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Reducing Heavy Metal Contamination in Soil with Biochar and Zeolite

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This study investigates the effectiveness of biochar and zeolite as soil amendments in mitigating the availability and mobility of heavy metals in various contaminated soils across Egypt. Soil samples were collected from four distinct locations, each characterized by different levels of heavy metal contamination: Kafr El-Batikh, Kafr Soliman, Talkha, and Kafr El-Manazla. An incubation experiment was conducted under controlled laboratory conditions, maintaining soil samples at 70% water-holding capacity over a 28-day period. Treatments included a control (no addition), biochar at 10% and 20%, and zeolite at 10% and 20%. The results indicated that both biochar and zeolite significantly reduced the availability of heavy metals (Hg, Cd, Cr, Ni, Pb, Sr,), with higher application rates resulting in greater metal fixation. These findings highlight the potential of biochar and zeolite as sustainable soil amendments for enhancing soil quality and reducing heavy metal pollution, paving the way for future agricultural practices focused on soil remediation. Further research is recommended to explore the long-term efficacy of these amendments in field conditions and their interactions with other soil management practices.

INTRODUCTION

Soil contamination with heavy metals is a critical environmental issue that poses serious risks to ecosystems and human health. Heavy metals such as lead, nickel and cadmium are persistent in the soil and cannot be easily removed through natural processes (**Peng *et al.* 2018)**. These contaminants often accumulate due to various human activities, including industrial discharges, sewage sludge application, and irrigation with contaminated water (**Głąb *et al.* 2021)**. In Egypt, soil pollution varies significantly across regions, influenced by the type and intensity of human activities (**Alnaimy *et al.* 2021)**.

Chemical remediation is a key strategy for addressing heavy metal contamination in soils, involving the application of chemical agents to immobilize or transform pollutants into less toxic forms (**Zheng *et al.* 2020)**. Two effective amendments commonly used in chemical remediation are biochar and zeolite. These materials have shown promise in reducing the bioavailability and mobility of heavy metals, thereby minimizing their environmental impact and risks to human health **(Song *et al.* 2022).**

Biochar is a carbon-rich material produced through the pyrolysis of organic matter, such as agricultural residues, under limited oxygen conditions **(Hornung *et al.* 2021).** It has gained attention as an effective soil amendment for heavy metal remediation due to its high surface area, porous structure, and ability to adsorb and immobilize heavy metals. When applied to contaminated soils, biochar can enhance soil properties by increasing pH and improving soil structure, which in turn reduces the mobility of heavy metals like lead, cadmium, and nickel (**Boostani *et al.* 2021)**. The porous nature of biochar allows it to act as a sorbent, trapping heavy metal ions within its matrix. Furthermore, biochar's functional groups, such as carboxyl and hydroxyl, form stable complexes with metal ions, preventing their uptake by plants. By immobilizing these contaminants, biochar helps to reduce their bioavailability, making it a sustainable option for soil remediation (**Li *et al.* 2024)**.

Zeolite, on the other hand, is a natural aluminosilicate mineral known for its high cation exchange capacity and affinity for heavy metal ions. Zeolites possess a unique crystalline structure that enables them to exchange cations, such as sodium or potassium, with heavy metals like lead and nickel in the soil **(Chai *et al.* 2021).** This cation exchange process reduces the concentration of free heavy metal ions, thus decreasing their bioavailability and toxicity. Zeolite's high surface area also enhances its ability to adsorb and immobilize contaminants, making it particularly effective in polluted soils. Moreover, the use of zeolite as a soil amendment not only stabilizes heavy metals but also improves soil properties, such as water retention and nutrient availability, which can further support plant growth and recovery in contaminated areas (**Li *et al.* 2024)**.

Therefore, the major aim of this study is to evaluate the effectiveness of biochar and zeolite as chemical soil amendments in immobilizing and reducing the bioavailability of heavy metals in contaminated soils. By applying these amendments at different rates, the study seeks to determine their potential to stabilize heavy metal concentrations and minimize environmental risks, thereby providing sustainable solutions for soil remediation and management.

MATERIALS AND METHODS

1. Study Area

The experiment was conducted using soil samples collected from four different locations in Egypt: Kafr El-Batikh, Kafr Soliman, Talkha and Kafr El-Manazla. These locations were selected based on varying levels of soil contamination:

Kafr El-Batikh: Agricultural land irrigated with agricultural drainage water.

Kafr Soliman: Agricultural land adjacent to a sewage station, irrigated with sewage water.

Talkha: Agricultural land adjacent to an industrial factory and a drain polluted with both sewage and industrial wastewater.

Kafr El-Manazla: Uncontaminated land irrigated with fresh water from the Nile River, serving as the control site for comparison.

2. Soil Sampling and Preparation

Soil samples were collected from each location and were air-dried, ground, and passed through a 2 mm sieve to remove debris and standardize the sample size. Initial soil properties, such as pH and electrical conductivity (EC)...*etc*, were determined according to the standard methods of **Tandon (2005)** (Table 1). Heavy metal concentrations were analyzed using standard laboratory procedures before the application of treatments. The analysis was performed using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) at the Soil Fertility and Fertilizer Quality Testing Laboratory, Faculty of Agriculture, Mansoura University **(Bettinelli *et al.* 2000)** (Table 2).

Table 1. Initial properties of the tested soils

Soil location	Particle size distribution,%			Texture	pH (1:5)	EC, dSm^{-1} (1:5)	Organic matter, g 100g^{-1}	CaCO$_3$, g 100g^{-1}
	Sand	Silt	Clay					
Kafr El-Batikh	**26**	**26**	**48**	**Clay**	**7.92**	**5.60**	**1.34**	**3.81**
Kafr Soliman	**23**	**28**	**49**	**Clay**	**7.80**	**6.78**	**1.88**	**2.71**
Talkha	**16**	**35**	**49**	**Clay**	**7.88**	**5.95**	**1.40**	**2.56**
Kafr El- Manazla	**22**	**30**	**48**	**Clay**	**8.02**	**2.75**	**1.26**	**2.50**

Table 2. Initial heavy metal concentrations (available, mg kg^{-1}) of the tested soils

Soil location	Hg	Cd	Cr	Ni	Pb	Sr
Kafr El-Batikh	**1.0**	**1.87**	**108.64**	**25.14**	**2.749**	**40.79**
Kafr Soliman	**1.56**	**4.54**	**375.38**	**65.2**	**7.30**	**159.48**
Talkha	**1.1**	**5.11**	**255.9**	**26.25**	**16.5**	**286.08**
Kafr El-Manazla	**0.501**	**3.29**	**154**	**49.59**	**8.97**	**158.13**
FAO/WHO guideline for limits of heavy metals that are not allowed to be exceeded in agricultural lands						
FAO/WHO (2001)	**0.5**	**3.0**	**100**	**50**	**10**	**/**
Note: The FAO/WHO does not specifically outline permissible levels for strontium (Sr) in agricultural soils						

Source: FAO/WHO (2001); Shehata *et al.* (2019)

3. Biochar and Zeolite Characterization

Biochar was prepared from agricultural residues, specifically corn stover and sugar cane residues, through a pyrolysis process as described by **Wang and Wang (2019).** The selected agricultural residues were air-dried to remove excess moisture. The dried feedstock was subjected to pyrolysis at 600°C under a controlled atmosphere (absence of oxygen) for 3 hours. This process converts the biomass into biochar, concentrating its carbon content and enhancing its stability in soil. After pyrolysis, the biochar was allowed to cool and then ground to a fine powder to facilitate its incorporation into the soil.

Zeolite used in this study was obtained from the commercial market in Egypt. The zeolite was selected for its high cation exchange capacity and its ability to adsorb heavy metals from contaminated soils. The physical and chemical properties of the zeolite were analyzed to determine its suitability as a soil amendment.

The characteristics of both biochar and zeolite, including their pH, electrical conductivity (EC), surface area, and cation exchange capacity (CEC), are presented in Table 3 according to the standard methods of **Tandon (2005)**

Table 3. The characteristics of the studied biochar and zeolite

Biochar amendment	
Properties and unit	**Values**
pH (1:10)	8.8
EC, dSm^{-1} (1:10)	4.9
CEC, cmolc kg^{-1}	73.9
N,%	0.52
C,%	78.02
Zeolite amendment	
Properties and unit	**Values**
pH (1:10)	7.8
EC, dSm^{-1} (1:10)	5.0
CaO,%	9.00
P_2O_5,%	1.30
SiO_2, %	64.0
Na_2O,%	1.00
CEC, cmolc kg^{-1}	157

4. Experimental Design

The study employed a completely randomized design (CRD) with five treatments applied to each soil sample from the four locations. The treatments included:

Control: No addition

Biochar at 10%: Biochar was applied at a rate of 10% (w/w) to the soil.

Biochar at 20%: Biochar was applied at a rate of 20% (w/w) to the soil.

Zeolite at 10%: Zeolite was applied at a rate of 10% (w/w) to the soil.

Zeolite at 20%: Zeolite was applied at a rate of 20% (w/w) to the soil.

Each treatment was replicated three times for each location to ensure reliability.

5. Incubation Experiment

An incubation experiment was conducted under laboratory conditions (Damietta University) to evaluate the effectiveness of the amendments in immobilizing heavy metals. The treated soil samples were placed in plastic containers and maintained at 70% of their water-holding capacity by regular irrigation. The incubation period lasted for 28 days, with soil samples collected at intervals of 7, 14 and 28 days to monitor changes in heavy metal concentrations.

6. Heavy Metal Extraction and Analysis

At each sampling interval, soil samples were collected from each treatment and analyzed for available heavy metal concentrations. The heavy metals analyzed included mercury (Hg), cadmium (Cd), chromium (Cr), nickel (Ni), lead (Pb) and strontium (Sr). The extraction of available heavy metals was performed using ammonium bicarbonate-diethylene triaminepenta acetic acid (AB-DTPA), a widely used chelating agent for assessing metal availability in soils. The concentrations of heavy metals were measured using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) at the Soil Fertility and Fertilizer Quality Testing Laboratory, Faculty of Agriculture, Mansoura University.

7. Evaluation of Holding Efficiency of Heavy Metals

The holding efficiency of heavy metals was evaluated by analyzing residual concentrations in soil samples after treatment with biochar and zeolite. Post-treatment, soil samples were collected at the specified intervals and analyzed for heavy metal concentrations using the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). The decrease in available heavy metal concentrations compared to the initial soil samples provides valuable insights into the effectiveness of each amendment in reducing metal bioavailability.

To quantify the holding efficiency of heavy metals, the following formula was used:

$$\boldsymbol{Holding\ effeciency} = \frac{\mathbf{A\ -B}}{\mathbf{A}}\ \mathbf{x\ 100}$$

Where;

A= Initial concentration of heavy metals in the soil (mg kg^{-1})

B = Final concentration of heavy metals in the soil after treatment (mg kg^{-1})

This formula calculates the percentage reduction in heavy metal concentrations, thereby indicating the efficacy of the applied soil amendments. A higher holding efficiency percentage signifies a more effective remediation process, highlighting the potential of biochar and zeolite to mitigate heavy metal contamination in agricultural soils.

RESULTS AND DISCUSSION

1. Status of Heavy Metals in the Studied Soils (Initial Status)

1.1. Kafr El-Batikh, Kafr Soliman and Talkha regions

The initial heavy metal concentrations in the studied soils, as presented in Table 2, reveal clear variations across the different locations. Kafr Soliman exhibits the highest concentrations of chromium (Cr) and nickel (Ni), with values of 375.38 and 65.2 mg kg^{-1}, respectively. This high level of Cr is particularly concerning, as it suggests the potential influence of nearby industrial activities or contaminated water sources, given chromium's common association with industrial effluents. The elevated levels of lead (Pb) and cadmium (Cd) in Talkha and Kafr Soliman further indicate serious soil contamination issues that require urgent attention.

Kafr El-Batikh shows relatively lower levels of heavy metals across the board, particularly with lead (Pb) and cadmium (Cd) concentrations of 2.749 and 1.87 mg kg^{-1}, respectively. However, even these lower concentrations pose risks, especially considering the cumulative effects of metal accumulation in the soil and potential uptake by crops.

Strontium (Sr) concentrations are notably high in Talkha, reaching 286.08 mg kg^{-1}. While strontium is less toxic than other heavy metals, its presence at such levels could indicate an ongoing issue with soil quality and health.

Generally, the initial assessment of heavy metal concentrations highlights the critical need for remediation strategies tailored to each location's specific contamination profile. The findings serve as a baseline for evaluating the effectiveness of subsequent treatments and interventions aimed at improving soil health and agricultural productivity **FAO/WHO (2006).** These results are in harmony with those of **Abou El-Anwar, (2019); El-Rawy *et al.* (2020).**

1.2. Kafr El-Manazla

The data presented in Table 2 also reveals that Kafr El-Manazla has the lowest concentrations of heavy metals among the studied locations. For instance, the concentration of mercury (Hg) is recorded at 0.501 mg kg^{-1}, which is significantly lower than the values observed in other locations such as Kafr Soliman and Talkha. This relatively low level of mercury is noteworthy, given its toxicity and potential to accumulate in the food chain.

In terms of cadmium (Cd) concentration, Kafr El-Manazla shows a value of 3.29 mg kg^{-1}, which is also lower than in the other sites, except Kafr El-Batikh location. Cadmium is a hazardous metal that can lead to various health issues, including renal dysfunction and bone damage, making its lower presence in this area advantageous for both agricultural practices and public health.

The chromium (Cr) concentration in Kafr El-Manazla stands at 154 mg kg^{-1}, which, although lower than the levels found in Kafr Soliman and Talkha, is still above the acceptable limits for agricultural soils. Chromium contamination can arise from various sources, including industrial discharges and improper waste disposal, highlighting the need for ongoing monitoring and management.

Lead (Pb) levels at 8.97 mg kg^{-1} in Kafr El-Manazla indicate that while contamination is present, it is not as severe as in the other regions. However, the potential for lead to negatively impact both soil health and crop safety underscores the importance of soil management practices that mitigate metal accumulation.

Strontium (Sr) levels are recorded at 158.13 mg kg^{-1}, which, while not classified as a heavy metal of significant toxicity, can indicate mineral imbalances in the soil and may affect plant growth if not properly managed.

Overall, Kafr El-Manazla presents a more favorable initial condition regarding heavy metal contamination compared to the other locations studied. However, the presence of even low concentrations of heavy metals calls for continued monitoring and the implementation of soil management strategies to prevent potential accumulation and ensure sustainable agricultural practices. The results from this site could serve as a benchmark for evaluating the effectiveness of the chemical remediation methods applied in the study **FAO/WHO (2001).** These results are in accordance with those of **Abou El-Anwar, (2019); El-Rawy *et al.* (2020).**

2. Effect of the studied treatments on heavy metals behavior in the studied soils

2.1. Mercury (Hg) behavior in the studied soils

The data presented in Table 4 demonstrate the impact of biochar and zeolite treatments on the availability of mercury (Hg) across different soil locations and incubation periods (7, 14 and 28 days). Overall, the results indicate that both amendments pronouncedly reduce Hg availability compared to the control treatments, with variations depending on the soil location and the application rate. The power fixation percentages of mercury (Hg) in the soil, as shown in Table 5, demonstrate the effectiveness of the applied treatments (biochar and zeolite) in immobilizing mercury over time.

The percentage of Hg fixation increases with the duration of the incubation period (7, 14, and 28 days), reflecting the progressive action of the treatments in binding and stabilizing mercury in the soil.

Kafr El-Batikh:

The control treatment showed minimal reduction in Hg levels over time, maintaining an average concentration of 0.99 mg kg^{-1}. However, both biochar and zeolite effectively reduced Hg availability. The 20% biochar treatment had the most pronounced effect, lowering the concentration to a mean value of 0.56 mg kg^{-1}. Similarly, the 20% zeolite treatment reduced Hg to a mean value of 0.66 mg kg^{-1}. The reduction is likely due to the high surface area and cation exchange capacity (CEC) of these amendments, which enhance metal adsorption and immobilization in soils. regarding the holding efficiency, Table 5 shows that the application of biochar and zeolite clearly increased the power fixation percentage of mercury. Biochar at a 20% rate shows the highest fixation efficiency, reaching 61% by day 28. Zeolite also improved fixation, with a 20% rate leading to a 54% reduction in available mercury after 28 days. This suggests that biochar, particularly at higher concentrations, is more effective in reducing mercury bioavailability compared to zeolite in this location. **(Peng *et al.* 2018; Zheng *et al.* 2020).**

Kafr Soliman:

This location exhibited a higher initial Hg concentration (1.55 mg kg^{-1} in the control). Similar trends were observed, where biochar and zeolite reduced Hg availability, particularly at higher application rates. The 20% biochar treatment decreased Hg levels to a mean of 0.75 mg kg^{-1}, while the 20% zeolite treatment resulted in a mean value of 0.96 mg kg^{-1}. The higher reduction efficacy of biochar is likely due to its greater affinity for heavy metals, as noted by **Zheng *et al.* (2020); Boostani *et al.* (2021); Głąb *et al.* (2021); Li *et al*. (2024).** The fixation percentages are higher overall compared to Kafr El-Batikh. Biochar at a 20% rate shows the most substantial impact, with 67.09% of Hg fixed by day 28. Similarly, zeolite at a 20% rate also shows good performance, achieving a 58.06% reduction in available Hg. This indicates that both amendments are effective, with biochar again showing a slightly superior effect.

Talkha:

In this soil, the control maintained an average Hg concentration of 1.06 mg kg^{-1}. The use of 20% biochar led to a significant reduction, with a mean Hg value of 0.50 mg kg^{-1}. Zeolite also showed effectiveness, with the 20% treatment reducing the mean concentration to 0.66 mg kg^{-1}. The observed reductions align with findings by **Li *et al.* (2024),** who reported similar effectiveness of these amendments in heavy metal-contaminated soils. The fixation efficiency of mercury follows a similar trend to other mentioned regions, with biochar at a 20% rate resulting in the highest fixation (70.9%) by day 28. Zeolite also improves mercury immobilization, reaching 61.81% fixation with a 20% application rate. These findings align with previous observations, suggesting that higher concentrations of these amendments consistently enhance mercury stabilization in soils.

Kafr El-Manazla:

The initial Hg concentration in the control was relatively low (0.496 mg kg^{-1}). Biochar and zeolite treatments effectively lowered Hg availability, with the 20% biochar application showing the greatest reduction, achieving a mean concentration of 0.12 mg kg^{-1}. Zeolite also performed well, with the 20% application resulting in a mean value of 0.31 mg kg^{-1}. These results confirm the potential of both biochar and zeolite to adsorb and immobilize heavy metals in soils, as highlighted by **Boostani *et al.* (2021); Głąb *et al.* (2021); Li *et al*. (2024).** This location exhibits the highest power fixation percentages overall, particularly with biochar at a 20% rate, which reaches 84.03% by day 28. Biochar at 10% also shows significant effectiveness (74.05%), indicating that even lower rates of biochar are highly efficient in this soil. Zeolite, while effective, shows a lower fixation percentage compared to biochar, with a maximum of 62.07% at the 20% rate. This suggests that the soil properties at Kafr El-Manazla may enhance the interaction between the amendments and mercury, leading to higher stabilization rates.

The reduction in the availability of mercury (Hg) in the soil over time, reaching the lowest level after 28 days, indicates the positive impact of different treatments (biochar and zeolite) in reducing the availability of heavy metals.

This gradual decrease in mercury across the time intervals (7, 14, and 28 days) can be explained by the increased capacity of the added materials (biochar and zeolite) to adsorb and immobilize heavy metals over time. When these materials are added to the soil, the high porosity and carbon content in biochar, along with the high cation exchange capacity of zeolite, interact with mercury, binding and immobilizing it, thus reducing its available concentration **(Li *et al.* 2024).** By 28 days, the available amounts of mercury have decreased to their lowest levels, reflecting the continuous interaction between the added amendments and mercury, leading to greater stabilization of mercury into insoluble or less mobile compounds. These findings are consistent with previous studies that demonstrate the effectiveness of using biochar and zeolite to improve soil quality by reducing heavy metal contamination (**Boostani *et al.* 2021; Głąb *et al.* 2021; Li *et al*. 2024).**

The data reveal that the efficiency of both biochar and zeolite in reducing Hg availability increases with higher application rates and longer incubation periods. Biochar generally showed a slightly better performance compared to zeolite, likely due to its higher carbon content and surface properties, which enhance metal adsorption. These findings support the use of these amendments as effective strategies for managing heavy metal contamination in agricultural soils, promoting safer and sustainable agricultural practices.

2.2. Cadmium (Cd) behavior in the studied soils

The data presented in Tables 6 and 7 highlight the impact of biochar and zeolite treatments on cadmium (Cd) availability and fixation in different soil locations. The results illustrate how these soil amendments can effectively reduce available Cd levels and increase fixation percentages over time, suggesting their potential for remediating Cd-contaminated soils.

Kafr El-Batikh:

In the control treatment, the available Cd levels remain consistent across the incubation period (1.83 mg kg^{-1}). Biochar, particularly at 20%, shows the greatest reduction in available Cd, decreasing from 1.13 mg kg^{-1} at day 7 to 0.68 mg kg^{-1} at day 28. Zeolite also reduces Cd availability, but to a lesser extent than biochar. The 20% zeolite application lowers the Cd concentration from 1.42 mg kg^{-1} at day 7 to 0.85 mg kg^{-1} by day 28. Power fixation percentages are highest with biochar at 20%, reaching 63.63% at 28 days, while zeolite at the same rate achieves a 54.54% fixation.

Kafr Soliman:

The control treatment shows minimal changes in Cd levels (around 4.5 mg kg^{-1}) throughout the incubation period. Biochar, especially at 20%, is again the most effective treatment, reducing available Cd from 3.65 mg kg^{-1} at day 7 to 2.18 mg kg^{-1} by day 28, with a fixation percentage of 51.98%. Zeolite treatments also lower Cd levels, though less effectively than biochar. The 20% application rate results in a Cd level of 2.48 mg kg^{-1} and a fixation percentage of 45.37% by day 28.

Talkha:

Cd availability remains steady in the control (approximately 5.1 mg kg^{-1}). The use of biochar, particularly at 20%, significantly decreases Cd levels, with values dropping to 2.30 mg kg^{-1} and achieving a fixation percentage of 54.99% by day 28. Zeolite treatments also show effectiveness, with a 20% application reducing Cd levels to 2.76 mg kg^{-1} and reaching a fixation rate of 45.98%.

Kafr El-Manazla:

In the control treatment, Cd levels remain relatively constant around 3.2 mg kg^{-1}. Biochar applications show substantial reductions in available Cd, with the 20% rate bringing levels down to 1.45 mg kg^{-1} and a fixation percentage of 55.92% at day 28. Zeolite also contributes to Cd immobilization, achieving a 47.72% fixation percentage with a 20% application rate by the end of the incubation period.

Generally, the findings indicate that biochar, especially at higher application rates, is the most effective amendment for reducing Cd availability and enhancing fixation across all studied soils. Zeolite also shows promising results but is generally less effective compared to biochar. The previous results are attributed to the role of zeolite in holding cadmium due to its high cation exchange capacity and its large porous surface, which allows for the absorption and fixation of cadmium. Meanwhile, biochar was more effective because it contains functional groups that enhance its adsorption capacity and its ability to increase soil pH, reducing cadmium solubility and promoting greater fixation (**Boostani *et al.* 2021; Głąb *et al.* 2021; Li *et al*. 2024).** The consistency of these results supports the use of biochar as a primary amendment for Cd stabilization in contaminated soils.

2.3. Chromium (Cr) behavior in the studied soils

The behavior of chromium (Cr) in the studied soils was pronouncedly influenced by the application of biochar and zeolite treatments.

Table 8 shows the effect of biochar and zeolite at different rates on the available Cr values in different soil locations over varying incubation periods. In Kafr El-Batikh, the application of biochar (at both 10% and 20% rates) led to a notable decrease in available Cr, with mean values of 65.83 mg kg^{-1} and 55.30 mg kg^{-1}, respectively, compared to the control value of 108.4 mg kg^{-1}. Similarly, in Kafr Soliman, the biochar treatments reduced available Cr to mean values of 263.43 mg kg^{-1} and 248.67 mg kg^{-1}. In contrast, zeolite treatments demonstrated a lesser capacity for reducing available Cr values across the soil locations. For instance, the mean available Cr in Kafr El-Batikh with zeolite at 20% was 70.53 mg kg^{-1}, while the control remained high at 108.4 mg kg^{-1}. This trend was consistent in other locations like Talkha and Kafr El-Manazla, where zeolite exhibited less effectiveness in Cr retention compared to biochar.

Table 9 illustrates the percentage of Cr fixation power, highlighting that biochar consistently outperformed zeolite in fixing chromium in all soil types. For example, in Kafr El-Batikh, biochar at a rate of 20% achieved a Cr fixation of 60.14%, while zeolite at the same rate fixed only 49.09%. Similarly, the trends continued across other locations, with biochar demonstrating significantly higher Cr fixation percentages.

Finally, Tables 8 and 9 indicate that biochar is more effective in reducing available chromium and enhancing its fixation in soils than zeolite, primarily due to its superior adsorption capabilities and structural properties. The obtained results attributed to the vital role of both biochar and zeolite as mentioned above. The findings are in harmony with those of **Głąb *et al.* (2021); Li *et al.* (2024).**

2.4. Nickel (Ni) behavior in the studied soils

The behavior of nickel (Ni) in the studied soils was assessed through the application of biochar and zeolite treatments, which influenced the availability and fixation of nickel over various incubation periods.

Table 10 presents the effect of biochar and zeolite treatments on the available nickel (Ni) values (mg kg^{-1}) across different soil locations. In Kafr El-Batikh, the control soil had an average available Ni value of 25.06 mg kg^{-1}. Upon applying biochar at rates of 10% and 20%, the available Ni values decreased prononcedly to means of 15.53 and 12.53 mg kg^{-1}, respectively. Conversely, zeolite treatments resulted in less reduction, with mean values of 18.61 and 16.77 mg kg^{-1} for the 10% and 20% rates, respectively.

In Kafr Soliman region, the control soil showed a higher available Ni value of 65.06 mg kg^{-1}, which decreased to 48.93 and 45.32 mg kg^{-1} with biochar applications at 10% and 20% rates. Zeolite also performed relatively well, with mean values of 53.00 and 50.40 mg kg^{-1}for the respective rates.

In Talkha region, the available Ni values followed a similar trend, with the control showing 26.19 mg kg^{-1} and biochar treatments reducing this to mean values of 15.51 mg kg^{-1} and 12.19 mg kg^{-1} for 10% and 20% rates, respectively. Zeolite treatments maintained available Ni levels at 19.61 and 18.28 mg kg^{-1}.

In Kafr El-Manazla, the control value was 49.57 mg kg^{-1}, with biochar reducing available Ni to 33.05 and 30.48 mg kg^{-1} for 10% and 20% rates, respectively. Zeolite also decreased available Ni, with mean values of 37.03 and 34.57 mg kg^{-1}.

Table 11 summarizes the power fixation percentage of available nickel (%). Biochar significantly enhanced the fixation of nickel in all soil locations. For instance, in Kafr El-Batikh, the 20% biochar treatment resulted in a fixation percentage of 60.77%, compared to 47.69% for zeolite at the same rate. Similarly, in Talkha, biochar at 20% achieved a remarkable fixation of 63.58%.

In Kafr Soliman, the biochar treatment at 20% achieved a fixation percentage of 45.50%, whereas zeolite treatments demonstrated lower fixation capabilities. The results indicate that biochar is significantly more effective than zeolite in reducing available nickel and enhancing its fixation in the soils studied.

The results of the nickel (Ni) behavior in the studied soils demonstrate a clear trend over the different incubation periods. Initially, at the 7-day mark, biochar and zeolite treatments show varying degrees of effectiveness in reducing the available Ni concentrations, but the changes are relatively modest. As the incubation period extends to 14 days, a notable reduction in available Ni is observed, particularly with higher rates of biochar, which suggests that the adsorption processes are becoming more pronounced as biochar interacts with the nickel ions. By the 28-day period, the mean available Ni values show a significant decline for both biochar and zeolite treatments, indicating that these amendments continue to enhance their effectiveness over time.

The higher power fixation percentages of nickel at 28 days further confirm the increasing capacity of both biochar and zeolite to immobilize nickel ions in the soil. This can be attributed to the gradual establishment of chemical and physical interactions between the amendments and the nickel, allowing for improved retention and reduced leaching. The cumulative effects observed over the extended incubation periods highlight the importance of time in the stabilization and fixation of nickel in soil environments treated with biochar and zeolite.

Generally, the application of biochar effectively reduces available nickel levels in soils while enhancing its fixation, which can be beneficial in managing nickel contamination in agricultural settings. The behavior of nickel (Ni) in the studied soils is significantly influenced by the application of biochar and zeolite. Biochar, with its high surface area and porosity, effectively adsorbs nickel ions, reducing their availability by forming complexes and raising soil pH, which can precipitate nickel as less soluble compounds. Additionally, its ability to enhance soil cation exchange capacity facilitates further immobilization of nickel. Zeolite, while also capable of ion exchange, is less effective than biochar due to lower surface area. Over time, increased incubation allows for more interactions between nickel ions and these amendments, leading to higher fixation percentages. Microbial activity and changes in soil organic matter from biochar applications further contribute to the reduced mobility of nickel in the soil. Thus, both amendments play crucial roles in managing nickel behavior and availability in agricultural soils. The findings are in harmony with those of **Zheng *et al.* (2020); Boostani *et al.* (2021).**

2.5. Lead (Pb) behavior in the studied soils

Table 12 illustrates the effect of boichar and zeolite treatments on available Pb value (mg kg^{-1}), while Table 13 shows the power fixation percentage for lead (Pb).

The behavior of lead (Pb) in the studied soils indicates a gradual reduction in the available Pb levels over the incubation periods with biochar and zeolite treatments.

Biochar, at both 10% and 20% rates, shows a clear decrease in the available Pb levels across all soil locations and incubation periods. This suggests that biochar is effective in adsorbing and immobilizing Pb, with the higher rate (20%) providing more pronounced results.

The decrease in Pb availability with biochar treatments can be attributed to the high surface area, porosity, and functional groups of biochar, which enhance its ability to bind heavy metals. The presence of organic carbon in biochar also improves cation exchange capacity, facilitating the retention of Pb in a less bioavailable form.

Zeolite treatments, while also effective, show a less dramatic reduction in Pb availability compared to biochar. Zeolite's crystalline structure and high ion-exchange properties enable it to retain Pb ions, but its impact appears less efficient than biochar, possibly due to differences in surface characteristics and affinity for Pb ions.

As the incubation period extends from 7 to 28 days, the availability of Pb decreases further, indicating that the effectiveness of both amendments improves over time. Initially, at the 7-day mark, the changes in Pb availability are moderate, as the amendments may still be undergoing interaction processes with the soil and Pb ions. By the 14-day mark, these processes intensify, leading to a more substantial reduction in Pb levels. At 28 days, the lowest values of available Pb are recorded, showing the maximum effect of both biochar and zeolite treatments.

The increase in power fixation percentage over time supports this trend, demonstrating that the longer the incubation, the more Pb becomes immobilized and stabilized in the soil. This extended effect is likely due to the gradual development of physical and chemical bonds between Pb ions and the amendments, enhancing their retention capacity and reducing Pb mobility and bioavailability.

The same trend was found for all tested soils. The obtained results are in harmony with those of **Zheng *et al.* (2020); Boostani *et al.* (2021); Głąb *et al.* (2021); Li *et al*. (2024).**

2.6. Strontium (Sr) behavior in the studied soils

The behavior of Strontium (Sr) in the studied soils under different treatments and incubation periods reveals how biochar and zeolite can influence the availability and fixation of Sr (Table 14).

In all soil locations (Kafr El-Batikh, Kafr Soliman, Talkha, and Kafr El-Manazla), the control groups (no addition) showed minimal changes in the available Sr concentration over the incubation periods of 7, 14, and 28 days. The values remained relatively stable, indicating that without amendments, the natural retention and fixation of Sr in the soil are limited. Biochar application at both 10% and 20% significantly reduced the available Sr values across all locations and incubation periods. For instance, in Kafr El-Batikh, biochar at a 20% rate reduced Sr availability from 30.00 mg kg^{-1} on day 7 to 20.25 mg kg^{-1} on day 28.The effect was more pronounced at the 20% biochar rate, suggesting that increasing biochar concentration enhances the fixation of Sr in soils. Biochar's porous structure and high surface area may facilitate the adsorption and immobilization of Sr ions, reducing their availability in the soil solution.

Similar to biochar, zeolite also showed a reduction in Sr availability, although the effect was generally less pronounced compared to biochar, especially at the 10% rate. For example, in Talkha, zeolite at 10% reduced Sr availability from 275.9 mg kg-1 on day 7 to 186.23 mg kg-1 on day 28.

Zeolite's cation exchange capacity (CEC) plays a crucial role in trapping Sr ions, but the extent of fixation appears dependent on the concentration of zeolite used. The 20% application rate showed more significant reductions, indicating that higher doses enhance its Sr-immobilizing capacity.

The power fixation percentage of Sr (Table 15) provides further evidence of the effectiveness of biochar and zeolite in immobilizing Sr in soils.

The data in Table 15 indicate that biochar is particularly effective in enhancing Sr fixation over time. In Kafr El-Batikh, for instance, the fixation percentage with a 20% biochar rate increased from 26.45% on day 7 to 50.35% on day 28.The clear increase in Sr fixation over the incubation period highlights biochar's long-term impact on stabilizing Sr in soils. The biochar likely provides binding sites that become more effective as it interacts with the soil matrix over time. Zeolite treatments also contributed to Sr fixation, but the efficiency was generally lower than biochar. In Kafr Soliman, the fixation percentage with a 20% zeolite rate increased from 14.84% on day 7 to 42.52% on day 28. The lesser but still notable effectiveness of zeolite can be attributed to its CEC, which facilitates ion exchange and adsorption processes, thus reducing the availability of Sr. The gradual increase in fixation percentages suggests that zeolite becomes more effective with extended incubation periods as it continues to interact with soil components (**Abou El-Anwar, 2019; El-Rawy *et al.* 2020)**.

At the early stage (short-term dynamics, 7 Days), the treatments showed initial reductions in available Sr levels, but the effects were moderate. This suggests that both biochar and zeolite require time to establish interactions with soil particles and Sr ions.

By the second week (mid-term dynamics, 14 Days), the impact of both treatments became more apparent, with further reductions in available Sr. This indicates that the soil amendments gradually alter the soil environment, promoting Sr adsorption and fixation.

At 28 days (Long-term dynamics), the maximum reduction in available Sr and the highest fixation percentages were observed, particularly in soils treated with higher rates of biochar and zeolite. The extended interaction period likely allows for more stable binding of Sr ions to the soil amendments.

The study demonstrates that biochar and zeolite are effective soil amendments for reducing the availability of Sr in soils, with biochar showing a more significant impact, especially at higher application rates. The effectiveness of these amendments is enhanced over time, as indicated by the increasing fixation percentages throughout the incubation periods. These findings highlight the potential of using biochar and zeolite to manage Sr contamination in agricultural soils, ensuring a safer and more sustainable environment for crop production. The obtained results are in harmony with those of **Li *et al.* (2024).**

Table 4. Effect of boichar and zeolite treatments on available Hg value (mg kg^{-1})

Soil location	Treatments	Incubation period(days)			Mean
		7	14	28	
		Available Hg value (mg kg^{-1})			
Kafr El-Batikh	**No addition (Control)**	1.00	0.99	0.99	**0.99**
	Biochar at rate of 10%	0.75	0.67	0.43	**0.62**
	Biochar at rate of 20%	0.68	0.61	0.39	**0.56**
	Zeolite at rate of 10%	0.88	0.79	0.51	**0.73**
	Zeolite at rate of 20%	0.80	0.72	0.46	**0.66**
	Mean	**0.822**	**0.756**	**0.556**	**0.7**
Kafr Soliman	**No addition (control)**	1.55	1.54	1.55	**1.55**
	Biochar at rate of 10%	1.15	0.95	0.62	**0.90**
	Biochar at rate of 20%	0.95	0.78	0.52	**0.75**
	Zeolite at rate of 10%	1.36	1.12	0.74	**1.07**
	Zeolite at rate of 20%	1.22	1.012	0.66	**0.96**
	Mean	**1.25**	**1.08**	**0.82**	**1.05**
Talkha	**No addition (control)**	1.06	1.06	1.05	**1.06**
	Biochar at rate of 10%	0.77	0.65	0.37	**0.59**
	Biochar at rate of 20%	0.65	0.55	0.32	**0.50**
	Zeolite at rate of 10%	0.93	0.78	0.45	**0.72**
	Zeolite at rate of 20%	0.85	20.7	0.42	**0.66**
	Mean	**0.852**	**0.752**	**0.522**	**0.70**
Kafr El-Manazla	**No addition (control)**	0.50	0.50	0.49	**0.496**
	Biochar at rate of 10%	0.29	0.24	0.13	**0.22**
	Biochar at rate of 20%	0.15	0.13	0.08	**0.12**
	Zeolite at rate of 10%	0.45	0.38	0.22	**0.35**
	Zeolite at rate of 20%	0.40	0.34	0.19	**0.31**
	Mean	**0.358**	**0.318**	**0.222**	**0.299**

Table 5. Power fixation percentage (Hg)

Soil location	Treatments	Incubation period (days)		
		7	14	28
		Power fixation of available Hg (%)		
Kafr El-Batikh	No addition (Control)	0.00	1.000	1.000
	Biochar at rate of 10%	25.00	33.00	57.00
	Biochar at rate of 20%	32.00	39.00	61.00
	Zeolite at rate of 10%	12.00	21.00	49.00
	Zeolite at rate of 20%	20.00	28.00	54.00
Kafr Soliman	No addition (control)	0.640	1.290	0.640
	Biochar at rate of 10%	26.45	39.35	60.64
	Biochar at rate of 20%	39.35	50.32	67.09
	Zeolite at rate of 10%	12.90	28.38	52.90
	Zeolite at rate of 20%	21.93	35.35	58.06
Talkha	No addition (control)	3.630	3.630	4.540
	Biochar at rate of 10%	30.00	40.90	66.36
	Biochar at rate of 20%	40.90	50.00	70.90
	Zeolite at rate of 10%	15.45	29.09	59.09
	Zeolite at rate of 20%	22.72	34.54	61.81
Kafr El-Manazla	No addition (control)	0.199	0.199	2.19
	Biochar at rate of 10%	42.12	52.09	74.05
	Biochar at rate of 20%	70.06	74.05	84.03
	Zeolite at rate of 10%	10.18	24.15	56.08
	Zeolite at rate of 20%	20.16	32.13	62.07

Table 6. Effect of boichar and zeolite treatments on available Cd value (mg kg^{-1})

Soil location	Treatments	Incubation period(days)			Mean
		7	14	28	
		Available Cd value (mg kg^{-1})			
Kafr El-Batikh	No addition (control)	1.83	1.82	1.83	**1.83**
	Biochar at rate of 10%	1.36	1.13	0.81	**1.10**
	Biochar at rate of 20%	1.13	0.94	0.68	**0.92**
	Zeolite at rate of 10%	1.65	1.37	0.98	**1.33**
	Zeolite at rate of 20%	1.42	1.17	0.85	**1.14**
	Mean	**1.478**	**1.286**	**1.03**	**1.26**
Kafr Soliman	No addition (control)	4.50	4.51	4.49	**4.50**
	Biochar at rate of 10%	3.95	3.28	2.36	**3.19**
	Biochar at rate of 20%	3.65	3.03	2.18	**2.95**
	Zeolite at rate of 10%	4.33	3.60	2.58	**3.50**
	Zeolite at rate of 20%	4.15	3.44	2.48	**3.36**
	Mean	**4.116**	**3.572**	**2.818**	**3.50**
Talkha	No addition (control)	5.11	5.10	5.10	**5.10**
	Biochar at rate of 10%	4.30	3.56	2.56	**3.47**
	Biochar at rate of 20%	3.85	3.19	2.30	**3.11**
	Zeolite at rate of 10%	4.86	4.03	2.90	**3.93**
	Zeolite at rate of 20%	4.62	3.83	2.76	**3.73**
	Mean	**4.548**	**3.942**	**3.124**	**3.87**
Kafr El-Manazla	No addition (control)	3.25	3.20	3.20	**3.22**
	Biochar at rate of 10%	2.69	2.23	1.60	**2.17**
	Biochar at rate of 20%	2.43	2.01	1.45	**1.96**
	Zeolite at rate of 10%	3.06	2.53	1.82	**2.47**
	Zeolite at rate of 20%	2.88	2.39	1.72	**2.33**
	Mean	**2.862**	**2.472**	**1.958**	**2.43**

Table 7. Power fixation percentage (Cd)

Soil location	Treatments	Incubation period (days)		
		7	14	28
		Power fixation of available Cd (%)		
Kafr El-Batikh	**No addition (Control)**	2.14	2.673	2.139
	Biochar at rate of 10%	27.27	39.57	56.68
	Biochar at rate of 20%	39.57	49.73	63.63
	Zeolite at rate of 10%	11.76	26.73	47.59
	Zeolite at rate of 20%	24.06	37.43	54.54
Kafr Soliman	**No addition (control)**	0.88	0.660	1.101
	Biochar at rate of 10%	12.99	27.75	48.01
	Biochar at rate of 20%	19.60	33.25	51.98
	Zeolite at rate of 10%	4.62	20.70	43.17
	Zeolite at rate of 20%	8.59	24.22	45.37
Talkha	**No addition (control)**	0.00	0.195	0.195
	Biochar at rate of 10%	15.85	30.33	49.90
	Biochar at rate of 20%	24.65	37.57	54.99
	Zeolite at rate of 10%	4.89	21.13	43.24
	Zeolite at rate of 20%	9.58	25.05	45.98
Kafr El-Manazla	**No addition (control)**	1.22	2.74	2.735
	Biochar at rate of 10%	18.24	32.22	51.36
	Biochar at rate of 20%	26.14	38.90	55.92
	Zeolite at rate of 10%	6.99	23.10	44.68
	Zeolite at rate of 20%	12.46	27.35	47.72

Table 8. Effect of boichar and zeolite treatments on available Cr value (mg kg^{-1})

Soil location	Treatments	Incubation period(days)			Mean
		7	14	28	
		Available Cr value (mg kg^{-1})			
Kafr El-Batikh	**No addition (control)**	108.5	108.4	108.3	**108.4**
	Biochar at rate of 10%	78.9	67.0	51.6	**65.83**
	Biochar at rate of 20%	66.3	56.3	43.3	**55.30**
	Zeolite at rate of 10%	96.3	81.8	63.0	**80.36**
	Zeolite at rate of 20%	84.5	71.8	55.3	**70.53**
	Mean	**86.9**	**77.06**	**64.3**	**76.09**
Kafr Soliman	**No addition (control)**	375.15	375.09	375.05	**375.09**
	Biochar at rate of 10%	315.6	268.2	206.5	**263.43**
	Biochar at rate of 20%	297.9	253.2	194.9	**248.67**
	Zeolite at rate of 10%	355.6	302.2	232.7	**296.83**
	Zeolite at rate of 20%	325.5	276.6	213.0	**271.7**
	Mean	**333.95**	**295.058**	**244.43**	**291.15**
Talkha	**No addition (control)**	255.6	255.45	255.56	**255.54**
	Biochar at rate of 10%	219.3	186.4	143.5	**183.06**
	Biochar at rate of 20%	198.6	168.8	129.9	**165.76**
	Zeolite at rate of 10%	243.3	206.8	159.2	**203.10**
	Zeolite at rate of 20%	235.6	200.2	154.2	**196.67**
	Mean	**230.48**	**203.53**	**168.472**	**200.83**
Kafr El- Manazla	**No addition (control)**	153.9	153.8	153.9	**153.87**
	Biochar at rate of 10%	118.5	100.7	77.5	**98.90**
	Biochar at rate of 20%	97.2	82.6	63.6	**81.13**
	Zeolite at rate of 10%	143.5	121.9	93.9	**119.76**
	Zeolite at rate of 20%	136.3	115.8	89.2	**113.77**
	Mean	**129.88**	**114.96**	**95.62**	**113.48**

Table 9. Power fixation percentage (Cr)

Soil location	Treatments	Incubation period (days)		
		7	14	28
		Power fixation of available Cr (%)		
Kafr El-Batikh	No addition (Control)	0.12	0.22	0.31
	Biochar at rate of 10%	27.37	38.32	52.50
	Biochar at rate of 20%	38.97	48.17	60.14
	Zeolite at rate of 10%	11.35	24.70	42.010
	Zeolite at rate of 20%	22.22	33.91	49.09
Kafr Soliman	No addition (control)	0.061	0.077	0.087
	Biochar at rate of 10%	15.92	28.55	44.98
	Biochar at rate of 20%	20.64	32.54	48.079
	Zeolite at rate of 10%	5.26	19.49	38.00
	Zeolite at rate of 20%	13.28	26.31	43.25
Talkha	No addition (control)	0.117	0.175	0.132
	Biochar at rate of 10%	14.30	27.15	43.92
	Biochar at rate of 20%	22.39	34.036	49.23
	Zeolite at rate of 10%	4.92	19.18	37.78
	Zeolite at rate of 20%	7.93	21.76	39.74
Kafr El-Manazla	No addition (control)	0.064	0.129	0.064
	Biochar at rate of 10%	23.05	34.61	49.67
	Biochar at rate of 20%	36.88	46.36	58.70
	Zeolite at rate of 10%	6.81	20.84	39.02
	Zeolite at rate of 20%	11.49	24.80	42.07

Table 10. Effect of boichar and zeolite treatments on available Ni value (mg kg^{-1})

Soil location	Treatments	Incubation period (days)			Mean
		7	14	28	
		Available Ni value (mg kg^{-1})			
Kafr El-Batikh	No addition (control)	25.10	25.10	25.00	**25.06**
	Biochar at rate of 10%	18.60	15.81	12.18	**15.53**
	Biochar at rate of 20%	15.00	12.75	9.86	**12.53**
	Zeolite at rate of 10%	22.30	18.95	14.59	**18.61**
	Zeolite at rate of 20%	20.10	17.08	13.15	**16.77**
	Mean	**20.22**	**17.938**	**14.956**	**17.70**
Kafr Soliman	No addition (control)	65.10	65.10	65.00	**65.06**
	Biochar at rate of 10%	58.60	49.81	38.39	**48.93**
	Biochar at rate of 20%	54.30	46.15	35.53	**45.32**
	Zeolite at rate of 10%	63.30	53.85	41.85	**53.00**
	Zeolite at rate of 20%	60.30	51.25	39.65	**50.40**
	Mean	**60.32**	**53.232**	**44.084**	**52.54**
Talkha	No addition (control)	26.25	26.21	26.13	**26.19**
	Biochar at rate of 10%	18.60	15.81	12.13	**15.51**
	Biochar at rate of 20%	14.60	12.41	9.560	**12.19**
	Zeolite at rate of 10%	23.50	19.97	15.38	**19.61**
	Zeolite at rate of 20%	21.90	18.61	14.33	**18.28**
	Mean	**20.97**	**18.602**	**15.506**	**18.35**
Kafr El-Manazla	No addition (control)	49.59	49.58	49.55	**49.57**
	Biochar at rate of 10%	39.60	33.66	25.91	**33.05**
	Biochar at rate of 20%	36.50	31.06	23.88	**30.48**
	Zeolite at rate of 10%	44.36	37.71	29.03	**37.03**
	Zeolite at rate of 20%	41.23	35.55	26.95	**34.57**
	Mean	**42.256**	**37.512**	**31.064**	**36.94**

Table 11. Power fixation percentage (Ni)

Soil location	Treatments	Incubation period (days)		
		7	14	28
		Power fixation of available Ni (%)		
Kafr El-Batikh	No addition (Control)	0.159	0.159	0.556
	Biochar at rate of 10%	26.01	37.11	51.55
	Biochar at rate of 20%	40.33	49.28	60.77
	Zeolite at rate of 10%	11.29	24.62	41.96
	Zeolite at rate of 20%	20.04	32.06	47.69
Kafr Soliman	No addition (control)	0.153	0.153	0.306
	Biochar at rate of 10%	10.12	23.60	41.11
	Biochar at rate of 20%	16.71	29.21	45.50
	Zeolite at rate of 10%	2.914	17.40	35.81
	Zeolite at rate of 20%	7.515	21.39	39.18
Talkha	No addition (control)	0.000	0.152	0.457
	Biochar at rate of 10%	29.14	39.77	53.79
	Biochar at rate of 20%	44.38	52.72	63.58
	Zeolite at rate of 10%	10.47	23.92	41.40
	Zeolite at rate of 20%	16.57	29.10	45.40
Kafr El-Manazla	No addition (control)	0.000	0.020	0.080
	Biochar at rate of 10%	20.145	32.12	47.75
	Biochar at rate of 20%	26.396	37.36	51.84
	Zeolite at rate of 10%	10.546	23.95	41.45
	Zeolite at rate of 20%	16.858	28.31	45.65

Table 12. Effect of boichar and zeolite treatments on available Pb value (mg kg^{-1})

Soil location	Treatments	Incubation period(days)			Mean
		7	14	28	
		Available Pb value (mg kg^{-1})			
Kafr El-Batikh	No addition (control)	2.70	2.70	2.68	**2.69**
	Biochar at rate of 10%	1.98	1.62	1.12	**1.57**
	Biochar at rate of 20%	1.65	1.35	0.94	**1.31**
	Zeolite at rate of 10%	2.35	1.92	1.33	**1.86**
	Zeolite at rate of 20%	2.15	1.76	1.22	**1.71**
	Mean	**2.166**	**1.87**	**1.458**	**1.83**
Kafr Soliman	No addition (control)	7.30	7.29	7.28	**7.29**
	Biochar at rate of 10%	6.48	5.31	3.66	**5.15**
	Biochar at rate of 20%	5.18	4.24	2.90	**4.10**
	Zeolite at rate of 10%	7.15	5.86	4.04	**5.68**
	Zeolite at rate of 20%	7.00	5.74	3.96	**5.56**
	Mean	**6.622**	**5.688**	**4.368**	**5.55**
Talkha	No addition (control)	16.45	16.42	16.41	**16.42**
	Biochar at rate of 10%	11.80	9.670	6.66	**9.37**
	Biochar at rate of 20%	9.80	8.038	5.54	**7.79**
	Zeolite at rate of 10%	14.30	11.76	8.090	**11.38**
	Zeolite at rate of 20%	12.90	10.56	7.290	**10.25**
	Mean	**13.05**	**11.28**	**8.798**	**11.04**
Kafr El-Manazla	No addition (control)	8.92	8.90	8.90	**8.90**
	Biochar at rate of 10%	5.86	4.82	3.315	**4.66**
	Biochar at rate of 20%	4.98	4.08	2.816	**3.95**
	Zeolite at rate of 10%	6.98	5.72	3.94	**5.54**
	Zeolite at rate of 20%	6.00	4.92	3.39	**4.77**
	Mean	**6.548**	**5.688**	**4.472**	**5.56**

Table 13. Power fixation percentage (Pb)

Soil location	Treatments	Incubation period (days)		
		7	14	28
		Power fixation of available Pb (%)		
Kafr El-Batikh	No addition (Control)	1.78	1.782	2.510
	Biochar at rate of 10%	27.97	41.06	59.25
	Biochar at rate of 20%	39.97	50.89	65.80
	Zeolite at rate of 10%	14.51	30.15	51.61
	Zeolite at rate of 20%	21.78	35.97	55.62
Kafr Soliman	No addition (control)	0.00	0.136	0.273
	Biochar at rate of 10%	11.23	27.26	49.86
	Biochar at rate of 20%	29.04	41.91	60.27
	Zeolite at rate of 10%	2.054	19.72	44.65
	Zeolite at rate of 20%	4.109	21.36	45.75
Talkha	No addition (control)	0.303	0.484	0.545
	Biochar at rate of 10%	28.48	41.39	59.63
	Biochar at rate of 20%	40.60	51.28	66.42
	Zeolite at rate of 10%	13.33	28.72	50.9
	Zeolite at rate of 20%	21.81	36.00	55.81
Kafr El-Manazla	No addition (control)	0.557	0.780	0.780
	Biochar at rate of 10%	34.67	46.26	63.04
	Biochar at rate of 20%	44.48	54.51	68.60
	Zeolite at rate of 10%	22.18	36.23	56.07
	Zeolite at rate of 20%	33.11	45.15	62.20

Table 14. Effect of boichar and zeolite treatments on available Sr value (mg kg^{-1})

Soil location	Treatments	Incubation period(days)			Mean
		7	14	28	
		Available Sr value (mg kg^{-1})			
Kafr El-Batikh	No addition (control)	40.75	40.74	40.73	**40.74**
	Biochar at rate of 10%	32.00	28.80	21.60	**27.46**
	Biochar at rate of 20%	30.00	27.00	20.25	**25.75**
	Zeolite at rate of 10%	36.50	32.85	24.60	**31.31**
	Zeolite at rate of 20%	33.50	30.15	22.90	**28.85**
	Mean	**34.55**	**31.908**	**26.016**	**30.82**
Kafr Soliman	No addition (control)	159.4	159.2	159.15	**159.25**
	Biochar at rate of 10%	122.3	110.07	82.60	**104.99**
	Biochar at rate of 20%	106.9	96.21	72.15	**91.75**
	Zeolite at rate of 10%	145.6	131.04	98.28	**124.97**
	Zeolite at rate of 20%	135.8	122.22	91.66	**116.56**
	Mean	**134**	**123.748**	**100.768**	**119.50**
Talkha	No addition (control)	286.0	285.98	285.95	**285.97**
	Biochar at rate of 10%	245.6	221.04	165.78	**210.80**
	Biochar at rate of 20%	222.8	200.52	150.39	**191.23**
	Zeolite at rate of 10%	275.9	248.31	186.23	**236.81**
	Zeolite at rate of 20%	270.3	243.27	182.45	**232.00**
	Mean	**260.12**	**239.824**	**194.16**	**231.36**
Kafr El-Manazla	No addition (control)	158.0	158.0	157.9	**157.96**
	Biochar at rate of 10%	130.0	117.00	87.75	**111.58**
	Biochar at rate of 20%	109.2	98.28	73.71	**93.73**
	Zeolite at rate of 10%	146.3	131.67	98.75	**125.57**
	Zeolite at rate of 20%	140.9	126.81	95.10	**120.93**
	Mean	**136.88**	**126.35**	**102.64**	**121.95**

Table 15. Power fixation percentage (Sr)

Soil location	Treatments	Incubation period (days)		
		7	14	28
		Power fixation of available Sr (%)		
Kafr El-Batikh	**No addition (Control)**	0.098	0.122	0.147
	Biochar at rate of 10%	21.54	29.39	47.04
	Biochar at rate of 20%	26.45	33.80	50.35
	Zeolite at rate of 10%	10.51	19.46	39.69
	Zeolite at rate of 20%	17.87	26.08	43.85
Kafr Soliman	**No addition (control)**	0.050	0.175	0.206
	Biochar at rate of 10%	23.31	30.98	48.20
	Biochar at rate of 20%	32.96	39.67	54.75
	Zeolite at rate of 10%	8.703	17.83	38.37
	Zeolite at rate of 20%	14.84	23.36	42.52
Talkha	**No addition (control)**	0.027	0.034	0.045
	Biochar at rate of 10%	14.15	22.73	42.05
	Biochar at rate of 20%	22.11	29.90	47.43
	Zeolite at rate of 10%	3.56	13.20	34.90
	Zeolite at rate of 20%	5.51	14.96	36.22
Kafr El-Manazla	**No addition (control)**	0.082	0.082	0.14
	Biochar at rate of 10%	17.78	26.01	44.50
	Biochar at rate of 20%	30.94	37.84	53.38
	Zeolite at rate of 10%	7.481	16.73	37.55
	Zeolite at rate of 20%	10.89	19.80	39.85

CONCLUSION

In conclusion, the study demonstrated that biochar and zeolite are effective soil amendments for reducing the availability and enhancing the fixation of heavy metals in contaminated soils. Their application, particularly at higher rates, significantly reduced metal mobility over time, suggesting their potential as sustainable solutions for soil remediation. It is recommended to implement these treatments in agricultural practices, especially in areas with high contamination levels, to improve soil health and crop safety. Future research should explore the long-term effects of these amendments under field conditions and investigate their combined use with other organic or inorganic materials to maximize soil rehabilitation outcomes.

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الملخص العربي

تخفيف تلوث التربة بالمعادن الثقيلة باستخدام الفحم الحيوي والزيوليت

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تقيم هذه الدراسة فعالية الفحم الحيوي والزيوليت كمعدلات للتربة في التخفيف من توافر المعادن الثقيلة في أراضي ملوثة مختلفة بمصر. تم جمع عينات التربة من أربعة مواقع ، كل منها يتميز بمستويات مختلفة من التلوث بالمعادن الثقيلة: كفر البطيخ، كفر سليمان، طلخا، وكفر المنازلة. تم إجراء تجربة تحضين تحت ظروف معملية محكمة، مع الحفاظ على عينات التربة عند 70% من السعة الحقليه على مدى 28 يومًا. تضمنت المعاملات مجموعة الكنترول (بدون إضافة)، وفحم حيوي بنسبة 10% و20%، وزيوليت بنسبة 10% و20%. أظهرت النتائج أن كل من الفحم الحيوي والزيوليت قد خفضا بشكل كبير من توافر المعادن الثقيلة (الزئبق، الكادميوم، الكروم، النيكل، الرصاص، السترانشيوم)، حيث أدت معدلات الاضافة الأعلى إلى زيادة أكبر في تثبيت المعادن الثقيلة. تسلط هذه النتائج الضوء على إمكانيات الفحم الحيوي والزيوليت كمعدلات تربة مستدامة لتحسين جودة التربة وتقليل تلوثها بالمعادن الثقيلة، مما يمهد الطريق لممارسات زراعية مستقبلية تركز على معالجة التربة. يُوصى بمزيد من البحث لاستكشاف الفعالية على المدى الطويل لهذه المعاملات في ظروف الحقل وتفاعلاتها مع ممارسات إدارة التربة الأخرى.