# EFFECTS OF MINE WATER IRRIGATION ON VERTICAL DISTRIBUTION OF SOIL NUTRIENTS, SALTS AND METALS

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**Abstract.** In North China, the shortage of water resources is one of the main restricting factors of agricultural production. In order to alleviate the two problems of agricultural water shortage and mine water discharge and promote the safe utilization of mine water resources. In this paper, the soil column test was used to study the effects of different models of mine water irrigation on the vertical distribution of soil nutrients, salinity and metals. The results show that mine water irrigation can improve soil fertility, and increase the risk of soil and groundwater pollution; mine water irrigation can increase soil salinity, the contents of $K^+$, $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $Cl^-$ and $SO_4^{2-}$ increased significantly in 0-10 cm and 60-80 cm soil layers, which did not cause soil salinization and alkalization in a short time, and the pH value of soil was not affected by irrigation water quality; mine water irrigation increased the concentrations of Cd and Pb in soil, which accumulated most obviously in 0-20 cm soil layer, which caused soil Cd exceeding the secondary soil environmental standard ($Cd = 1.00\ mg \cdot kg^{-1}$); the mixed irrigation (mine water and clean water) and rotational irrigation could reduce the pollution risk of nitrogen of groundwater, soil salinization, alkalization, Cd and Pb metals.

**Keywords:** *irrigation, mine water, North China, unconventional water, water quality*

## Introduction

Mine water is an unconventional water resource for solving the shortage of agricultural irrigation water and can be used to solve the shortage of agricultural irrigation water under the reasonable irrigation model and method in the mineral-grain complex area of northern China. Previous studies mainly investigated the effects of brackish water and reclaimed water irrigation on crops, soil and groundwater (Hu et al., 2018; Urbano et al., 2017). However, the effects of mine water on agricultural irrigation is still little known (Ma et al., 2015). Moreover, with the increase of mining volume, mine water discharge becomes more and more serious problem (Guo et al., 2014; Yan et al., 2020). Rational utilization of mine water plays a significant role in alleviating the contradiction between supply and demand of freshwater resources and reducing the risk of ecological environmental pollution caused by mine drainage. Because mine water contains a lot of suspended solids, high salinity and metals, especially untreated mine water with high salinity can easily cause soil salinization and affect crop growth (Deinlein et al., 2014). Irrigation with wastewater containing metals Cd and Pb will damage soil environment and affect crop photosynthesis (Farahat et al., 2017;

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Numanbakth et al., 2019). Mine water in some areas of south China and Africa is acidic, if it is directly used for irrigation it will cause soil acidification, however, acid mine water treated with lime and fly ash can be used for irrigation (Madzivire et al., 2019; Nemutanzhela et al., 2017).

In recent years, many scholars have evaluated whether mine water can be used for irrigation or domestic water (Eyankware et al., 2020; Mahato et al., 2018; Shabalala and Ekolu 2019; Wang et al., 2019). In Northeast and North China, mine water can be used for irrigation and domestic water (Hu et al., 2018；Dai et al, 2020), while in the Northwest and South China, mine water can only irrigated after treatment (Wang et al., 2019; Yang et al., 2012). After the mine water is treated to meet the corresponding water quality standards, it can be reused for the production and domestic water of the coal mine itself, the production and domestic water of the downstream enterprises of the coal mine, the ecological restoration water of the mine area and the agricultural irrigation water, etc, so that it can bring significant economic, social and environmental benefits (Zhang et al., 2022). There are also studies on soil improvement experiments in mining areas and obvious effect has been achieved after mine water irrigation (Fairgray et al., 2020; Zhang 2020). However, there are few researches on the effects of different mine water irrigation on soil environment. In this paper, the vertical distribution characteristics of soil nutrients, salinity and metals under the different models of mine water irrigation (mixed irrigation and rotation irrigation) were studied by simulating the test of mine water irrigation in the overlapped areas of crop and mineral production of southern Hebei in China. It will provide theoretical basis for the promotion and utilization of mine water irrigation in North China.

## Materials and methods

### *Overview of the study area*

The experiment was carried out under the canopy in the irrigation test ground of Hebei University of Engineering, which is located in the North China Plain, 114.45° E, 36.63° N, and belongs to the semi-humid continental monsoon climate zone of warm temperate zone. The soil was obtained from the mineral-grain complex area of Handan city in Hebei province China. The annual average temperature is 14℃, the annual frost-free period is 200 d, the annual sunshine is 2557 h, and the annual precipitation is 575.9 mm. The research area has low rainfall and is concentrated from June to August. The winter wheat season is dry and water scarce, and only irrigation can achieve high yield.

### *Experimental design*

*Figure 1* is the schematic diagram of the experimental treatment. One control treatment: Clean water irrigation (CK) and three treatments of mine water were set up in the experiment: 1. Mixed irrigation of mine water and clean water (1:1, M1), 2. Rotational irrigation of mine water and clean water (M2), 3. Irrigation of mine water (M3). The clean water in the test was local tap water. Each treatment was repeated three times.

The experiment is mainly divided into filling, settlement, irrigation, soil sampling, soil testing and other processes. The first is the filling process. The soil is taken from the silty loam in southern Hebei in China. The five-point-sampling method was used to obtain the soil and mix it evenly. The soil was naturally dried and screened by 2 mm mesh. The soil column used in the experiment is a unified rigid PVC pipe with inner diameter of 15 cm and height of 100 cm. The bottom of the soil column was filled with 2 cm quartz sand filter layer to drain water naturally, and then the soil was filled in layers with a depth of 80 cm and tamped once every 10 cm to make it reach the field soil bulk density of 1.30 $g \cdot cm^{-3}$. The basic physical and chemical properties of the tested soil are shown in *Table 1*.

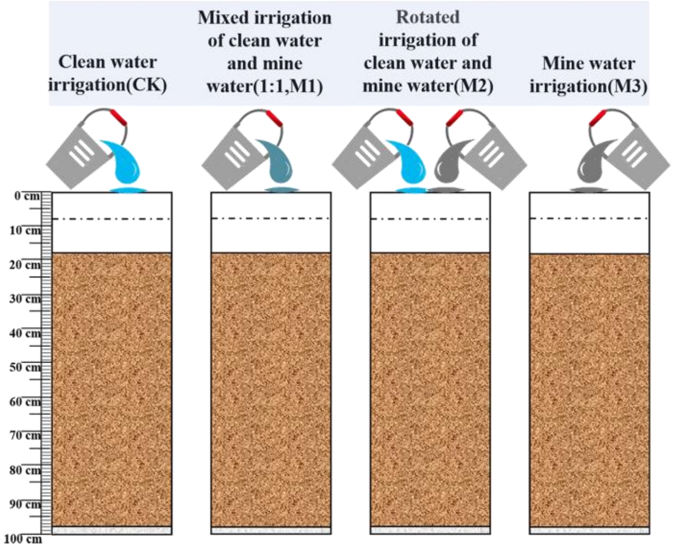

***Figure 1.*** *Schematic diagram of experimental design*

***Table 1.*** *The basic physical and chemical properties of the tested soil*

| Items | Detection result | Items | Detection result |
|---|---|---|---|
| Soil texture | Silty loam | pH | 8.31 |
| Bulk density ($g \cdot cm^{-3}$) | 1.30 | EC ($dS \cdot m^{-1}$) | 0.42 |
| O. M. ($g \cdot kg^{-1}$) | 8.46 | $K^+$ ($mg \cdot kg^{-1}$) | 47.13 |
| TN ($g \cdot kg^{-1}$) | 0.88 | $Na^+$ ($mg \cdot kg^{-1}$) | 148.21 |
| Avail-N ($mg \cdot kg^{-1}$) | 68.56 | $Ca^{2+}$ ($mg \cdot kg^{-1}$) | 186.65 |
| TP ($g \cdot kg^{-1}$) | 0.82 | $Mg^{2+}$ ($mg \cdot kg^{-1}$) | 129.78 |
| Avail-P ($mg \cdot kg^{-1}$) | 7.81 | $HCO_3^-$ ($mg \cdot kg^{-1}$) | 197.23 |
| TK ($g \cdot kg^{-1}$) | 21.51 | $Cl^-$ ($mg \cdot kg^{-1}$) | 112.34 |
| Avail-K ($mg \cdot kg^{-1}$) | 88.36 | $SO_4^{2-}$ ($mg \cdot kg^{-1}$) | 206.57 |

Organic mature (O.M.), total nitrogen (TN), available nitrogen (Avail-N), total phosphorus (TP), available phosphorus (Avail-P), total potassium (TK), available potassium (Avail-K)

Before the first irrigation, each soil column was fertilized according to the local custom, 3 g urea and 3 g diammonium phosphate should be evenly mixed with the surface soil (<10 cm), and then irrigated with tap water until saturated for natural settlement.

According to the local ecological climate and soil conditions, the mine water irrigation system of winter wheat is as follows: irrigation water for 6 times in the whole growth period of winter wheat, once before sowing, tillering, jointing, heading and filling stage respectively, irrigation water for water before sowing, in case of drought in later stage, irrigation water can be increased once in mature stage. The irrigation times of the soil column simulation experiment was 6 times, and each time the soil column was irrigated to the field capacity (θ = 22.7%), and the lower limit of soil water content was controlled at 70% of the field capacity, and Each irrigation reaches 90% of the field capacity. The total amount of irrigation per treatment for each irrigation is 1041.5 ml. The mine water is taken from the Wutong Zhuang coal mine in Fengfeng coal field in China and the clean water is local tap water. *Table 2* shows the physical and chemical properties of the irrigation water used in the experiment.

***Table 2.*** *The quality of irrigation water used in the experiment*

| **Water quality index** | **Mass concentration (mg·L$^{-1}$)** | | | | | | | | | **EC (dS·m$^{-1}$)** | **pH** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **$K^+$** | **$Na^+$** | **$Ca^{2+}$** | **$Mg^{2+}$** | **$Cl^-$** | **$HCO_3^-$** | **$SO_4^{2-}$** | **Cd** | **Pb** | | |
| Clean water | 3.60 | 69.25 | 47.60 | 28.06 | 22.87 | 13.70 | 46.21 | 0.00 | 0.55 | 1.35 | 7.33 |
| Mine water | 183.51 | 821.40 | 353.13 | 122.21 | 698.60 | 19.70 | 463.90 | 0.05 | 2.17 | 6.11 | 7.72 |

## *Measurement Items and methods*

When the soil column was irrigated to a specified number of times, destructive sampling was carried out. The soil column was cut into 5 sections, which were 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm and 60-80 cm soil layers. Two bulk density rings were used in each section to take undisturbed soil to measure soil bulk density. The rest of the soil samples were air dried, crushed and screened by 1 and 0.475 mm. One part of the soil samples was used to determine soil nutrients and heavy metals. The other part of the soil samples were mixed with distilled water without $CO_2$ according to the soil water ratio of 1:5, fully shaken and filtered, and the supernatant was taken to determine soil soluble salt. The determination items and methods are shown in *Table 3* (Note: The measurements in *Table 3* were made using the corresponding methods of soil agrochemical analysis).

***Table 3.*** *Determination items and methods*

| **Measurement items** | | **Methods** |
|---|---|---|
| Soil nutrient | O.M. | Potassium dichromate volumetric method and external heating method |
| | Avail-N | Alkali hydrolysis diffusion method |
| | Avail-P | Olsen method |
| | Avail-K | Flame photometry method |
| Soil salinity | EC | DDS-307 conductivity meter |
| | pH | PHBJ-260 portable pH meter |
| | $Ca^{2+}$, $Mg^{2+}$ | EDTA titration |
| | $Na^+$, $K^+$ | FP6400 flame photometer method |
| | $HCO_3^-$ | Double indicator neutralization titration |
| | $Cl^-$ | $AgNO_3$ titration |
| | $SO_4^{2-}$ | Barium Sulfate Turbidimetry (GB7871-87) |
| Heavy metals | Cd, Pb | Soil samples were digested by hydrochloric acid nitric acid hydrofluoric acid perchloric acid. The digested solution was determined by aa-7000 series atomic absorption spectrophotometer |

Conductivity meter DDS-307 is manufactured by Shanghai Yi dian Scientific Instrument Company. PHBJ-260 portable pH meter manufactured by Beijing An wei Company; The FP6400 flame photometer is manufactured by Shanghai Yue feng Instrument Company; A-7000 series atomic absorption spectrophotometer is manufactured by Zhejiang He pu Instrument Company

### *Data processing and analysis*

Sodium adsorption ratio (SAR) of soil extract, the unit is (mmol·L$^{-1}$) $^{0.5}$, and can be calculated as follows:

$$SAR = \frac{\left[Na^{+}\right]}{\left[Ca^{2+} + Mg^{2+}\right]^{\frac{1}{2}}} \tag{Eq.1}$$

Among them, the unit of Na$^{+}$, Ca$^{2+}$ and Mg$^{2+}$ is mmol·L$^{-1}$.

Excel was used to organize the data, SPSS17.0 software was used to analyze the difference significance of the data, and LSD method was used for multiple comparisons, with a confidence level of 0.05.

## Results and analysis

### *Influence of mine water irrigation on soil nutrients*

The mine water used in this experiment contains organic and inorganic substances such as coal powder, human excreta and high concentration of K$^{+}$, which can improve the content of soil nutrient. The coal powder contains humic, which can improve the content of O.M. It can be seen from *Figure 2* that the nutrient accumulation in the surface soil (<20 cm) of each treatment is obvious, and the total nutrient contents of the soil after the mine water irrigation is higher than those of the clean water treatment, which indicates that the sewage irrigation can improve the soil nutrient of the plough layer, which is consistent with the previous research results (Perull et al., 2019). The Avail-N first decreased and then increased with the increase of depth, and the minimum value was found in 20-40 cm soil layer, indicating that Avail-N would migrate and accumulate downward with the increase of irrigation times (*Fig. 2a*). The accumulation of Avail-K was obvious in 0-10 cm soil layer and 40-60 cm soil layer (*Fig. 2c*). The vertical distribution of organic matter and Avail-P is similar, which decreases with the increase of depth, and reaches the minimum at 80 cm depth (*Fig. 2b, d*). Compared with O.M. and Avail-P, available N and Avail-K were easier to migrate downward, while O.M. and Avail-P were easier to accumulate in 0-20 cm surface layer, which indicated that available N and Avail-K moved downward faster. Although mine water irrigation can improve soil nutrients, the downward migration of Avail-N may cause the risk of groundwater pollution.

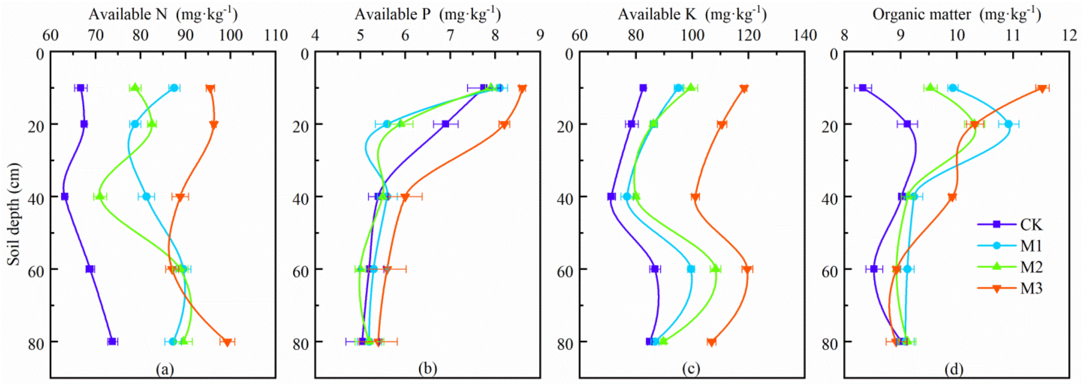

***Figure 2.*** *Changes of soil typical nutrient ions (Avail-N, P, K and O.M.) with soil depth under different irrigation treatments*

LSD analysis showed that the change range of Avail-P in 10-20 cm soil layer was high, while the variation range of Avail-P in 0-10 cm and 20-80 cm soil layer was very low, and there was no significant difference among the treatments ($p < 0.05$). The variation range of O.M. in 0-20 cm soil layer was high, but the variation range of O.M. in 20-80 cm soil layer was low, and there was no significant difference among the treatments ($p < 0.05$). There were significant differences in Avail-N and Avail-K between M1, M2 and M3 treatments and CK treatments ($p < 0.05$).

Compared with the CK, the average Avail-N of M1, M2 and M3 was 25.01%, 20.91% and 35.95% higher, the average Avail-K was 9.40%, 14.62% and 36.66% higher, the average O.M. was 7.31%, 5.11% and 9.62% higher, and the average Avail-P was -0.11%, -1.63% and 10.56% higher respectively. The decrease of Avail-P of M1 and M2 may be due to the combination of Avail-P with calcium ions in alkaline environment to form insoluble substances.

### *Influence of mine drainage irrigation on soil salinity*

#### *The effect on soil pH*

Because of the buffering capacity of soil, it is generally considered that irrigation water has no significant effect on soil pH value, which is least affected. The change law among the treatments is basically similar (*Fig. 3a*), but not significant ($p < 0.05$), which is the same as the previous research results (Yang et al., 2006). In 0-10 cm soil layer, the pH of M1, M2 and M3 is lower than that of CK, which may be caused by humic composition in mine water, and O.M. can be decomposed into organic acid and $CO_2$, which can reduce the pH of soil.

#### *Electrical conductivity (EC) of soil*

Electrical conductivity (EC) of soil reflects the degree of soil salinization to a certain extent. Mine water contains a lot of salts. Therefore, it is generally believed that mine water irrigation will increase the soil salt content. The soil EC of each treatment decreased first and then increased with depth, reaching the maximum at 80 cm, and CK, M1 and M2 were the minimum at 20-40 cm soil layer, M3 was the minimum at 10-20 cm soil layer (*Fig. 3b*). Compared with CK, the EC of M1, M2 and M3 in different soil layers increased by 54.02-146.22%, 97.32%-151.14% and 147.71%-237.63% respectively, which was related to the high salt content of mine water. Compared with M3, the EC of M1 and M2 in different soil layers decreased by 16.24%-50.06% and 13.45%-35.92% respectively. M1 and M2 irrigation model can reduce the risk of soil salinization to a certain extent.

The average EC of M1, M2, M3 and CK treatments were 0.80 $dS \cdot m^{-1}$, 0.87 $dS \cdot m^{-1}$, 1.24 $dS \cdot m^{-1}$ and 0.43 $dS \cdot m^{-1}$, respectively (*Fig. 4a*). The mean value of EC in M1, M2 and M3 increased significantly, which were respectively 87.46%, 103.21% and 190.23% higher than that in CK. Multiple LSD comparative analysis showed that the soil salt content of 0-80 cm in M1, M2 and M3 was significantly different from that in CK ($p < 0.05$). It may not cause salinization in the short term, but long-term mine water irrigation may result in the risk of soil salinization.

#### *Effect of soil sodium adsorption ratio (SAR)*

The SAR of soil reflects the degree of soil alkalization. Acidic mine water will make soil acidified, while alkaline mine water will make soil alkalized. As shown in

*Figure 3c*, the SAR of each treated soil increased with depth and reached the maximum value at the 60-80 cm soil layer. In each soil layer, the SAR of the three mine water treatments all are higher than that of clean water treatment. At the soil depth of 0-40 cm, the SAR of the soil is M3 > M2 > M1 > CK. In the depth of 40-80 cm, the SAR of soil is M3 > M1 > M2 > CK. Compared with CK, the increase ranges of M1, M2 and M3 treatment were 49.11%-78.85%, 32.23%-78.62% and 87.46%-137.37%, respectively. However, the maximum SAR of 5.72 ((mmol·L$^{-1}$)$^{0.5}$) in different soil layers under the four treatments was far lower than the critical SAR of 13.00 ((mmol·L$^{-1}$)$^{0.5}$) for soil alkalization. Therefore, the use of mine water irrigation would not cause soil alkalization in the short term.

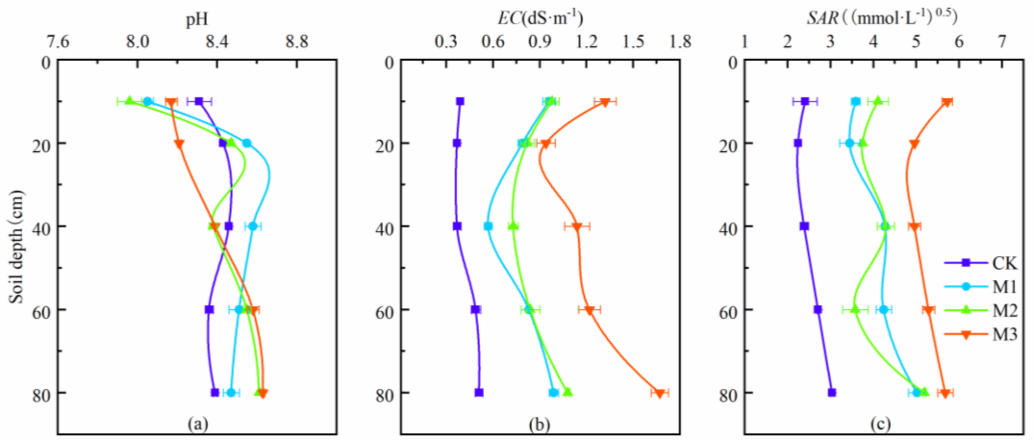

***Figure 3.*** *Variation of pH (a), EC (b) and SAR (c) of soil with depth under different irrigation treatments*

The average soil SAR of M1, M2, M3 and CK were 4.16 (mmol·L$^{-1}$)$^{0.5}$, 4.16 (mmol·L$^{-1}$)$^{0.5}$, 5.27 (mmol·L$^{-1}$)$^{0.5}$ and 2.57 (mmol·L$^{-1}$)$^{0.5}$, respectively (*Fig. 4b*). Compared with CK, the average SAR of M1, M2 and M3 increased significantly by 61.87%, 61.87 and 105.06%, respectively, that is M3 > M1 > M2 > CK. LSD multiple comparison analysis showed that the SAR of M1, M2 and M3 soil profiles (0-80 cm) were significantly different from those of CK ($p < 0.05$), while the average SAR of M1 and M2 soil were not significantly different ($p < 0.05$).

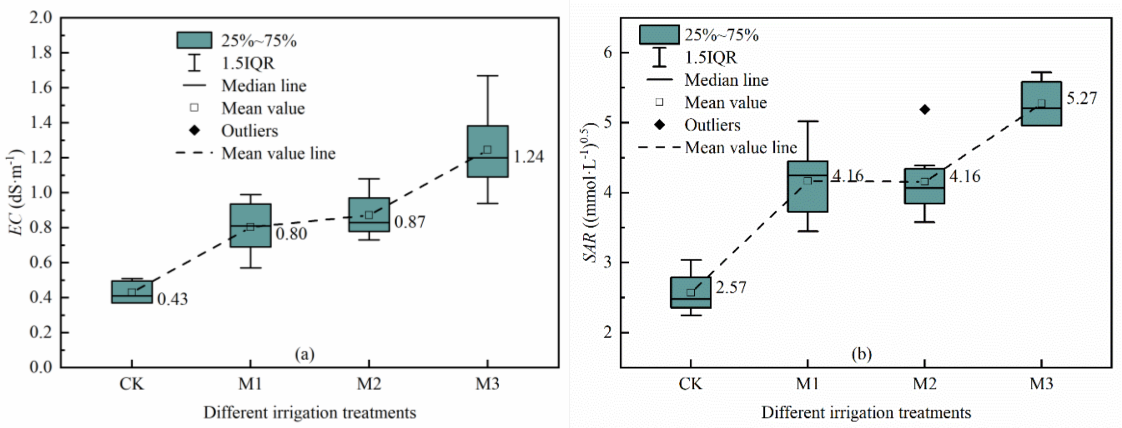

***Figure 4.*** *Box plot of soil EC and SAR under different irrigation treatments*

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Mine water contains a large amount of sodium salt. The salt moves down under irrigation leaching, is absorbed by soil, and will accumulate in the soil. Therefore, the SAR of soil profiles (0-80 cm) of CK, M1 or M2 and M3 are significantly different, but there is little difference between M2 and M1. The reason why there is no significant difference between M1 and M2 is that both of them reduce the concentration of mine water input.

According to the above analysis, the salt accumulation occurred in different soil layers under M1, M2 and M3 treatments after 6 times of continuous irrigation, but will not lead to soil salinization in the short time, which is similar to the previous research results (Xu et al., 2010). The average SAR of soil in M1 and M2 were 19.8% and 20.1% lower than those of M3 treatment, respectively, indicating that long-term M3 treatment may lead to the changes of properties in soil, but the risk of soil alkalization can be reduced through mixed irrigation or rotational irrigation. According to the experiment, mine water irrigation will lead to a significant increase EC and SAR in soil. Therefore, long-term mine water irrigation may produce soil salinization and alkalization.

### *Effect on $K^+$, $Na^+$, $Ca^{2+}$, $Mg^{2+}$*

Compared with clean water, there are a large amount of $K^+$, $Na^+$, $Ca^{2+}$ and $Mg^{2+}$ in mine water, especially the highest content of $Na^+$, and ion exchange of $K^+$, $Na^+$, $Ca^{2+}$ and $Mg^{2+}$ had occurred in the soil (*Table 2*). After irrigation, the concentrations of $K^+$, $Na^+$, $Ca^{2+}$ and $Mg^{2+}$ in M3 soil profile (0-80cm) changed significantly ($p < 0.05$), and the average $K^+$, $Na^+$, $Ca^{2+}$ and $Mg^{2+}$ in M3 soil were 70.02%, 165.34%, 44.41% and 109.76% higher than those in CK, respectively (*Figs. 5a, b, c* and *d*). From the soil longitudinal profile, $K^+$, $Na^+$, $Ca^{2+}$ and $Mg^{2+}$ in the soil after each treatment is the most obvious at 60-80cm soil layer, indicating that the accumulation effect of salt was the strongest in the deep layer after 6 times of irrigation and leaching. LSD analysis showed that the soil $Mg^{2+}$ and $Na^+$ in mine water irrigation were significantly different from those in clean water irrigation ($p < 0.05$). The average content of $Mg^{2+}$ of soil in M1, M2 and M3 was 24.92%, 31.14% and 110.41% higher than that in CK, respectively, and the average content of $Na^+$ in M1, M2 and M3 was 74.45%, 75.12% and 164.83% higher than that in CK. The difference analysis showed that the average contents of $Ca^{2+}$ and $K^+$ after M1 and M2 treatments were not significantly different from those of CK ($p < 0.05$).

### *Effect on $HCO_3^-$, $Cl^-$, $SO_4^{2-}$*

Compared with clean water, the treatment of mine water irrigation contains a lot of $Cl^-$ and $SO_4^{2-}$, while the content of $HCO_3^-$ is similar to that of clean water irrigation (*Table 2*). The contents of $Cl^-$ and $SO_4^{2-}$ in different processing showed a trend of increase with depth (*Fig. 6*). The average contents of $Cl^-$ in M1, M2, and M3 were respectively 99.82%, 84.36%, 165.11% higher than those of CK and the average contents of $SO_4^{2-}$ in M1, M2, and M3 were respectively 55.21%, 76.62%, 208.86% higher than those of CK. LSD analysis showed that the difference of average contents of $Cl^-$ and $SO_4^{2-}$ between M1, M2, M3 and CK was significant ($p < 0.05$). In the soil layer of 60-80 cm, the accumulation of $Cl^-$ and $SO_4^{2-}$ was significant in each treatment ($p < 0.05$), which indicated that the $Cl^-$ and $SO_4^{2-}$ of soil migrated down obviously after 6 irrigation times.

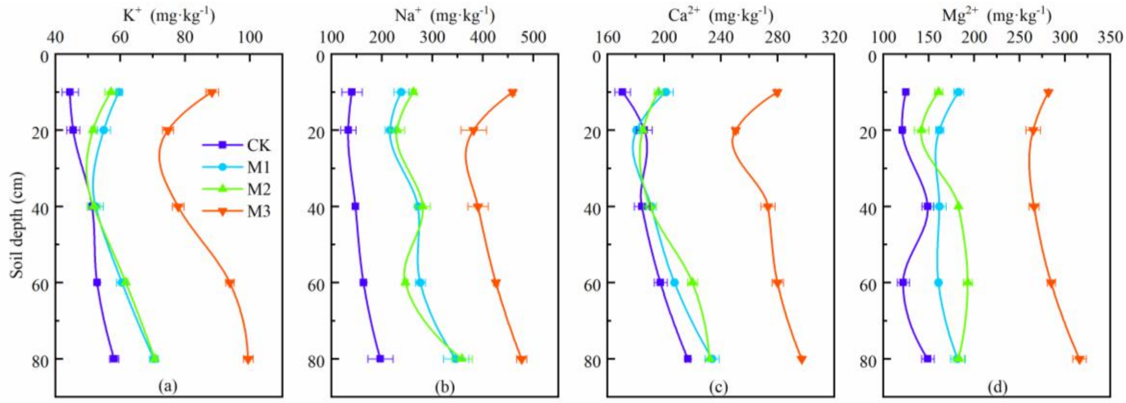

***Figure 5.*** *Variation of soil typical cations with depth under different irrigation treatments*

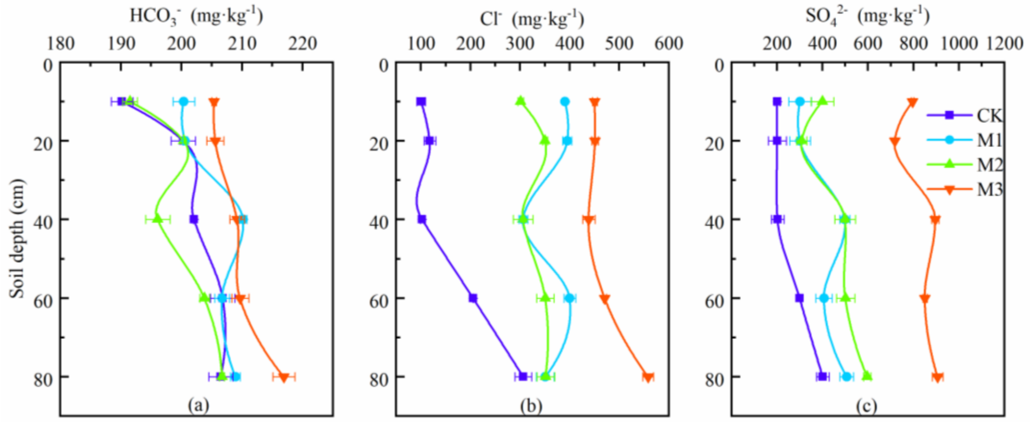

***Figure 6.*** *Variation of soil typical anions with depth under different irrigation treatments*

LSD analysis showed that there was no significant change of $HCO_3^-$ in soil profile (0-80 cm), and there was no significant difference between different treatments ($p < 0.05$). Therefore, the harm of soil salinization caused by carbonate precipitation does not occur in the treatments of mine water irrigation, which is similar to the previous research results (Xu et al., 2010).

From the above, according to data from the typical cationic and anionic under the different models of mine water irrigation, $K^+$, $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $Cl^-$ and $SO_4^{2-}$ of soil increased significantly. the accumulation phenomenon is the most significant at 0-10 and 60-80 cm soil layer. Long-term mine water irrigation can lead to those ions downward migration and accumulation in the soil, cause soil salinization. However, compared with M3, M1 and M2, the CK greatly reduced the contents of typical ions in deep soil, and there was no significant difference in the contents of typical ions between M1 and M2 ($p < 0.05$). This indicates that rational mine water irrigation t (such as rotational irrigation and mixed irrigation) can markedly reduce the negative effects of mine water application.

### *Influence of mine water irrigation on metals*

Mine water contains a lot of pulverized coal and metal mineral substances, and whether it can be used for agricultural irrigation depends on whether the metals contents in the soil, groundwater and crops after irrigation exceeds the standard. The contents of

Cd and Pb in all the treated soils showed a decreasing trend with depth, and the contents of Cd and Pb in the topsoil were the highest (*Fig. 7*). Cd content in 0-20 cm soil layer is M3 > M1 ≥ M2 > CK, while the content of Cd in 20-80 cm soil layer is M3 > M2 ≥ M1 > CK. The content of Pb in 0-40 cm soil layer is M3 > M1 ≥ M2 > CK, while Pb content in the 40-80 cm soil layer is M3 > M2 ≥ M1 > CK. Although there was no significant difference in soil average contents of Cd and Pb between M1 and M2 ($p < 0.05$), Cd and Pb were more easily to migrate down in M2.

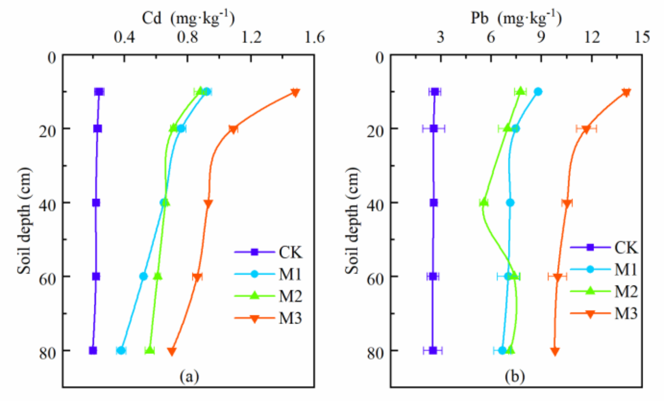

***Figure 7.*** *Variation of soil Cd and Pb metals with depth under different irrigation treatments*

The average contents of Cd of soils in M1, M2, M3 and CK were 0.62 mg·kg$^{-1}$, 0.67 mg·kg$^{-1}$, 0.97 mg·kg$^{-1}$ and 0.22 mg·kg$^{-1}$, respectively (*Fig. 8a*). The average contents of Cd of soils in M1, M2 and M3 were 181.82%, 204.55% and 340.91% higher than those of CK, respectively, with significant difference ($p < 0.05$). The average contents Cd of M1 and M2 did not exceed the second-level soil environmental standard (Cd = 1.00 mg·kg$^{-1}$), while the average content of Cd in M3 exceeded the second-level soil environmental standard, indicating that mine water irrigation may lead to excessive heavy metal content of Cd in soil, resulting in soil pollution.

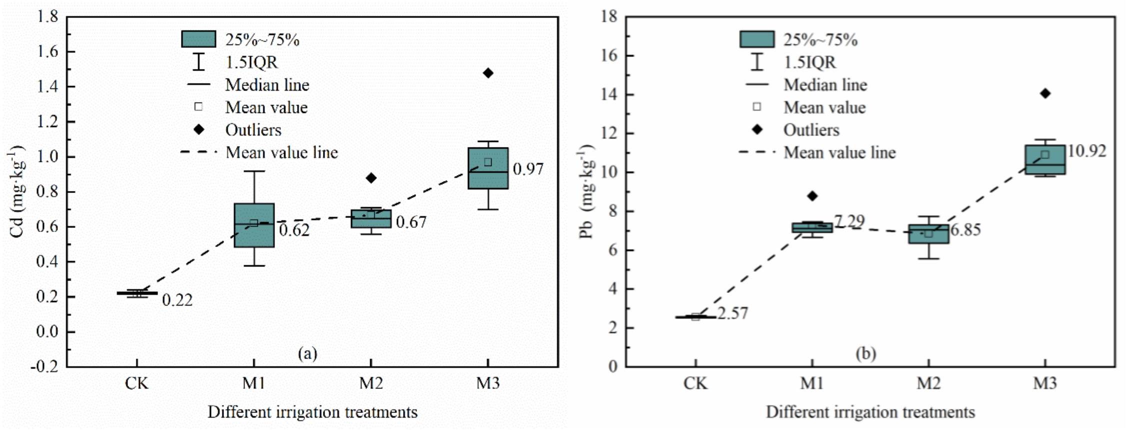

***Figure 8.*** *Box plot of soil Cd and Pb content under different irrigation treatments*

The average contents of Pb in M1, M2, M3 and CK were 7.29 mg·kg$^{-1}$, 6.85 mg·kg$^{-1}$, 10.92 mg·kg$^{-1}$ and 2.57 mg·kg$^{-1}$, respectively (*Fig. 8b*). The average contents of Pb in

M1, M2 and M3 were 183.66%, 166.54% and 324.90% higher than that of CK, with significant difference ($p < 0.05$). The maximum average content of Pb in soil after the four treatments was 10.8 $mg \cdot kg^{-1}$, which was far lower than the primary soil environmental standard (Pb = 35.00 $mg \cdot kg^{-1}$). In the short term, mine water irrigation will not cause the content of Pb of soil exceeding standard, but long-term mine water irrigation can result in the risk of content of Pb in soil exceeding standard.

## Discussion

### *Effect of mine water irrigation on soil nutrient*

Experiments in South Africa have shown that scientific and reasonable mine water irrigation can not only improve crop yield and economic benefits, but also avoid environmental issues (Annandale et al., 2001). In our study, mine water irrigation can improve soil nutrients, but the downward migration of alkali-hydrolyzed nitrogen and available potassium may pollute groundwater, which is similar to the results of Alghobar (Alghobar et al., 2016).

### *Effect of mine water irrigation on soil salt*

Long-term use of highly mineralized mine water for farmland irrigation can cause secondary salinization of the soil (Zhao, 2009). The mine water with $F > 5.0\ mg \cdot L^{-1}$ in the Shendong mining area has extremely high salinity and alkalinity hazards, which is not suitable for irrigation and can easily cause soil salinization. However, low F-mine water ($F < 1.0\ mg \cdot L^{-1}$) has low salt and alkali damage, making it suitable for irrigation (Chen et al.2022). Crop production under irrigation with mine water rich in Ca and sulphate was found to be feasible and sustainable, if properly managed (Grewar, 2019). This is consistent with our experimental results. M1 and M2 irrigation modes can reduce the risk of soil salinization to some extent, which may not cause salinization in the short term, but long-term irrigation with mine water may result in the risk of soil salinization (Yang et al., 2020).

### *Effect of mine water irrigation on soil pollution*

The five LOE are multivariate statistical analysis of an extensive groundwater analyte suite, groundwater sulfur isotope data, probabilistic calculations of groundwater velocity and flow distance, isotopic estimates of groundwater age, and extent of nitrate in groundwater originating from agricultural irrigation (McCulley et al., 2023). Mine wastewater irrigation resulted in accumulation of heavy metals in wheat grain (Ma. et al., 2014). The soil of short-term irrigation with mine water did not produce heavy metal pollution (Tedrow et al., 2022). In our experiments, although mine water irrigation can improve soil nutrients, the downward migration of nitrate may cause the risk of groundwater pollution. The content of heavy metals in soil at different depths can well describe the degree of soil heavy metal pollution. Under different irrigation models, the content of Pb and Cd in soil does not exceed the secondary soil environmental standard in the short term, which will not cause soil pollution.

## Conclusions

Mixed irrigation, rotational irrigation and mine water irrigation increased the content of Avail-N, Avail-K and O.M. in soil, while mixed irrigation and rotational irrigation decreased the content of Avail-P, mainly reduced the content of Avail-P in soil layer of 10-20 cm. The Avail-P and O.M. were mainly accumulated in soil layer of 0-20 cm, while Avail-N and Avail-K were more likely to migrate downward, which may cause the pollution risk of groundwater.

The $K^+$, $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $Cl^-$ and $SO_4^{2-}$ of soil increased significantly in mine water irrigation, and the accumulation was most significant in soil layers of 0-10 cm and 60-80 cm. Long-term irrigation with mine water would lead to the accumulation of salt ions in the soil and soil salinization. There was no significant effect on the pH of soil. The overall level of soil SAR was in the appropriate range ($SAR \leq 10\ (mmol \cdot L^{-1})^{0.5}$) and at a low level. The risk of soil salinization and alkalization is further reduced during rainy season leaching.

After mixed irrigation, rotational irrigation and mine water irrigation, the contents of Cd and Pb in soil increased significantly, and decreased with depth. The accumulation of Cd and Pb was most obvious in the surface layer (<10 cm), among which mine water irrigation would lead to Cd of soil exceeding the soil environmental standard.

Long-term irrigation with mine water will result in the risks of groundwater being polluted by nitrogen and soil salinization, alkalization and exceeding the metals standard. Reasonable irrigation treatment (such as mixed irrigation and rotational irrigation) can reduce the pollution risk of soil and groundwater and realize the safe utilization of mine water resources.

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