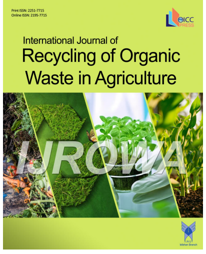

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Analysis of the fertilizing potential of sewage sludge and its impact on agriculture and the environment

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Abstract:
Purpose: The management of sewage sludge represents a major environmental challenge on a global scale, as poor management can lead to significant risks for public health and the environment. This study aims to assess the fertilizing potential of sludge and its impact on agriculture and the environment, offering a sustainable solution for recovering this waste while improving soil fertility.
Method: First, a physico-chemical study was carried out to identify the nutrients and organic and metallic pollutants present in the sludge analysed. Subsequently, the potential of this sludge as an organic fertilizer was evaluated. The impact of sludge application was studied on plants, with a quantification of heavy metals in the aerial and root tissues of the inoculated plants.
Result: The sludge analyzed contains high organic matter (85.57%) and moisture (53.67%), making it ideal as a soil improver to enhance structure and water retention. Rich in phosphorus (71%), it supports plant growth. Organic and metallic micropollutants are present only at trace levels, well below AFNOR limits. Sludge application promotes heavy metal absorption by plants, with accumulation in aerial parts and soil. It also boosts plant dry biomass in aerial and root tissues, while heavy metal levels in plant tissues remain within regulatory thresholds.
Conclusion: These promising results allow recommendations to be considered for promoting increased use of sludge in agriculture to improve yields. Integrating sludge recovery into a circular bioeconomy approach not only helps to reduce the amount of sludge generated, but also to limit their environmental impact.

Keywords: Agriculture; Heavy metals; Fertilizer; Valorization

1. Introduction

During the treatment of municipal and industrial wastewater, large quantities of sludge are generated. Estimates suggest that the United States produces 240 million tonnes of sludge every year (Pritchard et al., 2010). In Union Europe. the total annual production of sewage sludge is estimated at 10 million tons per year (Buta et al., 2021). In China, production is estimated at 39 million tons per year (Wei et al., 2020). In the Maghreb, sludge production in Morocco reaches 2 million tons (Arisily and Hajji, 2020). In Algeria, specifically in the western region, the quantity of sludge produced is estimated at around 225,000 tons per year (Sahnoun, 2019). The management of this sludge is one of the world's most pressing environmental challenges, with adverse impacts on public health and the environment (Gulnar Sugurbekova et al., 2020).
Sludge makes a significant contribution in terms of organic matter, nitrogen, phosphorus, trace elements and humic compounds (Karbaout et al., 2021). This richness has given rise to the promising idea of using them effectively in agriculture (Chowdhury et al., 2022), a practice considered beneficial for the environment (Eugen et al., 2023). Indeed, the use of these sludge in crops can improve agricultural productivity by providing plants with essential nutrients (Karlsons

et al., 2016) while preserving soil fertility (Losada et al., 2012). This approach has demonstrated positive results, including increasing the nitrogen content of leaf tissue (Zouari et al., 2021), substituting chemical fertilizers (Boudjabi and Chenchouni, 2021), improving the amount of organic matter and soil porosity (Sohail et al., 2022), as well as stimulating microbial activity (Boudjabi et al., 2023). These results highlight the importance of considering sludge as a valuable resource in sustainable agricultural management, in line with the concept of the circular bioeconomy.

The application of sewage sludge rapidly improves soil fertility by increasing nutrient levels, including nitrogen and phosphorus, as opposed to practices such as composting and green manure, which enrich the soil more gradually and at a slower pace (Eriksen et al., 1999). Unlike crop rotation and agroforestry, which promote long-term soil health, sewage sludge provides an immediate nutrient supply, which is particularly beneficial for depleted soils or intensive cropping systems (Jose, 2009).

However, sludge from wastewater treatment plants contains a diversity of pathogenic microorganisms, whose survival depends on the consumption of nutrients present in the sludge (Godoy et al., 2018). Sludge contains harmful compounds such as organic micropollutants (Ayub et al., 2022) and heavy metals (Bouzekri and Houhamdi, 2023). However, these potential risks can be mitigated by appropriate treatment (Roychoudhury and Das, 2022).

Today, sludge management has become essential to cope with the constant increase in this type of waste. The use of sludge as a soil improver presents a potential risk of contamination by the heavy metals it contains, jeopardizing soil and crop quality. These heavy metals can cause phytotoxic effects if their concentrations exceed regulatory standards (Keller et al., 2002).

The aim of this article is to analyze the impact of sludge application on the properties of the cultivated soil, the development of *Phaseolus vulgaris* and *Medicago sativa* crops and to determine the fate of heavy metals introduced by sludge. Safe and effective sludge management is crucial to safeguarding human health and ensuring environmental sustainability. The use of sludge in agriculture makes it possible to manage the considerable quantities generated while reducing dependence on chemical fertilizers, thus contributing to a more sustainable approach to waste management.

2. Material and methods

Sludge and soil sampling

The sludge used in this study was taken from the Cap Falcon wastewater treatment plant (Fig. 1), located 3 km from the commune of Aïn El Turk, northwest of Oran, Algeria (35º45′38.8″ N latitude and 0º48′32.8″ W longitude). As for the substrate, we used sand from the Terga Ain Témouchent sand pit (Fig. 1), located 85 km west of Oran, Algeria (35º26′33.03″ North latitude and 1º13′33.48″ West longitude). The region has a semi-arid Mediterranean climate, with approximately 405 mm of annual precipitation and an average temperature of 18 ºC. Sampling was carried out at a depth of 0 to 20 cm.

Physico-chemical analysis of sewage sludge and substrate

The biological material studied, i.e. sand and sludge, was subjected to physico-chemical analysis at Public Laboratory Consulting, Expertise and Analysis (LABOCEA). Nitrogen was determined by the Kjeldahl method, in accordance with standard NF13342, while phosphorus was mineralized in accordance with standard NF en ISO 11885. pH was measured by the potentiometric method in accordance with standard NF15933. Moisture content was assessed using an infrared desiccator (KERN), and organic matter (OM), dry matter (DM) and total carbon (TC) contents were calculated. Extraction of organic pollutants from the sludge was carried out using LABOCEA's in-house method, in compliance with standard XPX33012.

Determination was then performed using a gas chromatograph (GC/MS). Heavy metals were determined after min-

Figure 1. Geographical location of sampling sites.

eralization in accordance with NF en ISO 11885, using an inductively coupled plasma optical emission spectrometer (ICP-OES).

Experimental design

Research focused on two leguminous plants, *Phaseolus vulgaris* and *Medicago sativa*, of the *Fabaceaes* family, because of their nutritional and economic importance. For cultivation, healthy *Phaseolus vulgaris* seeds were disinfected using the method recommended by Tillard and Drevon (1988), while *Medicago sativa* seeds were disinfected using the technique of Baha and Bekki (2015). The pre-germinated seeds were placed in pots containing sand. Variable amounts of 0%, 5%, 10%, 15%, 20%, 25%, 75% and 100% (W/V). The liquid slurry were then added to the *Phaseolus vulgaris* and *Medicago sativa* crops. This experiment took place over a three-month period in a greenhouse, under controlled conditions.

Analysis of crop parameters

To assess the impact of the various sludge concentrations examined on the development of the two plants, a first growth parameter was evaluated by measuring the dry weight of the aerial and root parts of each plant for the different concentrations of liquid sludge. Heavy metal accumulation in the aerial parts of the plants was extracted by mineralization using the method of Tauzin and Juste (1986). The levels of these elements were then measured using an inductively coupled plasma optical emission spectrometer (ICP-OES).

Statistical analysis

Statistical analyses were carried out using STATISTICA version 6.0 software. A normality test was performed and, depending on the result, the variables were subjected to a one-way analysis of variance. The threshold used to determine the probability of significance for all tests was 5%. Duncan's test was used to determine homogeneous groups.

3. Results and discussion

Fertilizing elements

Sludge from wastewater treatment contains essential plant nutrients. Their use in agriculture contributes to the fertility of the soil while enhancing these resources. The main objective of this section is to present the nutrients contained in the soil and sludge studied (Table 1).

Table 1. Fertilizing element contents in the sludge studied.

Parameters	Quantity in %	
	The Sludge	**The Support**
Organic matter (OM)	85.57	0.12
Humidity	53.67	39.69
Dry matter (DM)	89.40	99.01
Phosphorus (P)	31	0.16
Total phosphorus (P_2O_5)	71	1.25
Nitrogen	50	0.11
Total carbon (C)	49.75	0.53
pH	6.85	8.72
C/N	0.99	4.81

The sludge studied has a high content of organic matter (85.57%) and moisture (53.67%), which makes it favorable as an amendment to improve soil structure and water retention. It also contains significant levels of phosphorus (31% P and 71% P_2O_5), essential for plant development. However, the low C/N ratio (0.99) suggests a rapid decomposition of organic matter. With a pH close to neutrality (6.85), the sludge is suitable for most crops, thus facilitating the availability of nutrients. Overall, these characteristics show that sludge could be an effective soil amendment to enrich soils with nutrients while improving their structure. The substrate studied is characterized by a very low content of organic matter (0.12%) and essential nutrients such as phosphorus, nitrogen, and total carbon. High dry matter (99.01%), making it stable and easy to handle. Alkaline pH (8.72) could limit the availability of nutrients to plants. With a low C/N ratio (4.81), the substrate could promote rapid decomposition of organic matter, although this is minimal. The results clearly show that sewage sludge used represents a valuable source of nutrients, reflected by its richness in organic matter, total phosphorus bioavailable in its assimilable form, carbon and nitrogen. The high concentration of organic matter suggests a sludge rich in carbon compounds, which is beneficial for biological processes in soil. The high phosphorus content in sludge indicates that it could be a potential source of this essential nutrient for plant growth. The high nitrogen concentration suggests that sludge can also be a source of nitrogen, another essential nutrient for plants. The high carbon content of sludge can also contribute to improved soil structure.

The C/N (carbon/nitrogen) ratio is an indicator of substrate nitrogen content and biological activity, which reveals the ability of an organic product to decompose. A low C/N ratio means easier biodegradation of sludge. Excess nitrogen turns to ammonia and nitrate (sludge with C/N < 10) (Bipfubusa et al., 2006). These findings are corroborated by Cellier et al. (2014), who demonstrated that the reduction in C/N ratio is correlated with an increase in biological activity, a finding that aligns with the results presented in our study. The amount of organic matter present in the sludge varies according to its origin, and in the present case is around 86%. This result is in line with Smith (2009) analyses, which reported percentages varying between 30% and 80%. For phosphorus, an essential element for the survival and growth of bacteria, the content obtained is particularly interesting (70%), which suggests that the studied sludge could meet the needs of microorganisms and plants, as observed for red clover growth (Wollmann and Möller, 2022). The moisture content of the sludge studied was 53.6%, a value which, although relatively high, is lower than that of up to 98.12% in other sludge samples (Lopes et al., 2021). However, sludge dry matter, generally above 50%, is in good agreement with the results obtained, slightly exceeding 89%. The proportion of nitrogen in the sludge studied is also remarkable, varying between 50% and 54%, in line with the proportions of 50 to 90% of dry matter indicated by Sommers (1977) and confirmed by the work of Quoc et al. (2021), attesting to proportions between 70% and 90%. The carbon content of the sludge studied ranged from 49.75% to 50.43%, significantly exceeding the 15.17% reported by Douaer et al. (2021). These results confirm that carbon, together with nitrogen, constitutes the predominant part of the organic matter in the sludge studied. The pH of the sludge studied is neutral (6.85), in agreement with other works such as those by Karbaout et al. (2021), who noted the neutrality of the sludge pH.

Heavy metals

Wastewater treatment generates purified water on one side and a residue called sludge on the other. This sludge contains heavy metals, which can be attributed to various activities such as domestic, urban or commercial activities. These metals are illustrated in Fig. 2.

The results of this analysis show that the sludge studied contains a wide range of heavy metals, namely cadmium, lead, copper, chromium, nickel, zinc, selenium, mercury and arsenic. It should be noted that the concentration of zinc is significantly higher than that of the other metals. Overall, the concentration of all metals is well below the AFNOR standard (Table 2).

The cadmium supplied by the sludge studied showed concentrations six times lower than the regulatory threshold, in line with the study by Shamuyarira and Gumbo (2014). Notably, cadmium was not detected in the sludge analyzed by Kyayesimira et al. (2019). As for lead in the sludge studied, its concentrations are six times lower than the regulatory threshold. Analyses by Shamuyarira and Gumbo (2014) show a concentration of around 171.85 mg/kg, while the sludge studied by Lopes et al. (2021) has a content equivalent to 80 mg/kg. For copper, the concentration is four times lower than the threshold set by the AFNOR standard, and chromium is 24 times lower than the recommended standard. Although these metals can be toxic at high concentrations (Su et al., 2004), at low levels they are essential for plant development (Chang et al., 1992). Nickel levels are ten times lower than the threshold recommended by the standard, showing no toxic effect on rhizobia. This finding is confirmed by the work of Chaintreuil et al. (2007), who highlight the resistance of *Bradyrhizobium* and *Rhizobium metallicole* (RP5) (Wani et al., 2008) to this element. The zinc concentration in the sample is three times lower than the AFNOR standard, which is favorable for our study. When studying the tolerance of *Rhizobium leguminosarum* and *Ensifer medicae* to this element. Concentrations of selenium and mercury in the sludge studied are very low compared to the regulatory threshold. Selenium, which can have toxic effects on micro-organisms (Pier-Anne, 2009), is present in trace amounts. Mercury, on the other hand, whose quantity can vary depending on the origin of the sludge, has no effect on *Rhizobium leguminosarum* (Nonnoi et al., 2012). The arsenic supplied by the sludge studied, resulting from the treatment of urban wastewater, presents relatively higher concentrations than those found by Donguy and Chenon (2017), which are of the order of 4.63 mg/kg dry matter.

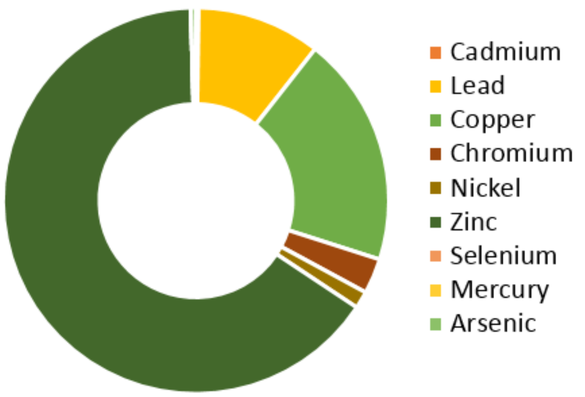


Figure 2. Heavy metals (mg/kg MS) contained in the sludge studied.

Table 2. Heavy metal content limits in sludge.

Heavy metals	
Cadmium	10
Lead	800
Copper	1000
Chromium	1000
Nickel	200
Zinc	3000
Selenium	100
Mercury	10
Arsenic	-

Sludge content limits (mg/kg MS) in accordance with AFNOR standards (NF en ISO11-885).

Organic pollutants

Chromatographic analysis of the sludge confirms the presence of organic pollutants such as Polycyclic Aromatic Hydrocarbons (PAHs), Polychlorobiphenyls (PCBs), TriButylEtains (TBTs) and Benzene Toluene Ethyl-benzene Xylenes (BTEXs). Their concentrations are listed in Table 3.

The results obtained show that the concentrations of organic pollutants contained in the sludge studied all comply with AFNOR standards.

These low concentrations can be attributed to the fact that the sludge studied is of domestic origin, which means that it can be used without any risk. Chromatographic analysis of the sludge studied identified the presence of eight families of polycyclic aromatic hydrocarbons (PAHs), namely Anthracene, Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Fluoranthene and Benzo(g.h.i) Perylene, in trace form, with concentrations well below standards. These low concentrations can be attributed to the fact that the sludge studied comes from domestic sources, allowing its use without major risk, given that, in most works, the

Table 3. Concentrations of organic pollutants in the sludge studied.

		Chemical Formula	Content (Mg/Kg MS)	Standard (Mg/Kg MS)
HAP	Anthracene	$C_{14}H_{10}$	< 0.1	-
	Benzo(a)pyrene	$C_{20}H_{12}$	< 0.1	2
	Benzo(b)Fluoranthene	$C_{20}H_{12}$	< 0.1	2.5
	Benzo(g.h.i)Perylene	$C_{22}H_{12}$	0.47	-
	Benzo(k)Fluoranthene	$C_{20}H_{12}$	< 0.1	-
	Fluoranthene	$C_{16}H_{10}$	< 0.1	5
TBT	(C H)493 Sn-X	< 5	-	
BTEXS	Benzene	C_6H_6	< 0.05	-
	Ethyl Benzene	C_8H_{10}	< 0.05	-
	Isopropyl Benzene	C_9H_{12}	< 0.05	-
	Toluene	C_7H_8	0.06	-
	Ortho Xylene	C_8H_{10}	< 0.05	-
PCB	PCB	$C_{12}H$ (10-n) Cln	0.2	0.8

average concentrations of PAHs in sludge generally range from 1 to 10 mg/kg (Poluszyńska et al., 2017). The presence of tributyltins (TBTs) in sewage sludge is associated with chemical-rich domestic activities such as paint, insecticides, detergents, etc. (David et al., 2012). The literature presents a limited number of studies on the presence of TBTs in sewage sludge. One study, for example, by Olofsson et al. (2012), highlighted an amount equal to 0.074 mg/kg dry matter of TBT in sludge.

BTEXs, composed of benzene, toluene, ethylbenzene and xylene, are volatile pollutants, considered carcinogenic (Masekameni et al., 2019) and are biodegradable by certain bacterial strains such as *Pseudoxanthomonas spadix* BDa59 (Choi et al., 2013) and *Bacillus sphaericus* (MTCC 8103) (Rahul et al., 2013). Other microorganisms, such as *Streptomyces*, use benzene, toluene and xylene as a source of carbon and energy (Hocinat et al., 2020). Polychlorinated biphenyls (PCBs) are commonly found in waste sludge, either from contamination by industrial effluents (Guo et al., 2020) or atmospheric deposition (Clarke et al., 2010). Patel et al. (2015) detected PCBs in sludge, but at very low concentrations of around 0.497 mg/kg.

Effect of sludge on the growth of *Phaseolus vulgaris* and *Medicago sativa*

Fig. 3 shows the effect of adding the sludge studied on the dry biomass of the above-ground and root parts of cultivated plants compared with the control (0% of the sludge).

The results shown in Fig. 3 (A) highlight the positive effect of the sludge studied on *Phaseolus vulgaris* cultivation. This observation probably suggests that the plants studied assimilate the elements necessary for their growth from the sludge, resulting in an increase in the dry biomass of above-ground parts at sludge concentrations ranging from 5% to 20%. Notably, the increase in root dry biomass is particularly noticeable at sludge concentrations of 5%. Similar effects were observed with *Medicago sativa* (Fig. 3 (B)), where significant changes in the biomass of the above-ground part were observed with slurry concentrations of 5% and 15%, reaching a maximum with a slurry concentration of 10%. As for the root part, biomass improved with sludge concentrations ranging from 5% to 15%.

The sludge studied helped improve the growth of *Phaseolus vulgaris* and *Medicago sativa*, corroborating the study carried out by Kassaoui et al. (2009), certifying that sludge application improves the dry biomass of tomato and lettuce, in particular by promoting the development of the root system of Schinus terebinthifolia at concentrations of 70 and 80% (Trigueiro and Guerrini, 2014). It also stimulates the growth of Passiflora alata (Freitas and Melo, 2013). A few years later, Soudani et al. (2017) demonstrated that sludge application increases the biomass of Eucalyptus camaldulensis seedlings. Sludge, which is often available to farmers, has proved useful for a number of crops, including barley (Soriano-Disla et al., 2014), rice (Fusi et al., 2017), Italian zucchini (Lopes et al., 2021), olive (Zouari et al., 2021), spinach (Krishna et al., 2021), sweet potato (Ragonezi et al., 2022), durum wheat (Boudjabi and Chenchouni, 2021), tomato (Benkhedda and Boudour, 2023), sorghum (Dimakas and Sakellariou-Makrantonaki, 2023), soybean (Marin and Rusănescu, 2023), fescue (Ongun et al., 2023) and Vigna radiata L (Bhagyashree et al., 2023). Our study complements the existing literature by confirming that the sludge under investigation offers specific advantages for legume growth, particularly for the species *Phaseolus vulgaris* and *Medicago sativa*.

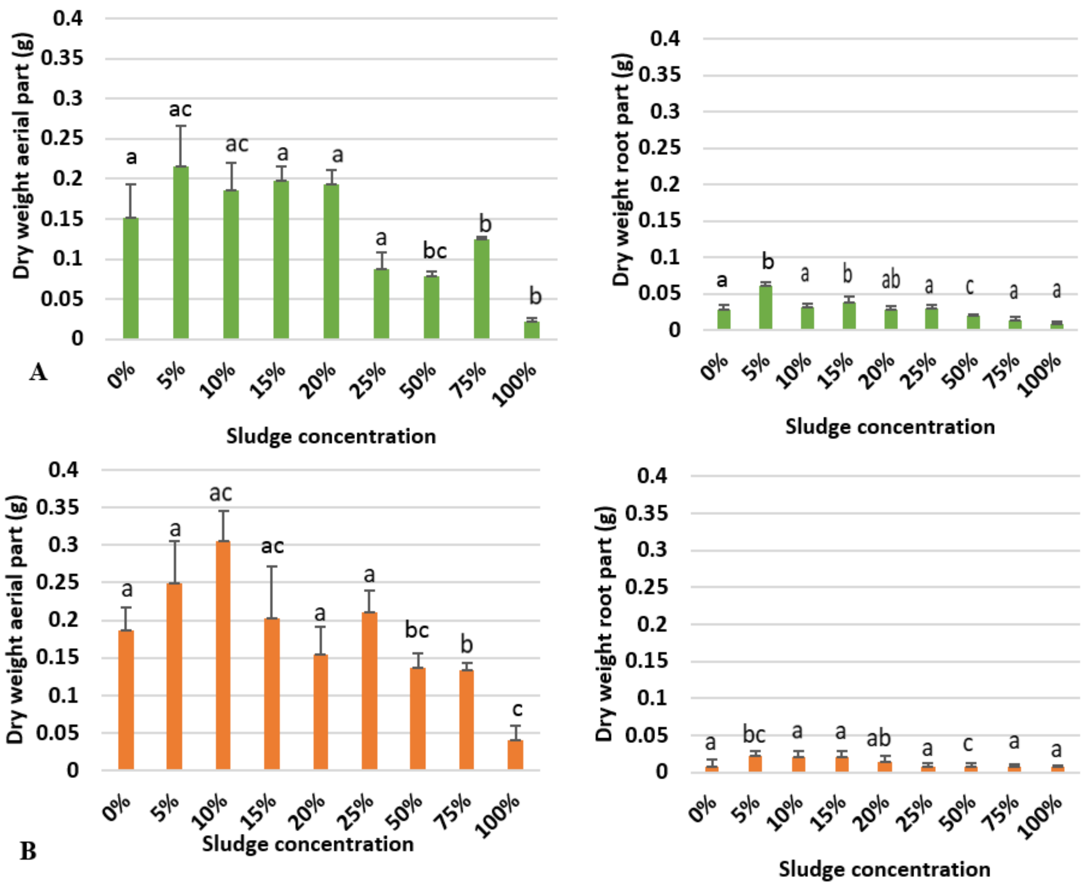


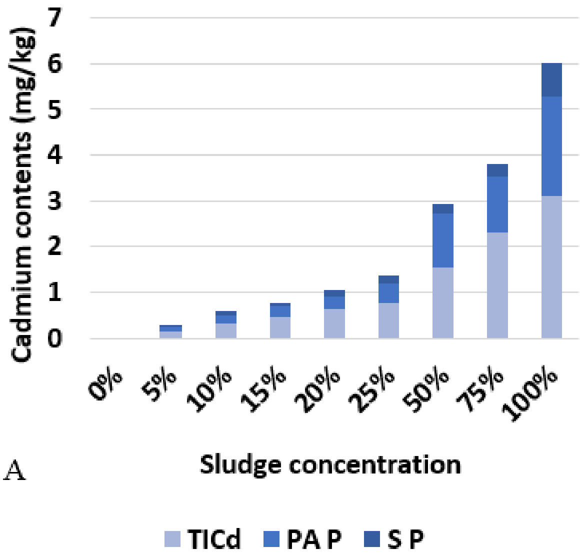
Figure 3. Application of sludge at different concentrations on the dry weight of the aerial and root parts of (A) *Phaseolus vulgaris* and (B) *Medicago sativa*.
Data represent the mean ± standard deviation of three replicates. Means for each parameter followed by different letters indicate a significant difference at the 5% threshold according to the Duncan test.

Although sewage sludge enriches the soil with essential nutrients such as nitrogen and phosphorus, it also introduces contaminants, notably cadmium, lead and mercury, which can gradually accumulate in the soil. This accumulation can lead to toxicity for plants, compromise microbial biodiversity, and pose risks to human health if these metals are absorbed by food crops (Nunes et al., 2021). Recent studies indicate that, despite strict regulations, heavy metals in sludge can persist and accumulate in the environment, particularly in the case of repeated or high-dose applications, underlining the need for continuous monitoring and appropriate management strategies to mitigate these long-term risks (Achkir et al., 2023). The use of sewage sludge in agriculture presents risks of contamination by heavy metals and organic micropollutants, which can affect human health and soil biodiversity (Sung et al., 2023; Kumar et al., 2023). These impacts vary depending on the composition of the sludge, influenced by its source and the treatment received (Cui et al., 2024).

Heavy metal accumulation

Sewage sludge provides appreciable quantities of nutrients. However, it also contains heavy metals such as cadmium, chromium, copper, nickel, lead and zinc. These products can be assimilated and stored by the plant and accumulate in the soil (Fig. 4).

The results obtained clearly show that the application of the sludge studied led to an accumulation of cadmium in the cultivated soils as well as in the aerial part of *Phaseolus vulgaris* and *Medicago sativa*. Cadmium uptake by *Phaseolus vulgaris* ranged from 46% to 66% following sludge application, while cadmium accumulation in soil cultivated with *Phaseolus vulgaris* varied from 11% to 23%. For *Medicago sativa*, cadmium uptake ranged from 48% to 61% following mud application, with cadmium accumulation in cultivated soil varying from 13% to 39%. Chromium uptake by *Phaseolus vulgaris* after application of the slurry ranged from 11% to 50%, with chromium accumulation in cultivated soil ranging from 3% to 28%. For *Medicago sativa*, uptake of this metal varies from 11% to 43% following application of the slurry, with chromium accumulation in cultivated soil ranging from 9% to 37%. A fraction of this metal is stored in the roots of the plants studied. The results indicate lower copper uptake in plants grown after slurry application, ranging from 2% to 8% for *Phaseolus vulgaris* and from 2% to 9% for *Medicago sativa*. Copper accumulation in soil grown with *Phaseolus vulgaris* ranged from 1% to 15%, and for *Medicago sativa* from 1% to 13%. The trend is similar for nickel, with lower uptake by *Phaseolus vulgaris*, ranging from 15% to 32%, and nickel accumulation in soil grown with *Phaseolus vulgaris* ranging from 8% to 21%. Nickel uptake by *Medicago sativa* ranged from 18% to 42%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Sludge concentration
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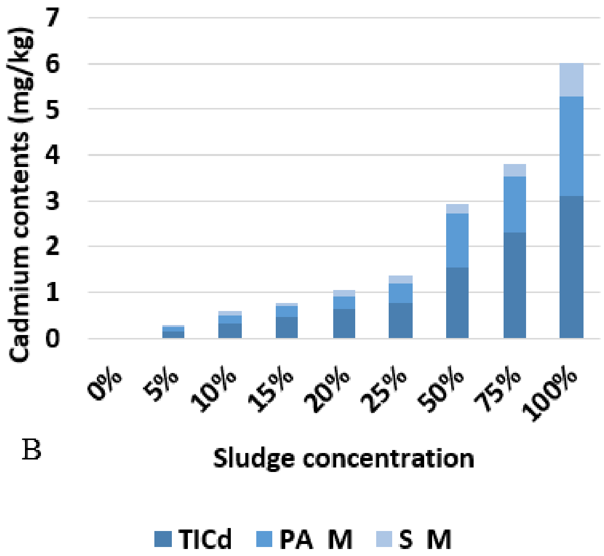
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Sludge concentration
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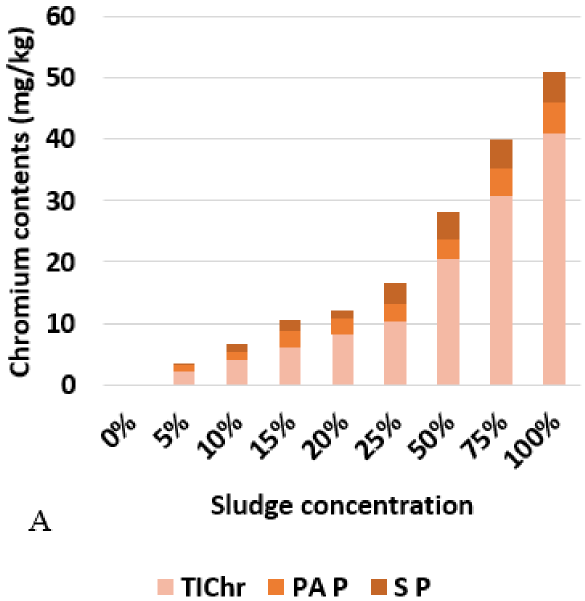
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0% 5% 10% 15% 20% 25% 50% 75% 100%
Sludge concentration
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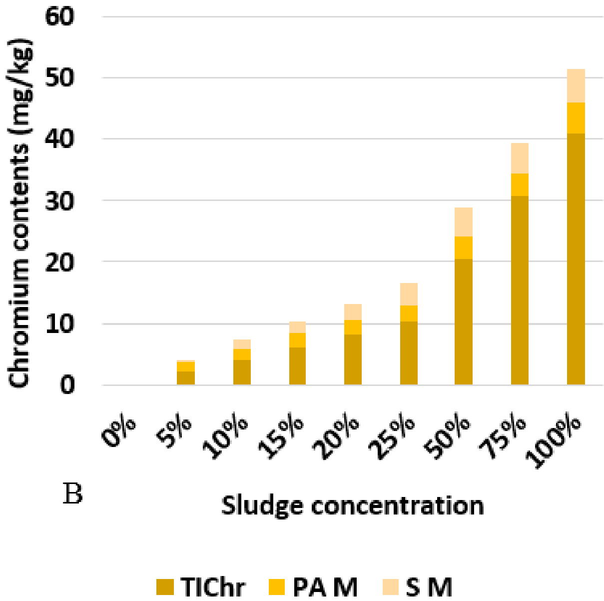
Chromium contents (mg/kg)
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Sludge concentration
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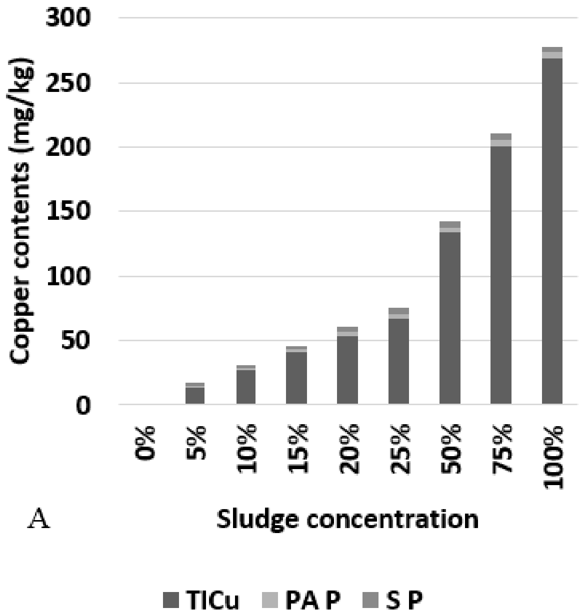
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Sludge concentration
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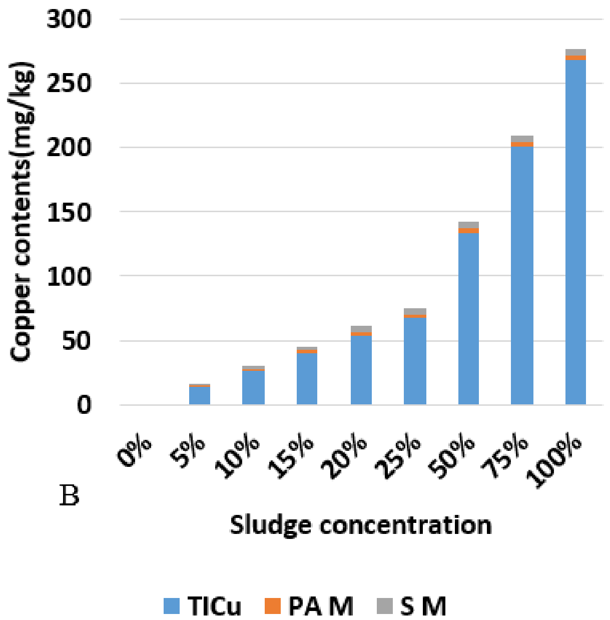
Copper contents(mg/kg)
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Sludge concentration
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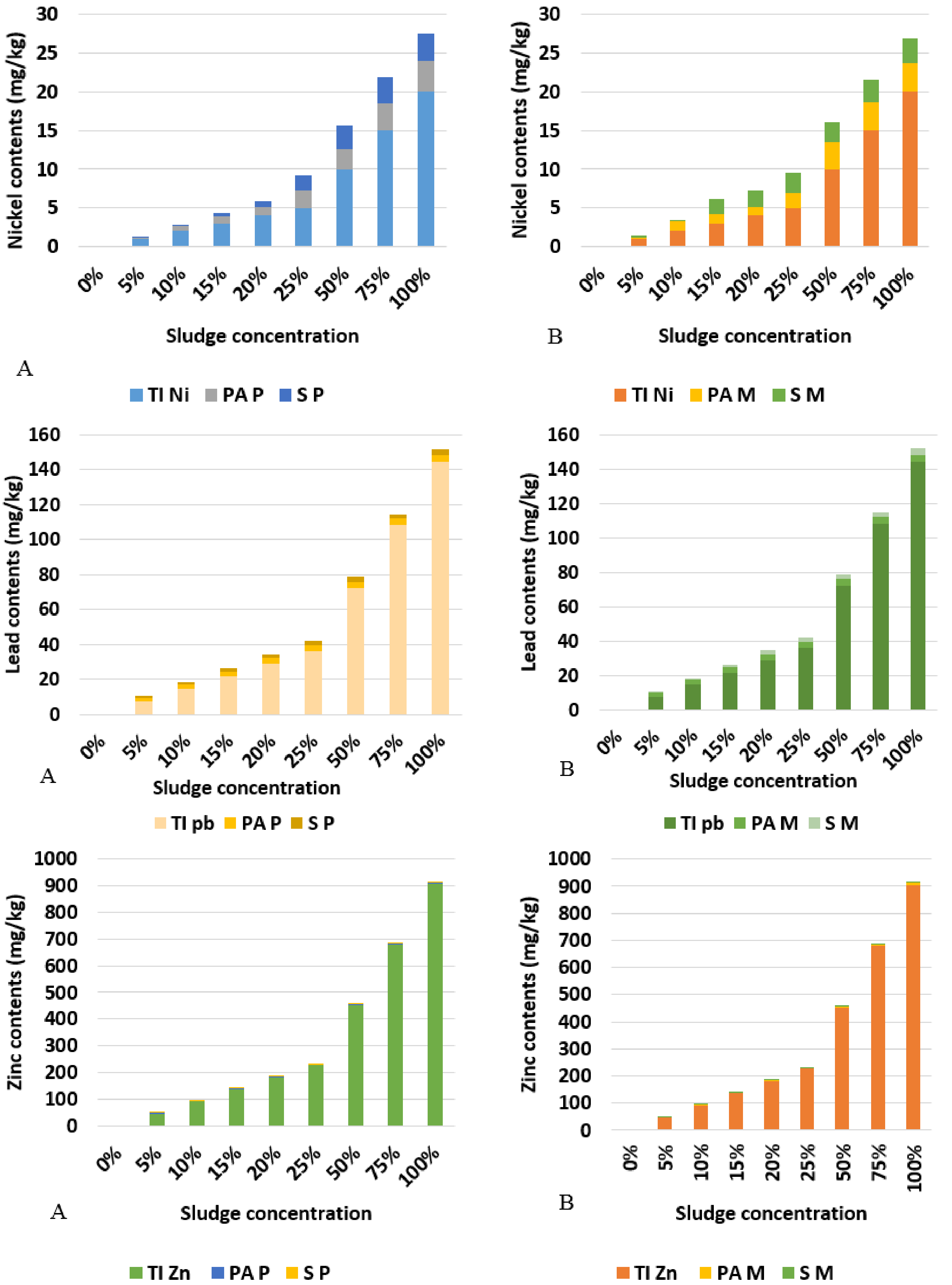

Figure 4. Heavy metal content in the aerial parts of (A) *Phaseolus vulgaris* and (B) *Medicago sativa*.
TI Cd: Initial cadmium content; TI Chr: Initial chromium content; TI Cu: Initial copper content; TI Ni: Initial nickel content; TI Pb: Initial lead content; TI Zn: Initial zinc content; PAP: Aerial part of *Phaseolus vulgaris*; PAM: Aerial part of *Medicago sativa*; SP: Soil cultivated with *Phaseolus vulgaris*; SM: Soil cultivated with *Medicago sativa*.

following the addition of sludge, with nickel accumulation in cultivated soil ranging from 9% to 30%. Lead uptake by *Phaseolus vulgaris* ranged from 2% to 31%, with lead accumulation in cultivated soil varying from 2% to 16%. For *Medicago sativa*, lead uptake ranged from 2% to 35% following addition of the slurry, with lead accumulation in cultivated soil ranging from 2% to 16%. Zinc uptake by *Phaseolus vulgaris* and *Medicago sativa* following sludge application ranged from 1% to 7%, with zinc accumulation in soil grown with *Phaseolus vulgaris* and *Medicago sativa* ranging from 1% to 5%.

The accumulation of heavy metals in plants is influenced by sludge concentration, as well as by soil properties, the nature of the metals and plant species (Hechmi et al., 2020). Cadmium, due to its ease of uptake by plants, probably led to significant accumulation of this metal in *Medicago sativa* and *Phaseolus vulgaris*. These observations are consistent with the results obtained by Hooda and Alloway (1994), highlighting the high mobility of cadmium compared with other metals. Cadmium transfer from soil to plant depends mainly on soil pH and concentration (Tudoreanu and Phillips, 2004). Chromium, which is soluble and bioavailable, has lower mobility in soil (Gupta et al., 2019). Copper, essential to plant metabolic function at concentrations below 100 mg/kg, is considered beneficial to plants (Lukowski and Dec, 2018). Nickel, also essential for plant growth, its uptake depends on its bioavailability and chemical form in the soil (Brown et al., 1987; Molas and Baran, 2004). Lead is relatively immobile and binds easily to soil particles (Chouti et al., 2018). Zinc, as an essential element for plant development, participates in various enzymatic reactions and key physiological functions (Noulas et al., 2018). Various studies have investigated the presence of heavy metals in different parts of plants. For example, Deng et al. (2004) found a high concentration of lead, up to 325 mg/kg, in the roots of *Typha latifolia* L. This amount is significantly higher than that found by Pazou Yehouenou et al. (2010), who recorded 0.459 mg/kg in the aerial part of *Amaranthus hybridus*. The results of Samake et al. (2011) also showed a level of 0.035 mg/kg in the aerial part of *Brassica oleracea*, well below the concentration observed by Deng et al. (2004). Agueh et al. (2015) highlighted a lead concentration of around 11.74 mg/kg in the roots of *Vernonia amygdalina*, while Senou et al. (2019) recorded a high zinc concentration, reaching 108.74 mg/kg, in the roots of *Lactuca sativa* L. Pazou et al. (2020), a year later, claimed that *Vernonia amygdalina* and *Brassica oleracea* are among the greatest bioaccumulators of heavy metals. These findings highlight the diversity of metal levels in different parts of plants, with specific species showing an increased capacity to accumulate these metals, underlining the importance of understanding these variations to assess potential risks to plant and consumer health. The application of sludge to agricultural soils represents a curative option aimed at replacing costly chemical fertilizers. Several key recommendations are essential to ensure the safe and efficient use of sewage sludge. Pre-analysis of sludge is crucial to assess contaminants such as heavy metals and pathogens (Kumar et al., 2023). The amount of application should be controlled to avoid overloading of the soil (Li et al., 2023).

Adapting the application to environmental conditions helps minimize leaching risks (Chen et al., 2024). This practice must take into account the nutritional needs of plants without compromising soil quality, or that of surface and ground water. Studies indicate that a 40% sludge fraction enhances soil fertility (Ouadah et al., 2022). However, excessive use of sludge on the same site could increase the bioavailability of heavy metals in the soil (Praveen et al., 2022), leading to toxicity risks for soil micro-organisms (Lassoued and Essaid, 2022). Some heavy metals are potentially toxic to the environment, it is necessary to identify the sources of these metals and their mobilization processes in plants (Mechouet et al., 2024). Several effective methods are used to mitigate high levels of heavy metals from sludge application. The addition of chemical reagents reduces metal mobility, making them less soluble and bioavailable (Suthar et al., 2023). Composting stabilizes heavy metals by forming organic complexes with sludge (Zhang et al., 2023). Electrokinetic treatment extracts heavy metals from sludge through an electric field (Li et al., 2023). Each method offers advantages depending on the sludge characteristics and application context.

4. Conclusion

The current study highlights the significant impact of mud application on *Phaseolus vulgaris* and *Medicago sativa* crops. This positive effect is reflected in a significant increase in the dry biomass of these plants. Both plant species absorb various heavy metals, and these assimilation rates vary according to the concentration of sludge applied, while remaining within normative limits.

With regard to the soil's chemical characteristics, the analyses carried out revealed that the sludge studied boosted levels of organic matter, carbon, nitrogen and phosphorus. These results indicate an improvement in the soil's nutrient potential and structure. Thus, the sludge examined is positioned as a potential organic fertilizer, capable of enriching the agrochemical properties of soils, providing additional nutrients to plants, rehabilitating degraded soils and replacing artificial fertilizers while contributing to the bioeconomic circular economy. Over-application of sludge can lead to increased concentrations of heavy metals in the soil, with adverse impacts on soil properties and toxicity to soil micro-organisms. Nevertheless, it is important to stress that the use of urban sludge remains safe, particularly in the short to medium term.

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Authors contributions
Mesbah Nadjet: Sampling, Methodology, Data collection and writing articles; Rezki-Bekki Meriem Amina; Bekki Abdelkader: Supervision; Rouane Hacene Omar: Statistical analysis; Durand Gaël: Visualization and editing; Aouad Linda: Editing and language correction. The results were evaluated by all authors and the final version of the manuscript was approved.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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