA application has a positive effect on SPAD index values [17,21]. These observations may be correlated with research results indicating a better nutritional status of plants under the conditions of WBA application [5,13,14].

However, apart from the positive effects of using WBA, one should remember the potential adverse impact of WBA on the natural environment, including the content of xenobiotics in crops. Environmental management of ash is often limited by the presence of significant amounts of toxic trace elements and various inorganic compounds that are formed during biomass combustion as a result of thermochemical reactions [1]. WBA may contain harmful heavy metals [5–7], such as Cd [5,6], Pb, and Zn [6], and there are
concerns that the accumulation of these metals in plants may be increased [5]. According to Mayer et al. [6], the direct use of most WBA fractions is not possible due to the high content of Cd, Pb, and Ni. Due to this fact, the WBA use as fertilizer purposes may be limited. Another problem that determines the management of WBA is a significant difference in the concentrations of trace elements resulting from differences in the characteristics of the biomass itself [7]. The composition of WBA is significantly influenced by the type of wood we burn, the location of the plantation, the nature of the parent rock and anthropogenic activities on and around the plantation [12]. The accumulation of trace elements in WBA may depend on the combustion temperature of wood fuel [7]. As the combustion temperature increases, the content of Cd, Zn, Pb, and Cu decreases, indicating that these elements transition to the gaseous phase at higher temperatures. More heat-resistant and therefore less volatile metals such as Cr, Ni, and Fe accumulate in the ash at higher combustion temperatures [7]. Due to the above-mentioned problems regarding the variable composition of biomass ash [1,6], developing a safe method of managing WBA is very difficult. Therefore, it is necessary to constantly monitor the composition of WBA with respect to heavy metal content so that its use does not pose environmental hazards [7,10] and health risks in the food use of the obtained crops [12]. Despite a considerable amount of literature data on the impact of WBA on the properties of soils [1,5,11,14], on the chemical composition of plants [5,13,19], and on the possible accumulation of toxic elements in them [5,6], it is still justified to conduct research in this area. Arguments supporting the advisability of such research include the influence of the type of biomass burned on the properties of WBA and the different technological processes used for biomass combustion in bioheating plants, which differentiate the chemical composition of WBA. Developing an environmentally safe management method for WBA is difficult even on the scale of one bioheating plant because the type of biomass burned varies and is often differentiated by changing the location of the plantation. Due to the above, this type of research is absolutely justified in the interests of environmental safety.

Based on the available literature and the type of the wood ash (WBA) used, a research hypothesis was formulated assuming a positive impact of WBA on the yield and the formation of the chemical composition of corn (Zea mays L.). In addition, the content and uptake of heavy metals by corn with increasing doses of WBA were evaluated in this study.

2. Materials and Methods

The results presented in this paper concern the impact of WBA on the yield and macro- and micronutrients of plants and constitute the second part of the research on the possibilities of using WBA in nature. The first part of the research results regarding the effect of WBA on soil properties was published in a paper by Rolka et al. [11]. Therefore, only a brief description of the soil and WBA parameters is given in this paper.

2.1. Research Experiment

The research was based on a pot experiment. The place where the research was carried out was a greenhouse belonging to the Faculty of Agriculture and Forestry of the University of Warmia and Mazury in Olsztyn (Poland). The test plant was corn (Zea mays L.). The study evaluated the impact of six doses of WBA on corn. The material came from biomass combustion in the energy production process. The following treatments were used: control treatment—without WBA (T0) and 15 (T1), 30 (T2), 45 (T3), 60 (T4), 75 (T5), and 90 g WBA pot$^{-1}$ (T6), corresponding to 0, 5, 10, 15, 20, 25, and 30 Mg WBA ha$^{-1}$. All experimental treatments were performed in triplicate. NPK mineral fertilization was applied once in the doses of 112 mg, 67 mg, and 134 mg of N, P, and K kg$^{-1}$ of soil, respectively. WBA and mineral fertilizers (NPK) were introduced into the soil and thoroughly mixed during the experiment setup. WBA was used as a powder, while NPK was used as a water solution. Nitrogen was used in the form of CO(NH$_2$)$_2$ 46% N, phosphorus in the form of KH$_2$PO$_4$, and potassium in the form of KH$_2$PO$_4$ and K$_2$SO$_4$. The experiment used polyethylene pots filled with 9 kg of soil. The number of seeds sown per pot was 24.
After emergence, the plants were thinned out, leaving 8 plants, which were cultivated for 66 days.

2.2. Plant

In the experiment, corn of the medium early variety LG 3252 (Limagrain Polska, Poznań, Poland) was used as a test plant. This medium early variety has the potential to regenerate after spring frosts and is recommended for cultivation all over Poland. Additionally, the variety is characterized by a high silage yield potential and the highest digestibility of the whole plant, which is very important for the nutrition of farm animals. The average silage yield is estimated to be 54 Mg ha\(^{-1}\) of fresh matter with a dry matter content of 34.8%.

The leaf greenness index (SPAD) was measured on June 1st, 15th, and 29th. The first greenness measurement was made on the third leaf at BBCH 15 phase (five leaves unfolded), the second on the fifth leaf during BBCH 17 (seven leaves unfolded), and the third on the seventh leaf at BBCH 19 phase (nine leaves unfolded). Measurements were taken on each plant, with 4 measurements per leaf, and the obtained results were averaged. Finally, 8 observations were made per pot. The measurement was performed with a chlorophyll meter SPAD-502Plus [26]. According to the recommendation of Vig et al. [22], the reading points were evenly distributed along the maize leaf blade, which is very important due to the uneven distribution of SPAD values on the corn leaf. According to Vig et al. [22], SPAD values increase from the base of the leaf to the middle of the leaf blade and then begin to decrease. Several measurements should be taken on one leaf to obtain an accurate result. Corn was harvested on July 5 at BBCH 53 stage (panicle development). At harvest, the height of each plant and the weight of all plants from each pot were measured. Then, the plants were crushed and dried in a FED 700 model dryer [27] at a temperature of 60 °C to constant weight. This process was completed with the determination of the dry matter content. The material was ground in an SM 200 cutting mill [28] and transferred to polyethylene (PP) containers. The thus-prepared material was subjected to chemical analyses.

2.3. Pot Experiment

The soil used for the experiment was collected from the arable humus level (0–25 cm) of the agricultural field of the Research Station located in Tomaszkowo near Olsztyn (Poland). The soil was described as brown soil [29] and classified as loamy sand (73.9% of sand 0.005–2.00 mm, 24.1% silt 0.002–0.05 mm, and 2.0% clay ≤ 0.002 mm) based on soil particle size distribution [30].

The initial soil had an acidic reaction (pH\(_{\text{KCl}}\)) of 4.85, low electrical conductivity (EC) of 51.27 µS m\(^{-1}\), and a rather poor sorption complex, including sum of basic cations (SBC), hydrolytic acidity (HAC), and cation exchange capacity (CEC), which were 50.67, 25.50, and 76.17 mmol(+) kg\(^{-1}\). The degree of saturation with basic cations (BSs) was 66.50%. The contents of total carbon (TC) and total nitrogen (N\(_{\text{tot}}\)) were 6.46 and 0.78 g kg\(^{-1}\), respectively, and the C/N ratio was equal to 8.28. The concentrations of available forms of phosphorus (P\(_{\text{av}}\)), potassium (K\(_{\text{av}}\)), and magnesium (Mg\(_{\text{av}}\)) were 194.1, 119.0, and 34.89 mg kg\(^{-1}\), respectively. The total content of trace elements in the soil was low and corresponded to the natural content assumed for soils in Poland [31] and amounted to iron (Fe\(_{\text{tot}}\)) 9437, manganese (Mn\(_{\text{tot}}\)) 330.0, zinc (Zn\(_{\text{tot}}\)) 20.61, cobalt (Co\(_{\text{tot}}\)) 10.07, nickel (Ni\(_{\text{tot}}\)) 6.54, lead (Pb\(_{\text{tot}}\)) 6.50, copper (Cu\(_{\text{tot}}\)) 2.53, chromium (Cr\(_{\text{tot}}\)) 2.06, and cadmium (Cd\(_{\text{tot}}\)) 0.403 mg kg\(^{-1}\) of soil. The content of the available forms of these elements in the soil was as follows: Fe\(_{\text{av}}\) 1000, Mn\(_{\text{av}}\) 117.8, Zn\(_{\text{av}}\) 6.15, Pb\(_{\text{av}}\) 5.15, Cu\(_{\text{av}}\) 2.03, Co\(_{\text{av}}\) 1.94, Ni\(_{\text{av}}\) 1.43, Cr\(_{\text{av}}\) 0.809, and Cd\(_{\text{av}}\) 0.188 mg kg\(^{-1}\) of soil.
2.4. Origin of Ash and Ash Properties

In this research, waste ash from the combustion of woody biomass from the Bioheating Plant (MPEC Olsztyn, Poland) was used. Wood biomass ash (WBA) is produced from burning wood chips, mainly from Scots pine (*Pinus sylvestris* L.).

WBA contained 80.41% dry matter, 4.29 g N$_{\text{tot}}$ kg$^{-1}$, 208.0 g TC kg$^{-1}$, and the C/N ratio was 48.48. The total contents of P$_{\text{tot}}$, K$_{\text{tot}}$, Mg$_{\text{tot}}$, Ca$_{\text{tot}}$, and Na$_{\text{tot}}$ in WBA were, respectively, 6.36, 17.18, 6.20, 43.97, and 1.36 g kg$^{-1}$, and the available forms P$_{\text{av}}$, K$_{\text{av}}$, and Mg$_{\text{av}}$ were 110.0, 410.0, and 57.0 mg kg$^{-1}$, respectively. The reaction of WBA was alkaline (pH$_{\text{KCl}}$—10.31), with EC at the level of 51.27 mS m$^{-1}$, SBC—3507 mmol(+) kg$^{-1}$, HAC—750.0 mmol(+) kg$^{-1}$, CEC—4257 mmol(+) kg$^{-1}$, and BS—82.38%. However, the content of heavy metals in the WBA was in a decreasing order: Fe$_{\text{tot}}$ (5684) > Zn$_{\text{tot}}$ (448.5) > Mn$_{\text{tot}}$ (237.3) > Pb$_{\text{tot}}$ (74.53) > Ni$_{\text{tot}}$ (49.95) > Cr$_{\text{tot}}$ (30.41) > Cu$_{\text{tot}}$ (26.54) > Co$_{\text{tot}}$ (4.81) > Cd$_{\text{tot}}$ (1.50 mg kg$^{-1}$). Their content did not exceed the limits for metal content established by national legislation [32].

2.5. Analytical Methods

The description of the methods used for the chemical analyses of the initial soil (soil), the woody biomass ash (WBA), and the aboveground part of the corn (plant) [33–39] is given in Table S1.

CEC and BS were calculated based on the formula used by other authors [11,25,40,41]. Analysis of the chemical composition of the aboveground mass of corn in terms of the content of N, P, K, Mg, Ca, Na, Fe, Mn, Zn, Cu, Cd, Pb, Ni, Cr, and Co allowed the calculation of the uptake of these elements by plants according to the following formula [42,43].

$$UP_{me} = \frac{Y \times C (Ma \ or \ Me)}{1000}$$

where:

- $UP_{me}$—element uptake with plant yield, mg pot$^{-1}$;
- $Y$—plant yield, g pot$^{-1}$;
- $C$—$Ma$—macronutrient content, g kg$^{-1}$ of dry matter (DM);
- $Me$—trace metal content, mg kg$^{-1}$ DM;
- 1000—conversion factor of the content per 1 kg of soil.

2.6. Statistical Methods

Statistical analysis of the results included the Pearson’s correlation coefficient ($r$) and the standard deviation (SD), calculated with Microsoft Excel® for Microsoft 365 MOS 222 (version 2206) (Microsoft, Redmond, WA, USA) [44]. The significance of the ($r$) value was determined on the basis of statistical tables [45]. The impact of WBA on the studied corn characteristics was evaluated using the LSD test of one-way ANOVA with Statistica® (version 13.3 PL) (TIBCO Software Inc., Palo Alto, CA, USA) [46].

3. Results

3.1. Plant Height, Corn Yield, and Dry Matter

Increasing doses of WBA affected the height of corn plants, which had a direct effect on the yield of the fresh mass (FM) of the aboveground part of corn (Figures 1 and 2). The average height of corn plants was 154.4 cm. All treatments (T1–T6) increased plant height, but this characteristic was significantly influenced only by the third dose of WBA (T3) (Figure 1a). The average yield of the aboveground corn mass was 682.7 g of FM pot$^{-1}$ (Figure 1b). WBA application usually had an unambiguous effect on the corn yield, with a significant effect recorded after T1–T4. In these treatments, the yield was nearly 7 to 10% higher than in the T0 treatment. The first dose of WBA (T1) had the most positive effect on the corn yield, with a recorded yield that was 708.8 g of FM pot$^{-1}$. However, at the remaining doses (T5 and T6), no significant increase in corn yield was observed.
WBA treatments: T0 without WBA, T1 (15), T2 (30), T3 (45), T4 (60), T5 (75), and T6 (90 g of WBA pot⁻¹); means followed by the same letter do not differ at p≤0.05 in the LSD test within the analyzed features; n=3; ± SE; (r) correlation coefficient; n.s. – not significant.

Figure 1. (a) Corn plant height; (b) corn aboveground weight yield.

Figure 2. Corn plants during vegetation: (a) 39th day of growth; (b) 64th day of growth.

WBA application to the soil increased yield but decreased the DM content in corn (Table 1). The average DM content in corn was 12.88%. All WBA doses (T1–T6) reduced the DM content of the corn plants from 0.47 to 1.37% compared to the control object (T0). LSD analysis showed a significant effect of T2, T4, and T5 treatments.

Table 1. Dry matter (DM) content (%) in corn plants.

<table>
<thead>
<tr>
<th>WBA Treatments</th>
<th>T0</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>Mean</th>
<th>r</th>
<th>LSD p≤0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry mass (%)</td>
<td>13.69 b</td>
<td>13.22 ab ± 0.75</td>
<td>12.32 ± 0.44</td>
<td>13.05 ab ± 0.30</td>
<td>12.43 a ± 0.12</td>
<td>12.52 a ± 0.86</td>
<td>12.94 ab ± 0.15</td>
<td>12.88 ± 0.62 n.s.</td>
<td>4.31</td>
<td></td>
</tr>
</tbody>
</table>

Explanations are provided in Figure 1.

3.2. SPAD Index

During corn vegetation, the leaf greenness, expressed by the SPAD index, was determined three times (Figure 3d). The average value of this indicator was 32.86 SPAD units. The highest greenness index (45.88 SPAD units) was recorded during the first measurement (Figure 3a). As the growing season progressed, the value of the SPAD index decreased. On the subsequent measurement dates, the SPAD values were almost 15 and 25 units lower than during the first measurement (Figure 3b,c). The results indicate that the most intense
effect of WBA doses on this trait occurred at the beginning of growth (from emergence to the fifth unfolded leaf) (Figure 3a). The correlation coefficient calculated at this time indicated a negative impact of the WBA addition on the SPAD index ($r = -0.589^{**}$). The LSD analysis showed a significant effect only at the WBA dose (T6), at which the SPAD index was 3.11 units lower compared to the control object (T0). Subsequent SPAD measurement dates did not show such significant changes, except for the second dose of WBA (T2) at the second measurement date (Figure 3b). This dose (T2) resulted in an unexpectedly significant reduction in the SPAD index value of 3.72 units compared to the control object. The calculated average SPAD value for three measurements (Figure 3d) indicates a decrease in leaf greenness with increasing WBA doses, but a significant change was recorded only at the second dose (T2), which was influenced by the result of the second measurement.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Effect of WBA application on the corn leaf greenness index (SPAD): (a) first measurement; (b) second measurement; (c) third measurement; (d) means for three measurements.

### 3.3. Macronutrients

The addition of WBA to the soil changed the content of macronutrients in the aboveground part of the corn (Table 2). The highest average content was recorded for K, slightly lower for N and Ca, and the lowest for Mg, P, and Na. These contents were respectively, 18.94, 9.92, 3.31, 1.10, 0.363, and 0.340 g kg$^{-1}$ of DM. The Pearson coefficient indicates a positive impact of the biomass ash on the content of N, K, Mg, Ca, and Na ($0.466^{*} \leq r \leq 0.827^{**}$) in corn biomass, except for the P content, which decreased with increasing WBA doses ($r = -0.486^{*}$). The LSD test showed a significant increase in the contentation of K, Mg, Ca, and Na with
WBA application. The significant increase in K content occurred at the third dose of WBA (T3), increases in Mg and Ca occurred at the second dose (T2), and Na increase occurred at the fourth dose (T4). An increase in the concentration of the mentioned elements in relation to increasing WBA doses occurred up to the fifth WBA dose (T5), where the highest contents of K, Mg, Ca, and Na were, respectively, higher by 54, 38, 43, and 19% regarding the concentration of these macronutrients in the corn biomass collected from the control combination (T0).

Table 2. Contents of macronutrients in the aboveground part of corn.

<table>
<thead>
<tr>
<th>WBA Treatments</th>
<th>Nitrogen (N)</th>
<th>Phosphorus (P)</th>
<th>Potassium (K)</th>
<th>Magnesium (Mg)</th>
<th>Calcium (Ca)</th>
<th>Sodium (Na)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g kg⁻¹ DM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T0</td>
<td>9.33 ± 1.41 a</td>
<td>0.383 ± 0.021 a</td>
<td>14.71 ± 1.74 a</td>
<td>0.89 ± 0.13 b</td>
<td>2.67 ± 0.36 c</td>
<td>0.324 ± 0.011 ac</td>
</tr>
<tr>
<td>T1</td>
<td>9.05 ± 0.81 a</td>
<td>0.356 ± 0.014 ab</td>
<td>15.14 ± 0.53 ab</td>
<td>0.96 ± 0.10 b</td>
<td>3.07 ± 0.21 ac</td>
<td>0.311 ± 0.037 a</td>
</tr>
<tr>
<td>T2</td>
<td>9.89 ± 0.86 a</td>
<td>0.377 ± 0.024 a</td>
<td>18.03 ± 1.61 abc</td>
<td>1.10 ± 0.03 a</td>
<td>3.20 ± 0.36 a</td>
<td>0.314 ± 0.032 a</td>
</tr>
<tr>
<td>T3</td>
<td>9.99 ± 1.13 a</td>
<td>0.365 ± 0.028 ab</td>
<td>18.53 ± 1.93 bcd</td>
<td>1.15 ± 0.08 a</td>
<td>3.17 ± 0.25 a</td>
<td>0.296 ± 0.021 a</td>
</tr>
<tr>
<td>T4</td>
<td>10.36 ± 1.01 a</td>
<td>0.369 ± 0.024 ab</td>
<td>21.91 ± 2.16 de</td>
<td>1.19 ± 0.02 a</td>
<td>3.52 ± 0.12 ab</td>
<td>0.384 ± 0.026 b</td>
</tr>
<tr>
<td>T5</td>
<td>10.64 ± 0.84 a</td>
<td>0.359 ± 0.027 ab</td>
<td>22.65 ± 3.66 e</td>
<td>1.23 ± 0.06 a</td>
<td>3.83 ± 0.04 b</td>
<td>0.385 ± 0.014 b</td>
</tr>
<tr>
<td>T6</td>
<td>10.17 ± 0.43 a</td>
<td>0.330 ± 0.010 b</td>
<td>21.61 ± 0.74 cde</td>
<td>1.15 ± 0.01 a</td>
<td>3.73 ± 0.19 b</td>
<td>0.364 ± 0.007 bc</td>
</tr>
<tr>
<td>Mean</td>
<td>9.92 ± 0.97</td>
<td>0.363 ± 0.025</td>
<td>18.94 ± 3.51</td>
<td>1.10 ± 0.13</td>
<td>3.31 ± 0.44</td>
<td>0.340 ± 0.041</td>
</tr>
<tr>
<td>r</td>
<td>0.466 *</td>
<td>−0.486 *</td>
<td>0.827 **</td>
<td>0.767 **</td>
<td>0.844 **</td>
<td>0.615 **</td>
</tr>
<tr>
<td>LSD₀.05</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>0.13</td>
<td>0.43</td>
<td>0.041</td>
</tr>
</tbody>
</table>

WBA treatments are described in the Section 2; means with the same letter are not different at p ≤ 0.05; n = 3. Level of significance for r: *—p ≤ 0.01; **—p ≤ 0.05; n.s.—not significant; n = 21.

The strong effect of WBA on the change in the contents of macronutrients also influenced their mutual relationships (Table 2). The contents of macronutrients (N, K, Mg, Ca, and Na) in corn biomass were significantly correlated (0.537 * ≤ r ≤ 0.862 **) or highly significantly correlated (0.597 ** ≤ r ≤ 0.843 **) and it was a relationship positive in nature (Table S2). The exception was the P content, which was only positively significantly correlated with the N content (r = 0.479 *). The observed numerous and significant correlations between the contents of N, K, Mg, Ca, and Na prove that WBA addition was the source of these macronutrients for corn plants. Although P was also added to the soil with WBA, it probably remained in forms unavailable to plants, as evidenced by the decrease in its content in the corn biomass.

The highest average uptake of macronutrients with the corn yield was recorded for K (1.653 g) and N (0.869 g) and the lowest for P (0.032 g) and Na (0.030 g pot⁻¹) (Figure 4). WBA application significantly increased the uptake of K, Mg, and Ca (0.598 ** ≤ r ≤ 0.845 **) by the aboveground mass of corn. A significant increase in K and Mg uptake was already observed in T2 and in Ca uptake in T1 treatment. The changes in soil conditions with WBA significantly reduced phosphorus uptake (r = −0.745 **). A significant decrease was noted in the two highest doses of WBA (T5–T6). The observed changes in N and Na uptake with corn biomass in relation to WBA application were insignificant.

3.4. Trace Elements

The analyzed treatments had various effects on the concentration of trace elements in the aboveground part of corn (Table 3). The highest average content was recorded for Mn and Fe, much lower for Ni, Cr, Co, Pb, Zn, and Cu, and the lowest for Cd. Despite the high average content of Mn and Fe in corn biomass, no significant influences were noted among the analyzed treatments. The only exception was the object with the second dose of WBA (T2), which had a significantly higher Fe content compared to the other objects. However, an increase in the contents of Pb, Cd, and Ni in corn biomass was observed under the higher doses of WBA. All WBA treatments significantly increased Pb content but not regularly. A linear increase was observed for Cd (r = 0.479 *) and Ni (r = 0.777 **). Among the WBA doses used, the Cd content was significantly influenced by the T2 and T5 doses, and the
Ni content was significantly influenced by the T2 to T6 doses. In turn, the use of WBA resulted in a significant decrease in the case of Zn ($r = -0.501^*$) and a highly significant decrease in the case of Cu ($r = -0.634^{**}$), Cr ($r = -0.962^{**}$), and Co ($r = -0.828^{**}$) in corn biomass. The T2 and T6 treatments significantly reduced the Zn content, while the T5 only influenced Cu content. However, in the case of Co, WBA doses ranged between T2 and T6, and in the case of Cr, the WBA doses ranged between T3 and T6 and significantly reduced the mentioned trace metal contents in the corn biomass.

The observed changes in the contents of trace metals due to the use of WBA also translated into correlations between them (Table S3). A positive and significant relationship was noted for Cu vs. Fe and Co and Zn vs. Cr and Co ($0.461 \leq r \leq 0.598^{**}$). A positive and highly significant relationship was found for Cr vs. Cu and Co and Pb vs. Ni ($0.587^{**} \leq r \leq 0.800^{**}$). However, a significant and negative correlation was recorded in the relationship for Zn vs. Pb ($r = -0.459^*$), and a highly significant and negative correlation was found for Cr vs. Cd and Ni and Co vs. Ni ($-0.765^{**} \leq r \leq -0.599^{**}$).

The contents of trace metals in corn biomass were differently related to macronutrient contents (Table S4). The most significant relationships were observed between the contents of Ni, Cr, and Co and K, Mg, Ca, and Na. The amount of trace elements taken up by the aboveground mass of corn depended on both the type of metal and the applied dose of WBA. The average uptake of trace metals was within the range between 0.026 and 7.63 mg pot$^{-1}$ (Figure 5). The highest uptake was recorded for Mn and Fe and definitely the lowest was recorded for Cd. WBA application had a significant effect on the uptake of Zn, Cu, Cd, Ni, Cr, and Co. The uptake of Zn, Cu, Cr, and Co was negatively and highly significantly correlated with the applied WBA doses ($-0.931^{**} \leq r \leq -0.583^{**}$). However, the uptake of Cd was significantly correlated ($r = 0.459^*$), and the uptake of Ni was highly significantly correlated ($r = 0.741^{**}$) with WBA treatments. On the other hand, the amount of Fe, Mn, and Pb uptake (Figure 5), as well as the content of these elements (Table 3), did not show any significant correlations with the applied WBA doses.
Table 3. Contents of trace elements in the aboveground part of corn.

<table>
<thead>
<tr>
<th>WBA Treatments</th>
<th>Iron (Fe)</th>
<th>Manganese (Mn)</th>
<th>Zinc (Zn)</th>
<th>Copper (Cu)</th>
<th>Lead (Pb)</th>
<th>Cadmium (Cd)</th>
<th>Nickel (Ni)</th>
<th>Chromium (Cr)</th>
<th>Cobalt (Co)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg kg⁻¹ DM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T0</td>
<td>48.35 ± 13.45</td>
<td>92.94 ± 12.48</td>
<td>8.01 ± 0.38</td>
<td>5.22 ± 0.19</td>
<td>1.43 ± 0.36</td>
<td>0.122 ± 0.069</td>
<td>0.39 ± 0.92</td>
<td>18.94 ± 14.21</td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>43.89 ± 11.93</td>
<td>84.64 ± 1.01</td>
<td>7.09 ± 0.77</td>
<td>4.79 ± 0.77</td>
<td>7.42 ± 1.32</td>
<td>0.156 ± 0.21</td>
<td>7.98 ± 17.78</td>
<td>12.51 ± 1.30</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>67.21 ± 15.58</td>
<td>81.81 ± 11.46</td>
<td>6.51 ± 0.44</td>
<td>5.33 ± 0.33</td>
<td>9.81 ± 0.00</td>
<td>0.456 ± 0.241</td>
<td>18.47 ± 7.65</td>
<td>11.38 ± 2.94</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>48.07 ± 3.91</td>
<td>84.60 ± 10.58</td>
<td>7.04 ± 1.16</td>
<td>4.89 ± 0.51</td>
<td>11.61 ± 1.56</td>
<td>0.122 ± 0.102</td>
<td>25.06 ± 1.34</td>
<td>14.66 ± 0.43</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>47.99 ± 5.81</td>
<td>86.37 ± 6.62</td>
<td>6.82 ± 0.45</td>
<td>4.67 ± 0.33</td>
<td>7.65 ± 1.47</td>
<td>0.278 ± 0.168</td>
<td>24.08 ± 0.50</td>
<td>13.34 ± 0.71</td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>49.80 ± 2.11</td>
<td>89.74 ± 15.27</td>
<td>7.22 ± 0.23</td>
<td>4.32 ± 0.02</td>
<td>6.79 ± 0.73</td>
<td>0.644 ± 0.051</td>
<td>23.06 ± 0.50</td>
<td>11.4 ± 0.54</td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>40.81 ± 5.40</td>
<td>89.13 ± 4.63</td>
<td>5.80 ± 0.75</td>
<td>4.28 ± 0.05</td>
<td>7.90 ± 0.278</td>
<td>0.333 ± 0.120</td>
<td>21.79 ± 1.23</td>
<td>11.0 ± 1.25</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>49.45 ± 11.35</td>
<td>87.04 ± 9.10</td>
<td>6.93 ± 0.89</td>
<td>4.78 ± 0.51</td>
<td>7.52 ± 3.23</td>
<td>0.302 ± 0.219</td>
<td>17.77 ± 8.41</td>
<td>14.62 ± 2.81</td>
<td></td>
</tr>
</tbody>
</table>

r: n.s.    LSD_{p=0.05} = 16.87   LSD_{p=0.01} = 17.50  LSD_{p=0.001} = 1.27

WBA treatments: T0 without WBA, T1 (15), T2 (30), T3 (45), T4 (60), T5 (75), and T6 (90 g of WBA pot⁻¹); means followed by the same letter are not different at p≤0.05 in the LSD test within the analyzed trace elements; r=3; ±SE; (r) correlation coefficient; * = significant for p≤0.05; ** = significant for p≤0.01; *** = not significant.

Figure 5. Trace element uptake from soil by aboveground parts of corn (mg pot⁻¹).
4. Discussion

The presented research indicates the potential of WBA, produced from the process of woody biomass combustion for energy purposes, as a good soil-improving amendment. According to some researchers [7], the abundance of WBA in macroelements, especially Ca and K, and microelements such as Fe, Zn, and Mn suggests the possibility of agricultural use of this material. Elements such as K, Ca, and Mg are present in biomass mainly in the form of carbonates. However, the high temperature of wood biomass combustion leads to their mineralization, and basic cations are converted to oxides [3]. In turn, the P contained in WBA is in the form of phosphates \( (\text{PO}_4^{3-}) \) [6]. In addition, some macro- and microelements found in WBA are related to minerals such as calcite, hematite, albite, and dolomite [12]. Due to the abundance of fertilizer components and the alkaline nature of WBA, some researchers [3] suggest that it can be used as a fertilizer on agricultural and forest soils. The high content of elements (K, Ca, Mg, Zn, and Fe) increases the yield of crops [15]. The positive impact of applying WBA to the soil on the yield of corn (\textit{Zea mays}) (Figure 1a) has been confirmed by numerous studies \[10,13,19,21\]. In studies also conducted on corn \[19,21\], the introduction of WBA to acidic soil resulted in better growth of plants, improved growth of shoots and roots \[10\], and increased grain yield \[13\]. An increase in the grain yield of corn was also observed after introducing a WBA mixture with mineral fertilizers (NPK) into the soil against the background of exclusive mineral fertilization \[17\]. WBA application had a positive influence not only on the growth of corn but also on other plants, such as black and white spruce (\textit{Picea mariana} and \textit{Picea glauca}) [14], the growth of wavy hair-grass (\textit{Deschampsia flexuosa}) [5], the green matter of ray grass (\textit{Lolium perenne}), and white mustard (\textit{Sinapis alba}) [47]. Gill et al. [16] observed higher yields of rapeseed (\textit{Brassica napus}), field pea (\textit{Pisum sativum}), and barley (\textit{Hordeum vulgare}) after application of WBA. These positive effects persisted for the several years. The results available in the literature indicate that the effect on the growth or yield of plants depends on the dose of WBA used, the type of soil, the additives used, or the plant species. A reduction in the number of germinating Indian mustard (\textit{Brassica juncea}) seeds in relation to increasing WBA doses was also observed by Gautama et al. [48]. In the present study, an increase in corn weight was observed up to the fourth dose of WBA (T4)—20 Mg ha\(^{-1}\). Higher doses of WBA (T5 and T6) did not show such positive results (Figure 1a). Similarly, Szostek et al. [49] observed positive effects on the yield of spring oilseed rape (\textit{Brassica napus}) in the dose range of 1.0 to 2.0 Mg WBA ha\(^{-1}\). Lower and higher doses of WBA had less effect. In turn, Saletnik et al. [50] showed that the highest increase in dry matter yield in the cultivation of giant miscanthus (\textit{Miscanthus giganteus}) occurred after the application of WBA at a dose of 1.5 Mg ha\(^{-1}\), together with biochar, and in the mixture of biochar with WBA at the same dose. These effects were seen after the first and second year of the study. The positive effect of WBA on plant yield may be the result of the high concentration of K, Mg, Ca, Na, Fe, and Zn in this material [15]. According to Romdhane et al. [10], the positive effect of WBA on the growth and development of corn is related to the reduction in transpiration and could therefore be one of the cost-effective options to counteract drought episodes in the cultivation of this crop. The currently presented research seems to confirm this thesis, indicating a reduction in the dry matter content in corn biomass after the use of WBA (Table 1).

In addition to affecting plant growth and yield, WBA can also alter the chlorophyll content in plants. The chlorophyll content is expressed as the leaf greenness. The SPAD index, measured at critical phases of corn growth, is often used as a predictor of the plant yield destined for silage production [24]. Moreover, this indicator is used to estimate N deficiency [22,23,51], nutrient demand, and the effect of fertilizer treatments on crop conditions [22]. In the present research, WBA had a negative effect on the value of the SPAD index (Figure 2), which additionally depended on the growth period of the plant, with the most intense effect observed in the BBCH 15 phase (Figure 2a). Similar results were also presented by Romdhane et al. [10], indicating a more significant effect of WBA on the reduction in the SPAD index in plant leaves in the later phase of growth. However,
in the study conducted by Ajala et al. [21], the addition of WBA to the soil resulted in a higher chlorophyll content in corn leaves. The increase in the greenness of corn leaves was also noted by Adekayode and Olojugba [17] after introducing a WBA mixture with mineral fertilizers into the soil. Ajala et al. [21] explain the increase in chlorophyll content under the influence of WBA on the higher rates of photosynthesis and in this way better potential to increase yield. The greenness of leaves is affected not only by the soil properties depending on the application of various materials or by the phase of plant growth shown in the presented research but also by the plant species, as shown in the research of Zolnowski et al. [25], which showed much higher values of the SPAD index in common sunflower (Helianthus annuus) and rapeseed (Brassica napus) than in corn. The leaf greenness index is influenced by the temperature and humidity conditions of the growing season. The SPAD values obtained during the later phases of vegetation are also correlated with the method of applying N fertilization [24]. The increase in the SPAD index in later phases is achieved as a result of the double application of N, before sowing and as top dressing in the BBCH 15/16 phase. Significantly, in our research, the lower SPAD value in the BBCH 19 phase may be the result of N deficiency, which was applied once before corn sowing. The observed decrease in the value of the greenness in the critical phases of corn growth, regardless of the WBA dose, may be an indication for additional top dressing of N fertilization.

WBA is a rich source of nutrients for plants, the content of which can be presented as follows: Ca > C > K > Mg > P > S > N. According to the literature data [52], 1 Mg of WBA introduces significant amounts of C (160 kg), N (6 kg), P (20 kg), K (98 kg), Ca (302 kg), Mg (39 kg), and S (18 kg) into the soil. The composition of WBA used in our studies was slightly different from that used in the cited works. WBA was characterized by higher TC content and significantly lower P, K, Ca, and Mg content. WBA used in the presented research had a higher TC content and significantly lower P, K, Ca, and Mg contents. From 1 Mg of WBA used in our research, 208 kg of C, 4.29 kg of N, 6.36 kg of P, 17.18 kg of K, 43.97 kg of Ca, 6.20 kg of Mg, and 18 kg of Na per hectare can be introduced into the soil. These differences are probably due to the composition of the burned biomass, as pointed out by Zajac et al. [7] and Asare and Hejcm [12]. Despite these differences, in the presented studies, WBA application increased the content of macronutrients in the aboveground part of the corn plants, which was observed up to the fifth dose of WBA (T5) (Table 2). The exception was the P content, which was lower in the WBA-treated objects. In turn, Meller and Bilenda [19] observed higher values in the content of both divalent elements such as Ca and Mg and monovalent elements such as K and Na in the green matter of corn plants after the WBA treatments of 15–120 Mg ha$^{-1}$ of soil. In the study of Iderawumi [13], increasing doses of WBA (2, 4, 6, and 8 Mg ha$^{-1}$ soil) increased the content of K, Ca, and Mg in corn leaves. Iderawumi [13] explains the increased content of macronutrients in plants with the increased solubility of K and P resulting from the deacidifying effect of WBA. In turn, Szostek et al. [49], in addition to the increase in soil alkalinity, attribute the increased content of macronutrients in plants to the higher availability of soluble forms of these elements in the soil after application of WBA. These observations are also confirmed by Rolka et al. [11], who reported a significant increase in soil pH and in the content of available forms of macronutrients ($P_{av}$, $K_{av}$, and $Mg_{av}$) after WBA application to the soil.

WBA application also results in increased macronutrient uptake by plants. In the study performed by Johansen et al. [5], similar effects were received. The application of WBA at doses ranging from 1.1 to 33 Mg ha$^{-1}$ resulted in increased N uptake by wavy hair-grass plants. According to the authors, the higher N uptake is the result of the stimulating effect of WBA on the mineralization of organic nitrogen in the soil. According to Iderawumi [13], the positive effect of WBA in increasing the availability of macronutrients for plants may persist for several years after the use of WBA material. However, the effect of WBA on the plants’ chemistry may depend on the species, as shown by the research of Park et al. [9], in which there was no impact of WBA on the concentration of nutrients in the leaves and
stems of purple willow (Salix purpurea). Ozolinčius and Varnagirytė [53] also found no significant effect of WBA on the chemical composition of Scots pine (Pinus sylvestris).

The influence of WBA on the macronutrient content in corn is similar to the effect of hard coal ash studied by Antonkiewicz [54]. After applying hard coal ash in the dose range of 13.33 to 800 g pot\(^{-1}\), the author also observed an increase in the concentration of Mg, Ca, K, and Na, and a reduction in the content of P in corn plants. However, despite similar trends in changes in the contents of macronutrients, the work of Antonkiewicz [54] showed similar contents of K and Na but significantly higher contents of P, Mg, and Ca in corn plants compared with the corn plants in the studies presented here. These observed differences may be caused by a different composition and higher doses used in the cited studies [54] than in our own studies. The decrease in phosphorus content in both our own research and the literature data [54] was probably caused by chemical sorption of phosphates in the soil. This sorption involves the formation of insoluble magnesium and calcium phosphates [54].

The average uptake of macronutrients by corn decreased in the following order: K (1.653 g) > N (0.869 g) > Ca (0.290 g) > Mg (0.096 g) > P (0.032 g) > Na (0.030 g pot\(^{-1}\)) (Figure 4). A slightly different relationship was noted by Meller and Bilenda [19], who reported the highest uptake of K, P, Ca, and Mg and the lowest uptake of Na. These differences may be due to the field nature of their investigation [19]. In the present study, an increase in the uptake of K, Mg, and Ca and a decrease in the uptake of P by the biomass of corn plants were observed after the application of WBA. Antonkiewicz [54] also noted a systematic increase in Mg uptake and a parallel decrease in P uptake by the aboveground parts of maize. Meller and Bilenda [19] showed higher uptake of most macronutrients (P, K, Mg, Ca, and Na) by corn, which persisted up to a WBA dose of 60 kg ha\(^{-1}\) of soil. Comparable results were noted by Romdhane et al. [10]. The root system of maize plays a specific role in the uptake of macronutrients by this plant, which largely limits the translocation of Na, Mg, and Ca to the aboveground parts of the plant [54]. The decrease in P uptake shown in our research may be the result of a relatively low P content in the WBA used for research and/or probably the ongoing process of phosphorus retrogradation from the effect of the high concentration of Mg and Ca in the WBA. Due to the slow release of phosphorus, some researchers [54] suggest using higher doses of phosphorus on soils fertilized with ash.

In addition to the high content of macronutrients, WBA also contains xenobiotics, including toxic metals (Cd, Pb). According to Zając et al. [7], the high content of Pb, Ni, and Cr in WBA is mainly due to the longer period of wood growth, which results in a greater accumulation of metals. The investigated WBA was mainly high in Fe, Zn, and Mn. However, WBA introduction to the soil resulted in a reduction in the content of Zn, Cu, Cr, and Co and an increase in Pb, Cd, and Ni in the corn biomass (Table 3). In the study by Johansen et al. [5], after WBA application at doses ranging from 1.1 to 33 Mg ha\(^{-1}\), the Cd content in corn biomass increased significantly only at the highest dose (33 Mg ha\(^{-1}\)). On the other hand, in the study of Meller and Bilenda [19], the content of Mn, Zn, and Cu in the corn biomass was the highest at 120 Mg WBA ha\(^{-1}\) and Fe and Ni at 60 Mg WBA ha\(^{-1}\). The results available in the literature indicate that the increase in the content of trace elements depends on the species and organ of the plant [20,49,55] but also on the dose used [20]. According to some, a dose of WBA above 10 g kg\(^{-1}\) of soil may be harmful to plants.

However, it should be clearly emphasized that despite the increase in the content of some metals in corn biomass after the application of WBA, their content was much lower than the legal limits for animal feed according to Directive 2002/32/EC of the European Parliament and of the Council of 7 May 2002 on Undesirable Substances in Animal Feed [56].

According to some authors [12], the use of WBA in agricultural fields requires great caution due to the presence of potential xenobiotics, including heavy metals such as Zn and Pb. Special attention is paid to the risk of increasing heavy metal content in plants with long-term use of WBA [49]. Romdhane et al. [10] emphasize that it is important
to be particularly careful and not to fertilize the soil with ash from wood contaminated with metals. In addition to rigorous WBA chemical analysis, compliance with permissible limits in the soil is recommended \[12\]. The research carried out shows the potential possibilities of using WBA in nature, with particular caution and implementation of heavy metal content control. Due to the increase in Cd, Pb, and Ni content in corn biomass shown in the presented research, as well as the observed increase in these elements in the soil \[11\], it would be highly advisable to carry out continuous monitoring of WBA in terms of chemical composition. The frequency of testing should be determined separately for different bioheating installations, taking into account the variability of the sources of biomass burned. Monitoring should also include checking the heavy metal content of the harvested crops and checking the soil where WBA is to be applied.

The inconvenience of applying WBA to the soil seems to be the application itself due to the high dusting process of this material. Therefore, the use of WBA could be considered after changing its physical properties by curing, granulating, or pelletizing. Some researchers \[13\] recommend using WBA in combination with organic fertilizers, such as manure. Liquid digestate—a byproduct of agricultural biogas plants—seems to be suitable for this purpose. In addition to binding WBA, the digestate would be a source of easily available forms of nitrogen for plants.

Among the possibilities to give biomass ash the appropriate form, it seems interesting to subject WBA to the process of stabilization by carbonation. According to Cruz et al. \[57\], the application of raw WBA as a soil improver or fertilizer is limited. This is due to its high chemical reactivity and the presence of potential xenobiotics. According to the authors, these materials should be previously granulated and stabilized. These treatments are intended to reduce the harmfulness of WBA to human health and the environment, as well as to enhance the intended functions of biomass ash as a soil amendment. Attention should also be paid to another role that WBA may play in the soil environment, namely the role of a material immobilizing toxic substances. Considering the affinity of WBA for biochar, which, according to some authors \[58\], can immobilize chlorinated organic pollutants in the soil, WBA should also be considered for such applications.

These solutions could be a good way to rationally manage WBA, facilitating their storage, long-distance transport, and application at the destination. It should be noted that further studies under real field conditions with other soil types and plant species should be carried out before final recommendations for the application of WBA to soil are developed. Due to the relatively narrow range of results in the presented work and literature data \[58\], it is necessary to consider broadening the tests that will allow the identification of WBA not only in terms of fertilizing properties but also in terms of immobilization properties in relation to pollutants. In the case of long-term soil application of WBA, it is important not to cause excessive alkalinization and salinization of the soil environment, which may lead to increased accumulation of trace elements in plants \[49\].

5. Conclusions

WBA application had a positive effect on corn yield and height, with a significantly higher yield (from 7 to 10%) observed after the first four doses (T1–T4) and plant height after the third dose (T3). The application of WBA reduced the dry matter concentration of the harvested corn biomass, ranging from 0.47 to 1.37%. WBA also modified the leaf greenness index (SPAD), especially in the first period of plant growth (BBCH 15 phase).

The application of WBA also favorably affected the uptake and content of N, K, Mg, Ca, and Na in corn biomass, except for the P content, which decreased with increasing WBA dose. A significant increase in the content was observed for K, Mg, Ca, and Na, which were 54, 38, 43, and 19%, respectively. The highest average uptake of macronutrients by corn was recorded for K (1.653 g) and N (0.902 g) and the lowest for P (0.032 g) and Na (0.030 g kg\(^{-1}\) s.m.). An increase in the content of Pb, Cd, and Ni and a decrease in Zn, Cu, Cr, and Co in corn biomass were also observed with increasing WBA dose. WBA can be a good material for use in nature, but only if the levels of potentially toxic components are
under control. The reduction in the content of Zn, Cu, Cr, Co, and P in corn plants as a result of the use of WBA should be an incentive to control the content of macroelements and especially xenobiotic available forms in agricultural soils. The obtained results in terms of improving the yield and chemical composition of plants while maintaining legal limits for the content of heavy metals in plants indicate the possibility of using WBA in the environment.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17112783/s1, Table S1: Methods used for analysis; Table S2: Significant correlation coefficients between the contents of macronutrients in the aboveground part of corn; Table S3: Significant correlation coefficients between the contents of trace elements in the aboveground part of corn; Table S4: Significant correlation coefficients between the contents of trace elements and macronutrients in the aboveground part of corn.


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**Data Availability Statement:** Data are contained within the article.

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