Importance of Compost, Bentonite, and Calcium Oxide in Reducing Trace Element Content in Maize on Agricultural Soil Contaminated with Diesel Oil

Miroslaw Wyszkowski * and Natalia Kordala

Department of Agricultural and Environmental Chemistry, University of Warmia and Mazury in Olsztyn, Łódzki 4 Sq., 10-727 Olsztyn, Poland
* Correspondence: miroslaw.wyszkowski@uwm.edu.pl

Abstract: Soil contaminated with petroleum substances is classified as hazardous, i.e., particularly harmful to the proper functioning of environmental ecosystems. It is therefore necessary to take measures to restore the homeostasis and ecological potential of degraded areas. The study aim was to determine the impact of bentonite, compost, and calcium oxide (CaO) on trace element content in the maize grown on diesel oil (DO)-contaminated soil. Increasing doses of the petroleum substance increased the accumulation of chromium (Cr), lead (Pb), copper (Cu), nickel (Ni), manganese (Mn), cobalt (Co), and cadmium (Cd) in maize. The largest increases were found for Cu (by 76%), Co (by 73%), and Pb (by 42%). All soil amendments proved useful for in situ stabilization of anthropogenically transformed soils. Bentonite reduced Cr (by 94%), Cu (by 84%), and Mn content (by 53%), while compost reduced the contents of Cu (by 53%), Mn (by 44%), and iron (Fe—by 29%) in maize. CaO significantly reduced the levels of Cr (by 94%), Cu (by 84%), Ni (by 66%), Mn (by 32%), Co (by 72%), zinc (Zn—by 30%), and Cd (by 22%) in maize. The effects of compost and bentonite on maize chemical composition were smaller than that achieved with CaO, and the direction of changes in elements content depended on the DO dose and the element type.

Keywords: diesel oil (DO); compost; bentonite; CaO; trace elements; maize

1. Introduction

Rapid industrial development, urbanization, and population growth have increased the demand for arable land and food production [1], while contributing to environmental degradation and pollution [2]. Human industrial activities often involve high fuel consumption. Petroleum compounds are one of the most dangerous pollutants that can permeate the soil [3,4]. Soil contaminated with petroleum and its derivatives, including diesel oil (DO), is classified as a hazardous area [5], i.e., particularly harmful to the proper functioning of the ecosystem and biological life, including human health [6]. The most harmful of these pollutants are polycyclic aromatic hydrocarbons, which exhibit carcinogenic and mutagenic effects as well as cause various neurological problems in the kidneys and liver [7]. Diesel oil that has penetrated the soil modifies its physical and chemical properties, reducing its sorption capacity [8] and assimilability of potassium (K), magnesium (Mg), and phosphorus (P), while contributing to excess levels of carbon (C) [9,10]. In addition, it affects soil microbes by altering their quantitative and qualitative compositions and modifying the enzymatic activity of the soil [11]. The resulting disturbances in the biological homeostasis lead to water, nitrogen (N), P, and oxygen (O) deficiencies in the soil, which stay unavailable to plants [12]. The consequences of these unbenefficial changes include damage to the seed material and reduction of soil fertility, both leading to the ultimate deterioration of crop yield [13,14]. At the structural level, DO adversely affects the plant root system development [15], which may reduce water transport and transpiration [16]. In addition, it reduces the rate of photosynthesis [17], causes leaf necrosis and defoliation [18], and
also general plant growth disturbances [16]. It has been estimated that there are about 2.8 million identified sites in Europe that are potentially contaminated with petroleum substances [19]. Soil contamination with DO also increases its acidity [16] and trace element content [20], which under such conditions may become more available to plants and, by this means, accumulate in the food chain. According to Gospodarek et al. [10], the contents of cadmium (Cd), manganese (Mn), nickel (Ni), and lead (Pb) in the soil increased after its exposure to a DO. In addition to petroleum substances, heavy metals pose a majority threat to the environment. There are 600,000 ha of agricultural ecosystems in the USA, 400,000 ha in Germany, Spain, Denmark, and Finland, and 200,000 ha in Slovakia and Hungary, which all require remediation [21,22]. It is a result of heavy metal accumulation in soils.

Due to the environmental and health hazards posed by petroleum products, including DO, in the natural environment, it is necessary to undertake measures to restore the homeostasis and agricultural potential of degraded areas. There are many techniques used in the remediation of DO-contaminated soil that aim to remove or reduce the contents of petroleum. The most common of these include the following: physical (e.g., extraction, sonication, sorting, and rinsing) [23,24], thermal (e.g., thermal desorption, vitrification, and combustion) [25,26], chemical (e.g., stripping, dehalogenation, hydrolysis, oxidation–reduction, and stabilization) [27–29], and biological (e.g., bioremediation and phytoremediation) [30,31]. The main drawbacks of the physical and thermal methods include high costs, time consumption [32], and the generation of a significant amount of waste that requires proper disposal [33]. In addition, these processes radically interfere with soil properties and inhibit its bioactivity [34]. Although combustion and chemical oxidation can remove the majority (99.0% and 92.3%, respectively) of all petroleum-derived hydrocarbons, they both have certain drawbacks [33,35]. One of the most important is the formation of toxic compounds (including polychlorinated biphenyls (PCBs), furans, and dioxins) and volatile heavy metals as a result of incomplete combustion of crude oil [36]. Another negative effect is the reduction in C content (by 49–98%), organic matter [37], and the total count of soil microorganisms [33]. The biodegradation of hydrocarbons in the natural environment is a relatively slow process [38], mainly due to the hydrophobic properties and inadequate water solubility of petroleum-derived substances [39], and hence their limited bioavailability to microorganisms, which use hydrocarbons as a source of C and energy [40].

The phytoremediation technique also has a number of limitations and disadvantages. One of the most fundamental problems is the relatively long time of environment remediation [38,39] and the risk of contaminants being introduced into the food chain [41,42]. Their effectiveness is limited by the depth of plant root penetration and contaminant availability [43,44], whereas the plant species used may disturb the biodiversity of the remediated area [43]. Implementation of the phytoremediation techniques on soils contaminated with DO may be hampered by other serious obstacles, i.e., the increased phytotoxicity of the soils and the detrimental effects of DO on seed viability and germination rates of remediation plants [45,46]. As a result, practical application of this remediation method becomes very difficult [46].

In view of the above, in situ stabilization of soils contaminated with DO appears to be an interesting and promising alternative. It is based on minimizing the risk of contaminant migration by converting pollutants into less soluble, immobilized, and thus less toxic ones [47,48]. Pollutant mobility can usually be reduced using materials with a very high sorption capacity or through increasing the soil pH [49]. Considering the above, the in situ stabilization technique is an inexpensive, environmentally friendly, minimally invasive, and technologically simple method [50,51]. Its other advantages include the high immobilizing materials availability and long-lasting effect in the soil [52]. The in situ stabilization of soils contaminated with petroleum-derived products may be effective with various materials, including calcium compounds [8], clay materials [53,54], and organic ones (e.g., compost and sewage sludge) [29,55]. Organic or mineral soil amendments used to immobilize pollutants affect soil pH, its redox potential, and other soil properties, especially cation
exchange capacity (CEC) and organic matter content [47,48]. These changes, in turn, affect the trace element’s mobility and bioavailability [56]. The amount of trace elements taken up by plants is limited, as they either form insoluble complexes under alkaline conditions or are bound by organic matter, which effectively prevents their bioaccumulation in the food chain [57].

The use of bentonite, compost, and calcium oxide (CaO) (compared when applied under the same conditions) for stabilization in situ of DO-contaminated soil has not been extensively investigated so far. Therefore, an experiment was held to determine the impact of using the abovementioned amendments (compost, bentonite, and CaO) on trace element content in maize above-ground parts grown on soil contaminated with DO. Maize is a high biomass crop. It plays a diverse and dynamic role in agri-food systems.

2. Materials and Methods

2.1. Experimental Methodology

The experiment was conducted on a soil with a textural composition of light loamy sand in a vegetation hall [58]. Two factors were considered in the experiment. The first was contamination with DO, which was used in the following doses: 0, 2.5, 5, and 10 cm$^3$ kg$^{-1}$. Another experimental factor was the application of different materials to the soil, which included the following: compost, bentonite, and CaO. The unamended series was used for comparison. Compost and bentonite were applied at doses of 3% and 2% of the soil weight in the pot—9 kg, respectively, and 50% CaO at a dose of 1.08 g kg$^{-1}$ of soil. Maize was selected for this study. Macronutrients and selected micronutrients (such as N, K, Mg, Mn, molybdenum—Mo, and boron—B) were added in equal amounts to all pots. The soil was added in plastic pots and then maize was sown with 8 seeds per pot. Basic soil properties and trace element contents in amendments and soil were presented in our previous paper [59]. Plants were irrigated with distilled water. The experiment was conducted in 4 replicates. Maize was cut at the panicle shooting phase (BBCH 59). The results of the analyses of the effect of the same materials on trace element content in DO-contaminated soil were included in our previous paper [60].

2.2. Methodology of Laboratory Analyses and Statistical Calculations

Plant samples were crushed and dried to a constant weight at 60 °C in a drying and heating chamber Binder FED720 model (Binder GmbH, Tuttlingen, Germany). They were then ground into flour in preparation for the determination of trace elements. The plant material was digested in 65% nitric acid using the US-EPA3051 microwave method [61]. Trace elements were determined using the classical and widely used atomic absorption spectrometry (ASA) method [62]. The NCS ZC 73030 CRM and Fluka reference materials were used to achieve the highest possible precision in the laboratory analyses.

Statistica 13 software [63] was used to statistically verify the results of this study. Calculations were performed using several statistical methods (** $p \leq 0.01$ and * $p \leq 0.05$), such as the simple coefficient of correlation, analysis of variance (ANOVA) with Tukey’s HSD test, and principal component analysis (PCA).

3. Results

DO soil contamination and soil amendments application (bentonite, compost, and CaO) caused significant differences in the chemical composition of maize (Tables 1–3), with the final impact depending on the contamination dose, the soil amendment type, and the trace element analyzed.
Table 1. Effect of different materials on Cd, Pb, and Cr content in maize on DO-contaminated soil (mg kg\textsuperscript{-1} d.m.).

<table>
<thead>
<tr>
<th>Amendment</th>
<th>DO Dose (cm\textsuperscript{3} kg\textsuperscript{-1} d.m. of Soil)</th>
<th>Average</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td>Without amendments</td>
<td>0.181 \textsuperscript{a}</td>
<td>0.202 \textsuperscript{b,d}</td>
<td>0.208 \textsuperscript{d}</td>
</tr>
<tr>
<td>Compost</td>
<td>0.186 \textsuperscript{bc}</td>
<td>0.207 \textsuperscript{d}</td>
<td>0.200 \textsuperscript{cd}</td>
</tr>
<tr>
<td>Bentonite</td>
<td>0.192 \textsuperscript{b-d}</td>
<td>0.198 \textsuperscript{b-d}</td>
<td>0.201 \textsuperscript{cd}</td>
</tr>
<tr>
<td>CaO</td>
<td>0.194 \textsuperscript{b-d}</td>
<td>0.161 \textsuperscript{a}</td>
<td>0.163 \textsuperscript{a}</td>
</tr>
<tr>
<td>Average</td>
<td>0.188 \textsuperscript{A}</td>
<td>0.192 \textsuperscript{A}</td>
<td>0.193 \textsuperscript{A}</td>
</tr>
<tr>
<td>Bentonite</td>
<td>5.193 \textsuperscript{c}</td>
<td>0.599 \textsuperscript{c-e}</td>
<td>0.620 \textsuperscript{d-e}</td>
</tr>
<tr>
<td>CaO</td>
<td>0.369 \textsuperscript{a}</td>
<td>0.598 \textsuperscript{c-e}</td>
<td>0.504 \textsuperscript{b-c}</td>
</tr>
<tr>
<td>Average</td>
<td>0.440 \textsuperscript{B}</td>
<td>0.558 \textsuperscript{A}</td>
<td>0.539 \textsuperscript{A}</td>
</tr>
</tbody>
</table>

Table 2. Effect of different materials on Ni, Zn, and Cu content in maize on DO-contaminated soil (mg kg\textsuperscript{-1} d.m.).

<table>
<thead>
<tr>
<th>Amendment</th>
<th>DO Dose (cm\textsuperscript{3} kg\textsuperscript{-1} d.m. of Soil)</th>
<th>Average</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td>Without amendments</td>
<td>1.176 \textsuperscript{a}</td>
<td>8.133 \textsuperscript{e}</td>
<td>8.233 \textsuperscript{e}</td>
</tr>
<tr>
<td>Compost</td>
<td>2.940 \textsuperscript{b}</td>
<td>7.499 \textsuperscript{e}</td>
<td>7.933 \textsuperscript{e}</td>
</tr>
<tr>
<td>Bentonite</td>
<td>5.193 \textsuperscript{c}</td>
<td>6.399 \textsuperscript{d}</td>
<td>7.466 \textsuperscript{e}</td>
</tr>
<tr>
<td>CaO</td>
<td>6.337 \textsuperscript{d}</td>
<td>2.300 \textsuperscript{b}</td>
<td>1.133 \textsuperscript{a}</td>
</tr>
<tr>
<td>Average</td>
<td>3.912 \textsuperscript{B}</td>
<td>6.083 \textsuperscript{A}</td>
<td>6.191 \textsuperscript{A}</td>
</tr>
<tr>
<td>Bentonite</td>
<td>6.859 \textsuperscript{e}</td>
<td>2.666 \textsuperscript{a-d}</td>
<td>2.000 \textsuperscript{a-e}</td>
</tr>
<tr>
<td>CaO</td>
<td>4.376 \textsuperscript{c-e}</td>
<td>4.333 \textsuperscript{b-e}</td>
<td>4.000 \textsuperscript{b-d}</td>
</tr>
<tr>
<td>Average</td>
<td>3.552 \textsuperscript{A}</td>
<td>3.083 \textsuperscript{A}</td>
<td>6.333 \textsuperscript{B}</td>
</tr>
</tbody>
</table>

\*\* \(p \leq 0.01\) and * \(p \leq 0.05\) for correlation coefficient (r). Different letters (capital letters—DO doses and amendments; small letters—interaction between the DO and amendments) indicate significant differences for \(p \leq 0.01\).
In the series without amendments, the above-ground parts of maize responded to an increase in the dose of DO to 10 cm$^3$ kg$^{-1}$ d.m. with an increased accumulation of all trace elements, with the exception of Cd, zinc (Zn), and iron (Fe). This dose of DO caused the greatest changes in the accumulation of copper (Cu), chromium (Cr), and Ni as their levels in maize increased 18-fold, 7-fold, and 2-fold, respectively, compared to the control (uncontaminated) series. The DO dose of 10 cm$^3$ kg$^{-1}$ was also more effective than that achieved with CaO (Tables 1–3). The addition of the object with the highest DO dose reduced the contents of Cu (by 75%), Mn (by 76%), cobalt (Co) (by 73%), and Pb (by 42%) in maize. However, in the case of Zn and Fe, the impact of DO soil contamination was not statistically significant. In contrast, no significant effects were observed for Pb and Cd, Fe, and Zn in plants increased (by 12%, 22%, and 38%, respectively), unlike in the pots with the highest level of contamination (10 cm$^3$ kg$^{-1}$).

The remediation of soil contaminated with DO using bentonite, compost, or CaO affected the chemical composition of maize in different ways (Tables 1–3). All amendments significantly reduced the mean contents of Cu and Mn in maize. Calcium oxide was the most effective soil additive that mitigated the adverse effects of DO soil contamination. In objects with a DO dose of 10 cm$^3$ kg$^{-1}$, bentonite application reduced the contents of Cr (by 94%), Cu (by 84%), Ni (by 66%), Mn (by 53%), Co (by 51%), Zn (by 30%), and Cd (by 22%), compared to the unamended series. In contrast, no significant effects were observed for Pb and Fe. Importantly, soil remediation with CaO restored trace element content in maize to maize grown on uncontaminated soil. The liming of uncontaminated soil helped to reduce the contents of Cu and Mn (by 76%), cobalt (Co) (by 73%), and Pb (by 42%) in maize. However, in the case of Zn and Fe, the impact of DO soil contamination was not statistically significant.

The impact of compost and bentonite on trace element content in maize, although positive (limiting), was weaker than that achieved with CaO (Tables 1–3). The addition of compost to the object with the highest DO dose reduced the contents of Cu (by 75%), Mn (by 44%), Fe (by 29%), Co (by 15%), Pb (by 16%), and Zn (by 10%) in maize compared to the series without its application. No statistically significant effects were observed for Pb and Fe. Importantly, soil remediation with CaO restored trace element content in maize to maize grown on uncontaminated soil, its amendment with compost did not cause a significant increase in most of the elements in maize, except for Cr.
the mean content of which in the above-ground biomass of maize increased 2.5 times in relation to the control series.

The amendment of soil contaminated with bentonite was the only one that increased the content of any of the elements in maize (Tables 1–3). The highest contamination dose promoted the accumulation of Fe (by 66%) in maize, in relation to the soil without its addition. Under the same conditions, a negative correlation was observed for Cu, Mn, Co, Zn, Ni, and Cr, as their contents in maize decreased by 71%, 41%, 39%, 17%, 11%, and 6%, respectively, compared to the control series. The addition of bentonite to the uncontaminated soil increased the contents of Cu, Cr, and Fe in maize, without significantly affecting the mean contents of other elements.

The cumulative effect of DO contamination and its amendment with compost, bentonite, and CaO on trace element content in maize is presented in Figure 1 as vector variables determined based on principal component analysis (PCA). PCA showed that the studied components’ contribution accounted for 72.60% of the total dataset’s correlation. The vectors characterizing the contents of Mn, and especially Cu, shortened in length compared with the others, indicating their lower contributions to the correlation of the dataset. In addition, PCA showed significant correlations between the trace element contents in maize. The contents of Cd and Cr were positively correlated with the accumulation of Ni; that of Pb with Fe; that of Cu with Mn and, to a lesser extent, that of Cd with Co and Mn. A negative correlation was observed between the contents of Pb and Zn and between the content of Fe and those of Zn, Cd, and Co. The distribution of PCA cases indicates that soil amendment generally reduced trace element content in maize (Figure 2). Calcium oxide had the greatest impact on maize chemical composition on DO-contaminated soil.

By determining the observed variability percentages (as \( \eta^2 \) coefficients), it was found that the trace element contents in maize were mainly dependent on the amendment type (Figure 3). Soil additives had a much stronger impact than DO on the contents of Fe (76.38%), Co (73.60%), Cd (60.14%), Mn (57.32%), Ni (49.90%), and Zn (48.32%), and to a lesser extent on the levels of Cr (37.82%) and Cu (29.67%) in maize. DO only had a significant impact on Pb content (52.85%) in maize. The interaction between the amendments and DO soil
pollution had a stronger impact on the contents of Cu (54.12%) and Cr (50.37%) in maize compared to their individual effects.

Figure 2. Effect of different materials on trace element content in maize on DO-contaminated soil (PCA method). Key: the dots (WMA—without material amendments; C—compost; B—bentonite; CaO—calcium oxide; and DO doses: 0 (control), 2.5, 5, and 10 cm$^3$ per kg of soil).

Figure 3. Relative factor contributions as a function of trace element content in maize.
4. Discussion

Soil contamination with increasing doses of DO in our study increased the contents of Cr, Mn, Pb, Ni, Cu, and Co in maize. The contents of Cd, Zn, and Fe only increased in response to the low and medium doses of DO (2.5 and 5 cm³ kg⁻¹, respectively). Our previous study found similar results [64], where a 20 cm³ kg⁻¹ dose of Eco-DO increased the levels of all analyzed elements in maize, except for Pb and Ni. Rusin et al. [65] reported a comparable impact of DO soil contamination (9 g kg⁻¹) on Cu and Pb accumulation in the aerial parts of wheat. In another experiment, the same authors [66] showed that *Vicia faba* L. leaves responded to soil exposure to a DO dose (6 g kg⁻¹) with increased accumulation of Pb, Ni, Cu, and Mn. At the same time, they decreased Cd content compared to the un-contaminated soil. Petroleum-derived products contamination not only modifies soil trace element content [26], but also in plants grown on it [67,68]. Adesina and Adelasoye [69] reported a positive correlation between petroleum soil contamination and trace element content in the biomass of maize. They showed that contents of all analyzed trace elements (Cd, Fe, Ni, Zn, Cu, and especially Pb and Cr) increased. The levels of Pb and Cr increased by six times and four times, respectively, which also partially agrees with what was found in our experiment.

Diesel oil is composed of a hydrocarbons mixture (alkanes and polycyclic aromatic hydrocarbons), sulfur compounds, N, O, and trace elements (Zn, Cu, Cr, Pb, and Cd) [70,71]. Thus, soil contamination with DO leads to increased contents of these components and, consequently, to the formation of soil being semi-contaminated with these trace elements [72]. Trace elements found in DO are derived from elements present in petroleum, which in turn are derived from bedrocks necessary for the formation or occurrence of hydrocarbons [73]. Another source of these elements may be drilling muds and barite, which are introduced into wells during the extraction process [74]. Ujowundu et al. [20] showed that soil contamination with DO resulted in the accumulation of Cd, Ni, Cu, Zn, Pb, and Cr in soil. Soil contamination with DO was also found to modify its physicochemical properties, including a decrease in pH [75]. Soil pH affects the solubility, bioavailability, and migration of trace elements [76]. A low pH increases the amount of trace element bioavailable forms [56], as does their translocation to plant tissues [77]. DO in soil also creates an anaerobic-reducing environment, which increases trace element mobility and availability for plants [78]. The above reasons may explain the increased contents of Cr, Cu, Pb, Mn, Ni, Co, and Cd in maize found in this study.

The basic role of immobilizing soil amendments is to modify the speciation of trace elements from initially highly bioavailable forms to more geochemically stable forms through combined mechanisms of adsorption, complexation, and precipitation [50]. Soil liming is commonly used to reduce soil acidity, thereby reducing trace element mobility and availability [50]. In this study, CaO application to soil contaminated with the highest DO dose reduced the contents of most of the elements in maize. The exceptions were Pb and Fe. The results obtained are partly similar to those of previous research [59], in which the CaO application to petrol-contaminated soil resulted in reduced levels of Mn (by 68%), Pb (by 19%), Zn (by 23%), and Fe (by 24%) in maize compared to the series without its application. Radziemska et al. [79] also reported reductions in the levels of Cu, Ni, and Zn in maize on soil contaminated with Cr after CaO application. In turn, Tlustoš et al. [80] observed that CaO (3.0 g kg⁻¹) and CaCO₃ (5.36 g kg⁻¹) addition increased soil pH from 5.7 (control) to 7.3 and reduced Cd (by 32–35%), Pb (57–61%), and Zn (by 64–68%) contents in spring wheat straw. Soil pH changes caused via lime addition may also induce trace element hydrolysis and/or co-precipitation with carbonates, reducing their bioavailable forms [50]. A significant reduction in Cd uptake (by 40–50% on average) by five analyzed vegetables (Brassica rapa, Lactuca sativa, Amaranthus tricolor, Brassica oleracea, and Amaranthus viridis) as a response to liming (3 g kg⁻¹) was also demonstrated by Tan et al. [81]. According to these authors, alkaline materials increase the stability of Cd in soil due to their neutralizing impact on soil pH and also increase the absorption competition between lime and Cd, thus limiting the trace element availability for plants. Lime increases trace element adsorption through deprotonating the soil particle surface [82].
In our study, compost and bentonite had a weaker impact on maize chemical composition on DO-contaminated soil than the liming process. Soil amendment with compost contributed to the reduced accumulation of Zn, Mn, Pb, Fe, Co, and Cu in maize. Karami et al. [83] reported partially similar results on the effects of compost and biochar (used individually and in combination as soil amendments) on, among other things, the contents of Cu and Pb in perennial ryegrass shoots cultivated on heavily polluted soil of the former mining area. Compost reduced the contents of Pb and Cu in ryegrass shoots and reduced their translocation from the soil to the plant. It also improved soil physicochemical properties more effectively than biochar (by increasing the contents of organic matter, N, and P and reducing soil acidity). Compost also contributed to the greatest reduction in Pb content in soil pore water (<5 mg dm\(^{-3}\)) compared to the control series (>80 mg dm\(^{-3}\)). Jakubus and Bakinowska [57] also demonstrated reduced Cu and Zn contents in plants on compost-amended soils (by 21–37% for oats and by 14–34% for camelina). The potential of compost in the remediation of contaminated soils has also been confirmed by Awasthi et al. [84]. The mechanism of trace element immobilization using compost involves the following processes: (1) adsorption—wherein compost acts as a biosorbent [85], and (2) complexation [86]—where compost rich in humic substances containing functional groups (including hydroxyl and carboxyl ones) interacts with trace elements ions [87], leading to stable complex formation [88]. In addition, amendment with compost affects soil physicochemical properties (increases organic matter level, pH, and redox potential) and increases the surface charge [89], which promotes the adsorption of trace elements on phosphates and carbonates [50]. Compost is a source of biosorptive/biomineralizing microorganisms [90]. The application of other organic materials, such as fermented horse manure, bamboo biochar, fly ash, and vermicompost, also has a positive effect on limiting trace element uptake by cereals [91,92]. The high trace element levels in soils, especially in pore water, have a very important role in excessive plant trace element uptake.

Bentonite application in the present investigation reduced the accumulation of Cu, Mn, Co, Zn, Cr, and Ni in maize, while Fe accumulation was enhanced. A reduction in the Mn content (by 68%) in maize biomass after bentonite application was also reported by Wyszkowski and Sivitskaya [93]. Bentonite and other clay materials have a highly negatively charged surface that adsorbs cations. The hydroxyl groups of sorption materials effectively reduce the availability of trace elements via adsorption or complexation [94]. These processes reduce trace element mobility and their leaching into the soil profile [82]. Similar correlations were observed in the research conducted by Klik et al. [95], where soil amendment with bentonite (3% \(\text{w/w}\)) reduced the levels of Zn (by 32%), Cu (by 24%), Cd (by 23%), and Ni (by 20%) in soil. The ability of bentonite for the immobilization of Cu, Zn, Cd, and Ni in heavy metal-contaminated soil was observed by Kumararaja et al. [96]. In turn, Zulkurnain Haider et al. [97] showed that soil amendment with bentonite resulted in a 39% reduction in Pb content in \textit{Pisum sativum} shoots. It also reduced the translocation and bioaccumulation rates of the analyzed element. The reduction in Zn content by 28% in maize grown on soil irrigated with sewage after bentonite application (90 t ha\(^{-1}\)) was demonstrated by Tito et al. [98]. Bentonite has been shown to improve soil fertility by increasing soil pH, Ca and K content, and detainment of P in fertilizer [99], while improving the water relations in sandy soils during periods of drought [100]. Czaban and Siebielec [101] showed that the bentonite application to acid sandy soil increased macronutrient availability for plants (up to 30%). Due to its properties, bentonite plays a dual role in the in situ stabilization process; in addition to immobilizing contaminants in the soil environment, it also supports the re-growth of depleted vegetation in degraded areas [102].

Based on the research results and the source literature, it can be concluded that the amendments used, and in particular CaO, are effective in reducing trace element levels in plants. The materials used in this study give good results when the soil was contaminated with low doses of diesel. It seems necessary to carry out further experiments on soils contaminated with higher levels of this (or other) petroleum substances.
5. Conclusions

Soil contamination with DO significantly modified the chemical composition of maize. Its doses, which were increased up to 10 cm$^3$ kg$^{-1}$ in the first series, contributed to an increased accumulation of most trace elements in corn. The exceptions were Cd, Zn, and Fe, whose contents increased, but only up to the medium DO dose (5 cm$^3$ kg$^{-1}$). The largest increases were observed for Cu, Cr, and Ni.

All soil additives used in this study proved to be useful for the in situ stabilization of anthropogenically transformed soils. Their application did not increase trace element accumulation in maize (with the exception of Fe in the series with bentonite), while significantly reducing the contents of most heavy metals, especially Cu and Mn. Soil remediation with CaO was the most effective, reducing the ecotoxic impact of DO to a greater extent than bentonite and compost. The introduction of CaO into the soil reduced the content of seven (Cr, Cu, Ni, Mn, Co, Zn, and Cd), than that of bentonite—six (Cr, Mn, Cu, Co, Ni, Zn), and that of compost—five (Mn, Cu, Co, Fe, Pb, Zn) of the analyzed trace elements in maize.

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