Phyton-
International Journal of
Experimental Botany

Tech Science Press

Doi:10.32604/phyton.2025.072520

ARTICLE

Effects of Mineral and Organic Fertilizers on Potato Yield, Soil Fertility, and Metal Accumulation in a Semi-Arid Field Trial

Abd Al Karim Jaafar[1], Suleiman Salim[1], Dema Altheb[1], Mukhtar Iderawumi Abdulraheem[2,3] and Andrés Rodríguez-Seijo[4,5,*]

[1]Department of Soil Science, College of Agricultural Engineering, Damascus University, Damascus, P.O. Box 30621, Syria
[2]Department of Agricultural Science Education, Oyo State College of Education, Lanlate, Ibadan, 201102, Nigeria
[3]Department of Electrical Engineering, Henan Agricultural University, Zhengzhou, 450002, China
[4]Departamento de Bioloxía Vexetal e Ciencias do Solo, Área de Edafoloxía e Química Agrícola. Facultade de Ciencias de Ourense, Universidade de Vigo, As Lagoas s/n, Ourense, 32004, Spain
[5]Instituto de Agroecoloxía e Alimentación (IAA), Campus Auga Ourense, Universidade de Vigo, Ourense, 32004, Spain
*Corresponding Author: Andrés Rodríguez-Seijo. Email: andresrodriguezseijo@uvigo.gal

Received: 28 August 2025; Accepted: 14 November 2025; Published: 29 December 2025

ABSTRACT: The use of organic fertilizers can be an opportunity to increase crop yield and improve soil fertility in semi-arid regions, since soils from these regions usually have unfavourable conditions for plant growth. This research investigates the effects of organic and mineral fertilization on the impact of soil properties (pH, electrical conductivity and organic matter), availability of macro- (N, P and K), micro-nutrients (Fe, Mn, Cu and Zn) and the accumulation of heavy metals (Pb, Cd, Cr) in soil and potato tubers grown under semiarid conditions. A field experiment was conducted in Raqqa Governorate (Syria) using a randomized complete block design with six treatments: control, mineral fertilizer, fermented cow manure, municipal compost, sewage sludge and olive oil solid waste. At harvest, soil and plant samples were analyzed to assess nutrient dynamics in the soil and potato tubers, including metal uptake. The results showed that the highest yields were obtained with mineral fertilizer (22.87 t ha^{-1}) and sewage sludge (22.15 t ha^{-1}). Organic amendments significantly improved soil organic matter, total nitrogen, and the bioavailability of phosphorus, potassium, and micronutrients after harvest. Compost and sewage sludge notably enhanced the soil and plant contents of Mn and Cu. However, these amendments also increased the amounts of Pb and Cd in soils and their uptake by plants, with Cd contents exceeding the Codex Alimentarius limit for potatoes (>0.1 mg kg^{-1}). These findings highlight the potential of treated organic waste as a valuable nutrient input for potato cultivation, especially in resource-limited areas. However, continuous monitoring is required due to the risk of heavy metal accumulation. Integrating organic fertilizers with mineral sources appears to be an effective strategy for improving crop productivity, soil health, and environmental sustainability.

KEYWORDS: Organic fertilizers; heavy metals; nitrogen; micronutrients; protein; soil fertility; food security; sustainable agriculture

1 Introduction

Potato (*Solanum tuberosum* L.) is the largest non-cereal crop and is ranked as the world's fourth most important food crop after rice, wheat, and maize in more than 150 countries. Potatoes are typically regarded as a food security crop due to their high mineral and vitamin content, high productivity per cultivated area, and short crop cycle, as well as their adaptability to grow in various environments and under different farming systems [1–5]. In general, potato cultivation requires larger amounts of macronutrients, including

N, P, and K, as well as significant quantities of other macro- and microelements, such as Mg, Ca, S, Fe, and Zn. However, the potato crop has a relatively low ability to take up available soil mineral nitrogen [6–10].

Conventional agricultural farming practices use high amounts of mineral fertilizers to enhance crop yield and quality. Still, these practices usually can provoke a long-term degradation of soil quality, especially due to nutrient imbalances for excessive fertilization or accumulation of heavy metals due to phosphate fertilizers (e.g., Cd and Pb) [6,8,11,12]. Excessive N fertilization can lead to excessive plant growth, accompanied by low tuber quality and yield [13], a similar issue observed with excessive K fertilization, primarily due to nutrient imbalances involving macro- and micronutrients [14]. Therefore, effective fertilization management practices are necessary.

In this sense, organic fertilization practices (farmyard manure, compost, treated sewage sludge, olive oil mill residual solid wastes, etc.) can represent a more sustainable way to obtain moderate to high crop yields, with an improved long-term fertilization for plants, improving soil properties (e.g., soil structure, water-holding capacity or nutrient cycling) and reducing potential issues by nutrient imbalances [9,15,16]. However, the composition and quality of organic fertilizers are highly variable and depend on feedstock origin, treatment processes, and application rate. Some materials, particularly sewage sludge and municipal composts, may contain elevated levels of potentially toxic elements such as Cd, Cr or Pb, among others, which can accumulate in soils and enter the food chain over time [16,17]. In this sense, the accumulation of heavy metals in edible plant sections has grown to be a major concern, and potatoes have been advised as an interest crop due to their vulnerability to heavy metal uptake because of their high transpiration rates and direct soil contact [18].

In semiarid regions, the use of organic fertilizers presents an opportunity to increase crop yield and improve soil fertility, as soils from these regions typically have a low organic carbon content [16,19]. In these areas, naturally calcareous soils can occur, typically found in regions with limited rainfall, high presence of calcium carbonate ($CaCO_3$) and low availability of nutrients and heavy metals. However, the repeated use of inorganic fertilizers and contaminated organic materials can nevertheless lead to a gradual accumulation of heavy metals [16].

Despite the research on organic amendments, data from semi-arid Mediterranean environments remain limited. In these areas, naturally calcareous soils can occur, typically found in regions with limited rainfall, high presence of calcium carbonate ($CaCO_3$) and low availability of nutrients and heavy metals [16]. Most previous studies in semi-arid areas have focused either on yield response or soil fertility, with few integrating both agronomic and food-safety dimensions. Understanding these relationships is crucial for developing practical recommendations tailored to local conditions.

This study aims to evaluate the effects of organic and mineral fertilizers on the soil properties, potato yield, and quality in a field experiment carried out in Raqqa Governorate (Syria), focusing on the availability of micronutrients and the accumulation of heavy metals in soils and their uptake by potato tubers. Therefore, this study aims to evaluate the effects of mineral and organic fertilizers on soil fertility, potato yield, and heavy-metal accumulation under semi-arid field conditions in Raqqa Governorate, Syria. We specifically hypothesize that: (i) organic amendments applied at nitrogen-equivalent rates can enhance soil fertility and potato yield relative to unfertilized control; (ii) different organic fertilizers have distinct effects on soil nutrient availability and heavy-metal (Cd, Pb) concentrations; and (iii) sewage sludge and municipal compost may increase Cd and Pb accumulation beyond permissible limits in soil and tubers. By addressing these hypotheses, the study provides evidence to guide the safe agricultural reuse of organic wastes and inform national policies for sustainable fertilization in semi-arid cropping systems.

2 Materials and Methods

2.1 Crop Selection

The potato (*Solanum tuberosum* L. cv. Spunta) was used in this experiment. This cultivar was provided by the General Organization for Seed Multiplication (Damascus, Syria). It is characterized by medium maturity, vigorous vegetative growth, and large, round tubers. The average yield is moderate, and the cultivar is known for its drought resistance. It is widely cultivated in Raqqa Governorate.

2.2 Experimental Site

The field experiments were conducted during the summer growing season of 2024 in the Al-Halah village (Raqqa Governorate, Syria). The experimental site is situated at an elevation of 742 m above sea level, with an average annual rainfall of approximately 200 mm. The soil was classified as a sandy-loam Typic Calciorthid with a slightly alkaline pH (7.8) and low organic matter content.

2.3 Soil Analysis

Soil sampling of each subplot was conducted at the beginning and end of the field experiment. Soil samples from each subplot treated with conventional and organic fertilizers were thoroughly characterized at the beginning and end of the trial. The following soil characteristics were analyzed in the 0–20 cm depth: soil texture by the hydrometer method [20], bulk density and total soil porosity by the cylinder method [21], soil pH and electrical conductivity were measured in a 1:5 soil-to-water suspension [22,23]. Calcium carbonate was measured using the calcimeter method, and the active lime (active calcium carbonate equivalent) was determined using the NH4-oxalate method [24]. The organic matter content was determined via wet oxidation with potassium dichromate [25]. The total nitrogen was analyzed using concentrated sulfuric acid and then determined by Kjeldahl distillation [26]; the available phosphorus was analyzed by the Olsen method [27]. The available potassium (AK) was determined by flame photometry after ammonium acetate extraction [28]. The available contents of micronutrients and heavy metals (Fe, Mn, Cu, Pb, Cd, Cr) were extracted by DTPA extraction [29] and analyzed by Atomic Absorption Spectroscopy (AAS) (Varian SpectrAA-880/GTA100 Atomic Absorption Spectrometer).

2.4 Mineral and Organic Fertilizers Used in the Experiment

Conventional fertilizers were supplied by a local company, and three fertilizers, supplying N, P, or K, were used. Mineral fertilizers included urea (46% N), triple superphosphate (46% P_2O_5), and potassium sulfate (50% K_2O).

Four organic fertilizers were used in this study: (i) fermented cow manure (FCW) obtained in a fermented form from local livestock farms; (ii) olive oil solid waste (OSW) collected in a semi-fermented state from a nearby olive press in the study area; (iii) sewage sludge (SW) collected from the wastewater treatment plant in Raqqa City (Syria); and (iv) municipal solid waste compost (MSWC), acquired from a municipal waste processing facility. Organic fertilizers were characterized before the experiment. The pH and EC were measured in a 1:5 dilution of the fertilizer in water. The total nitrogen (N) was determined using the Kjeldahl method. The total phosphorus (P) was determined after dry ash and quantified colourimetrically using the ammonium molybdate–vanadate method with a UV–Vis spectrophotometer [30]. The organic matter was determined by the loss-on-ignition method at 600°C [31], while the organic carbon was estimated using the dichromate oxidation method [25]. Total contents of selected micronutrients and heavy metals were determined after dry ashing (450°C, digested with HCl and HNO_3) and analyzed by AAS [32]. Microbial safety (total coliforms, *E. coli*) and organic-contaminant checks were conducted according to USEPA 503 standards [33]; the results were below the permissible limits.

Organic fertilizers were applied on a nitrogen-equivalent basis (120 kg N ha^{-1}). Although small variations in P and K inputs existed among treatments, these were recorded and statistically evaluated to account for nutrient imbalance effects.

2.5 Experimental Design and Agronomic Practices

The experiment followed a Randomized Complete Block Design (RCBD) with three replicates, providing sufficient representation under field heterogeneity. Each plot (3 × 5 m; 15 m^2) included four rows spaced 0.8 m apart and 0.25 m between tubers, Mineral fertilizers were applied following national recommendations (180 kg N, 120 kg P_2O_5, 120 kg K_2O ha^{-1}). Phosphorus and potassium fertilizers were applied entirely before planting. Nitrogen was split into three doses: pre-planting, post-emergence, and flowering. Organic fertilizers were incorporated 15 days before planting. The respective application rates were: (i) 9.23 t ha^{-1} (fermented cow manure), 12.85 t ha^{-1} (olive oil solid waste), 6.43 t ha^{-1} (sewage sludge) and 13.23 t ha^{-1} (municipal solid waste compost).

The fields were irrigated using a micro-sprinkler (microjet) system, with water applied every four days. All treatments received equal amounts of water to ensure consistency across plots and between replicates. Irrigation was withheld two weeks before harvest to facilitate tuber maturation.

2.6 Potato Harvesting and Analysis

The potato harvesting was conducted manually using traditional methods on August 15th, approximately 100 days after planting. All potato tubers were collected from each experimental plot, and yield was calculated with fresh tuber weight [34]. The potato plants were also analyzed. First, the total N, P and K were analyzed in the leaves using the Kjeldahl method, ammonium molybdate–vanadate method and dry ash and flame photometric analysis, respectively, following the methods previously described for organic fertilizers. The potato tubers were randomly collected from each sampling plot (five per plot) and leaf samples (at flowering), washed with tap water, analyzed (without peeling), and dried at 70°C until a constant weight was reached [35]. Once dried, the total nitrogen was determined by the Kjeldahl method [36]. Total phosphorus was measured after dry ashing using a spectrophotometer and through the molybdate reactive P method, and total potassium was determined after ashing and analyzed using a flame photometer [35]. Finally, the crude protein content was estimated by multiplying total nitrogen (from Kjeldahl analysis) by a conversion factor of 6.25 [36]. The micronutrient and heavy metal contents in leaves and tubers were also analyzed by aqua regia digestion and measured by AAS. As Syria has no specific standard for heavy metals in foodstuffs, heavy metals found in the potato samples were compared with limit and critical values according to FAO [37].

2.7 Statistical Analysis

All chemical analyses were carried out in triplicate. Certified reference materials (NIST 2711a), blanks, and duplicates were used for quality control. Metal recoveries ranged from 92 to 106%. Data were tested for normality (using the Shapiro–Wilk test) and variance homogeneity (using the Levene test). One-way ANOVA + Tukey's HSD ($p < 0.05$) were used to assess treatment effects. All statistical analyses were performed with GraphPad Prism 8 (GraphPad software, San Diego, CA, USA).

3 Results

3.1 Physicochemical Characterization of the Field Area and Organic Amendments

The soil physicochemical characteristics before the field experiment are presented in Table 1. The results indicated that the soil has a silty-clay texture (USDA classification), good porosity, and is slightly alkaline pH and non-saline conditions, with a high percentage of calcium carbonate, along with a moderate content of organic matter, macronutrients, and a low available content of heavy metals (Cd, Cr, and Pb), that indicates a minimal contamination risk before fertilizer application.

Organic fertilizers were characterized before the experiment (Table 2). The fermented cow manure (FCW) has a neutral-alkaline pH with relatively high EC (3.3 dS m^{-1}), good organic matter content, moderate content of N, P and K, and a balanced C/N ratio with low content of heavy metals. The olive oil solid wastes (OSW) have a slightly acidic pH, with low EC and a high content of OM and N, moderate contents of P and K, and a high C/N ratio. As in the case of FCW, the OSW have low to moderate contents of heavy metals, especially Pb and Cr, similar to those indicated by other studies [16]. Both sewage sludge (SW) and municipal solid waste compost (MSWC) have a slightly acidic or neutral pH, with a high content of organic matter, but a low C/N ratio and low P and K contents. Very high concentrations of all studied heavy metals were found in both materials, exceeding the limits set by Chinese and European legislations, but similar to those reported in other studies [38,39]. Although both materials can be applied to soils due to their high organic matter content and nutrients, they should be applied at low rates to avoid excessive input of heavy metals into agricultural soils [38].

Table 1: Soil properties of the field area before the plant experiment.

Soil Properties	Units	Value
Sand	%	20
Silt	%	40
Clay	%	40
Texture classification		Silty clay
Bulk density	g cm^{-3}	1.27
Total porosity	%	51.71
pH (1:10, H_2O)		8.20
Electrical conductivity	dS m^{-1}	0.25
Organic matter	%	1.56
$CaCO_3$	%	45
Active lime	%	9.00
Total nitrogen	%	0.082
Available P	mg kg^{-1}	6.24
Available K	mg kg^{-1}	263
Available Cd	mg kg^{-1}	0.03
Available Cr	mg kg^{-1}	0.01
Available Cu	mg kg^{-1}	0.51
Available Pb	mg kg^{-1}	2.61
Available Mn	mg kg^{-1}	3.04

Table 2: Chemical properties of the organic fertilizers used in this study.

Fertilizer Type	Units	Fermented Cow Manure	Olive Oil Solid Waste	Sewage Sludge	Municipal Solid Waste Compost
pH $_{(1:5)\ (H2O)}$		7.50	6.74	6.50	7.20
EC $_{(1:5)}$	dS m^{-1}	3.30	1.40	3.70	3.70
Organic Matter	%	51.80	84	40	40

Table 2: *Cont.*

Fertilizer Type	Units	Fermented Cow Manure	Olive Oil Solid Waste	Sewage Sludge	Municipal Solid Waste Compost
Total N	%	1.95	1.40	2.80	1.36
Total C	%	30.08	52.20	23.20	23.20
C/N ratio		15.42	34.80	8.28	17.05
Total P	%	0.70	0.60	2	0.20
Total K	%	1.49	0.74	0.50	0.60
Total Fe	mg kg^{-1}	3908	128	5100	2700
Total Mn	mg kg^{-1}	250	78	150	369
Total Cu	mg kg^{-1}	29.52	14	168	560
Total Pb	mg kg^{-1}	7.24	3.75	**150**	**104**
Total Cd	mg kg^{-1}	0.51	0.35	**4.50**	**2.20**
Total Cr	mg kg^{-1}	**5.10**	**5.50**	**238**	**226**

Average values (n = 3). Values in bold are over the permissible limits for organic fertilizers according to European [40] and Chinese standards [41]: Cd (3 and 3 mg kg^{-1}, respectively), Cr (2 and 150 mg kg^{-1}, respectively), Cu (600 mg kg^{-1}, only covered by European legislation) and Pb (120 and 50 mg kg^{-1}, respectively).

3.2 Effect of Fertilizer Application on Soil Properties after Harvest

Soil properties after fertilizer application are shown in Table 3. In general, mineral and organic fertilizations significantly increased the EC, TN, AP and AK contents compared to their values before the plant experiment, while a significative reduction in soil pH was also observed (from 8.2 to ~8.0) across all treatments (Table 3). At the end of the plant harvest, no significant differences were found among the different treatments for soil pH and total N (Table 3).

In contrast, significant differences were found between treatments for EC, OM, AP, and AK. Both mineral (MF) and municipal solid waste compost (MSWC) significantly increased the soil electrical conductivity regarding the control treatment (no addition). Control and mineral fertilizers treatments reduced the organic matter content of the soils at the beginning of the experiment, whereas organic fertilizers (MSWC, FCW, OSW, and SW) significantly increased the organic matter content of the control treatment (no addition) and prior to the experiment (Table 3). Similarly, the available P (AP) and K (AK) were increased under fertilization treatments, especially under organic treatments, such as sewage sludge (SW) for AP, and FCW for AK.

Table 3: Soil chemical properties before and after plant harvest.

Treatment	Soil pH_{H2O}	Electrical Conductivity dS m^{-1}	Organic Matter %	Total Nitrogen %	Available Phosphorous mg kg^{-1}	Available Potassium mg kg^{-1}
Before experiment	8.20 a	0.25 *c*	1.56 *c*	0.08 *a*	6.24 *e*	263 *c*
Control treatment	8.05 *b*	0.27 *c*	1.38 *d*	0.09 *a*	7.15 *d*	213 *d*
Mineral fertilizer (MF)	8.04 *b*	0.37 *a*	1.39 *d*	0.10 *a*	11.60 *c*	270 *b*
Fermented cow manure (FCW)	8.04 *b*	0.32 *b*	1.72 *a*	0.11 *a*	12.35 *b*	275 *a*
Olive oil solid waste (OSW)	8.01 *b*	0.26 *c*	1.64 *b*	0.10 *a*	12.15 *b*	268.75 *bc*
Sewage sludge (SW)	8.03 *b*	0.33 *b*	1.58 *c*	0.13 *a*	13.95 *a*	265 *c*
Municipal solid waste compost (MSWC)	8.02 *b*	0.38 *a*	1.78 *a*	0.11 *a*	11.20 *c*	267 *bc*

Mean values (n = 3). In the same column, values sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

3.3 Effect of Fertilizer Application on Soil Available Micronutrient Content

Table 4 shows the effects of different fertilizer treatments on the available micronutrient content in the field soil. A significant increase in available micronutrients (Cu, Fe and Mn) was observed under organic fertilizer application, especially with SW and MSWC, compared to control and mineral fertilizer treatments (Table 4). The reduced amounts in the control treatment compared to the treatments before the experiment and fertilizations are explained by the removal of micronutrient by potato growth, as these micronutrients are essential for potato growth (Table 4).

Table 4: Soil available micronutrients before and after plant harvest.

Treatment	Available Cu mg kg^{-1}	Available Fe mg kg^{-1}	Available Mn mg kg^{-1}
Before experiment	0.51 *e*	2.49 *f*	3.04 *d*
Control treatment	0.49 *e*	2.40 *f*	3.01 *d*
Mineral fertilizer (MF)	0.81 *d*	2.70 *e*	3.07 *d*
Fermented cow manure (FCW)	1.22 *c*	3.70 *c*	3.25 *c*
Olive oil solid waste (OSW)	1.29 *b*	2.83 *d*	3.20 *c*
Sewage sludge (SW)	1.31 *b*	4.50 *a*	3.60 *b*
Municipal solid waste compost (MSWC)	1.42 *a*	4.10 *b*	4.00 *a*

Mean values (n = 3). In the same column, values sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

The municipal compost had the highest Mn contents, followed by SW > FCM > OSW > MF > Control (Table 4). Copper levels also significantly increased with organic fertilization compared to the control and MF treatment, being the highest value also under municipal compost and followed by SW > OSW > FCM > MF > Control (Table 4). Iron (Fe) levels also significantly increased after organic fertilizers incorporation, with the highest contents under SW and followed by > MSWC > FCM > OSW > and MF > Control (Table 4).

3.4 Effect of Fertilizer Application on Soil Available Heavy Metals

Table 5 shows the effects of different fertilizer treatments on the available heavy metals in the soil. No significant differences were observed between the pre-treatment, control treatment (no addition), and plots treated with MF, FCM, and OSW (Table 5). However, both sewage sludge and municipal compost treatments significantly increased the available heavy metals, especially sewage sludge, when compared with the control and mineral fertilization treatments (Table 5). Although still moderate, these concentrations could be a potential accumulation risk under repeated use.

Table 5: Soil available heavy metals before and after harvest.

Treatment	Available Cd mg kg^{-1}	Available Cr mg kg^{-1}	Available Pb mg kg^{-1}
Before experiment	0.03 *c*	0.01 *c*	2.61 c
Control treatment	0.02 *c*	0.02 *c*	2.59 *c*
Mineral fertilizer (MF)	0.02 *c*	0.02 *c*	2.60 *c*
Fermented cow manure (FCW)	0.02 *c*	0.02 *c*	2.58 *c*
Olive oil solid waste (OSW)	0.02 *c*	0.02 *c*	2.61 *c*
Sewage sludge (SW)	0.08 *a*	0.14 *a*	6.95 *a*
Municipal solid waste compost (MSWC)	0.05 *b*	0.05 *b*	4.89 *b*

Mean values (n = 3). In the same column, values sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

3.5 Effect of Different Fertilizers on Potato Yield

Significant differences between fertilization treatments were found for potato yields (Table 6). The mineral fertilizer treatment yielded the highest potato yield (22.87 t Ha^{-1}), followed by sewage sludge, fermented cow manure, municipal solid waste compost, olive oil solid waste, and no fertilization.

Table 6: Potato yields after fertilization treatments.

Treatment	Potato Yield t ha^{-1}
Control	14.35 *f*
Mineral fertilizer (MF)	22.87 *a*
Fermented cow manure (FCW)	19.44 *c*
Olive oil solid waste (OSW)	17.30 *e*
Sewage sludge (SW)	22.15 b
Municipal solid waste compost (MSWC)	18.05 *d*

In the same column, values sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

3.6 Effect of Different Fertilizers on Total Macronutrients in Potato Leaves

All treatments increased the macronutrient content on potato leaves compared to the control treatment (no addition) (Table 7). In general, application of fermented cow manure and mineral fertilizers increased the content of N, P and K on potato leaves (Table 7). Heavy metal contents were not measured.

Table 7: Total macronutrients in potato leaves after fertilization treatments.

Treatment	Total N %	Total P %	Total K %
Control	3.85 *d*	0.20 *c*	1.30 *e*
Mineral fertilizer (MF)	4.30 *b*	0.32 *ab*	1.95 *c*
Fermented cow manure (FCW)	4.90 *a*	0.32 *ab*	2.25 *a*
Olive oil solid waste (OSW)	4.10 *c*	0.29 *b*	2.10 *b*
Sewage sludge (SW)	5.00 *a*	0.34 *a*	1.96 *c*
Municipal solid waste compost (MSWC)	4.10 *c*	0.27 *b*	2.00 *d*

Mean values (n = 3). In the same column, values sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

3.7 Effect of Different Fertilizers on Total Macronutrients, Protein Content and Heavy Metals on Potato Tubers

All treatments significantly increased N levels in the tubers compared to the control, with significant differences among them (Table 8). The highest contents were observed under mineral fertilization and sewage sludge application, followed by FCM, MSWC, OSW, and finally the control treatment. The same pattern was observed for protein content, which ranged between 8.75 and 11.50% for mineral and organic treatments, twice that of the control treatment (around 4.30%) (Table 8). In any case, protein content in potato tubers was within the expected range for dry potato tubers (4.5–13.6%) [42].

All treatments increased P content in potato tubers compared to the control, with sewage sludge recording the highest P level. This was closely followed by FCM, MSWC, OSW and MF, with significant differences between treatments. Similarly, organic fertilizer treatments, mainly FCM, significantly increased the K content in potato tubers (Table 8).

Chromium contents were not detected, while Cd and Pb levels were significantly increased under sewage sludge and municipal solid waste compost treatments compared to the control (Table 8). In contrast, neither mineral fertilizers, fermented cow manure, nor olive oil solid waste significantly increased Cd contents; however, they did with Pb (Table 8). All values were higher than safe levels for potato tubers according to Codex Alimentarius [37], with 0.1 mg kg^{-1} for Cd and Pb. However, in this case, Codex Alimentarius refers to peeled potatoes, whereas in our case, whole potatoes, after being washed, were analyzed, which can explain these differences.

Table 8: Total macronutrients and heavy metals in potato tubers after fertilization treatments.

Treatment	Total N %	Total P %	Total K %	Cd mg kg^{-1}	Cr mg kg^{-1}	Pb mg kg^{-1}	Protein Content %
Control	0.7 *e*	0.35 *d*	3.53 d	0.14 *b*	Not detected	0.20 *c*	4.30 *e*
Mineral fertilizer (MF)	1.85 *a*	0.37 *d*	3.92 *c*	0.15 *b*	Not detected	0.25 *b*	11.50 *a*
Fermented cow manure (FCW)	1.59 *b*	0.75 *b*	4.52 *a*	0.14 *b*	Not detected	0.28 *b*	9.92 *b*
Olive oil solid waste (OSW)	1.40 *d*	0.43 *c*	4.23 *b*	0.15 *b*	Not detected	0.27 *b*	8.75 *d*
Sewage sludge (SW)	1.81 *a*	0.87 *a*	4.26 *b*	0.20 *a*	Not detected	0.39 *a*	11.30 *a*
Municipal solid waste compost (MSWC)	1.47 *c*	0.44 *c*	3.97 *c*	0.19 *a*	Not detected	0.36 *a*	9.20 *c*
Safe levels range (FAO)				0.1		0.1	

Mean values (n = 3). In the same column, values sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test. Permissible values according to Codex Alimentarius [37] for peeled potatoes: Cd (0.1 mg kg^{-1}) and Pb (0.1 mg kg^{-1}).

4 Discussion

4.1 Effect of Different Fertilizers on Soil Properties after Plant Harvest

The soil pH was slightly reduced compared to the soil before the experiment, which is within the expected range due to the inorganic and organic fertilization treatments [43]. However, the lack of significant differences between treatments may result from the buffering capacity of the calcareous soil and its high $CaCO_3$ content, which neutralizes acidity or also can be attributed to the reduced amounts of organic fertilizers used or the time required to induce such changes. In calcareous soils, the carbonate system can limit pH fluctuations even after organic matter addition [16,44]. Moreover, organic fertilizers can have $CaCO_3$ added, such as in cattle diets, which are excreted in manure [43]. Changes in EC were statistically significant, especially when municipal compost, sewage sludges and fermented cow manure were applied. This increase is attributed to the high content of soluble salts in the organic amendments, which contributed to an increase in the soil's soluble salt levels [43]. However, the olive mill waste treatment did not differ significantly from the control, likely due to its relatively low salt content compared to other organic fertilizers. Mineral fertilizers, being highly soluble, also significantly increased the soil EC [43]. Despite these increments, all EC values were within the non-saline soils (0–2 dS m^{-1}).

As expected, organic amendments increased the OM content in soils after harvest (FCM > MSWC > OSW > SW), while no significant differences were found between control and mineral fertilizers [43]. No changes in total N can be attributed to the amounts of fertilizers adjusted based on their nitrogen content and the nitrogen needs of the potato crop. Ozlu and Kumar [43] observed that an increase in total N only occurred under high N rates or beyond the crop's uptake capacity. Both mineral and organic fertilizers significantly increased the available contents of P and K (Table 3). These results align with studies demonstrating that sewage sludge amendments enhance phosphorus availability, primarily due to the presence of organic compounds and humic acids that facilitate phosphorus mobilization. The advantage of sewage sludge is attributed to its low C/N ratio (~8.2), which facilitates rapid decomposition and enhances soil properties. Overall, organic fertilizers significantly boosted soil phosphorus levels compared to the control, as they are rich sources of phosphorus [44,45].

Additionally, the mineralization of organic matter produces organic acids that compete with phosphate ions for binding sites on Ca, Fe and Al, thus decreasing the formation of insoluble calcium phosphate compounds. Similarly, organic amendments increased the available potassium (K) content compared to inorganic fertilizers [4]. In the case of available K contents, the control treatment (no addition) had lower values than the treatment before the experiment, probably due to nutrient removal by potatoes without nutrient input.

Despite these increments, the available P contents were still below the optimum levels for achieving high potato yields, as higher yields are typically achieved under 17–25 mg kg^{-1} of available P [46]. In contrast, the available K contents were too high to achieve good potato yields, as the highest potato yields are usually achieved between 150–250 mg kg^{-1} of available K [14]. In our case, only the control treatment (no addition) was within this range.

4.2 Effect of Different Fertilizer Applications on Soil Nutrients and Heavy Metals after Harvest

Observed results aligned with previous studies [44] showing that organic fertilization practices can improve micronutrient availability for plants. In any case, these contents appear lower for plant growth and are compared with similar studies [47], but are expected to have lower micronutrient availability on calcareous soils [16].

Safe levels of DTPA-extractable heavy metals in soil have not been universally established [48]. Kabata-Pendias [49] reviewed that safe levels of available heavy metals for plant growth are below 0.2 and 0.5 mg kg^{-1} for Cd and Pb, respectively. Yu et al. [50] suggested that the safe levels of Cr for extractable levels in crops are below 0.7 mg kg^{-1}. In our case, only available Pb values exceeded the safe levels for plant growth, especially under sewage sludge and municipal solid waste compost (Table 5). These findings align with previous studies, which have shown an increase in heavy metal availability following the incorporation of organic residue [51–54]. The rise in heavy metal content with organic amendments, particularly sewage sludge and compost, can be attributed to their composition and relatively initial high concentrations of beneficial and potentially toxic elements in used amendments and also to the formation of soluble metal-organic complexes during decompositon [51].

The findings highlight the need for stricter regulatory monitoring in regions like Syria, where threshold values are not well defined. Under long-term applications, the metal incorporation to the soil-plant systems, will lead to reduce soil microbial activity, plant phytotoxicity and risk foro food web, including human health risk.

4.3 Effect of Different Fertilizer Applications on Potato Yield

Potato yields were in line with expectations under alkaline soils, as high potato yields are typically achieved under acidic soil pH values (5.5–6) [55]. In any case, these findings were aligned with similar studies [44,56–58], which reported higher yields under conventional fertilization practices. This is because inorganic fertilizers typically maximize yield due to the rapid availability of N, P, and K in forms that are easily accessible for plant uptake. Organic fertilizers can improve potato productivity through their positive effects on the physical, chemical, and biological properties of the soil (e.g., improved soil structure, aeration or nutrient retention, among others). The observed yield increase with sewage sludge can be attributed to its low C/N ratio and rich N and P contents, supporting rapid mineralization [59]. Tyasmoro et al. [60] found that organic fertilizers can significantly increase potato yield, but when applied in liquid form instead of solid waste, reinforcing that nutrient availability for plant uptake plays a significant role in potato growth. Nevertheless, yields under organic fertilization were slightly lower than those under mineral inputs, reflecting slower nutrient release and possible competition with microbial immobilization. Similar yield patterns were also reported by [61], who found that mixed fertilization improved both productivity and nutrient use efficiency. Further studies should evaluate the mixture of inorganic and organic fertilization to achieve high yields and optimal nutritional parameters, in conjunction with both short- and long-term fertilization for plants [56], as well as with liquid applications [57].

4.4 Effect of Different Fertilizer Applications on Potato Leaves and Tubers' Chemical Composition

In the current study, the levels of N, P, and K in leaves were significantly enhanced by inorganic and organic fertilization, with results within the expected values and those reported by similar studies [62,63]. This enhancement is consistent with the findings that increasing NPK levels in soils through fertilization also increases the nutrient content in leaves.

According to [64], the N, P, and K contents in potato tubers usually are around 0.33, 0.037–0.059, and 0.36–0.42%, respectively. In our case, the macronutrients found were within these ranges for all macronutrients and across all treatments, suggesting a potential for excessive fertilization and, potentially, a reduction in potato yield [59]. Among the treatments, mineral fertilizers produced the highest nitrogen content in tubers, followed closely by sewage sludge. The ranking of treatments by effectiveness in increasing tuber nitrogen content was MF > SW > FCM > MSWC > OSW > Control (Table 8). The high nitrogen content and low C/N ratio of sewage sludge likely explain its effectiveness, as these factors promote rapid decomposition and provide more nitrogen to the plant. Considering that sewage sludge performed nearly as well as mineral fertilizer in boosting tuber nitrogen content, there is potential to replace some or all mineral nitrogen fertilizers with sewage sludge as a sustainable nitrogen source for potato farming. These results suggest that the application of organic manures is a more suitable source of available potassium (K) for potato tubers than inorganic inputs. Farmyard manure may be preferable due to its higher content of exchangeable potassium and desirable pattern of nutrient release. In fact, organic amendments can improve soil structure and microbial activity, thereby enhancing nutrient uptake efficiency, as reported by [64] for K uptake, once organic residues can release exchangeable K during decomposition [14].

Both Cd and Pb can easily accumulate in agricultural soils, primarily due to the uncontrolled use of phosphate fertilizers (Cd) [65–67], pesticide application, or polluted irrigation waters (Pb) [66,68,69], and can be taken up by crops. In the case of potatoes, they are considered an important source of cadmium (Cd) in human diets in several countries, as they can easily accumulate Cd [49]. According to [49], Cd concentrations in potato tubers are within the range of 0.016–0.3 mg kg^{-1}, and Pb concentrations are 0.5–3 mg kg^{-1}. Our values fall within the range for Cd and are below the range for Pb.

Similar observations were made by [70], who reported that Cd levels in potatoes often increase in calcareous soils due to higher metal availability under alkaline conditions. Similar trends were also found with inorganic and organic fertilizers, with an increase in metal contents under organic fertilization [57, 71–76] or under overused phosphate-fertilized soils [66]. Ashrafzadeh et al. [47] reviewed Cd contents in potato tubers from eight countries (Australia, Belgium, Canada, New Zealand, Norway, Poland, Switzerland, and Sweden), with median values ranging between 0.04 and 0.16 mg kg^{-1} (0.01–1.16 mg kg^{-1}), which is similar to our samples. In any case, Cd contents exceeded the Codex Alimentarius limit (0.1 mg kg^{-1}) [37], suggesting that unregulated application of such materials could pose a potential human health risk, that needs detailed study.

Musilova et al. [77,78] also reported a similar trend for Pb, not for Cd, in potato tubers grown under alkaline soil and with low organic matter, such as our soils. They indicated that under these conditions, the uptake of Cd and Pb by tubers could be increased. If, under these conditions, contaminated irrigation waters are also applied, the risk will increase, as reported by [79] for potatoes in Pakistan.

However, it's necessary to consider that metal accumulation in potatoes varies significantly among cultivar species [80] or with changes in soil temperature [81]. In fact, [82] found that the Spunta cultivar, the same cultivar that was used in our study, it's known to exhibit moderate-to-high Cd translocation potential [81]. Therefore, future studies should evaluate cultivar selection, irrigation quality, and pre-treatment of organic fertilizers to minimize contamination. In the long term, sustainable management practices such as blending organic and inorganic inputs, heavy-metal stabilization, and monitoring of soil thresholds are necessary to ensure safe agricultural production in Syria.

5 Conclusion

Our results confirm a positive effect of organic and mineral fertilizers on potato yield and soil fertility, with municipal compost and sewage sludge yielding the best response among the organic fertilizers. However, these amendments also increased the heavy metal content in the soil and the uptake of potatoes. To ensure sustainable use, the application of sewage sludge and compost should be limited to rates below 6–8 t ha^{-1} and accompanied by pre-treatment or mixed with mineral fertilizers to reduce heavy metal inputs to the soil-plant system. The results also underscore the importance of periodic monitoring of soil and plant metal content, as well as the establishment of national regulatory thresholds for organic waste application in Syria. The novelty of this research lies in providing the first integrated assessment of agronomic performance and food safety implications of organic waste fertilization in Syrian calcareous soils. Future studies should focus on multi-season trials to evaluate the cumulative impacts of these amendments on soil health, crop productivity, and heavy metal accumulation, ultimately contributing to the development of safe and sustainable nutrient management strategies for arid and semi-arid agricultural systems.

Acknowledgement: The authors wish to express their gratitude to the Faculty of Agricultural Engineering, Damascus University, with special thanks to the Department of Soil Science for their invaluable support throughout this study. ARS would like to acknowledge their JdCi research contract (IJC2020-044197-I) funded by MICIU/AEI/10.13039/501100011033 and European Union EU/PRTR.

Funding Statement: The authors received no specific funding for this study.

Author Contributions: Abd Al Karim Jaafar: Conceptualization, Methodology, Investigation, Formal Analysis, Writing—Original Draft, Writing—Review & Editing, Supervision. Suleiman Salim: Methodology, Investigation, Data Curation, Visualization, Writing—Review & Editing. Dema Altheb: Resources, Investigation, Validation, Writing—Review & Editing. Mukhtar Iderawumi Abdulraheem: Resources, Investigation, Validation, Writing—Review & Editing. Andrés Rodríguez-Seijo: Visualization, Validation, Writing—Review & Editing. All authors reviewed the results and approved the final version of the manuscript.

Availability of Data and Materials: The data used in this article are available within the article.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

References

1. Birch PRJ, Bryan G, Fenton B, Gilroy EM, Hein I, Jones JT, et al. Crops that feed the world 8: potato: are the trends of increased global production sustainable? Food Secur. 2012;4(4):477–508. [CrossRef].
2. Zhang H, Xu F, Wu Y, Hu HH, Dai XF. Progress of potato staple food research and industry development in China. J Integr Agric. 2017;16(12):2924–32. [CrossRef].
3. Burgos G, Zum Felde T, Andre C, Kubow S. The potato and its contribution to the human diet and health. In: The potato crop. Cham, Switzerland: Springer International Publishing; 2020. p. 37–74. [CrossRef].

4. Devaux A, Goffart JP, Petsakos A, Kromann P, Gatto M, Okello J, et al. Global food security, contributions from sustainable potato agri-food systems. In: The potato crop. Cham, Switzerland: Springer International Publishing; 2020. p. 3–35. [CrossRef].
5. Misgina NA, Beshir HM, Yohannes DB, Gebreyohanes GH. Growth, yield, and water productivity of potato genotypes under supplemental and non-supplemental irrigation in semi-arid areas of northern Ethiopia. Agronomy. 2025;15(1):72. [CrossRef].
6. Zhang N, Luo H, Li H, Bao M, Liu E, Shan W, et al. Maximizing potato tuber yields and nitrogen use efficiency in semi-arid environments by precision fertilizer depth application. Eur J Agron. 2024;156:127147. [CrossRef].
7. Pinochet D, Clunes J, Gauna C, Contreras A. Reasoned fertilization of potato in response to Nitrogen supply in Andisols. J Soil Sci Plant Nutr. 2018;18(3):790–803. [CrossRef].
8. Koch M, Naumann M, Pawelzik E, Gransee A, Thiel H. The importance of nutrient management for potato production part I: plant nutrition and yield. Potato Res. 2020;63(1):97–119. [CrossRef].
9. Ierna A, Distefano M. Crop nutrition and soil fertility management in organic potato production systems. Horticulturae. 2024;10(8):886. [CrossRef].
10. Sandaña P, Lizana CX, Pinochet D, Soratto RP. The nitrogen nutrition index as a tool to assess nitrogen use efficiency in potato genotypes. Eur J Agron. 2025;162:127397. [CrossRef].
11. Maier NA, McLaughlin MJ, Heap M, Butt M, Smart MK. Effect of current-season application of calcitic lime and phosphorus fertilization on soil pH, potato growth, yield, dry matter content, and cadmium concentration. Commun Soil Sci Plant Anal. 2002;33(13–14):2145–65. [CrossRef].
12. Oliveira RC, da Silva JRR, Lana RMQ, de Azevedo Pereira AI, Castoldi R, de Camargo R, et al. Fertilizer application levels in potato crops and the diagnosis and recommendation integrated system (DRIS). Agronomy. 2021;11(1):51. [CrossRef].
13. Goffart JP, Olivier M, Frankinet M. Potato crop nitrogen status assessment to improve N fertilization management and efficiency: past–present–future. Potato Res. 2008;51(3):355–83. [CrossRef].
14. Torabian S, Farhangi-Abriz S, Qin R, Noulas C, Sathuvalli V, Charlton B, et al. Potassium: a vital macronutrient in potato production—a review. Agronomy. 2021;11(3):543. [CrossRef].
15. Mancer H, Rouahna H, Souici S, Otmani Z, Bettiche F, Menasria H, et al. Effects of mineral and organic fertilization on potato production in sandy soil in arid region. Sci Afr. 2024;23:e02112. [CrossRef].
16. Khalil J, Al Karim Jaafar A, Habib H, Bouguerra S, Nogueira V, Rodríguez-Seijo A. The impact of olive mill wastewater on soil properties, nutrient and heavy metal availability—a study case from Syrian vertisols. J Environ Manage. 2024;351:119861. [CrossRef].
17. Olejnik D. Evaluation of the heavy metals content in sewage sludge from selected rural and urban wastewater treatment plants in Poland in terms of its suitability for agricultural use. Sustainability. 2024;16(12):5198. [CrossRef].
18. Shi X, Lin Q, Deng P, Feng T, Zhang Y. Assessment of heavy metal uptake in potatoes cultivated in a typical karst landform, Weining county, China. Foods. 2022;11(15):2379. [CrossRef].
19. Barajas-Aceves M. Organic waste as fertilizer in semiarid soils and restoration in mine sites. In: Larramendy ML, Soloneski S, editors. Organic fertilizers-from basic concepts to applied outcomes. London, UK: IntechOpen; 2016. p. 243–71 [cited 2025 Jan 1]. Available from: https://www.intechopen.com/chapters/50260.
20. Gee GW, Bauder JW. Particle-size analysis. In: Klute A, editor. Methods of soil analysis: part 1 physical and mineralogical methods. Madison, WI, USA: American Society of Agronomy, Soil Science Society of America; 1986. p. 383–411. [CrossRef].
21. FAO. Standard Operating Procedure for Soil Bulk Density, Cylinder Method [Internet]. Rome, Italy: FAO; 2023 [cited 2025 Jan 1]. Available from: https://openknowledge.fao.org/handle/20.500.14283/cc7568en.
22. Conyers MK, Davey BG. Observations on some routine methods for soil pH determination. Soil Sci. 1988;145(1):29–36. [CrossRef].
23. Jones JB. Laboratory guide for conducting soils tests and plant analysis. Boca Raton, FL, USA: CRC Press; 2001. [CrossRef].
24. Drouineau G. Dosage rapide du calcaire actif de sols. Ann Agron. 1942;12:441–450.
25. Walkley A, Black IA. An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 1934;37(1):29–38. [CrossRef].

26. Bremner JM. Nitrogen-total. In: Methods of soils analysis: chemical methods. Madison, WI, USA: American Society of Agronomy, Soil Science Society of America; 1996. p. 1085–211. [CrossRef].
27. Olsen SR, Cole CV, Watanabe FS, Dean LA. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Washington, DC, USA: U.S. Department of Agriculture; 1954.
28. Lu R. Methods of soil agricultural chemical analysis. Beijing, China: China Agricultural Science and Technology Press; 2000.
29. Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci Soc Am J. 1978;42(3):421–8. [CrossRef].
30. Chapman HD, Pratt FP. Ammonium vandate-molybdate method for determination of phosphorus. In: Methods of analysis for soils, plants and water. 1st ed. San Luis Obispo, CA, USA: California University, Agriculture Division; 1961. p. 184–203.
31. Tandon HLS. Methods of analysis of soils, plants, waters and fertilizers. New Delhi, India: Fertilizer Development and Consultation Organization; 2001.
32. Jorhem L. Determination of metals in foods by atomic absorption spectrometry after dry ashing: NMKL collaborative study. J AOAC Int. 2000;83(5):1204–11. [CrossRef].
33. USEPA. A Plain English Guide to the EPA Part 503 Biosolids Rule. Washington, DC, USA: United States Environmental Protection Agency; 1994 [cited 2025 Jan 1]. Available from: https://www.epa.gov/biosolids/plain-english-guide-epa-part-503-biosolids-rule.
34. Wang X, Duan Y, Zhang J, Ciampitti IA, Cui J, Qiu S, et al. Response of potato yield, soil chemical and microbial properties to different rotation sequences of green manure-potato cropping in North China. Soil Tillage Res. 2022;217:105273. [CrossRef].
35. Ali MME, Petropoulos SA, Selim DAFH, Elbagory M, Othman MM, Omara AE, et al. Plant growth, yield and quality of potato crop in relation to potassium fertilization. Agronomy. 2021;11(4):675. [CrossRef].
36. Jarén C, López A, Arazuri S. Advanced analytical techniques for quality evaluation of potato and its products. In: Advances in potato chemistry and technology. Amsterdam, The Netherlands: Elsevier; 2016. p. 563–602. [CrossRef].
37. CXS 193-1995. General standard for contaminants and toxins in food and feed. Rome, Italy: FAO; 2024.
38. Paradelo R, Villada A, Devesa-Rey R, Moldes AB, Domínguez M, Patiño J, et al. Distribution and availability of trace elements in municipal solid waste composts. J Environ Monit. 2011;13(1):201–11. [CrossRef].
39. Paradelo R, Cambier P, Jara-Miranda A, Jaulin A, Doublet J, Houot S. Mobility of Cu and Zn in soil amended with composts at different degrees of maturity. Waste Biomass Valorization. 2017;8(3):633–43. [CrossRef].
40. European Parliament. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 Laying Down Rules on the Making Available on the Market of EU Fertilizing Products and Amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and Repealing Regulation (EC) No 2003/2003. 2019 [cited 2025 Jan 1]. Available from: http://data.europa.eu/eli/reg/2019/1009/oj.
41. Chen F, Zhou B, Zhang Y, Chen X. Stricter cadmium and lead standards needed for organic fertilizers in China. Sci Total Environ. 2025;980:179561. [CrossRef].
42. Zarzecka K, Gugała M, Mystkowska I, Sikorska A. Total and true protein content in potato tubers depending on herbicides and biostimulants. Agronomy. 2020;10(8):1106. [CrossRef].
43. Ozlu E, Kumar S. Response of soil organic carbon, pH, electrical conductivity, and water stable aggregates to long-term annual manure and inorganic fertilizer. Soil Sci Soc America J. 2018;82(5):1243–51. [CrossRef].
44. Domínguez M, Paradelo Núñez R, Piñeiro J, Barral MT. Physicochemical and biochemical properties of an acid soil under potato culture amended with municipal solid waste compost. Int J Recycl Org Waste Agric. 2019;8(2):171–8. [CrossRef].
45. Singh VK, Malhi GS, Kaur M, Singh G, Jatav HS. Use of organic soil amendments for improving soil ecosystem health and crop productivity. In: Jatav HS, Rajput VD, editors. Ecosystem services: types, management and benefits. Hauppauge, NY, USA: Nova Science Publishers, Inc; 2022. p. 259–77.
46. Sandaña P, Orena S, Rojas JS, Kalazich J, Uribe M. Critical value of soil Olsen-P for potato production systems in volcanic soils of Chile. J Soil Sci Plant Nutr. 2018;18(4):965–76. [CrossRef].
47. Ashrafzadeh S, Gaw S, Genet R, Glover CN, Leung DWM. Natural variation in correlations between cadmium and micronutrients in potato tubers. J Food Compos Anal. 2017;59:55–60. [CrossRef].

48. Golui D, Datta SP, Dwivedi BS, Meena MC, Ray P, Trivedi VK. A new approach to establish safe levels of available metals in soil with respect to potential health hazard of human. Environ Earth Sci. 2021;80(19):667. [CrossRef].
49. Kabata-Pendias A. Trace elements in soils and plants. 4th ed. Boca Raton, FL, USA: CRC Press; 2011. [CrossRef].
50. Yu X, Li H, Yang Q, Sun Z, Ma Y. Accumulation of Cr in different vegetables and derivation of soil Cr threshold using the species sensitivity distribution method. Ecotoxicol Environ Saf. 2023;258:114993. [CrossRef].
51. Smith SR. A critical review of the bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge. Environ Int. 2009;35(1):142–56. [CrossRef].
52. Elloumi N, Belhaj D, Jerbi B, Zouari M, Kallel M. Effects of sewage sludge on bio-accumulation of heavy metals in tomato seedlings. Span J Agric Res. 2016;14(4):e0807. [CrossRef].
53. Urra J, Alkorta I, Garbisu C. Potential benefits and risks for soil health derived from the use of organic amendments in agriculture. Agronomy. 2019;9(9):542. [CrossRef].
54. Keçeci M, Usul M, Güçdemir I, Uygur V. Short-term residual effect of municipal sewage sludge on the soil properties and potato yield. Soil Stud. 2022;11(2):70–7. [CrossRef].
55. Jasim A, Sharma LK, Zaeen A, Bali SK, Buzza A, Alyokhin A. Potato phosphorus response in soils with high value of phosphorus. Agriculture. 2020;10(7):264. [CrossRef].
56. Kosolapova AI, Yamaltdinova VR, Mitrofanova E, Fomin DS, Teterlev IS. Yields of field crops and sod-podzolic soil fertility of west ural depending on fertilizer system. Bulg J Agric Sci. 2017;22(3):381–5.
57. Golbiak MS, Rutkowska B. Evaluating potential of municipal sewage sludge for agricultural use. Soil Sci Ann. 2023;74(2):169923. [CrossRef].
58. Zhapparbergenov R, Suleimenova N, Yeleuova E, Akmullayeva A, Kussainova G, Zhussupova L, et al. Effects of nitrogen application on potato (*Solanum tuberosum* L.) yield and soil nitrate dynamics in a sandy loam soil. Eurasian J Soil Sci Ejss. 2025;14(2):149–56. [CrossRef].
59. Gelaye Y. Effect of combined application of organic manure and nitrogen fertilizer rates on yield and yield components of potato: a review. Cogent Food Agric. 2023;9(1):2217603. [CrossRef].
60. Tyasmoro SY, Pratama GNB, Saitama A, Armandoni EA, Wicaksono KP, Setiawan A, et al. The effect combination of liquid organic fertilizer and inorganic fertilizer on potato (*Solanum tuberosum* L.) var. granola G2. Int J Environ Agric Biotechnol. 2024;9(2):124–30. [CrossRef].
61. Ferdoushi S, Farooque A, Alam M. Effects of organic and inorganic fertilizer management practices and mulch on the growth and yield of potato. J Agrofor Environ. 2010;3(2):175–8.
62. Idrees M, Raki AA, Baig KS, Akram M. Comparative effectiveness of different levels of NPK and potassium humate on leaf mineral content of potato (*Solanum tuberosum* L.). Int J Biosci. 2019;15(6):354–62. [CrossRef].
63. El-Sayed SF, Hassan HA, El-Mogy MM, Abdel-Wahab A. Growth, yield and nutrient concentration of potato plants grown under organic and conventional fertilizer systems. Am Eurasian J Agric Environ Sci. 2014;14(7):636–43. [CrossRef].
64. White PJ, Bradshaw JE, Finlay M, Dale B, Ramsay G, Hammond JP, et al. Relationships between yield and mineral concentrations in potato tubers. HortScience. 2009;44(1):6–11. [CrossRef].
65. Yuan J, Wang J, Ye J, Dai A, Zhang L, Wang J, et al. Long-term organic fertilization enhances potassium uptake and yield of sweet potato by expanding soil aggregates-associated potassium stocks. Agric Ecosyst Environ. 2023;358:108701. [CrossRef].
66. Cheraghi M, Lorestani B, Merrikhpour H, Rouniasi N. Heavy metal risk assessment for potatoes grown in overused phosphate-fertilized soils. Environ Monit Assess. 2013;185(2):1825–31. [CrossRef].
67. Moghtaderi T, Shakeri A, Rodríguez-Seijo A. Potentially toxic element content in arid agricultural soils in south Iran. Agronomy. 2020;10(4):564. [CrossRef].
68. Ballabio C, Jones A, Panagos P. Cadmium in topsoils of the European Union—an analysis based on LUCAS topsoil database. Sci Total Environ. 2024;912:168710. [CrossRef].
69. Paltseva AA, Cheng Z, McBride M, Deeb M, Egendorf SP, Groffman PM. Legacy lead in urban garden soils: communicating risk and limiting exposure. Front Ecol Evol. 2022;10:873542. [CrossRef].
70. Sawicka B, Pszczółkowski P, Messaoudi M, Skiba D, Barbaś P, Krochmal-Marczak B, et al. Genotype, environment, and heavy metals: variability of the content of elements in 40 potato varieties from central-eastern Poland. Chem Biodivers. 2025;22(6):e202403337. [CrossRef].
71. Mench MJ. Cadmium availability to plants in relation to major long-term changes in agronomy systems. Agric Ecosyst Environ. 1998;67(2–3):175–87. [CrossRef].

72. Karam NS, Ereifej KI, Shibli RA, AbuKudais H, Alkofahi A, Malkawi Y. Metal concentrations, growth, and yield of potato produced from *in vitro* plantlets or microtubers and grown in municipal solid-waste-amended substrates. J Plant Nutr. 1998;21(4):725–39. [CrossRef].
73. Antonious GF, Snyder JC. Accumulation of heavy metals in plants and potential phytoremediation of lead by potato, *Solanum tuberosum* L. J Environ Sci Health A Tox Hazard Subst Environ Eng. 2007;42(6):811–6. [CrossRef].
74. Setiyo Y, Harsojuwono BA, Wayan Gunam IB. The concentration of heavy metals in the potato tubers of the basic seed groups examined by the variation of fertilizers, pesticides and the period of cultivation. AIMS Agric Food. 2020;5(4):882–95. [CrossRef].
75. Orellana-Mendoza E, Camel V, Yallico L, Quispe-Coquil V, Cosme R. Effect of fertilization on the accumulation and health risk for heavy metals in native Andean potatoes in the Highlands of Perú. Toxicol Rep. 2024;12:594–606. [CrossRef].
76. Wang L, Zhou H, Yang K, Er Ze L, Lu Z, Li Y, et al. Reducing Cd and Pb accumulation in potatoes: the role of soil passivators in contaminated mining soils. Life. 2024;14(12):1615. [CrossRef].
77. Musilova J, Bystricka J, Vollmannova A, Volnova B, Hegedusova A. Factors affecting heavy metals accumulation in potato tubers/Czynniki wpływające na akumulację metali ciężkich w bulwach ziemniaka. Environ Prot Nat Resour. 2015;26(3):54–9. [CrossRef].
78. Musilova J, Bystricka J, Lachman J, Harangozo L, Trebichalsky P, Volnova B. Potatoes—a crop resistant against input of heavy metals from the metallicaly contaminated soil. Int J Phytoremediation. 2016;18(6):547–52. [CrossRef].
79. Khan ZI, Ahmad K, Yasmeen S, Akram NA, Ashraf M, Mehmood N. Potential health risk assessment of potato (*Solanum tuberosum* L.) grown on metal contaminated soils in the central zone of Punjab, Pakistan. Chemosphere. 2017;166:157–62. [CrossRef].
80. Ye Y, Dong W, Luo Y, Fan T, Xiong X, Sun L, et al. Cultivar diversity and organ differences of cadmium accumulation in potato (*Solanum tuberosum* L.) allow the potential for Cd-safe staple food production on contaminated soils. Sci Total Environ. 2020;711:134534. [CrossRef].
81. Baghour M, Moreno DA, Víllora G, Hernández J, Castilla N, Romero L. Phytoextraction of Cd and Pb and physiological effects in potato plants (*Solanum tuberosum* var. Spunta): importance of root temperature. J Agric Food Chem. 2001;49(11):5356–63. [CrossRef].
82. Brengi SH, El-Gindy AM, El-Sharkawy I, Abouelsaad IA. Variation in cadmium accumulation among potato cultivars grown on different agricultural sites: a potential tool for reducing cadmium in tubers. Horticulturae. 2021;7(10):377. [CrossRef].