



Article

Effects of Vermicompost Application on Growth and Heavy Metal Uptake of Barley Grown in Mudflat Salt-Affected Soils

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Abstract: China is facing a shortage of arable land resources, and the mudflat salt-affected soil along the east coast of China is an important reserve arable land resource. In this study, we conducted a randomized field trial to investigate the effects of vermicompost application rate (0, 25, 50, 125, and 250 t ha⁻¹) on barley growth and heavy metal accumulation in mudflat salt-affected soil. We found that vermicompost application decreased bulk density, electrical conductivity (EC), and pH of mudflat salt-affected soil while increasing its organic carbon, nitrogen, and phosphorus contents. With the increase in vermicompost application rate, the yield of grain and total biomass of barley plants increased. The yield of grain in the vermicompost application treatments of 25, 50, 125, and 250 t ha⁻¹ increased by 66.0%, 226.0%, 340.0%, and 512.0%, respectively, relative to the control. In addition, the concentrations of heavy metals (Cd, Cr, Cu, and Zn) in mudflat salt-affected soil and barley plant increased as the vermicompost application rate increased.

Keywords: mudflat soil; vermicompost; soil improvement; barley; heavy metals



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1. Introduction

There are approximately 36.6 million hectares of salt-affected soil in China. More than 6.6 million hectares are in areas of high management potential and agricultural value and approximately 1.0 million hectares are in coastal mudflat regions. Therefore, considering China's shortage of arable land resources, coastal mudflat salt-affected soil can be used as an important reserve arable land resource [1]. However, due to the short reclamation time, mudflat salt-affected soil lacks fully developed soil layers and thus a fully formed cultivation layer. It has a limited organic carbon pool and low nutrient content; poor soil structure, water retention, ventilation; and homogenous microbial flora and composition, resulting in extremely low soil fertility [2,3]. Key measures for improving mudflat salt-affected soil include reducing salinity and alkalinity and improving soil fertility [4]. Salinity and alkalinity reductions can be accelerated by freshwater irrigation and concentrated rainfall. At the same time, the rapid improvement in soil fertility requires increased soil organic matter content, which can also inhibit resalinization and consolidate the effects of salinity and alkalinity reductions [5]. Studies have shown that soil salinity is negatively correlated with organic matter content [6], mainly because soil organic matter can promote the formation of aggregates and increase noncapillary porosity and the downward movement of salt through leaching while reducing capillary action, preventing the upward movement of water and salt and thus inhibiting resalinization [7,8]. However, the organic matter content of mudflat salt-affected soil is very low. Under environmental conditions

such as high soil salinity and high pH, the accumulation of organic matter in mudflats can be extremely slow without supplementation [9]. Therefore, in addition to implementing salt reduction measures, manually supplementing large amounts of exogenous organic carbon to improve soil fertility is a prerequisite for promoting the transformation of mudflat into arable soil.

The area of salt-affected soil in mudflats is very large, and the use of commercial organic fertilizer to improve soil fertility would be very costly. Domestic sludge is an inexpensive byproduct of domestic sewage treatment and has an organic matter content of 30–50%, which is higher than pig or cow manure. It also contains other nutrients required by plants, such as nitrogen (N) and phosphorus (P) [10,11]. According to statistics, approximately 45% of the sewage sludge currently produced in China is applied to farmland [12]. Using sewage sludge that meets agricultural standards for soil fertilization in mudflat salt-affected soil recycles waste. It reduces the carbon emissions from sludge incineration and the number of land resources occupied by sludge landfills [6]. However, the heavy metals in sewage sludge are one of the main obstacles restricting its agricultural use [13], as such use may cause the accumulation of heavy metals in soil and plants, polluting the environment [14]. Studies have shown that after earthworms digest sewage sludge, the total amount and activity of heavy metals are reduced [15]. The earthworm vermicompost formed from sewage sludge can improve soil fertility, nutrient availability, soil organic matter content, and available nutrients such as available N, available P, and available potassium (K) [16]. However, studies of the agricultural use of vermicompost have been conducted mainly on farmland [17], and the ameliorating effects of vermicompost application on the mudflat salt-affected soils and the accumulation of heavy metals have not yet been examined.

In this study, through randomized field trials, we investigated the effects of vermicompost application on soil physical and chemical properties, barley plant growth, and heavy metal accumulation to identify a new method for accelerated fertilization of mudflat salt-affected soil.

2. Materials and Methods

2.1. Experimental Materials

The field experiment was conducted in a Fangling reclamation area (32°36′30″ N, 121°56′03″ E) in Rudong County, Jiangsu Province, China, and the experimental soil was a typical salt-affected soil. The location of the experiment site was reclaimed from coastal mudflats in 2010. This area has distinct seasons and marine monsoon climate characteristics. This area's annual average temperature and average annual evaporation are 15.8 °C and 866.6 mm, respectively. Rainfall is mainly concentrated between June and September. The barley cultivar used in this experiment was Yangnongpi 5 (*Hordeum vulgare* L.), beer barley bred by Yangzhou University and suitable for winter barley cultivation in Jiangsu. The vermicompost used for the plot experiment was gathered from Chunguang Ecological Agriculture Development Co., Ltd. of Taizhou in the Jiangsu province, formed from digested earthworm sewage sludge. The quality of sewage sludge complied with China's state standard for agricultural application of sewage sludge (GB/T 24600-2009). The basic properties of mudflat soil and vermicompost are shown in Table 1.

Table 1. Basic properties of the mudflat soil and vermicompost used in this study.

Items	Mudflat Soil	Vermicompost
pH	8.98	6.34
EC (mS cm ^{−1})	4.34	8.92
Organic carbon (g kg ^{−1})	2.23	270
Total N (N g kg ^{−1})	0.251	24.4
Total P (P g kg ^{−1})	0.512	15.9
Alkaline N (N mg kg ^{−1})	18.8	2467
Available P (P mg kg ^{−1})	9.69	869
Total Cd (mg kg ^{−1})	0.792	2.94
Total Cr (mg kg ^{−1})	41.3	141
Total Cu (mg kg ^{−1})	17.5	436
Total Zn (mg kg ^{−1})	39.6	805

EC, electric conductivity; N, nitrogen; P, phosphorus; Cd, cadmium; Cr, chromium; Cu, copper; Zn, zinc.

2.2. Experimental Design

A randomized field plot experiment was adopted, in which five vermicompost application treatments, i.e., 0, 25, 50, 125, and 250 t ha^{−1}, each with three replicates, were established in 3.6 × 3.6 m plots. In February 2016, vermicompost was applied to each plot and well mixed into the 0–20 cm surface soil using a rotary tiller. From June to September, sorghum was planted; then, on 15 October, barley was planted at 243 kg ha^{−1}. Weeds were controlled by hand weeding at 60 and 90 days after sowing; no other management measures were taken. Samples of soil and barley plants were collected on 15 May 2017. No chemical fertilizers were applied during the experiment.

2.3. Soil and Plant Analysis

Soil samples throughout the upper 20 cm were collected in quadruplicate from each plot. After the soil samples were air-dried, all samples were crushed and sieved (1 mm and 0.150 mm) for further physicochemical analysis. The aerial parts of barley plants from each experimental plot were hand-harvested at maturity. For a yield of total biomass determination, the harvested aerial parts were dried in the sun and then weighed. After that, artificial threshing in each plot was carried out to obtain grain yield.

Soil bulk density was measured via the cutting ring method. Soil pH and EC were detected in a 5/1 (water volume/soil weight) suspension by a pH meter (Model IQ150, Spectrum, Aurora, IL, USA) and conductivity meter (Item 2265FS, Aurora, IL, USA), respectively. For the analysis of soil organic matter, a 0.30 g air-dried soil sample was measured through a 0.150 mm mesh sieve by the potassium dichromate (K₂Cr₂O₇) external heating method [18]. Soil total N and total P were determined using the semi-micro Kjeldahl method and sulfuric acid-perchloric acid digestion-molybdenum-antimony colorimetric method. Soil alkaline N and available P were measured through the alkaline hydrolysis diffusion method and the sodium bicarbonate extraction-molybdenum-antimony colorimetric method, respectively [18]. N and P content in aerial parts of barley plants were analyzed by the indophenol blue colorimetric method and the molybdenum-antimony colorimetric method after digestion with concentrated sulfuric acid-hydrogen peroxide [18]. For extracting total heavy metals in the soil samples, a 0.35 g air-dried soil sample through the 0.150 mm mesh sieve was digested with 6 mL nitric acid (HNO₃), 3 mL hydrochloric acid (HCl), and 0.25 mL hydrogen peroxide (H₂O₂) by a microwave digestion system (Model MARS 6, CEM Corporation, Matthews, NC, USA). For extracting heavy metals in barley samples, a 0.50 g oven-dried barley sample through the 2 mm mesh sieve was digested with 9 mL nitric acid (HNO₃) and 0.50 mL hydrogen peroxide (H₂O₂) by a microwave digestion system (Model MARS 6, CEM Corporation, Matthews, NC, USA). The digestion solution of soil and barley samples was filtered and detected for Cd, Cr, Cu, and Zn by ICP-AES (Model iCAP 6300, Thermo Fisher Scientific Inc., Waltham, MA, USA).

2.4. Data Analysis

The one-way analysis of variance (ANOVA) for the data was carried out by SPSS 19.0 (SPSS Inc., Chicago, IL, USA) with the model of a randomized complete block (RCB) design. The multi-comparison applying least significant difference (LSD) at $p < 0.05$ was used to test significant differences between the treatments.

3. Results

3.1. Effects of Vermicompost Application on the Physical and Chemical Properties of Mudflat Salt-Affected Soil

As the application amount of vermicompost increased, the soil bulk density, pH, and EC of mudflat salt-affected soil decreased, while the content of soil organic matter increased (Figure 1). The soil bulk density of the control treatment (without vermicompost application) was 1.40 g cm^{-3} . The values in the vermicompost application treatments were lower, at 1.37, 1.34, 1.23, and 1.00 g cm^{-3} , representing decreases of 2.1%, 4.3%, 12.1%, and 28.6%, respectively, relative to the control value. At the 125 t ha^{-1} vermicompost application rate, the difference from the control treatment was significant. The soil pH and EC were 8.69 and 6.92 mS cm^{-1} , respectively, in the control treatment. The soil pH at the vermicompost treatments was decreased to 8.63, 8.45, 8.16, and 7.82, and the EC was decreased to 6.42, 5.62, 4.94, and 3.96 mS cm^{-1} . At the 50 t ha^{-1} vermicompost application rate, the differences in soil pH and EC from the control values were significant. In the control treatment, the soil organic carbon content was 4.45 g kg^{-1} and increased to 6.69, 7.30, 8.42, and 10.94 g kg^{-1} in the vermicompost treatments, representing 49.8%, 63.9%, 89.0%, and 145.7% increases, respectively. The soil organic carbon content in each vermicompost treatment was significantly higher than the control.

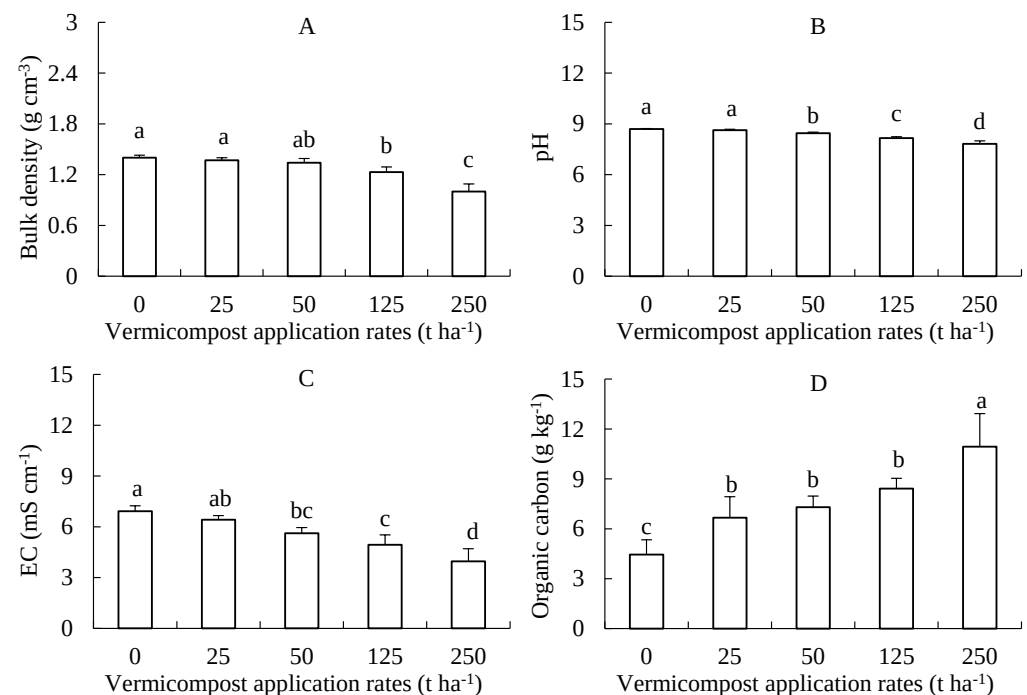


Figure 1. Effects of vermicompost application on bulk density (A), pH (B), EC (C), and organic carbon content (D) in mudflat salt-affected soil. Values are the mean of three replicates, and bars show standard deviation. Columns with different letters show a significant difference between sewage sludge amendment rates at $p < 0.05$ by LSD's multiple range test. EC, electric conductivity.

The content of the soil total N, the alkaline N, the total P, and the available P in mudflat salt-affected soil increased with increasing vermicompost application rates (Table 2). In the control treatment, the total N and total P content were 0.31 g kg^{-1} and 0.52 g kg^{-1} , respectively. In the vermicompost application treatments, the total N increased by 51.6%,

148.4%, 254.8%, and 393.5%, and the total P increased by 25.0%, 67.3%, 51.9%, and 69.2%. Except for those in the 25 t ha⁻¹ vermicompost treatment, the total N and P content in the vermicompost treatments was significantly higher than the control treatment. The alkaline N and available P contents in control were 17.60 and 27.75 mg kg⁻¹, respectively. In the vermicompost application treatments, the alkaline N increased by 92.2%, 235.1%, 265.3%, and 463.4%, and the available P increased by 156.7%, 241.4%, 503.5%, and 724.9%, with significant differences observed between the control and the vermicompost treatments. Furthermore, the increments in the alkaline N and available P content in the vermicompost-amended mudflat soil were significantly higher than those in the total N and the total P content.

Table 2. Effects of vermicompost application on total N, alkaline N, total P, and available P contents in mudflat salt-affected soil.

Application Rates of Vermicompost (t ha ⁻¹)	Total N (g kg ⁻¹)	Alkaline N (mg kg ⁻¹)	Total P (g kg ⁻¹)	Available P (g kg ⁻¹)
0	0.305 ± 0.05 e	17.6 ± 0.37 d	0.521 ± 0.01 c	27.8 ± 6.63 d
25	0.470 ± 0.03 d	33.8 ± 9.60 c	0.652 ± 0.02 ab	71.2 ± 10.32 c
50	0.768 ± 0.05 c	59.0 ± 1.36 b	0.874 ± 0.11 a	94.7 ± 9.93 c
125	1.10 ± 0.06 b	64.3 ± 1.56 b	0.792 ± 0.02 ab	167.5 ± 16.74 b
250	1.53 ± 0.08 a	99.2 ± 8.68 a	0.879 ± 0.01 a	228.9 ± 47.02 a

Values are mean ± SD (standard deviation) of three replicates. Columns with different letters show a significant difference between treatments at $p < 0.05$ by LSD's multiple range test. N, nitrogen; P, phosphorus.

3.2. Effects of Vermicompost Application on Growth and Nutrient Uptake of Barley

The application of vermicompost promoted barley plant growth in the mudflat. With the increasing vermicompost application rates, the height, yield of total biomass, and grain yield all increased (Table 3). In the vermicompost application treatments compared with the control treatment, plant height increased by 38.9%, 54.2%, 79.2%, and 119.4%, the yield of total biomass increased by 82.8%, 171.3%, 306.6%, and 739.6%, and the yield of grain increased by 66.0%, 226.0%, 340.0%, and 512.0%, with significant differences between the control and vermicompost treatments.

Table 3. Effects of vermicompost application on the height, total biomass yield, and barley plant grain grown in mudflat salt-affected soil.

Application Rates of Vermicompost (t ha ⁻¹)	Plant Height (cm)	Yield of Total Biomass (t ha ⁻¹)	Yield of Grain (t ha ⁻¹)
0	24.0 ± 2.00 d	0.771 ± 0.09 d	0.388 ± 0.08 e
25	33.3 ± 1.53 c	1.41 ± 0.10 cd	0.640 ± 0.06 d
50	37.0 ± 1.00 c	2.09 ± 0.52 c	1.25 ± 0.08 c
125	43.0 ± 2.65 b	3.13 ± 0.39 b	1.69 ± 0.11 b
250	52.7 ± 3.06 a	6.46 ± 0.73 a	2.36 ± 0.19 a

Values are mean ± SD (standard deviation) of three replicates. Columns with different letters show a significant difference between different treatments at $p < 0.05$ by LSD's multiple range test.

The application of vermicompost also promoted the absorption of N and P by barley plants in the mudflat (Figure 2). The N and P content of the barley plants were 3.09 g kg⁻¹ and 1.32 g kg⁻¹, respectively, in the control treatment. Under vermicompost application, the plant N increased to 4.09, 5.25, 6.48, and 7.04 g kg⁻¹, and the plant P increased to 1.89, 2.47, 2.33, and 2.50 g kg⁻¹, with significant differences between the control and vermicompost treatments.

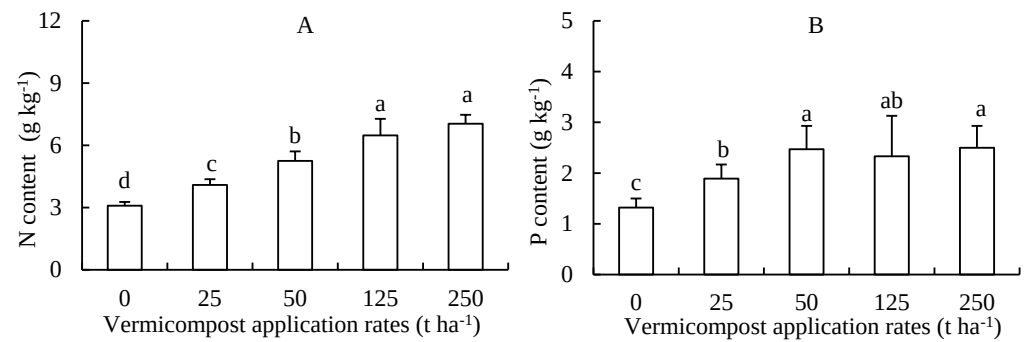


Figure 2. Effects of vermicompost application on N (A) and P (B) content of barley grown in mudflat salt-affected soil. Values are the mean of three replicates, and bars show standard deviation. Columns with different letters show a significant difference between sewage sludge amendment rates at $p < 0.05$ by LSD's multiple range test. N, nitrogen; P, phosphorus.

3.3. Effects of Vermicompost Application on Heavy Metal Accumulation in Mudflat Soil and Barley Plants

The total amounts of Cd, Cr, Cu, and Zn in the mudflat salt-affected soil increased with increasing vermicompost application rates (Figure 3). The Cd and Cr concentrations in the control mudflat soil were 0.63 and 33.09 mg kg⁻¹, respectively. Under the vermicompost application, the total Cd concentration increased by 10.4%, 14.1%, 25.1%, and 34.1%, and the total Cr concentration increased by 8.5%, 16.9%, 22.0%, and 34.4%. At the 25 t ha⁻¹ and 50 t ha⁻¹ vermicompost application rates, the total Cr concentration differed significantly from the concentration of the control treatment. The total Cu concentration was 14.72 mg kg⁻¹ in the control soil and increased by 11.4%, 36.1%, 80.7%, and 156.3% in the vermicompost-treated soil. The total Zn concentration was 35.97 mg kg⁻¹ in the control soil and increased by 7.5%, 33.8%, 133.8%, and 185.1% in the vermicompost-treated soil. At the 50 t ha⁻¹ vermicompost application rate, the differences in the total Cu and Zn concentrations from the control values were significant.

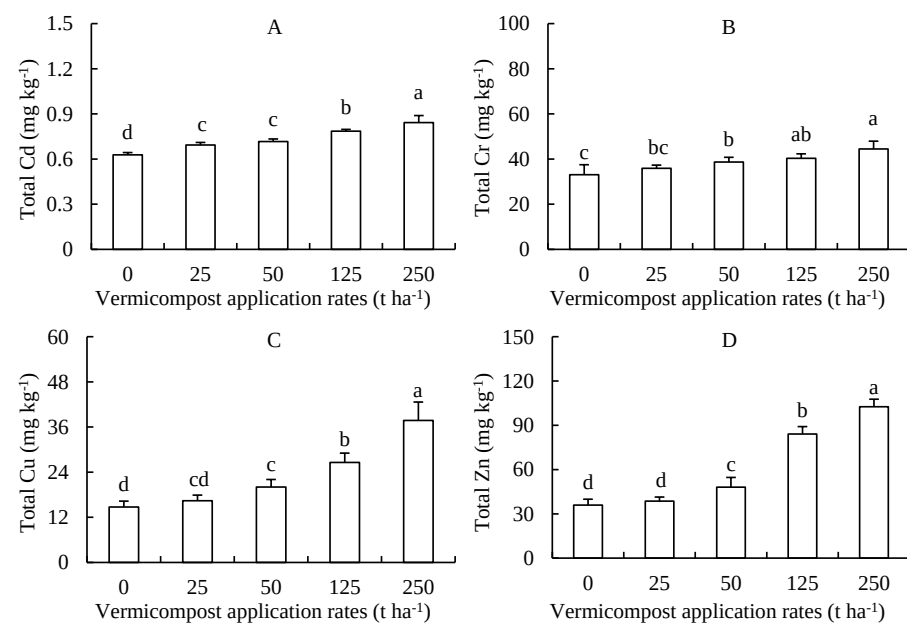


Figure 3. Effects of vermicompost application on total metal concentrations for Cd (A), Cr (B), Cu (C), and Zn (D) in mudflat salt-affected soil. Values are the mean of three replicates, and bars show standard deviation. Columns with different letters show a significant difference between sewage sludge amendment rates at $p < 0.05$ by LSD's multiple range test. Cd, cadmium; Cr, chromium; Cu, copper; Zn, zinc.

With increasing vermicompost application rates, the concentrations of Cd, Cu, and Zn in the grain of barley growing in mudflat salt-affected soil gradually increased (Figure 4). In the control treatment, the grain concentrations of Cd, Cu, and Zn were $15.07 \mu\text{g kg}^{-1}$, 1.68 mg kg^{-1} , 5.09 mg kg^{-1} , respectively. In the vermicompost treatments, the Cd concentration increased by 12.9%, 23.3%, 52.7%, and 99.1%, the Cu concentration increased by 6.9%, 24.7%, 58.4%, and 82.1%, and the Zn concentration increased by 15.1%, 15.3%, 46.4%, and 68.8%. At the 25 t ha^{-1} and 50 t ha^{-1} vermicompost application rates, Cd, Cu, and Zn of barley grain concentrations differed significantly from the control content. The application of vermicompost had no significant effect on the Cr concentration of barley grain.

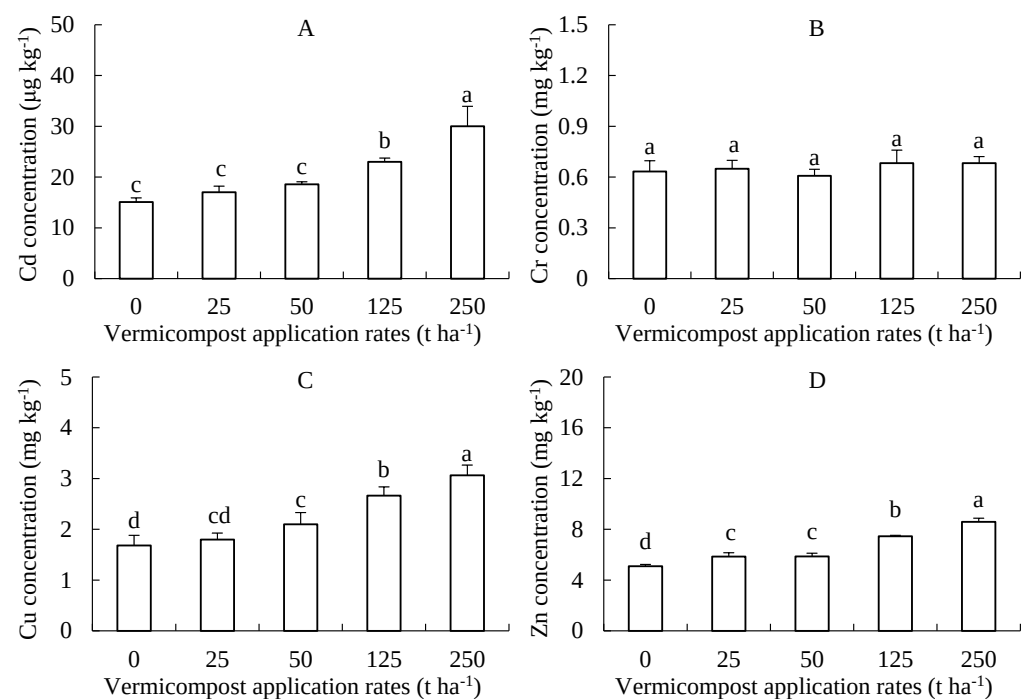


Figure 4. Effects of vermicompost application on metal concentrations for Cd (A), Cr (B), Cu (C) and Zn (D) of barley grown in mudflat salt-affected soil. Values are the mean of three replicates, and bars show standard deviation. Columns with different letters show a significant difference between sewage sludge amendment rates at $p < 0.05$ by LSD's multiple range test. Cd, cadmium; Cr, chromium; Cu, copper; Zn, zinc.

4. Discussion

The application of vermicompost can improve mudflat salt-affected soil's physical and chemical properties. In this study, we found that the application of vermicompost decreased the soil bulk density of mudflat salt-affected soil, which is consistent with observations by Li et al. in tobacco field soil [19]. Vermicompost is rich in organic matter and organic colloids, which can promote the formation of good soil structure in mudflat salt-affected soil, increase soil porosity and thus decrease soil bulk density [20]. A decrease in the soil bulk density will reduce soil capillary tension and thus the upward movement of water and salt through capillaries, thereby inhibiting soil resalinization [21]. This study confirmed that the application of vermicompost could reduce the EC in mudflat salt-affected soil [22]. The EC reduction is likely due to the acidity of the vermicompost and the resulting lowering of soil pH, and the small-molecule organic acids produced by vermicompost decomposition can further lower soil pH [20]. The application of vermicompost increased the content of soil organic matter, N, P, and other nutrients in mudflat salt-affected soil. This finding is consistent with Valdez-Pérez et al. [23], who stated that the application of vermicompost increased soil organic matter, N, and P content. These increases are due to the high content

of organic matter, N, and P in vermicompost, thus increasing the corresponding soil content and improving soil fertility [24].

The application of vermicompost promoted the growth of barley plants. Previous studies have shown that the application of vermicompost can significantly increase the biomass of maize [25] and the yields of cucumber and other vegetables [26,27]. Andis Karlsons and Rodríguez-Canché showed that the application of vermicompost could promote the growth of ryegrass [28] and pepper [17], with the highest biomass of ryegrass achieved at a ratio of vermicompost to quartz sand soil of 1:5 [28]. In this study, we found that the biomass and yield of barley were highest at the vermicompost application rate of 250 t ha⁻¹, which was consistent with the trends in the improvements to mudflat salt-affected soil due to vermicompost application. The soil bulk density, pH, and EC of mudflat salt-affected soil declined with increasing vermicompost application. The soil organic matter and nutrient content increased, which provided barley plants with an environment and nutrients conducive to growth in mudflat salt-affected soil and thus promoted their growth [29].

The application of vermicompost increased the accumulation of heavy metals in mudflat salt-affected soil and barley plants. We found that the concentrations of heavy metals in mudflat soil increased with increasing vermicompost application, which is consistent with the finding of Xing et al. that vermicompost application can increase the concentrations of heavy metals in farmland soil [30]. Although heavy metal concentration in sewage sludge is decreased after sludge ingestion by earthworms, it is still higher than in mudflat soil. The National Environmental Quality Standard for Soils (GB 15618-2008) limited soils' Cd, Cr, Cu, and Zn concentrations, with the highest values being 1.0, 250, 100, and 300 mg kg⁻¹ [31]. Although the application of vermicompost increased the concentrations of heavy metals (Cd, Cr, Cu, and Zn) in the mudflat salt-affected soil, these concentrations did not exceed the maximum permitted concentrations as specified in the National Environmental Quality Standard for Soils. Vermicompost application also led to the accumulation of heavy metals in barley plants, with the plant concentrations gradually increasing with increasing vermicompost application rates. This finding is consistent with Xu et al. [32], who stated that the heavy metal concentration of lettuce increases with increasing vermicompost application rates.

5. Conclusions

The application of vermicompost significantly improved the physical and chemical properties of mudflat salt-affected soil and promoted the growth of barley plants. Vermicompost decreased mudflat soil's bulk density, EC, and pH and increased the soil organic carbon, N and P content. With increasing vermicompost application rates, the yield and biomass of barley increased. Barley yield in the vermicompost application treatments (25, 50, 125, and 250 t ha⁻¹) were increased by 66.0%, 226.0%, 340.0%, and 512.0% relative to the control value. However, the application of vermicompost also increased the concentrations of heavy metals (Cd, Cr, Cu, and Zn) in mudflat salt-affected soil and barley plants. Therefore, vermicompost can effectively substitute sewage sludge for rapidly improving mudflat soil.

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