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Immobilization of Pb in Contaminated Soils with the Combination Use of Diammonium Phosphate with Organic and Inorganic Amendments

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Abstract: The intensive use of lead (Pb)-based insecticides (lead arsenate, $PbHAsO_4$) has led to Pb accumulation in agricultural soil, endangering human health through the possibility of transferring it to the food chain. The aim of this study was to evaluate the potential for the immobilization of Pb in the soil by applying organic (sludge, biocompost, yard compost, and peat) and inorganic (bonemeal, zeolite, lime, and wood ash) amendments, in combination with diammonium phosphate (DAP) in a greenhouse experiment. Two amendment rates were used: low and high, and three rates of DAP: 0 (zero), low (0.25 g of DAP/kg soil), and high (1.25 g DAP/kg soil). The results showed that the dry yield of carrot (*Daucus carota* susp. *sativus*) was the highest for the organic amendments in combination with the low rate of DAP. The high rate of inorganic amendments also increased the yield. Applications of inorganic bonemeal, inorganic lime, and inorganic wood ash yielded the lowest Pb tissue concentration (TC), and organic peat had the highest Pb TC. Inorganic bonemeal combined with DAP most effectively immobilized Pb in soil.

Keywords: heavy metals; metal toxicity; soil amendments; lead contamination; plant uptake; liming

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1. Introduction

Contamination of the environment with heavy metals has become one of the biggest health concerns all over the world due to their persistence in the environment and accumulation in the food chain posing significant threats to human health [1,2]. The major pathway of human exposure to heavy metals is soil to plant transfer where vegetables take up heavy metals by absorbing them from contaminated soils [3]. Heavy metal contamination of soil may occur due to anthropogenic activities through irrigation with contaminated water, the addition of fertilizers and metal-based pesticides, emissions from the metallurgical industry, transportation, and harvesting process [4,5]. Among the most common heavy metal contaminants, lead (Pb) has been reported as a major concern due to its high stability in soil, and accumulation in plants and animals, and it is considered the second most dangerous hazardous substance on the priority list of the U.S. Environmental Protection Agency [6]. It is estimated that approximately half of the human Pb intake is through food, with around half originating from plants [7]. The toxic level of Pb in plants inhibits germination, suppresses growth parameters, reduces the rate of photosynthesis, and alters the levels of photosynthetic pigments, transpiration, gaseous exchange in leaves, and total chlorophyll production [8,9]. It is well known that Pb is highly toxic for humans due to its interference with several biochemical processes, contributing to oxidative stress [10–12]. Because of its high toxicity, the concentrations of Pb in soil and vegetables are restricted by legislation.

The European Union has set standards for Pb at 0.1 mg kg^{-1} (f.w.) for fruits and roots and 0.3 mg kg^{-1} (f.w.) for leafy greens [13]. So far, there are no national health-based standards for Pb in vegetables, fruits, or other staple food crops in the United States [14], although FDA monitors and regulates Pb concentrations in foods and in consumer products.

Previous research has shown that the amount of phytoavailable heavy metal forms in soil and the level of their accumulation in plants depend on soil properties such as: pH, organic matter content, redox potential, cation exchange capacity, and soil texture [15], as well as plant species and root system, growth stage, type of metal, environmental conditions, and agricultural practices [16].

Among the remediation solutions for Pb-polluted soils to reduce the mobility and phytoavailability of this metal, the application of amendments has gained much attention in recent years as an environmentally friendly and low-cost agricultural management practice [17]. Codling [18] reported that the application of phosphorus (P) and iron (Fe) plus phosphorus as amendments on soils contaminated with Pb arsenate increased water extractable Pb concentration making it less accessible to plants. In another study, Ngole [19] found that Pb bioavailability for carrot plants in a sludge-amended soil decreased slightly with an increase in the sludge amendment rate. Recently, Guo et al. [20] reported that dolomite, slaked lime, and limestone applied as amendments to Pb-contaminated soil, significantly reduced Pb content in rice plants. In addition, amendments such as biochar, slag, and ferrous manganese can also successfully reduce the toxicity, leachability, and mobility of Pb in the environment [21].

Some agricultural soils in Nova Scotia, Canada, have high levels of Pb, due to the historic application of $PbHAsO_4$ insecticide in apple orchards several decades ago [22]. Pb arsenate was the most extensively used insecticide as a foliar spray to control codling moth in tree fruit orchards in countries throughout the world, including the USA, Canada, Australia, New Zealand, England, and France [23]. It remained the preferred insecticide for codling moth control because of its high efficacy and lower phytotoxicity and it was being applied in Nova Scotia as late as 1981 [24] until it was officially banned in 1988 [25].

Carrot is a major specialty cash crop in Nova Scotia. Previous studies have shown that carrots, just like other vegetables, take up Pb from contaminated soils by accumulating this metal in their tissues [26–28]. Chisolm [22] reported that Pb concentration in carrots grown in a lead arsenate-contaminated soil exceeded the Canadian tolerance of 2.0 ppm in fresh vegetables. The use of phosphate in Pb immobilization from water or soil is an accepted technique. Furthermore, amendments that contain P can transform the Pb fractions in soil, from highly available to bounded forms, such as pyromorphite Pb5(PO4)3X where X=F, Cl, Br, OH. These Pb compounds are stable under a wide range of pH and Eh. Numerous phosphate materials of natural or synthetic origin have been used to immobilize Pb: apatite and hydroxyapatite, rock phosphate, monoammonium phosphate, diammonium phosphate, biosolids, etc. [29].

The hypothesis in this study was that the application of different organic and inorganic amendments would bind Pb to soil and make it unavailable to plants cultivated under a lead arsenate-polluted soil from Canning, Nova Scotia.

Therefore, the objective of this study was to evaluate the potential for the immobilization of Pb in the soil by applying organic (sludge, biocompost, yard compost, and peat) and inorganic (bonemeal, zeolite, lime, and wood ash) amendments, in combination with diammonium phosphate (DAP) under greenhouse conditions. The Pb availability was assessed using carrot plants.

2. Materials and Methods

2.1. Greenhouse Experiment

The experiment was conducted in the Cox greenhouse of the Faculty of Agriculture of Dalhousie University (formerly Nova Scotia Agricultural College) under natural daylight with day temperatures of 22 to 25 °C and night temperatures of 18–19 °C. The soil used in this study was a sandy loam with 47% sand, 48.2% silt, and 4.8% clay, pH 6.2, and a cation exchange capacity of 17.9. The total Pb concentration of the soil was 109 mg/kg. The soil was collected from the surface layer (0–20 cm) in Canning, NS, Canada, that has a lead arsenate, $PbHAsO_4$ application history.

Plastic pots (20-cm diameter and 15-cm high, Classic 600; Nursery Supplies, Inc., Fairless Hills, PA, USA) were filled with 2 kg of air-dried soil each.

Certified seeds of carrots (*Daucus carota* L. Red Core Chantenay) were direct-seeded into the pots. After 10 days, seedlings were thinned to 6 per pot.

2.2. Experimental Design

A factorial experimental design with 3 replications was used in this experiment. Plants were fertilized with potassium (K) as potassium chloride (2 g/kg) and nitrogen (N) as ammonium nitrate (1.25 g/kg) through incorporation in the soil.

Treatments were represented by 3 application rates of diammonium phosphate (DAP): 0 (zero); low (0.25 g/kg), and high (1.25 g/kg), calculated to represent zero, low and high fertilizer application rates under field conditions; and soil amendments (organic and inorganic), also added at zero, low and high application rates (Table 1). The zero rates of application represents untreated pots in which no treatments (neither amendments nor fertilizers) were added.

Table 1. The application rates of soil amendments to immobilize Pb.

Inorganic	Low *	High *	Organic	Low *	High *
Bonemeal	10	100	Sludge	26	130
Zeolite	10	100	Biocompost	29	116
Lime	5	10	Yard Compost	29	116
Wood Ash	10	20	Peat	3	6

* dry weight basis in t ha^{-1} except the peat was added in units of cubic feet per 4 m^2.

The sludge and biocompost were obtained from Fundy Compost (http://www.fundycompost.com/index.php accessed on 10 June 2021) in Nova Scotia. The sludge originated from the city of Halifax, NS, Canada. The low rate of sludge was selected based on crop N requirements (130 kg ha^{-1}), and assuming a 25% availability of N in composts. The high rate was set at four times the amount of N required.

The yard compost was supplied by Peter Peill of Minas Seed Ltd. (Canning, NS, Canada). The low rate for each of the composts was decided based on crop N requirements (130 kg ha^{-1}), and assuming a 15% availability of N in composts. The high rate was set at four times the amount of N required.

Sphagnum peat moss (ASB Greenworld) was applied to the soil on a 50% (low) and 100% (high) v/v basis. The calculated volume of soil assumes an incorporating depth of 0.3 m over the plot area.

The bonemeal and zeolite were purchased from Digby O & E farms Ltd. (Drayton, ON, Canada). The rates of bonemeal and zeolite were applied to add 0.5% w/w and 5% w/w, according to the recommendations.

The lime (Easy Spread dolomitic limestone) was supplied by Mosher Limestone Co., Ltd. (Upper Musquodoboit, NS, Canada). The rates of lime were applied to change the soil pH from 6.2 to 6.5 (low) and to 7.0 (high) based on the calculation in [30].

The wood ash was supplied by the Faculty of Agriculture power plant facilities. Since the effectiveness of wood ash in changing the soil pH was assumed to be half of that of lime, the low and high rates of wood ash were doubled that of the lime rates.

The elemental compositions of the immobilization amendments were determined as described previously [31,32] (Tables 2 and 3).

Table 2. Mean elemental (mg kg^{-1}) composition of applied immobilization amendments.

Organic	P	Ca	Mg	Na	K	Mn	Fe	S
Sludge	7533	8823	1601	407	978	270	4310	6355
Sludge Compost	3336	3560	893	180	1102	434	3356	2857
Yard Compost	3624	7168	2514	440	3344	239	2784	4222
Peat	115	2048	1039	451	51	10	1201	2898
Inorganic								
Zeolite	424	16,680	6042	3553	1991	178	16,957	174
Bonemeal	42,740	88,444	1597	2217	185	nd *	41	1756
Wood Ash	3918	73,544	8592	744	6983	10,577	2032	453

* nd represents no concentrations detected.

Table 3. Mean elemental (mg kg^{-1}) composition of applied immobilization amendments.

Organic	Pb	Cu	Zn	Cd	Cr	Ni	B
Sludge	18.25	431	328	0.45	8.77	5.42	4.09
Sludge Compost	7.78	103	90	nd *	3.67	4.51	4.89
Yard Compost	14.55	26	90	nd	0.61	3.03	9.67
Peat	1.66	2	7	nd	nd	1.26	5.86
Inorganic							
Zeolite	8.10	48	34	0.18	5.90	10.12	150
Bonemeal	1.42	2	49	nd	nd	0.61	0.61
Wood Ash	7.33	35	166	1.36	3.36	6.20	57.5

* nd represents no concentrations detected.

2.3. Determination of Pb in Plant Samples

The plants were harvested 78 days after establishment, when carrots reached a marketable stage. The carrots were washed thoroughly to remove all soil particles, dried in a drying oven at 70 °C for 72 h, until a constant weight, and the dry weight was recorded. The concentration of Pb in tissue and soil samples was determined as described previously [31,32]. Briefly, heavy metal concentrations in tissue, soil amendments, and soil samples were determined by an inductively coupled argon plasma spectrometer (ICAP) model 61 (Thermo Jarrell Ash, Franklin, MA, USA) following nitric acid digestion as described previously [31,32]. Because of the expected relatively low concentrations of heavy metals in tissue, soil, and soil amendment samples, larger samples of 4 g were digested for 8 h in 250-mL digestion tubes. The available Pb concentration in soil was determined using extraction with 1 M $Mg(NO_3)_2$ to extract the exchangeable (bioavailable) Pb fraction [31,32].

2.4. Determination of Plant Nutrients in Soil Samples

The concentration of plant-available nutrients in soil samples was determined on ICAP by the Nova Scotia Soil Testing Laboratory following the Mehlich 3 extraction, which is a standard procedure in Atlantic Canada.

2.5. Statistical Analysis

The main and interaction effects of Amendment (Bio-compost, Bone Meal, Lime, Peat, Sludge, Wood ash, Yard-compost and Zeolite), Application Rate (Zero, Low and High) and diammonium phosphate (DAP: No DAP [Zero DAP], Low DAP and High DAP) on carrot dry yield, and the concentrations of Pb and P in the tissue (Pb TC, P TC), Pb and P tissue uptake (Pb TU, P TU), and soil available Pb and P (Pb SA, P SA) were determined by conducting Analysis of Variance (ANOVA) of an 8 × 3 × 3 factorial design with 3 replications.

The validity of normal distribution and constant variance assumptions on the error terms were verified by examining the residuals as described in Montgomery [33,34]. Some of the response variables required square root transformation; however, the means shown in the tables are back-transformed to the original scale. Independence assumption on the error terms was ensured by the proper randomization performed during the experiment.

All analyses were completed using the Mixed Procedure of SAS 9.4 (SAS Institute Inc., Cary, NC, USA). For significant (p-value < 0.05) effects, multiple means comparisons were completed by comparing the least squares means of the corresponding treatment combinations. Letter groupings were generated using the Tukey-Kramer method at a 5% level of significance for the main and two-way interaction effects, but for the three-way interaction effect, a 1% level of significance was used to reduce the potential overinflation of Type II experimentwise error rate due to the large number (72) of treatment combinations being compared. Figures 1–3 were produced using Minitab 21 software (State College, PA, USA).

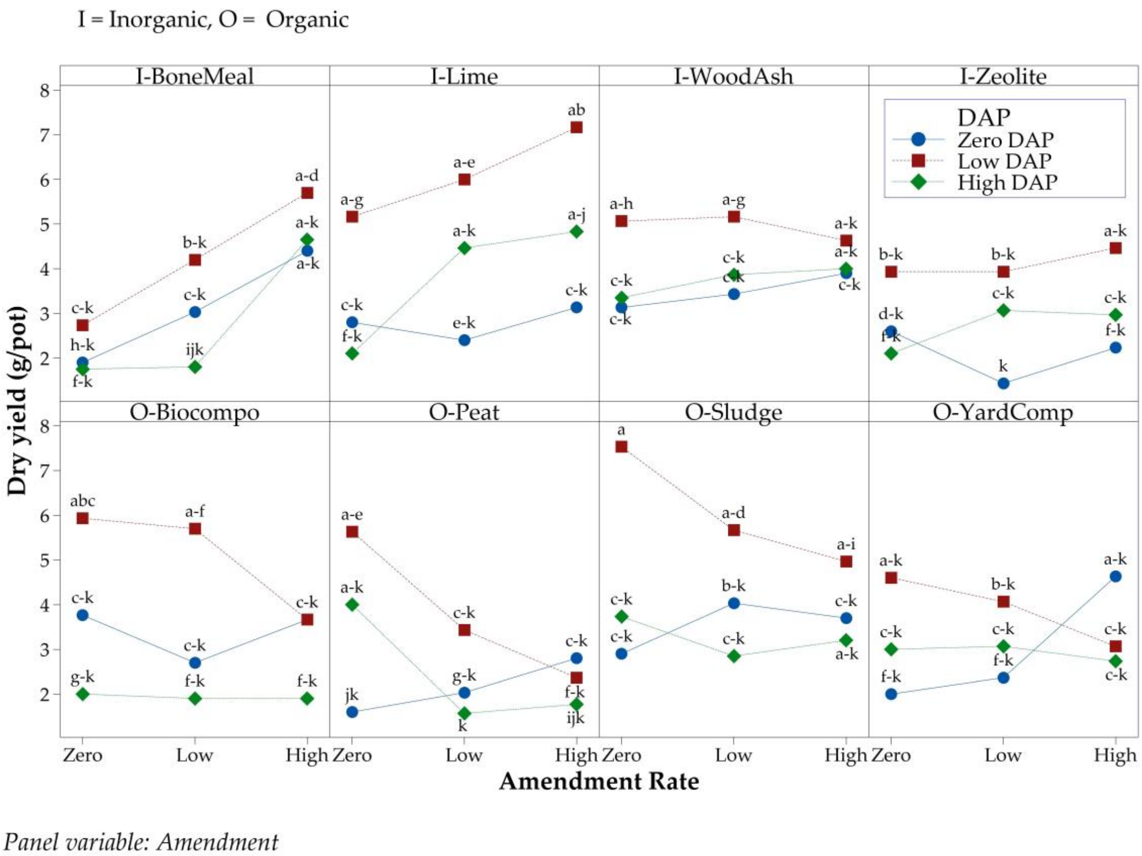

Figure 1. Amendment*Rate*DAP Interaction effect on carrot dry yield (g pot^{-1}). The amendments are grouped as Inorganic (I) and organic (O). Means sharing the same letter are not significantly different.

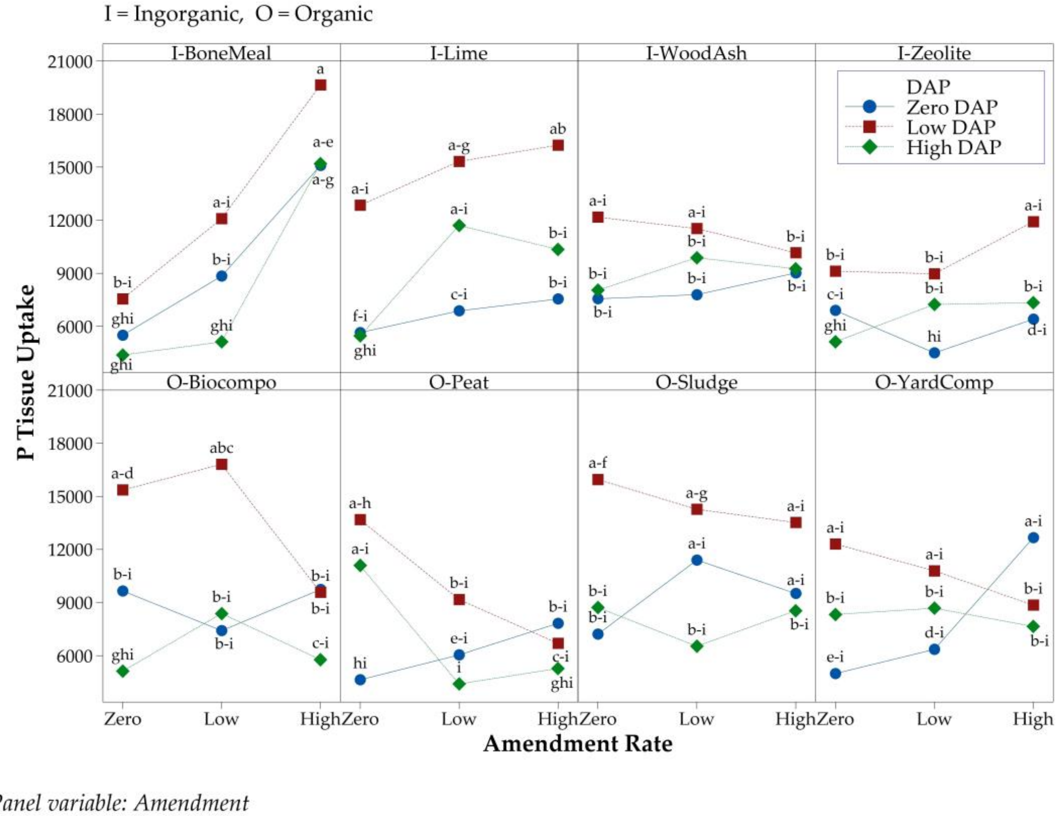

Figure 2. Amendment*Rate*DAP Interaction effect on P tissue uptake plot. The amendments are grouped as Inorganic (I) and organic (O). Means sharing the same letter are not significantly different.

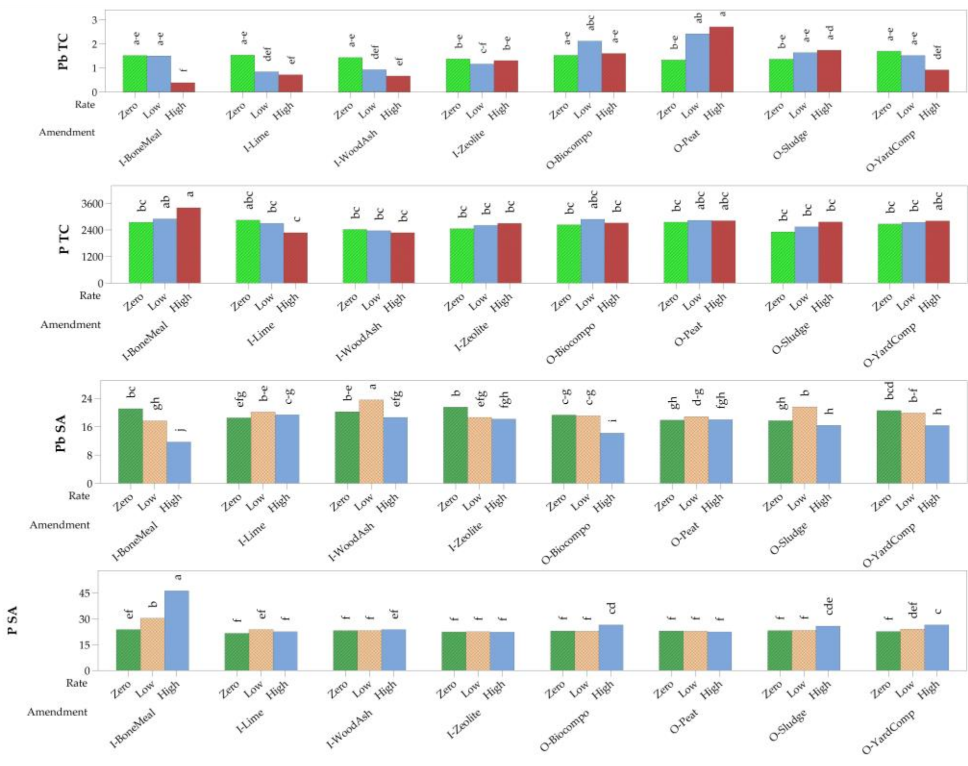

Figure 3. Amendment*Rate Interaction effect on Pb tissue concentration (TC), P TC, Pb soil available (Pb SA), and P SA. Within each response variable, means sharing the same letter are not significantly different.

3. Results

The ANOVA results indicated that there was a significant three-way (Amendment*Rate*DAP) interaction effect on carrot dry matter yield and P tissue uptake (P TU) (Table 4). The two-way interaction effect of Amendment and Rate was significant on Pb tissue concentration (Pb TC), P TC, Pb soil available (Pb SA), and P SA (Table 4). The Amendment by DAP interaction effect was significant only on Pb tissue uptake (Pb TU), but the Rate by DAP interaction effect was significant on Pb TC and Pb TU (Table 4). DAP had no interaction effect on P TC, Pb SA, or P SA, suggesting the differences among the three DAPs were consistent on these three response variables regardless of the amendment and rate.

Table 4. ANOVA *p*-values that show the significance of the main and interaction effects of Amendment (A), Application Rate (R), and Diammonium phosphate (DAP) on Dry yield (Yield), and tissue concentration (TC), tissue uptake (TU), and soil available (SA) Pb and P.

Source of Variation	Yield	Pb TC	P TC	Pb TU	P TU	Pb SA	P SA
A	0.001	0.001	0.001	0.001	0.001	0.001	0.001
R	0.043	0.003	0.131	0.068	0.002	0.001	0.001
A*R	0.001	**0.001**	**0.001**	0.141	0.001	**0.001**	**0.001**
DAP	0.001	0.471	**0.009**	0.001	0.001	**0.001**	**0.001**
A*DAP	0.001	0.066	0.081	**0.044**	0.009	0.550	0.537
R*DAP	0.001	**0.006**	0.541	**0.001**	0.011	0.851	0.908
A*R*DAP	**0.001** *	0.799	0.956	0.120	0.005	0.534	0.498

* Significant effects that require multiple means of comparison are shown in bold.

3.1. Dry Yield of Carrot Plants

Low DAP amendment rates gave the highest dry yield of carrot plants in all organic amendments (Figure 1). However, within the low DAP, the amendment rate played different roles among the organic and inorganic amendments. Carrot dry matter yield increased as the amendment rate of inorganic fertilizer increased, but decreased as the amendment rate of organic amendments increased. Among the inorganic fertilizers, increasing the amendment rate of bonemeal and lime showed a high increase in yield, and stayed about the same for wood ash and zeolite.

Although yield was lower when high DAP amendment rates were applied, the pattern in which the inorganic and organic amendments responded was similar to that of low DAP. With zero DAP, a high amendment rate of both inorganic and organic amendments boosted yield to some extent.

The release of nutrients from inorganic amendments is faster than that from organic amendments, leading to a faster growth rate. However, the highest carrot dry matter yield was obtained from the low DAP rate and no sludge, suggesting that all essential nutrients were available in this particular soil. The results from the three-way interaction effect on P tissue uptake (Figure 2) are consistent with those on carrot dry yield (Figure 1) except that the P tissue uptake from inorganic bonemeal was extreme.

3.2. Amendments' Effect on Pb Immobilization

A comparison of the treatment combinations of Amendment and Rate (interaction effect of Amendment and Rate) in terms of tissue concentration (TC) of Pb and P, and Pb and P soil available (SA) is shown in Figure 3.

When the amendment rate was zero, there was no significant difference in tissue concentration of Pb among the eight inorganic and organic amendments. However, when the rate was low the inorganic and organic amendments showed some differences, and when the rate was high, they showed significant differences, with inorganic bonemeal, inorganic lime, and inorganic wood ash having the lowest Pb TC, and organic peat having the highest Pb TC (Figure 3).

The amendment rate by DAP interaction effect on Pb TC showed that DAP had a more pronounced effect when there is no amendment, with high DAP and no amendment rate giving the highest Pb TC (Table 5).

Table 5. Mean Pb tissue concentration (Pb TC in mg kg^{-1}), and Pb tissue uptake (Pb TU mg kg^{-1}) obtained from the 9 combinations of Amendment Rate and DAP (Rate*DAP interaction effect) and Pb TU obtained from 24 combinations of Amendment and DAP (Amendment*DAP interaction effect).

Rate	DAP	Pb TC	Pb TU	Amendment	Pb TU from the 3 DAP Levels		
					No	Low	High
No	No	1.16 b *	2.66 d				
No	Low	1.43 ab	6.92 a	I-BoneMeal	3.13 cd	4.07 a–d	2.06 cd
No	High	1.85 a	4.80 abc	I-Lime	3.20 cd	3.73 bcd	2.82 cd
Low	No	1.66 ab	4.32 bcd	I-WoodAsh	3.62 bcd	4.06 a–d	3.99 a–d
Low	Low	1.35 ab	6.08 ab	I-Zeolite	1.79 d	5.70 abc	4.25 a–d
Low	High	1.41 ab	3.68 cd	O-Biocompo	5.52 abc	8.19 ab	3.81 a–d
High	No	1.27 ab	4.34 bcd	O-Peat	4.05 a–d	8.35 a	4.70 a–d
High	Low	1.12 b	4.54 bc	O-Sludge	5.83 abc	8.39 a	4.39 a–d
High	High	1.08 b	2.85 cd	O-YardComp	3.49 bcd	5.17 abc	4.30 a–d

* within each of Pb TC and Pb TU, means sharing the same lower case letter are not significantly different.

Having both amendment and DAP at high rates led to the lowest Pb TC. On the other hand, for Pb tissue uptake, low DAP was more favorable than high DAP when there was no amendment. The interaction between amendment and DAP revealed that organic amendment combined with low DAP maximized Pb TU, and the inorganic amendments gave consistently low Pb TU regardless of the DAP level used (Table 5).

In this study, a significant increase in Pb tissue uptake was found when the low rate of DAP was applied in combination with the organic amendments sludge, peat, and biocompost (8.39, 8.35, and 8.19 mg kg^{-1}, respectively) (Table 5). The lowest Pb uptake was obtained from zeolite amendment and without DAP application (1.79 mg kg^{-1}), while the high rate of DAP in combination with bonemeal and lime also significantly reduced Pb TU (2.06 mg kg^{-1} and 2.82 mg kg^{-1}).

Regardless of the amendment and its rate, zero DAP gave the highest P tissue concentration (2765 mg kg^{-1}) and soil available Pb, but high DAP gave the highest (26.61 mg kg^{-1}) soil available P (Table 6).

Table 6. Mean P tissue concentration (P TC in ug g^{-1}), soil available Pb (Pb SA), and soil available P (P SA) obtained from the three levels of DAP showing the main effect of DAP.

DAP	P TC	Pb SA	P SA
No	2765 a *	18.86 a	23.32 b
Low	2585 b	18.92 a	23.86 b
High	2659 ab	18.28 b	26.61 a

* Within each column, means sharing the same lower case letter are not significantly different.

4. Discussion

4.1. Dry Yield of Carrot Plants

Organic amendments, in addition to their essential nutrient content, and liming can improve soil structure, porosity, water retention capacity, pH, buffering capacity [34–36]. These characteristics improve the physiological state of the plant by increasing the chlorophyll content and photosynthesis and ultimately increasing biomass [37]. For instance, sludge was reported to increase the dry mass of basil due to a high content of OM and a whole array of micro and macronutrients [38,39].

The decrease of biomass in plants exposed to high Pb concentrations in soil could be due to the production of oxidative stress at the photosynthetic apparatus [40,41]. According to Zhou et al. [42], the photosynthetic-related parameters (net photosynthesis, stomatal conductance, transpiration rate) of *Ligustrum lucidum* decreased as a result of the deformation of the chloroplasts and separation of the thylakoid membrane from the cell wall.

4.2. Amendments' Effect on Pb Immobilization

Lead availability is highly dependent on soil physico-chemical characteristics (particle size, pH, cation exchange capacity) [40]. Although both organic and inorganic amendments led to a reduction in Pb mobility in the soil, except for peat (Figure 3), the mode of action is different.

Organic amendments increase soil OM, which determines the immobilization of metals in the soil by the formation of organo-mineral complexes that restrict Pb translocation in the plant [43]. The application of inorganic amendments causes an increase in soil pH that leads to the decrease of Pb mobility by the formation of hydroxides and carbonates precipitates, as was shown for lime, that increased the absorption of HM by varying the variable charge on soil and reducing the extractability [44]. Previously, it was proposed that Pb absorption in soil follows the Langmuir relation, increasing when pH rises from 3.0 to 8.5 [45]. Furthermore, in the case of soil with a pH of 5.5–7.5, Pb availability to plants is controlled by phosphate or carbonate precipitates [46].

On the other hand, the mean P TC obtained from all three rates and the eight amendments was pretty consistent, except for the high rate of inorganic bonemeal amendment, which gave the highest P TC (Figure 3). Inorganic bonemeal also showed the largest variation among the rates in terms of soil available Pb and soil available P, with the zero rate giving the highest and the high rate giving the lowest soil available Pb. Conversely, the zero rate of bonemeal gave the lowest and the high rate gave the highest soil available P (Figure 3). Bonemeal was most efficient at immobilizing Pb in soil and in reducing its transfer to the carrot plants, probably by forming P precipitates due to an increased P concentration (42,740 mg kg^{-1}) in its composition. Similarly, Cao et al. [47] found that phosphate application decreased Pb water solubility and its phytoavailability. Application of a high rate of DAP increased the P concentration in soil which further led to a reduction in the Pb availability in soil, probably by the formation of insoluble Pb phosphate precipitates [47].

The results of this study demonstrated the usefulness of inorganic and organic amendments in reducing the Pb availability for carrot plants through the mechanisms of changing pH and formation of insoluble precipitates. Similarly, it has been shown that the use of organic and inorganic amendments resulted in an immobilization of Pb and Cd in soil, reducing their bioavailability for wheat and maize crops [43]. Since these amendments contain essential nutrients for plants and have the capacity to improve the physical and chemical properties of the soil, a synergistic effect may be responsible for the reduced Pb tissue uptake. Therefore, future research is needed to elucidate the mechanism of action at the physiological level.

5. Conclusions

The use of organic and inorganic amendments may be a solution for the treatment of Pb-contaminated soils in Nova Scotia, and elsewhere. In this study, the use of organic and inorganic amendments in combination with phosphorus induced the immobilization of Pb in the soil and reduced its bioavailability for carrot plants. Amendment application was made based on the nutrient availability for plants as well as to increase the soil OM content and pH. The results revealed that bonemeal in combination with diammonium phosphate was most effective at immobilizing Pb. Furthermore, inorganic bonemeal, inorganic lime, and inorganic wood ash resulted in the lowest Pb tissue concentration, and organic peat resulted in the highest Pb tissue concentration. This study demonstrated the usefulness of applying organic and inorganic amendments to help tackle the Pb soil pollution in soils with a history of lead arsenate application. Future research is needed to verify the results under field conditions, and to elucidate the physiological mechanisms in carrot plants responsible for reducing the phytotoxic effects of Pb when organic and inorganic amendments are used.

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Abbreviations

Pb TC—Pb tissues concentration; Pb TU—Pb tissue uptake; Pb SA—soil available PB; P TC—P tissues concentration; P TU—P tissue uptake; P SA—available soil P.

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