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Determining the Cadmium Accumulation in Maize (*Zea mays* L.) and Soil Influenced by Phosphoric Fertilizers in Two Different Textured Soils

Muhammad Suleman [1,2], Muhammad Ashraf [1,3], Qurat-Ul-Ain Raza [3], Muhammad Amjad Bashir [4,*], Shafeeq Ur Rahman [5,6], Muhammad Aon [3], Saba Ali [4], Sher Muhammad Shahzad [1], Muhammad Usman Khalid [7], Hafiz Muhammad Ali Raza [3,4], Abdur Rehim [3,4] and Zhenjie Du [8,*]

1 Department of Soil & Environmental Sciences, University College of Agriculture, University of Sargodha, Sargodha 40100, Pakistan
2 Soil and Water Testing Laboratory, Marketing Division, PakArab Fertilizers Limited, Multan 60000, Pakistan
3 Department of Soil Science, FAS&T, Bahauddin Zakariya University, Multan 60800, Pakistan
4 College of Agriculture, Bahadur Sub-Campus Layyah, Bahauddin Zakariya University, Multan 60800, Pakistan
5 MOE Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China
6 School of Environment and Civil Engineering, Dongguan University of Technology, Dongguan 523015, China
7 In-Service Agricultural Training Institute, Rahimyar Khan 64200, Pakistan
8 Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences, Xinxiang 453000, China
* Correspondence: amjad.bashir@bzu.edu.pk or amjad.bashir941@gmail.com (M.A.B.); imdzj11@163.com or duzhenjie@caas.cn (Z.D.)

Citation: Suleman, M.; Ashraf, M.; Raza, Q.-U.-A.; Bashir, M.A.; Rahman, S.U.; Aon, M.; Ali, S.; Shahzad, S.M.; Khalid, M.U.; Raza, H.M.A.; et al. Determining the Cadmium Accumulation in Maize (*Zea mays* L.) and Soil Influenced by Phosphoric Fertilizers in Two Different Textured Soils. *Land* **2022**, *11*, 1313. https://doi.org/10.3390/land11081313

Academic Editors: Claude Hammecker and Richard Cruse

Received: 11 June 2022
Accepted: 12 August 2022
Published: 15 August 2022

Abstract: Non-nutritive metals, especially cadmium (Cd), are present in P fertilizers; the long-term application of these P fertilizers leads to Cd build-up in the soil. The current study aims to evaluate the impacts of P sources and rates on the growth of maize (*Zea mays* L.) and the bioavailability of Cd. Twelve treatments including rock phosphate 4 g kg^{-1} (RP1); 8 g kg^{-1} (RP2); 12 g kg^{-1} (RP3)); single super phosphate 333 mg kg^{-1} (SSP1); 444 mg kg^{-1} (SSP2); 555 mg kg^{-1} (SSP3); di-ammonium phosphate 130 mg kg^{-1} (DAP1); 174 mg kg^{-1} (DAP2); 218 mg kg^{-1} (DAP3); mono-ammonium phosphate 115 mg kg^{-1} (MAP1); 154 mg kg^{-1} (MAP2); 193 mg kg^{-1} (MAP3) in two soil textures (sandy and clayey) were assessed. Results revealed that all P sources significantly influenced the plant growth and yield characteristics of maize ($p \leq 0.05$). In both soil textures, P in soil and plant, plant growth and yield characteristics were maximized by MAP and DAP. Cadmium build-up in soil and uptake was also significantly ($p \leq 0.05$) affected by P sources, levels, and soil texture. It was observed that Cd build-up in soil and uptake by plants boosted with increasing P levels. Maximum Cd concentration in plant root and shoot was found with SSP3, and its concentration in soil increased with MAP3, whereas the concentration was higher in sandy texture. The study concludes that type of P fertilizer should be determined based on texture and human consumption of the crop to avoid Cd toxicity.

Keywords: phosphorus; cadmium; texture; maize; soil

1. Introduction

Maize (*Zea mays* L.), having good nutritious value and the highest yield potential among cereal crops, occupies an important position in the world food economy. Its grain contains about 72% starch, 10% protein, 5% vitamin A and B3, 5% oil, 3% sugar, 6% fiber and 1.8% ash. This has been estimated that there are approximately 361 calories of energy, 290 mg P, 140 mg vitamins, 74.4 g carbohydrate, 9.4 g protein, 1.8 g fiber, 4.3 g fat, 9 mg calcium, 10.6% water, 2.5 mg iron and 1.3 g ash in 100 g of fresh grains [1]. Ever-rising, maize is widely used for manufacturing corn oil, corn syrup, corn starch, corn flakes, dextrose, wax, cosmetics, alcohol and tanning material for the leather industry. This ranks as Pakistan's third important cereal crop grown after wheat and rice. The major part of maize yield is obtained as hybrid maize, which has offered significant yield increases to farmers over the past few years [2]. The share of maize in the country's GDP is 0.6%, whereas the share in agricultural value added is 3.4% during the 2020–2021 cropping season [3,4]. Thus, in Pakistan, there was about a 7.4% increase in maize production due to an increased cultivated area from 2020–2021 [5].

Thus, to meet the ever-rising demand for foodstuffs for the increasing population, the use of high-yielding crops is gradually amplifying. Generally, soil fertility level is decreasing due to intensified crop detachment of nutrients from the soil [6]. This fertility is unlikely to be replenished by natural processes or resources. Therefore, synthetic fertilizers are now extensively used to supplement crop nutrients. As 50% of overall nutrient resources are obtained through synthetic fertilizers, these fertilizers occupy a significant share of progressive farming [7]. Among all nutrients, P is of great importance for all living organisms due to its inherent role in the synthesis of RNA and the mechanism of energy transfer, as it is the main constituent of ATP [8]. Thus, this P is supplemented to plants by applying P fertilizers, an essential nutrient for optimal crop growth and production. Thus, natural or synthetic P sources are essential to obtain ideal crop yields in P-deficient soils. Generally, it is stated that the availability of supplemented P fertilizers to crops is minimal and that only about 10–15% of applied P is available to cultivated plants when contrasted with other nutrients [9]. The leftover is immobile in the soil by precipitation or adsorption (residual P); this fixed P may be made accessible to subsequent crops by dissolution and desorption processes [10].

Phosphorus is a key macronutrient that regulates average plant growth and development when supplied by the soil or by suitable amounts of fertilizers. For soils deficient in available P, the supplement must be supplemented in either natural or synthetic form to obtain ideal crop production [11]. Therefore, P fertilizers are crucial for sustainable productivity for the growing world population from 7.3 in 2015 to 9.7 billion in 2050 [12]. For this reason, synthetic P fertilizers could be farmers' real base of P. However, different P fertilizers contain varying amounts of heavy metals, and unnecessary utilization of P fertilizer may cause contamination of soil, water, and the environment. The perfect administration framework will utilize suitable sources, application rates, timing, and arrangement to reduce environmental impacts [13].

Cadmium (Cd) is one of the essential heavy metals released into the environment naturally or anthropogenically [14]. This is highly persistent and toxic and upsets industrial and agricultural activities by contaminating the soils, water, and food. Its long-duration endurance in soil and water results in higher accumulation and uptake into plants and the food chain [15]. This is generating severe global problems, threatening humans and animals for being part of the food chain. Living organisms, especially humans, are exposed to Cd through plants as one of the major vegetative food sources [16]. The abundance of Cd in the Earth's crust is about 0.1–0.2 ppm. Its abundance is mainly observed in phosphorites, marine phosphate, and sedimentary rocks [17].

In crop plants, the toxicity of Cd reduces the uptake and translocation of nutrients and water, increases oxidative damage, disrupts plant metabolism, and inhibits plant morphology and physiology [18]. Higher toxicity inhibits plant growth, tends to plant necrosis, inhibits the C-fixation, decreases chlorophyll content, and decreases photosynthetic activity [19]. In addition, it lowers the stomatal density, conductance, and CO_2 uptake, limiting photosynthesis [20]. Exposure of Cd in soil induces osmotic stress in plants by minimizing leaf relative water content and transpiration, resulting in physiological damage [21]. Moreover, its toxicity causes the overproduction of reactive oxygen species (ROS), damaging plant membranes and destroying cell biomolecules and organelles [22].

The Cd–P interaction induced a cascade of physiological and chemical changes in plants. An optimal P nutrition can attenuate Cd stress on the plant by the promotion of nitrogen (N) and potassium (K) uptake [23]. Data indicate that P fertilizers are the source of Cd as a contaminant; this varies from trace amounts to high levels [24]. Moreover, P fertilizers are often considered a vital source of Cd in crop plants. However, the increased plant Cd concentrations are not related to the Cd content in P fertilizers [25]. The need for the current study was generated to quantify the effects of these fertilizers on Cd accumulation and bioavailability in different textural classes. The objectives of the current study are to (i) examine the addition of Cd from P fertilizers, (ii) quantify the effects of P fertilizers on Cd accumulation in the agroecosystem, and (iii) differentiate the P fertilizers and Cd interaction in a different texture. We hypothesized that using a high dose of P fertilizers would improve maize yield and increase Cd accumulation.

2. Materials and Methods

A pot experiment was conducted at the experimental area of University College of Agriculture, University of Sargodha, aiming at the identification of contribution by P fertilizers in Cd build-up in soil and its effects on the growth and production of maize (*Zea mays* L.) crop in different textured soils from February 2016 to June 2016.

2.1. Location and Climate of the Experimental Site

Sargodha is located at 72.67° east longitude and 32.08° north latitude and 193 m altitude. It is situated in an arid climatic zone. The city has a climate of extreme heat in the summer between April and October (50 °C) and moderate cold in the winters from November to March (mini. temp. as low as 15 °C). The average yearly precipitation is highly seasonal, with about 400 mm in July and August.

2.2. Soil Preparation

The experiment was conducted on two different soil textures, clayey and sandy. The clayey soil (clay 55%, sand 23%, silt 22%) was collected from Khushab District at 0–15 cm depth, was air-dried, and used, whereas sandy soil was prepared using loam soil (25%) and pure sand (75%). The composed soil was passed through 2 mm sieve. Three pots for each treatment were aligned in a completely randomized block design (CRD) with the factorial arrangement and filled with respective soil. Before filling the pots, soil samples of prepared soil were taken for various physicochemical properties (Table 1).

Table 1. Physico-chemical properties of soils used in the experiment.

Soil Texture	pH	EC_e (µS cm^{-1})	Soil O.M (g kg^{-1})	Total N (mg kg^{-1})	Available P (mg kg^{-1})	Extractable K (mg kg^{-1})	Extractable Cd (mg kg^{-1})	SP (%)
Sandy	8.1 ± 0.51	1.12 ± 0.03	0.37 ± 0.04	1470 ± 1.2	3.00 ± 0.12	120 ± 1.4	0.28 ± 0.04	20 ± 1.8
Clayey	8.3 ± 0.34	1.51 ± 0.05	0.39 ± 0.02	1493 ± 1.4	4.52 ± 0.23	200 ± 1.6	0.89 ± 0.05	36 ± 1.6

Note: pH, soil pH; EC_e, electrical conductivity of soil extract; O.M, organic matter; total N, total nitrogen; available P, available phosphorus; extractable K, extractable potassium; SP, saturation percentage. All the values are given as mean ± standard deviation (n = 3).

2.3. Plant Growth and Treatments

For the pot experiment, maize hybrid seed of ICI Pakistan (Hi-Corn Plus 11) pretreated with chlorpyrifos was used. Maize seeds were sown in earthen pots filled with 10 kg of well-prepared soil. Initially, five seeds were planted in each pot. After seven days of germination, each pot was maintained with three healthy and uniform plants. The evacuated plants were encompassed in identical pots. The recommended doses of N as urea and K as potassium chloride (60 mg kg^{-1} soil and 167 mg kg^{-1} soil) were incorporated into the soil before filling the pots. Nitrogen was applied in 3 splits (at sowing, 40, and 70 days after sowing) while whole K was supplemented at the filling stage. The required level of P was applied in a single dose according to the treatment plan at the time of pot filling. Rock phosphate (RP) imported from Jordan was used in this study, whereas single super phosphate (SSP), di-ammonium phosphate (DAP), and mono-ammonium phosphate (MAP) were purchased from the local market. The experimental plan comprised twelve treatments including rock phosphate 4 g kg^{-1} (RP1); 8 g kg^{-1} (RP2); 12 g kg^{-1} (RP3); single super phosphate

333 mg kg^{-1} (SSP1); 444 mg kg^{-1} (SSP2); 555 mg kg^{-1} (SSP3); di-ammonium phosphate 130 mg kg^{-1} (DAP1); 174 mg kg^{-1} (DAP2); 218 mg kg^{-1} (DAP3); mono-ammonium phosphate 115 mg kg^{-1} (MAP1); 154 mg kg^{-1} (MAP2); 193 mg kg^{-1} (MAP3) with two soil textures (sandy and clayey) and three replications and performed under CRD. The applied concentration of each fertilizer was dependent on crop P_2O_5 requirements. The dose was further divided into three rates to understand Cd addition better. All agronomic practices were adopted uniformly to control insect pests and disease attacks during the growth period of the crop.

2.4. Chemical Analysis

At maturity, harvested plants were washed, separated into roots and shoots and weighed to obtain fresh weight, and dried in the oven at 72 °C for 48 h to obtain oven-dry weight. The samples (after oven drying) were finely ground in a grinder comprising stainless steel blades and a chamber (MF 10 IKA-WERKE, GMBH & Co., KG, Breisgau, Germany). A mixture of concentrated nitric acid and perchloric acid (2:1, *v/v*) at 250 °C was used to digest the 0.5 g portion of oven-dried samples of roots and shoots. The P concentration in root and shoot samples was estimated with a spectrophotometer (UV 1600 Shimadzu, Kyoto, Japan) according to [26], while Cd was determined by atomic absorption spectroscopy (AA 6300 Shimadzu, Kyoto, Japan) according to [27].

After harvesting, soil samples were collected from each pot and analyzed in triplicates to reduce standard error. Samples were air-dried, sieved, and stored. To determine available soil P, sodium bicarbonate was used for P extraction, and P concentration was estimated according to [28] using a spectrophotometer (UV 1600 Shimadzu, Kyoto, Japan), while Cd was extracted with DTPA and determined according to [29] by atomic absorption spectroscopy (AA 6300 Shimadzu, Kyoto, Japan).

2.5. Statistical Analysis

Statistical analysis was conducted using Statistics 8.1, and the experiment was planned and analyzed according to CRD with three replications. To compare the effects of treatments, data were subjected to analysis of variance (ANOVA) in a two-factorial design considering the applied dose and soil type. Differences between means were contrasted using the least significant difference test (LSD, $p \leq 0.05$). Microsoft Excel was used for data processing and visualization.

3. Results

3.1. Influence of Phosphorus on Plant Growth and Yield Characteristics

A significant ($p \leq 0.05$) effect of P was observed on plant growth and yield characteristics in terms of plant height, plant girth, fresh biomass, dry biomass, and grain yield of maize when grown under different sources and levels of P fertilization in different textured soils (Table 2). Maximum plant height was found in the case of MAP (86.5–116.83 cm), followed by DAP (105.83–114.08 cm), SSP (97.33–106.60 cm), and RP (68.08–84.50 cm) in sandy soil, while in clayey soil, maximum plant height was found in DAP (115–120.25 cm) followed by SSP (90.17–114.25 cm), MAP (112.17–113.42 cm) and RP (66.17–83.50 cm) in descending order. When comparing the different levels of applied fertilizers, it was found that plant height in both textures was linearly increased with increasing the level of applied fertilizer in the case of RP and SSP, while in the case of DAP and MAP, no consistent trend was found and P levels nonsignificantly influenced plant height. Similarly, maximum plant girth in sandy soil was found in DAP (17.24–18.20 mm), followed by MAP (16.5–18 mm) and SSP (15–16.5 mm), while in clayey soil, maximum plant girth was found in DAP (18–19.41 mm) followed by MAP (17.70–18.87 mm) and SSP (14.37–17.91 mm) in descending order. Minimum plant girth was found in RP in sandy soil (12.29–13.5 mm) and clayey soil (11.49–15 mm). When comparing the different levels of applied fertilizers, it was found that plant girth in both textures was linearly increased with increasing the level of applied fertilizer in the case of all fertilizers except for DAP, where plant girth was increased up to 174 mg kg^{-1} soil beyond which it was decreased shortly. Plant height and girth were higher in clayey soil in almost all P sources and P levels among both soil textures. This might be associated with the higher nutrient concentration in the clayey soils.

Maximum shoot fresh weight plant^{-1} was found in the case of MAP (155.07–159.88 g) followed by DAP (121.69–152.57 g) and SSP (84.75–127.02 g) in sandy soil, while in clayey soil, maximum shoot fresh weight plant^{-1} was found in the case of DAP (163.39–221.16 g) followed by MAP (181.09–209.10 g) and SSP (133.11–156.17 g). Minimum shoot fresh weight plant^{-1} was found in RP (37.27–57.65 g) in sandy soil and (68.56–128.90 g) in clayey soil. When comparing the different levels of applied fertilizers, it was found that shoot fresh weight plant^{-1} was linearly increased with increasing the level of applied fertilizer in the case of all fertilizers except for RP in clayey soil where shoot fresh weight plant^{-1} was increased up to 8 g kg^{-1} soil beyond which it was markedly decreased. Maximum root fresh weight plant^{-1} was found in the case of SSP (60.12–184.65 g), followed by DAP (98.99–135.10 g), MAP (56.77–73.22 g), and RP (19.99–39.35 g) in sandy soil, while in clayey soil, maximum root fresh weight plant^{-1} was found in the case of RP (24.62–164.15 g) followed by SSP (64.23–156.89 g), DAP (118.64–154.80 g) and MAP (61.96–98.76). When comparing the different levels of applied fertilizers, it was found that root fresh weight plant^{-1} was linearly increased with increasing the level of applied fertilizer in the case of RP and SSP fertilizers, while in the case of DAP and MAP fertilizers in both textures, root fresh weight plant^{-1} was increased up to 174 mg kg^{-1} soil beyond which it was markedly decreased. Among both soil textures, shoot fresh weight plant^{-1} and root fresh weight plant^{-1} was found to be higher in clayey soil in all P sources and P levels except for SSP, where root fresh weight plant^{-1} was found to be higher with SSP3.

Maximum shoot dry weight plant^{-1} was found in the case of MAP (41.37–46.29 g) followed by DAP (36.70–45.95 g) and SSP (34.43–40.90 g) in sandy soil, while in clayey soil, maximum shoot dry weight plant^{-1} was found in the case of MAP (52.51–61.23 g) followed by DAP (55.25–59.60 g) and SSP (41.25–52.35 g). Minimum shoot dry weight plant^{-1} was found in RP in sandy (18.11–23.50 g) and clayey (25.38–42.75) soil. When comparing the different levels of applied fertilizers, it was found that shoot dry weight plant^{-1} was linearly increased with increasing the level of applied fertilizer in the case of all fertilizers except for RP and SSP in clayey soil where shoot dry weight plant^{-1} was increased up to 8 g kg^{-1} soil and 444 mg kg^{-1} soil, respectively beyond which it was markedly decreased. Maximum root dry weight plant^{-1} was found in the case of SSP in sandy (16.05–55.81 g) and clay (20.01–44.35 g) soil, followed by DAP in sandy (24.15–35.04 g) and clayey (31.26–40.67 g) soil and MAP in sandy (15.18–19.63 g) and clay (16.14–24.76 g) soil, while minimum root dry weight plant^{-1} was found in RP in sandy (5.88–10.36 g) and clayey (6.25–28.73 g) soil. Moreover, root dry weight plant^{-1} was linearly increased with increasing the level of applied fertilizer in the case of RP and SSP fertilizers, while in the case of DAP and MAP fertilizers, root dry weight plant^{-1} was increased up to 174 mg kg^{-1}, and 154 mg kg^{-1} soil beyond which it was markedly decreased in both soil textures. Among both soil textures, shoot dry weight plant^{-1} and root dry weight plant^{-1} were found to be higher in clayey soil in all P sources and P levels except for SSP, where root dry weight plant^{-1} was found to be higher with SSP3 in sandy soil.

Maximum grain yield plant^{-1} was found in the case of MAP in sandy (8.42–14.90 g plant^{-1}) and clayey (22.80–29.45 g plant^{-1}) soil, followed by DAP in sandy (7.00–14.97 g plant^{-1}) and clayey (13.50–15.11 g plant^{-1}) in soil, and SSP in sandy (3.20–6.95 g plant^{-1}) and clayey (8.42–12.58 g plant^{-1}) soil, while minimum grain yield plant^{-1} was found in RP in sandy RP (1.76–6.00 g plant^{-1}) and clayey (5.01–9.66 g plant^{-1}) soil. When comparing the different levels of applied fertilizers, it was found that grain yield plant^{-1} was linearly increased with increasing the level of applied fertilizer in the case of all fertilizers except for DAP, where grain yield plant^{-1} was increased up to 174 mg kg^{-1} soil beyond which it was markedly decreased. In both soil textures, grain yield was higher in clayey soil in all P sources and P levels. This might be associated with the higher nutrients concentration in the clayey soils.

Table 2. Plant growth and yield characteristics of maize cultivar "Hi-Corn Plus 11" grown at different P sources and levels in different textured soils.

Treatment	Texture	Plant Height (cm)	Plant Girth (cm)	Shoot Fresh Biomass (g Plant^{-1})	Root Fresh Biomass (g Plant^{-1})	Shoot Dry Biomass (g Plant^{-1})	Root Dry Biomass (g Plant^{-1})	Grain Yield (g Plant^{-1})
RP1	Sandy	68.1 ± 1.5 e	12.2 ± 0.7 e	39.1 ± 1.2 d	19.9 ± 0.8 bc	18.0 ± 0.7 e	10.1 ± 0.1 bc	0.0 ± 0.0 c
	Clayey	66.2 ± 1.4 c	11.4 ± 0.5 d	45.7 ± 1.4 d	31.8 ± 1.1 ab	16.9 ± 0.6 c	14.7 ± 0.2 cd	3.2 ± 0.5 cd
RP2	Sandy	76.2 ± 1.2 de	12.7 ± 0.4 e	37.3 ± 1.1 d	5.8 ± 0.4 c	20.9 ± 0.8 de	3.9 ± 0.3 c	2.4 ± 0.4 c
	Clayey	68.2 ± 1.4 c	13.5 ± 0.6 d	116.6 ± 1.3 bcd	30.1 ± 1.2 ab	44.2 ± 0.9 ab	6.3 ± 0.5 d	1.7 ± 0.5 d
RP3	Sandy	77.5 ± 1.3 de	13.2 ± 0.5 e	57.7 ± 1.5 cd	9.2 ± 0.7 c	23.5 ± 0.4 cde	6.9 ± 0.4 c	2.0 ± 0.5 c
	Clayey	83.5 ± 1.1 bc	14.2 ± 0.6 cd	149.1 ± 1.1 abc	53.5 ± 0.8 ab	42.8 ± 0.5 ab	28.7 ± 0.5 a-d	2.0 ± 0.6 cd
SSP1	Sandy	97.3 ± 1.4 bc	15.2 ± 0.4 bcd	84.8 ± 1.2 bcd	21.4 ± 0.7 bc	34.4 ± 0.6 a-d	10.7 ± 0.2 bc	3.2 ± 0.5 c
	Clayey	90.2 ± 1.3 b	14.3 ± 0.6 bcd	88.7 ± 1.4 cd	30.2 ± 0.8 ab	27.5 ± 0.8 bc	13.3 ± 0.4 cd	7.1 ± 0.7 bcd
SSP2	Sandy	101.1 ± 1.2 abc	15.2 ± 0.5 cd	105.8 ± 1.6 abc	45.5 ± 1.1 abc	35.2 ± 0.6 a-d	24.8 ± 0.5 bc	2.3 ± 0.6 c
	Clayey	111.2 ± 1.5 a	18.9 ± 0.7 a	185.0 ± 1.3 ab	70.2 ± 1.3 ab	52.3 ± 0.4 a	44.4 ± 0.7 a	7.4 ± 0.8 bcd
SSP3	Sandy	101.2 ± 1.6 abc	16.3 ± 0.5 bcd	127.1 ± 1.2 ab	67.2 ± 1.4 a	40.9 ± 0.6 ab	55.8 ± 0.8 a	6.0 ± 0.6 bc
	Clayey	114.3 ± 1.4 a	17.2 ± 0.6 abc	156.2 ± 1.1 abc	56.9 ± 1.2 ab	50.6 ± 0.7 ab	36.8 ± 0.4 ab	8.4 ± 0.5 bcd
DAP1	Sandy	105.1 ± 1.3 ab	17.1 ± 0.4 abc	121.6 ± 1.2 ab	51.3 ± 1.1 ab	36.7 ± 0.4 abc	35.1 ± 0.3 ab	2.3 ± 0.3 c
	Clayey	115.2 ± 1.2 a	18.3 ± 0.7 ab	163.4 ± 1.3 abc	79.2 ± 1.4 a	55.2 ± 0.8 a	31.3 ± 0.3 a-d	8.8 ± 0.4 a-d
DAP2	Sandy	114.3 ± 1.5 a	18.2.2 ± 0.6 a	134.6 ± 1.6 ab	40.1 ± 1.3 abc	39.8 ± 0.4 ab	24.1 ± 0.4 bc	15.0 ± 0.7 ab
	Clayey	120.2 ± 1.3 a	19.4 ± 0.5 a	209.7 ± 1.4 a	75.0 ± 1.5 a	58.8 ± 0.7 a	40.7 ± 0.6 ab	7.1 ± 0.3 bcd
DAP3	Sandy	111.2 ± 1.3 ab	17.6 ± 0.5 ab	142.6 ± 1.5 a	13.6 ± 1.2 bc	45.9 ± 0.5 a	14.7 ± 0.2 bc	1.7 ± 0.1 c
	Clayey	114..1 ± 1.2 a	18.1 ± 0.6 a	192.6 ± 1.6 ab	58.1 ± 1.4 ab	59.6 ± 0.6 a	34.5 ± 0.4 abc	12.1 ± 0.5 a-d
MAP1	Sandy	116.3 ± 1.4 a	16.3 ± 0.7 a-d	155.1 ± 1.3 a	23.8 ± 0.8 bc	45.2 ± 0.4 a	19.6 ± 0.3 bc	17.4 ± 0.6 a
	Clayey	113.4 ± 1.1 a	17.7 ± 0.5 a	181.1 ± 1.2 ab	41.0 ± 0.9 ab	61.2 ± 0.6 a	24.8 ± 0.4 a-d	29.4 ± 0.6 a
MAP2	Sandy	86.5 ± 1.3 cd	15.5 ± 0.4 cd	99.9 ± 1.1 abc	9.4 ± 0.4 c	27.6 ± 0.5 b-e	10.1 ± 0.1 bc	0.72 ± 0.05 c
	Clayey	113.2 ± 1.2 a	18.4 ± 0.6 a	179.1 ± 1.3 ab	30.5 ± 0.9 ab	59.2 ± 0.7 a	20.4 ± 0.3 a-d	22.8 ± 0.9 abc
MAP3	Sandy	103.4 ± ab	17.2 ± abc	150.4 ± a	19.5 ± 0.8 bc	46.3 ± 0.5 a	17.2 ± 0.3 bc	2.8 ± 0.5 c
	Clayey	112.2 ± a	18.8 ± a	167.6 ± abc	15.9 ± 0.8 b	52.5 ± 0.6 a	16.1 ± 0.2 bcd	24.7 ± 0.8 ab

Note: All the values are given as mean ± standard deviation (n = 3), and the lowercase letters indicate the significant difference among the means.

3.2. Available Phosphorus in Soil and Maize

The concentration of P in soil, maize root and the shoot was significantly ($p \leq 0.05$) affected by P sources, P levels, and soil texture. Results presented in Figure 1 indicated that among different P sources, maximum soil P concentration was found in the case of SSP (3.83–4.17 mg kg^{-1}) followed by MAP (3.50–4.17 mg kg^{-1}), DAP (3.67–3.83 mg kg^{-1}) and RP (2.50–3.33 mg kg^{-1}) in sandy soil, whereas in clayey soil, highest soil P concentration was in the case of SSP (4.33–4.67 mg kg^{-1}) followed by DAP (4.17–4.67 mg kg^{-1}), MAP (3.50–4.50 mg kg^{-1}) and RP (2.83–3.50 mg kg^{-1}). When comparing the different levels of applied fertilizers, it was found that soil P concentration was linearly increased with increasing the level of applied fertilizer in the case of all fertilizers except for DAP2. Among both soil textures, soil P concentration was higher in clayey soil in all P sources and P levels. Clayey soils have a strong adsorption complex due to the presence of mineral clays compared to sandy soil, which provides an increased amount of plant available P.

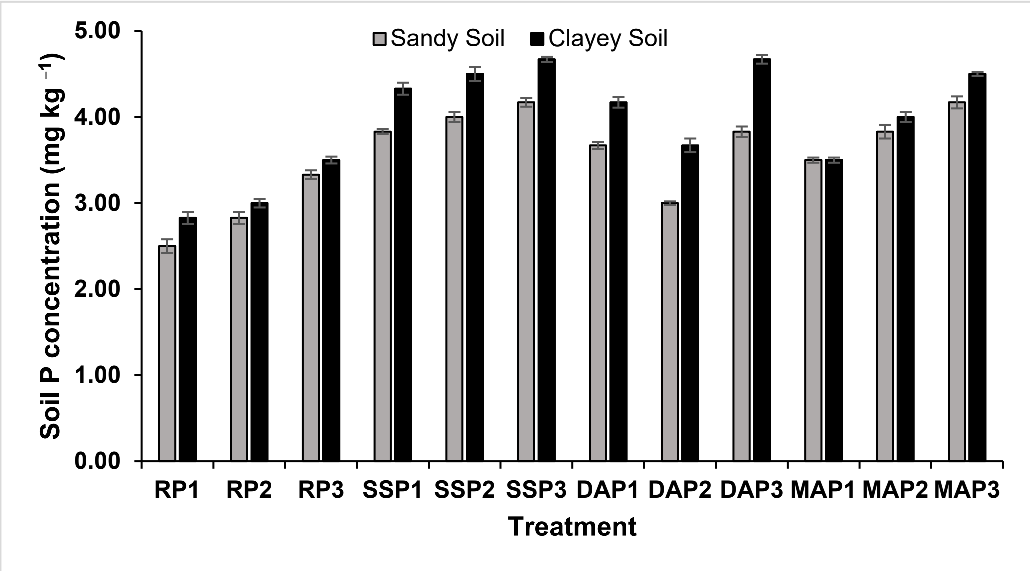

Figure 1. Soil P concentration of maize (*Zea mays* L.) grown at different P sources and levels in different textured soils. The treatments are: rock phosphate (4 g kg^{-1} (RP1); 8 g kg^{-1} (RP2); 12 g kg^{-1} (RP3)); single super phosphate (333 mg kg^{-1} (SSP1); 444 mg kg^{-1} (SSP2); 555 mg kg^{-1} (SSP3)); di-ammonium phosphate (130 mg kg^{-1} (DAP1); 174 mg kg^{-1} (DAP2); 218 mg kg^{-1} (DAP3)); mono-ammonium phosphate (115 mg kg^{-1} (MAP1); 154 mg kg^{-1} (MAP2); 193 mg kg^{-1} (MAP3)) in two soil textures (sandy and clayey).

Among different P sources, maximum root P concentration (Figure 2) was found in the case of MAP in sandy (0.35–1.24 g kg^{-1}) and clayey (0.56–1.01 g kg^{-1}) soil, followed by SSP in sandy (0.57–0.94 g kg^{-1}) and clayey (0.56–0.85 g kg^{-1}) soil and DAP in sandy (0.51–0.79 g kg^{-1}) and clayey (0.47–0.78 g kg^{-1}) soil, while minimum root P concentration was found in RP in sandy (0.51–0.78 g kg^{-1}) and clayey (0.71–0.75 g kg^{-1}) soil. When comparing the different levels of applied fertilizers, it was found that root P concentration was linearly increased with increasing the level of applied fertilizer in case all fertilizers. Among both soil textures, root P concentration was found to be higher in sandy soil in most of the treatments. Among different P sources, maximum shoot P concentration (Figure 3) was found in the case of MAP in sandy (274–298 g kg^{-1}) and clayey (193–270 g kg^{-1}) soil, followed by DAP in sandy (192–219 g kg^{-1}) and clayey (158–223 g kg^{-1}) soil and SSP in sandy (133–198 g kg^{-1}) and clayey (145–168 g kg^{-1}) while minimum shoot P concentration was found in RP sandy (85–113 g kg^{-1}) and clayey (74–109 g kg^{-1}) soil. When comparing the different levels of applied fertilizers, it was found that shoot P concentration was linearly increased with increasing the level of applied fertilizer in the case of all fertilizers.

Among both soil textures, shoot P concentration was found to be higher in sandy soil in most of the treatments.

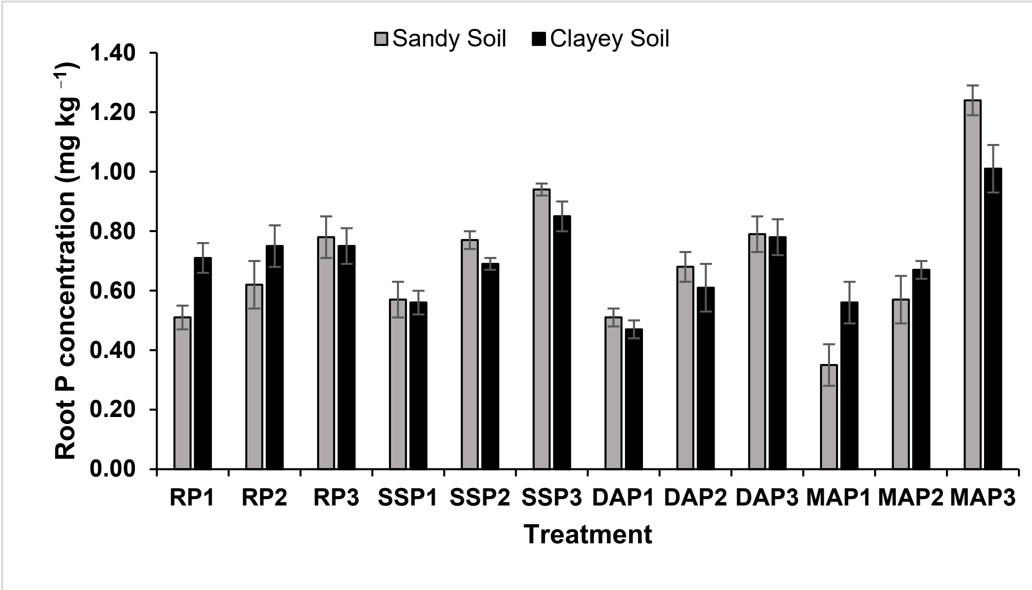

Figure 2. Root P concentration of maize (*Zea mays* L.) grown at different P sources and levels in different textured soils, whereas the treatments are: rock phosphate (4 g kg^{-1} (RP1); 8 g kg^{-1} (RP2); 12 g kg^{-1} (RP3)); single super phosphate (333 mg kg^{-1} (SSP1); 444 mg kg^{-1} (SSP2); 555 mg kg^{-1} (SSP3)); di-ammonium phosphate (130 mg kg^{-1} (DAP1); 174 mg kg^{-1} (DAP2); 218 mg kg^{-1} (DAP3)); mono-ammonium phosphate (115 mg kg^{-1} (MAP1); 154 mg kg^{-1} (MAP2); 193 mg kg^{-1} (MAP3)) in two soil textures (sandy and clayey).

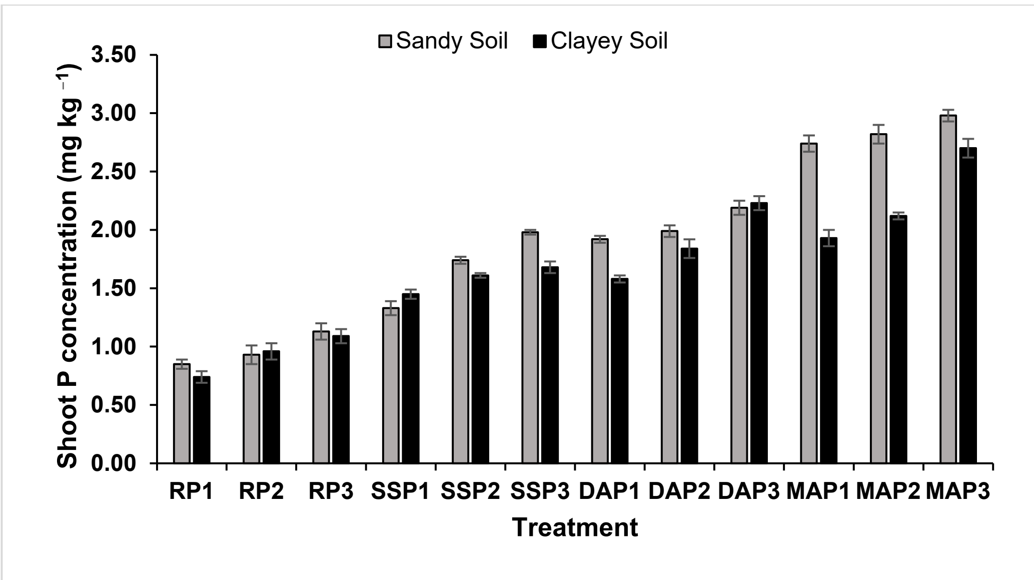

Figure 3. Shoot P concentration of maize (*Zea mays* L.) grown at different P sources and levels in different textured soils, whereas the treatments are: rock phosphate (4 g kg^{-1} (RP1); 8 g kg^{-1} (RP2); 12 g kg^{-1} (RP3)); single super phosphate (333 mg kg^{-1} (SSP1); 444 mg kg^{-1} (SSP2); 555 mg kg^{-1} (SSP3)); di-ammonium phosphate (130 mg kg^{-1} (DAP1); 174 mg kg^{-1} (DAP2); 218 mg kg^{-1} (DAP3)); mono-ammonium phosphate (115 mg kg^{-1} (MAP1); 154 mg kg^{-1} (MAP2); 193 mg kg^{-1} (MAP3)) in two soil textures (sandy and clayey).

3.3. Available Cadmium in Soil and Maize

Before the experiment, the intensity of bioavailable Cd was 0.28 mg and 0.89 mg kg^{-1} in sandy and clayey soil, respectively (Table 1). Following the growing cycle of maize, the Cd concentration increased in all treatments in both soil textures (Figure 4), ranging from in the case of MAP in sandy (67.83–74.67 mg kg^{-1}) and clayey (67–72.33 mg kg^{-1}) soil, followed by DAP in sandy (65–69.5 mg kg^{-1}) and clayey (64–68.5 mg kg^{-1}) soil and SSP in sandy (62–68 mg kg^{-1}) and clayey (59.83–64.17 mg kg^{-1}) soil, while minimum soil Cd concentration was observed in RP in sandy (55–61.5 mg kg^{-1}) and clayey (53–60.5 mg kg^{-1}) soil. When comparing the different levels of applied fertilizers, it was found that soil Cd concentration was linearly increased with increasing the level of applied fertilizer in the case of all fertilizers and all levels. Among both soil textures, soil Cd concentration was higher in sandy soil in all P sources and P levels. The evaluated increase in bioavailable Cd concentration in soil following maize harvest intimates the accumulation of Cd in soil by using P fertilizers.

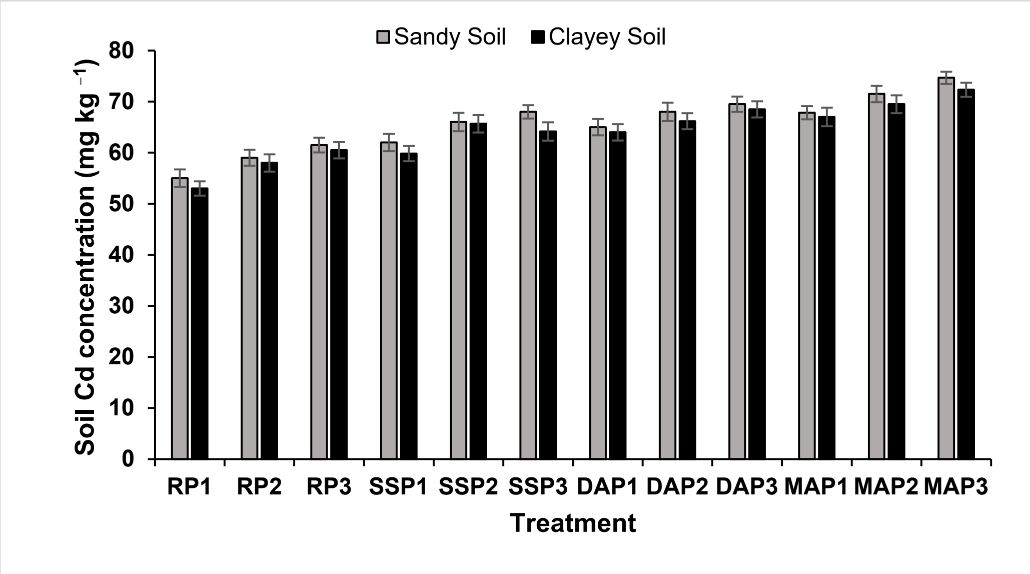

Figure 4. Soil Cd concentration of maize (*Zea mays* L.) grown at different P sources and levels in different textured soils, whereas the treatments are: rock phosphate (4 g kg^{-1} (RP1); 8 g kg^{-1} (RP2); 12 g kg^{-1} (RP3)); single super phosphate (333 mg kg^{-1} (SSP1); 444 mg kg^{-1} (SSP2); 555 mg kg^{-1} (SSP3)); di-ammonium phosphate (130 mg kg^{-1} (DAP1); 174 mg kg^{-1} (DAP2); 218 mg kg^{-1} (DAP3)); mono-ammonium phosphate (115 mg kg^{-1} (MAP1); 154 mg kg^{-1} (MAP2); 193 mg kg^{-1} (MAP3)) in two soil textures (sandy and clayey).

In both soil textures, the low concentration of bioavailable Cd before the trial was the consequence of their depressed natural concentration of Cd and other soil reactions (pH, clay type, Fe^{2+} and Mn^{2+} oxides, Cl^- content, soil organic matter content, ionic strength), which promptly persuaded a decrease in bioavailable Cd concentration in soil [30]. Significant differences in Cd concentration were observed in both soil textures, with the higher concentration recorded in sandy soil. The results were in accordance with the previous studies [31], which described a number of soil types to evaluate the harmful effects of P fertilizers and observed that the amount of bioavailable Cd in sandy soil increased with the increase in P fertilizer application. The use of MAP leads to increased Cd concentration in both soil textures. Similar results were also described [30]; they observed that the concentration of bioavailable Cd was boosted after treating the soil with MAP fertilizer. The increment in bioavailable Cd concentrations in soil may result from the development of soluble phosphate complex ($CdHPO_4$) [32].

Maximum Cd concentration in maize root (Figure 5) was found in the case of SSP (8–11.5 mg kg^{-1}) followed by RP (8.5–10.3 mg kg^{-1}), DAP (7.5–9.92 mg kg^{-1}), and MAP

(6.5–9.5 mg kg^{-1}) in sandy soil, while in clayey soil, maximum Cd concentration in maize root was found in the case of SSP (8.5–11 mg kg^{-1}) followed by MAP (6–10 mg kg^{-1}), DAP (6.5–9.85 mg kg^{-1}) and RP (7–9.7 mg kg^{-1}) in descending order. Similarly, maximum Cd concentration in maize shoot (Figure 6) was found in the case of SSP (5–13.5 mg kg^{-1}) followed by RP (7–13 mg kg^{-1}), MAP (6.5–11.5 mg kg^{-1}) and DAP (7.5–11 mg kg^{-1}) in sandy soil while in clayey soil, maximum shoot Cd concentration was found in the case of SSP (7.5–15.5 mg kg^{-1}) followed by MAP (7–13.5 mg kg^{-1}), DAP (5.5–12.5 mg kg^{-1}) and RP (5.5–11.5 mg kg^{-1}) in descending order. When comparing the different levels of applied fertilizers, it was observed that root and shoot Cd was linearly increased with increasing the level of applied fertilizer in the case of all fertilizers, as confirmed by previous studies [11]. Among both soil textures, root Cd concentration was higher in sandy soil in most treatments while shoot Cd concentration was higher in clayey soil in most treatments.

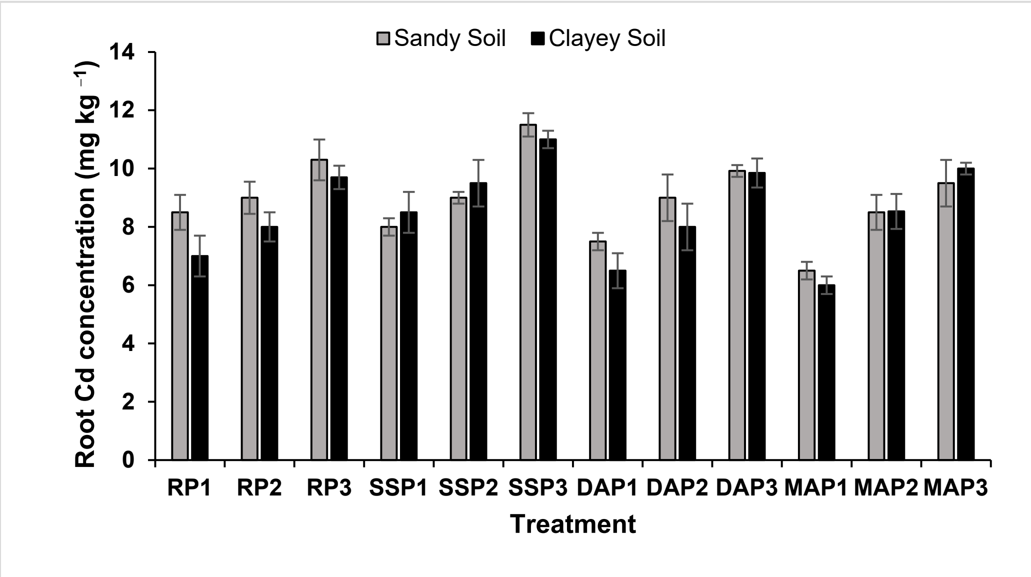

Figure 5. Root Cd concentration of maize (*Zea mays* L.) grown at different P sources and levels in different textured soils, whereas the treatments are: rock phosphate (4 g kg^{-1} (RP1); 8 g kg^{-1} (RP2); 12 g kg^{-1} (RP3)); single super phosphate (333 mg kg^{-1} (SSP1); 444 mg kg^{-1} (SSP2); 555 mg kg^{-1} (SSP3)); di-ammonium phosphate (130 mg kg^{-1} (DAP1); 174 mg kg^{-1} (DAP2); 218 mg kg^{-1} (DAP3)); mono-ammonium phosphate (115 mg kg^{-1} (MAP1); 154 mg kg^{-1} (MAP2); 193 mg kg^{-1} (MAP3)) in two soil textures (sandy and clayey).

In the present study, the values of Cd concentration in maize root and shoot were far higher than those obtained from control agricultural soil in all treatments. These exhibit high indications of Cd excess, which indicates the ability of maize to accumulate Cd, in addition to the fact that the Cd concentrations incorporated into the soil through different P fertilizers were phytotoxic. Their diverse Cd content was directly prompted by the dissimilarities studied in Cd concentrations in maize among MAP, SSP, DAP and RP. The Cd content of SSP was higher than those of DAP, MAP and RP, resulting in increased Cd concentrations in the plant root and shoot.

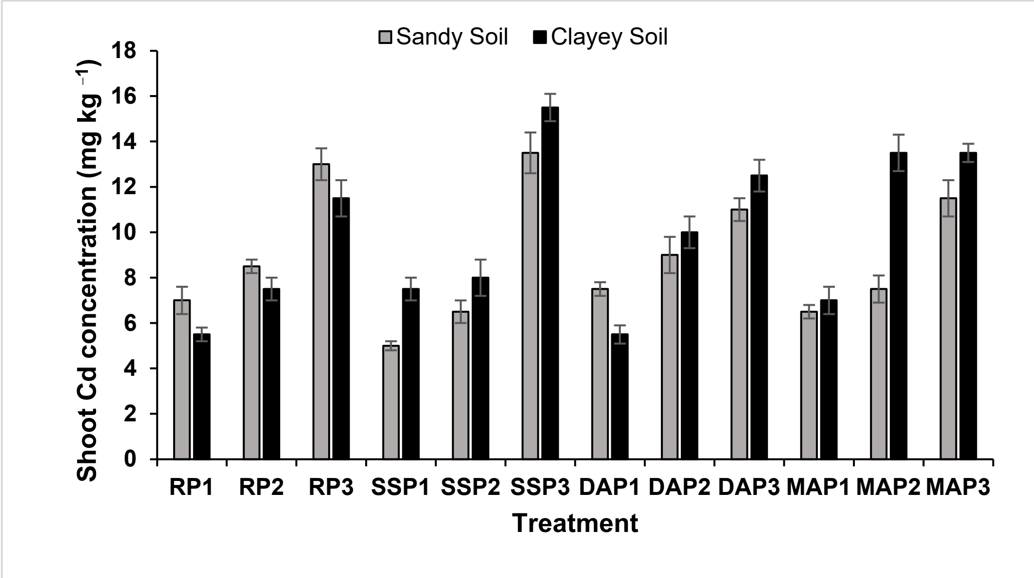

Figure 6. Shoot Cd concentration of maize (*Zea mays* L.) grown at different P sources and levels in different textured soils, whereas the treatments are: rock phosphate (4 g kg^{-1} (RP1); 8 g kg^{-1} (RP2); 12 g kg^{-1} (RP3)); single super phosphate (333 mg kg^{-1} (SSP1); 444 mg kg^{-1} (SSP2); 555 mg kg^{-1} (SSP3)); di-ammonium phosphate (130 mg kg^{-1} (DAP1); 174 mg kg^{-1} (DAP2)); 218 mg kg^{-1} (DAP3); mono-ammonium phosphate (115 mg kg^{-1} (MAP1); 154 mg kg^{-1} (MAP2); 193 mg kg^{-1} (MAP3)) in two soil textures (sandy and clayey).

4. Discussion

In the present experiment, four different P sources (RP, SSP, DAP, and MAP) and three different levels on two different textures (sandy and clayey) were used to explore the influence of P fertilizers on maize growth and yield characteristics and hazardous effects of varying P sources in agricultural soils in terms of metal contamination, particularly Cd in soil. Results revealed that maize plant growth and yield characteristics were significantly ($p \leq 0.05$) influenced by all P sources and levels in both soil textures. Cadmium build-up in soil and subsequent bioavailability to plants are also significantly influenced by all P sources and levels in both soil textures. It was observed that plant height and girth increased linearly with increasing P fertilizer rate. Among different sources, MAP and DAP performed better in affecting plant height and girth than SSP and RP in both soil textures. This might be due to the availability of essential nutrients, phosphorus that plays a part in various components of metabolism, including nucleic acids, phosphates, coenzymes, energy storage and transport, genetic material, and photosynthetic carbon assimilation [33]. It was also reported that DAP had enhanced maize height and girth as compared to the low levels of various P fertilizers [34].

Phosphorus influenced the root growth in all P sources and levels in both soil textures, thus impacting the overall plant growth performance. Soil nutrient availability significantly improves root morphology and physiology, which enhances root exudates and could contribute to increased P availability [35]. The maximum shoot fresh and dry weight was observed in MAP, while the root fresh and dry weight were observed in SSP in both soil textures. The grain yield of maize was significantly affected by all P sources and levels. This might be associated with increased P use efficiency (PUE) [36].

These results are compared with those obtained by studies of tropical soils [37–41]. However, the availability of the metal is higher in the alluvial soil under tropical crop use compared to the savannah soil under grassland use, possibly due to the initial levels of cadmium and to the fact that the mechanism that describes the movement and adsorption of this metal is slower, due to the physical and chemical characteristics of the soil and the intrinsic characteristics of the metal [39]. Soil pH also influences P availability. At low pH, the availability of P increases even if the P solubility is low as compared to high pH conditions. This might be associated with the plants that thrive better under acidic soil conditions, which exhibit an increase in apparent P solubility at low pH levels even though the soil P solubility in solution is low [37]. Soil microorganism also influences the P transformation, increasing P availability at low Ph [38]. Moreover, low pH promotes the dissolution of Al and Fe oxides and hydroxides and precipitation of P, thus reducing P availability [37].

The physical and chemical characteristics of the soil under the use of tropical crops (sugar cane, bananas, corn) were slightly acidic, with a medium content of organic matter and silty clay texture, presence of variable and permanent negative charges in addition to a high cation-exchange capacity (CEC), giving it a high cadmium adsorption capacity [40,41], unlike the soil under pasture use such that in the former, the availability of cadmium was lower at the end of the soil incubation test. The results establish that the soil under the use of grasslands was characterized by a high content of coarse particles (loamy sand) [42], and in the soil under the use of tropical crops, fine particles (silty clay) predominated.

The soils of Pakistan are primarily calcareous and alkaline in nature and have large amounts of Ca^{+2}, Mg^{+2} and Na^{+} due to which P fixation is a major issue in these soils, as the phosphate ions released from fertilizer fix with these cations [39]. For this reason, P deficiency hinders plant growth by 30% in the world's cultivated soils [40]. The current experimental results showed that among different sources, the highest soil P was found in SSP as compared to RP, DAP and MAP in both soil textures. This high level of P might be due to the higher solubility of SSP in soil [41].

In a report published by The Potash and Phosphorus Institute, it was described that P in a managed soil fertility program caused an increase in better root and shoot development and helped the plant to obtain maximum performance under low moisture conditions. Results revealed that P concentration in plant root and shoot increased with increasing P fertilization rate. Among different sources, MAP performed better for optimal P concentration in plant root and shoot than DAP, SSP and RP in both soil textures.

In addition, the Cd concentration obtained in root, shoot and soil was greatly influenced by all P sources and levels. There was a significant difference among all sources and levels regarding Cd concentration, and with the increase in P application rate, Cd concentration was also increased. The lowest Cd concentration in both soil textures was observed in RP due to its low solubility in our soils. It is also reported that Cd availability in soil from P fertilizers mainly depends on the fertilizer solubility [42]. The effectiveness of P fertilizers tends to be higher with more soluble sources to increase Cd bioavailability [43]. The observation of a pot experiment of sorghum–sudan grass concluded that reduced Cd concentration was found with high applications of finely ground P source as RP to an industrially contaminated soil as compared to other soluble P sources [44]. The highest Cd concentration in both soil textures was observed in MAP and DAP, which was far above the permissible limit (1 mg kg^{-1}) of Cd in soil. This might be associated with the reaction products (octacalcium phosphate and hydroxyapatite stone) of DAP in alkaline soil, where competitive and passivation effects of Ca^{2+} octacalcium phosphate and hydroxyapatite on Cd take place in soil resulting in low Cd availability. In addition, hydroxyapatite increases the soil pH that generates more charged sites and formation of metal cation hydroxyl groups leading to Cd^{2+} precipitation as $Cd(OH)_2$ or $CdCO_3$. Furthermore, Cd fixation can be from ion exchange, dissolution, surface complexation, and precipitation [45].

According to a North American survey, it was reported that Cd contents of DAP were up to 22 mg kg^{-1}, considering that the high application of phosphate fertilizers will result in higher Cd content reaching the soil every year [46]. Future research is recommended to identify the long-term effects of P fertilizers on Cd accumulation, changing the type of P fertilizers, and use of complex P fertilizers. Moreover, the concentration of Cd added through each fertilizer is a research gap that needs to be addressed in the future.

5. Conclusions

The results suggest that plant growth, yield characteristics, P concentration and Cd concentration of maize were significantly influenced by all P sources and levels in both soil textures. However, MAP and DAP performed better in terms of P concentration and improved maize growth and yield as compared to the SSP and RP in both soil textures. It was observed that minimum Cd concentrations in maize shoot and root were observed in plants that received MAP and DAP fertilizer, with the fact that maximum Cd concentration in soil was observed in MAP. Among both soil textures, growth and yield characteristics of maize, P concentration in soil and Cd concentrations in maize shoot were found to be higher in clayey soil in most of the treatments, while P concentration in maize root and shoot and Cd concentration in soil and maize root was found to be higher in sandy soil in most of the treatments. These results, however, need confirmation under field conditions and the economic viability of applying different sources and levels of P as well as their impact on heavy metal accumulation, especially Cd in soil and plants required to be investigated further.

Author Contributions: Conceptualization, M.S., M.A.B. and S.M.S.; data curation, M.A. (Muhammad Ashraf); formal analysis, Q.-U.-A.R. and M.U.K.; funding acquisition, Z.D. and A.R.; investigation, M.S., S.M.S. and M.U.K.; methodology, Q.-U.-A.R., S.M.S. and H.M.A.R.; project administration, M.A. (Muhammad Ashraf), M.A. (Muhammad Aon) and A.R.; resources, H.M.A.R., S.U.R. and Z.D.; software, M.A.B. and S.A.; visualization, S.U.R., M.A. (Muhammad Aon) and S.A.; writing—original draft, M.S.; writing—review and editing, M.A. (Muhammad Ashraf), Q.-U.-A.R., M.A.B., S.U.R., S.A., M.A. (Muhammad Aon), S.M.S., M.U.K., H.M.A.R. and A.R. All authors have read and agreed to the published version of the manuscript.

Funding: National Key R&D Program of China (2021YFD1700900), Central Public-interest Scientific Institution Basal Research Fund (Y2022GH10), and the Agricultural Science and Technology Innovation Program of the Chinese Academy of Agricultural Sciences (no. CAAS-ASTIP202101).

Institutional Review Board Statement: The authors approve that this work has not been submitted to any other journal or preprint service. The manuscript is the output of our original research and is not split up in several parts for publication.

Informed Consent Statement: All the authors agree with the content and gave consent to participate in publication. The authors all have the consent/right to publish the obtained data.

Data Availability Statement: All the required data have been added in the manuscript in the form of figures and table.

Conflicts of Interest: The authors have no relevant financial or non-financial interest to disclose.

References

1. Shafiq, S.; Adeel, M.; Raza, H.; Iqbal, R. Effects of Foliar Application of Selenium in Maize (*Zea mays* L.) under Cadmium Toxicity. *Biol. Forum Int. J.* **2019**, *11*, 29–37.
2. Ali, A.; Beshir Issa, A.; Rahut, D.B. Adoption and Impact of the Maize Hybrid on the Livelihood of the Maize Growers: Some Policy Insights from Pakistan. *Scientifica* **2020**, *2020*, 5959868. [CrossRef] [PubMed]
3. Raza, H.M.A.; Bashir, M.A.; Rehim, A.; Raza, Q.U.A.; Khan, K.A.; Aon, M.; Ijaz, M.; Rahman, S.U.; Ahmad, F.; Geng, Y. Effect of k and zn application on biometric and physiological parameters of different maize genotypes. *Sustainability* **2021**, *13*, 13440. [CrossRef]
4. Akhtar, S.; Abbas, A.; Iqbal, M.A.; Rizwan, M.; Samie, A.; Faisal, M.; Sahito, J.G.M. What Determines the Uptake of Multiple Tools to Mitigate Agricultural Risks among Hybrid Maize Growers in Pakistan? Findings from Field-Level Data. *Agriculture* **2021**, *11*, 578. [CrossRef]
5. Raza, H.M.A.; Bashir, M.A.; Rehim, A.; Raza, Q.U.A.; Berlyn, G.P.; Rahman, S.U.; Geng, Y. Application of K and Zn influences the mineral accumulation more in hybrid than inbred maize cultivars. *Plants* **2021**, *10*, 2206. [CrossRef]
6. Raza, Q.A.; Bashir, M.A.; Rehim, A.; Zafar-ul-Hye, M.; Tarar, Z.H. Achieving Sustainable rice production with the application of sugarcane industrial by-products. *Pakistan J. Agric. Agric. Eng. Vet. Sci.* **2021**, *37*, 1–10. [CrossRef]
7. Lu, D.; Song, H.; Jiang, S.; Chen, X.; Wang, H.; Zhou, J. Managing fertiliser placement locations and source types to improve rice yield and the use efficiency of nitrogen and phosphorus. *Field Crop. Res.* **2019**, *231*, 10–17. [CrossRef]
8. Bird, R.P.; Eskin, N.A.M. The emerging role of phosphorus in human health. In *Advances in Food and Nutrition Research*; Academic Press: Cambridge, MA, USA, 2021; Volume 96, pp. 27–88; ISBN 9780128206485.

9. Basavegowda, N.; Baek, K.H. Current and future perspectives on the use of nanofertilizers for sustainable agriculture: The case of phosphorus nanofertilizer. *3 Biotech* **2021**, *11*, 357. [CrossRef] [PubMed]
10. Wang, Y.; Huang, Q.; Gao, H.; Zhang, R.; Yang, L.; Guo, Y.; Li, H.; Awasthi, M.K.; Li, G. Long-term cover crops improved soil phosphorus availability in a rain-fed apple orchard. *Chemosphere* **2021**, *275*, 130093. [CrossRef] [PubMed]
11. Rafiullah; Khan, M.J.; Muhammad, D.; Fahad, S.; Adnan, M.; Wahid, F.; Alamri, S.; Khan, F.; Dawar, K.M.; Irshad, I.; et al. Phosphorus nutrient management through synchronization of application methods and rates in wheat and maize crops. *Plants* **2020**, *9*, 1389. [CrossRef] [PubMed]
12. Mogollón, J.M.; Beusen, A.H.W.; van Grinsven, H.J.M.; Westhoek, H.; Bouwman, A.F. Future agricultural phosphorus demand according to the shared socioeconomic pathways. *Glob. Environ. Chang.* **2018**, *50*, 149–163. [CrossRef]
13. Zhang, F.; Wang, Q.; Hong, J.; Chen, W.; Qi, C.; Ye, L. Life cycle assessment of diammonium- and monoammonium-phosphate fertilizer production in China. *J. Clean. Prod.* **2017**, *141*, 1087–1094. [CrossRef]
14. Robertsa, T.L. Cadmium and Phosphorous Fertilizers: The Issues and the Science. *Procedia Eng.* **2014**, *83*, 52–59. [CrossRef]
15. Park, H.J.; Kim, S.U.; Jung, K.Y.; Lee, S.; Choi, Y.D.; Owens, V.N.; Kumar, S.; Yun, S.W.; Hong, C.O. Cadmium phytoavailability from 1976 through 2016: Changes in soil amended with phosphate fertilizer and compost. *Sci. Total Environ.* **2021**, *762*, 143132. [CrossRef] [PubMed]
16. Shaari, N.E.M.; Tajudin, M.T.F.M.; Khandaker, M.M.; Majrashi, A.; Alenazi, M.M.; Abdullahi, U.A.; Mohd, K.S. Cadmium toxicity symptoms and uptake mechanism in plants: A review. *SciELO Bras.* **2022**, *84*, e252143. [CrossRef]
17. Saini, S.; Dhania, G. Ecological and Health Implications of Heavy Metals Contamination in the Environment and Their Bioremediation Approaches. In *Bioremediation*; CRC Press: Boca Raton, FL, USA, 2022; pp. 189–206.
18. Haider, F.U.; Liqun, C.; Coulter, J.A.; Cheema, S.A.; Wu, J.; Zhang, R.; Wenjun, M.; Farooq, M. Cadmium toxicity in plants: Impacts and remediation strategies. *Ecotoxicol. Environ. Saf.* **2021**, *211*, 111887. [CrossRef]
19. Matayoshi, C.L.; Pena, L.B.; Arbona, V.; Gómez-Cadenas, A.; Gallego, S.M. Biochemical and hormonal changes associated with root growth restriction under cadmium stress during maize (*Zea mays* L.) pre-emergence. *Plant. Growth Regul.* **2022**, *96*, 269–281. [CrossRef]
20. Baryla, A.; Carrier, P.; Franck, F.; Coulomb, C.; Sahut, C.; Havaux, M. Leaf chlorosis in oilseed rape plants (*Brassica napus*) grown on cadmium-polluted soil: Causes and consequences for photosynthesis and growth. *Planta* **2001**, *212*, 696–709. [CrossRef]
21. Rizwan, M.; Ali, S.; Abbas, T.; Zia-ur-Rehman, M.; Hannan, F.; Keller, C.; Al-Wabel, M.I.; Ok, Y.S. Cadmium minimization in wheat: A critical review. *Ecotoxicol. Environ. Saf.* **2016**, *130*, 43–53. [CrossRef]
22. Abbas, T.; Rizwan, M.; Ali, S.; Adrees, M.; Zia-ur-Rehman, M.; Qayyum, M.F.; Ok, Y.S.; Murtaza, G. Effect of biochar on alleviation of cadmium toxicity in wheat (*Triticum aestivum* L.) grown on Cd-contaminated saline soil. *Environ. Sci. Pollut. Res.* **2018**, *25*, 25668–25680. [CrossRef]
23. Chtouki, M.; Naciri, R.; Soulaimani, A.; Zeroual, Y.; El Gharous, M.; Oukarroum, A. Effect of Cadmium and Phosphorus Interaction on Tomato: Chlorophyll a Fluorescence, Plant Growth, and Cadmium Translocation. *Water. Air. Soil Pollut.* **2021**, *232*, 84. [CrossRef]
24. Umayangani, C.; Malaviarachchi, W.; Hettiarachchi, R.; Yapa, N. Different sources of phosphorus fertilizers and soil amendments affected the phosphorus and cadmium content in soil, roots and seeds of maize (*Zea mays* L.). *Turk. J. Agric.—Food Sci. Technol.* **2021**, *9*, 640–645. [CrossRef]
25. Yazici, M.A.; Asif, M.; Tutus, Y.; Ortas, I.; Ozturk, L.; Lambers, H.; Cakmak, I. Reduced root mycorrhizal colonization as affected by phosphorus fertilization is responsible for high cadmium accumulation in wheat. *Plant Soil* **2021**, *468*, 19–35. [CrossRef]
26. Chapman, H.D.; Pratt, P.F. *Methods of Analysis for Soils, Plants and Water*; University of California: Berkeley, CA, USA, 1961.
27. Azeem, M.; Ali, A.; Arockiam Jeyasundar, P.G.S.; Bashir, S.; Hussain, Q.; Wahid, F.; Ali, E.F.; Abdelrahman, H.; Li, R.; Antoniadis, V.; et al. Effects of sheep bone biochar on soil quality, maize growth, and fractionation and phytoavailability of Cd and Zn in a mining-contaminated soil. *Chemosphere* **2021**, *282*, 131016. [CrossRef] [PubMed]
28. Olsen, S.R. *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*; U.S. Development of Agriculture: Washington, DC, USA, 1954; pp. 1–19.
29. Lindsay, W.L.; Norvell, W.A. Development of a DTPA Soil Test for Zinc, Iron, Manganese, and Copper1. *Soil Sci. Soc. Am. J.* **1978**, *42*, 421–428. [CrossRef]
30. Rassaei, F. Effect of different acidic phosphorus agents on the cadmium chemical fractions in calcareous soil. *Arab. J. Geosci.* **2021**, *14*, 2234. [CrossRef]
31. Rezapour, S.; Kouhinezhad, P.; Samadi, A. Trace metals toxicity in relation to long-term intensive agricultural production in a calcareous environment with different soil types. *Nat. Hazards* **2020**, *100*, 551–570. [CrossRef]
32. Jiao, C.H.; He, C.H.; Geng, J.C.; Cui, G.H. Syntheses, structures, and photoluminescence of three cadmium(II) coordination polymers with flexible bis(benzimidazole) ligands. *J. Coord. Chem.* **2012**, *65*, 2852–2861. [CrossRef]
33. Rychter, A.M.; Rao, I.M.; Cardoso, J.A. Role of phosphorus in photosynthetic carbon metabolism. In *Handbook of Photosynthesis*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2016; ISBN 9781420027877.
34. Azeem, K. The Impact of Different P Fertilizer Sources on Growth, Yield and Yield Component of Maize Varieties. *Agric. Res. Technol.* **2018**, *13*, 555881. [CrossRef]

35. Zhang, D.; Zhang, C.; Tang, X.; Li, H.; Zhang, F.; Rengel, Z.; Whalley, W.R.; Davies, W.J.; Shen, J. Increased soil phosphorus availability induced by faba bean root exudation stimulates root growth and phosphorus uptake in neighbouring maize. *New Phytol.* **2016**, *209*, 823–831. [CrossRef]
36. Hopkins, B.G.; Hansen, N.C. Phosphorus Management in High-Yield Systems. *J. Environ. Qual.* **2019**, *48*, 1265–1280. [CrossRef] [PubMed]
37. Penn, C.J.; Camberato, J.J. A critical review on soil chemical processes that control how soil ph affects phosphorus availability to plants. *Agriculture* **2019**, *9*, 120. [CrossRef]
38. Hu, Y.; Chen, J.; Hui, D.; Wang, Y.P.; Li, J.; Chen, J.; Chen, G.; Zhu, Y.; Zhang, L.; Zhang, D.; et al. Mycorrhizal fungi alleviate acidification-induced phosphorus limitation: Evidence from a decade-long field experiment of simulated acid deposition in a tropical forest in south China. *Glob. Chang. Biol.* **2022**, *28*, 3605–3619. [CrossRef] [PubMed]
39. Qayyum, M.F.; Haider, G.; Iqbal, M.; Hameed, S.; Ahmad, N.; Rehman, M.Z.u.; Majeed, A.; Rizwan, M.; Ali, S. Effect of alkaline and chemically engineered biochar on soil properties and phosphorus bioavailability in maize. *Chemosphere* **2021**, *266*, 128980. [CrossRef] [PubMed]
40. Abbas, M.; Shah, J.A.; Irfan, M.; Memon, M.Y. Remobilization and utilization of phosphorus in wheat cultivars under induced phosphorus deficiency. *J. Plant. Nutr.* **2018**, *41*, 1522–1533. [CrossRef]
41. Soltangheisi, A.; Rodrigues, M.; Coelho, M.J.A.; Gasperini, A.M.; Sartor, L.R.; Pavinato, P.S. Changes in soil phosphorus lability promoted by phosphate sources and cover crops. *Soil Tillage Res.* **2018**, *179*, 20–28. [CrossRef]
42. Kuo, S.; Huang, B.; Bembenek, R. Release of cadmium from a triple superphosphate and a phosphate rock in soil. *Soil Sci.* **2007**, *172*, 257–265. [CrossRef]
43. Basta, N.T.; McGowen, S.L. Evaluation of chemical immobilization treatments for reducing heavy metal transport in a smelter-contaminated soil. *Environ. Pollut.* **2004**, *127*, 73–82. [CrossRef]
44. Zwonitzer, J.C.; Pierzynski, G.M.; Hettiarachchi, G.M. Effects of Phosphorus Additions on Lead, Cadmium, and Zinc Bioavailabilities in a Metal-Contaminated Soil. *Water Air Soil Pollut.* **2003**, *143*, 193–209. [CrossRef]
45. Tan, Y.; Zhou, X.; Peng, Y.; Zheng, Z.; Gao, X.; Ma, Y.; Chen, S.; Cui, S.; Fan, B.; Chen, Q. Effects of phosphorus-containing material application on soil cadmium bioavailability: A meta-analysis. *Environ. Sci. Pollut. Res.* **2022**, *29*, 42372–42383. [CrossRef]
46. Li, H.; Yang, Z.; Dai, M.; Diao, X.; Dai, S.; Fang, T.; Dong, X. Input of Cd from agriculture phosphate fertilizer application in China during 2006–2016. *Sci. Total Environ.* **2020**, *698*, 134149. [CrossRef] [PubMed]