

Eco-Friendly and Sustainable Remediation of Copper- and Zinc-Contaminated Farmland [†]

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Abstract: Copper and zinc are metals commonly used in industry. However, improperly disposed copper and zinc pollute soil seriously. In farmland where the concentrations of copper and zinc exceeded regulatory standards and farming has been banned for many years, we measured the copper and zinc concentrations in soil. The copper concentration ranged from 30.2 to 1082.3 mg/kg, while the zinc concentration was between 200.2 and 3335.3 mg/kg. To explore the correlation between the concentration of copper and zinc in soil and plants and plant growth, Pennisetum was chosen as the test crop. The economic and carbon reduction benefits of planting Pennisetum in copper- and zinc-polluted farmland were also investigated. The results indicated that the concentration levels of copper and zinc were not significantly impacted, and neither was the growth of Pennisetum. Farming Pennisetum produces a total of about 1100 tons of biomass per hectare per year. The income per hectare was about USD 48,000 per year. Pennisetum captures 578.8 tons of carbon every year, equivalent to 2124.2 ton-CO₂e. When used as fuel, it provides 23,649 GJ of bioenergy. Therefore, Pennisetum is an appropriate plant for the green and sustainable remediation of polluted soil.



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1. Introduction

Copper and zinc are commonly used in industry. Electroplating wastewater, sludge, and discarded wires and cables contain high concentrations of copper and zinc which pollute soil when disposed of inappropriately. Taiwan has regulatory standards for copper and zinc in agricultural soil, which are 220 and 600 mg/kg, respectively. When the concentrations of copper and zinc in soil exceed regulatory standards, farming is banned for remediation.

Different crops have different absorption capabilities of copper and zinc in soil. Vegetables have stronger absorption abilities, while food crops have weaker absorption abilities. When the concentrations of copper and zinc in soil are too high, their toxicity prevents plants from growing, which reduces yields. However, copper and zinc are essential nutrients and trace elements for plant growth and the human body [1,2]. In farmland polluted by copper and zinc, the quality and yield of crops are significantly

reduced. In soil that is not heavily polluted, crops can clean the soil and increase productivity again through phytoremediation.

Hou et al. planted four herbaceous energy plants, namely switch grass, barley, *Arundo donacea*, and *Pennisetum*, in lightly heavy metal-polluted land in the suburbs of Beijing [3]. The biomass yield of *Pennisetum* was the highest at 59.22 t/hm², and the accumulation rates of arsenic, mercury, copper, lead, and cadmium were 23.12, 0.35, 1132.62, 95.18, and 6.07 g/hm², respectively. *Pennisetum* showed a high absorption capacity for copper. *Pennisetum* is a perennial giant grass that produces a biomass yield of up to more than 200 t FW/hm² [4].

Zou et al. studied the accumulation of lead, cadmium, copper, and zinc in *Pennisetum* [5]. The accumulated contents of the four metals in the leaves were 29.51, 19.60, 182.8, and 178.2 µg/plant, respectively; in the stems, 8.89, 17.99, 61.68, and 205.4 µg/plant; and in the roots, 8.45, 2.18, 36.35, and 47.94 µg/plant. It was also shown that *Pennisetum* accumulated copper and zinc the most. Ko conducted pot experiments using native Taiwanese plants with energy potential, including *Pennisetum*, *miscanthus*, rapeseed, and water barnyard grass, in soil contaminated with copper, nickel, and chromium [6]. *Pennisetum* maintained the largest biomass and removed more heavy metals than other plants. It removed 11.99–27.30 mg of nickel, 26.69–53.82 mg of chromium, and 27.34–92.52 mg of copper per square meter. *Pennisetum* also extracted copper and zinc, but they were adsorbed on the root surface. The more extensive the root system, the more copper and zinc are retained, and the less they are transmitted to the shoots [7].

Pennisetum belongs to the Poaceae family and the genus *Pennisetum* and is a perennial grass plant. Its scientific name is *Pennisetum alopecuroides* L. *Pennisetum* is propagated by cuttings. It has strong regeneration ability, wide adaptability, and adaptability to various soil types [1,8,9]. Loose, fertile, neutral sandy loam with good drainage performance is the best soil for *Pennisetum* to grow in. There are few pests and diseases which affect its growth. It grows quickly and has a high yield. It can be harvested every 8 to 10 weeks. Its green leaves are rich in chlorophyll, β-carotene, multivitamins, phenolic compounds, and minerals, and they are the main feed for herbivores. *Pennisetum* is also used as an ingredient and material for field coverings, papermaking, and bio-alcohol production [10]. *Pennisetum*'s photosynthesis pathway is different from that of C3 plants as it is a C4 plant. After carbon dioxide is fixed, *Pennisetum* produces organic acids that absorb more carbon dioxide, generate more energy, and have a higher carbon fixation capacity than C4 plants. Therefore, C4 plants including *Pennisetum* play an important role in climate control [9].

This study was conducted on farmland in Tainan, Taiwan, where copper and zinc exceeded regulatory standards, and farming has been prohibited for many years. Using *Pennisetum* as a test crop, the correlation between soil and plant copper and zinc concentrations and plant growth was explored, and the economic and carbon reduction benefits of planting *Pennisetum* in copper- and zinc-contaminated soil were investigated.

2. Materials and Methods

The farmland was located at Land No. 732 and 733, Xingnong Section, Tainan City. It was contaminated by waste disposal, and the major pollutants were copper and zinc. The copper concentration was in the range of 30.2–1082.3 mg/kg, while that of zinc was 200.2–3335.3 mg/kg. *Pennisetum* Taiwan Livestock No. 2 was planted for experiments. This variety has the characteristics of high plant height, up to more than 200 cm; high yield; high sweetness; and excellent palatability. It is mechanically harvested. It is resistant to pests and diseases and does not require pesticides. *Pennisetum* was planted with a root segment of about 30 cm in this study. The planting row and spacing were 40 and 30 cm. In blocks A, B, C, and D, we planted 60 *Pennisetum* plants in each block (Figure 1).

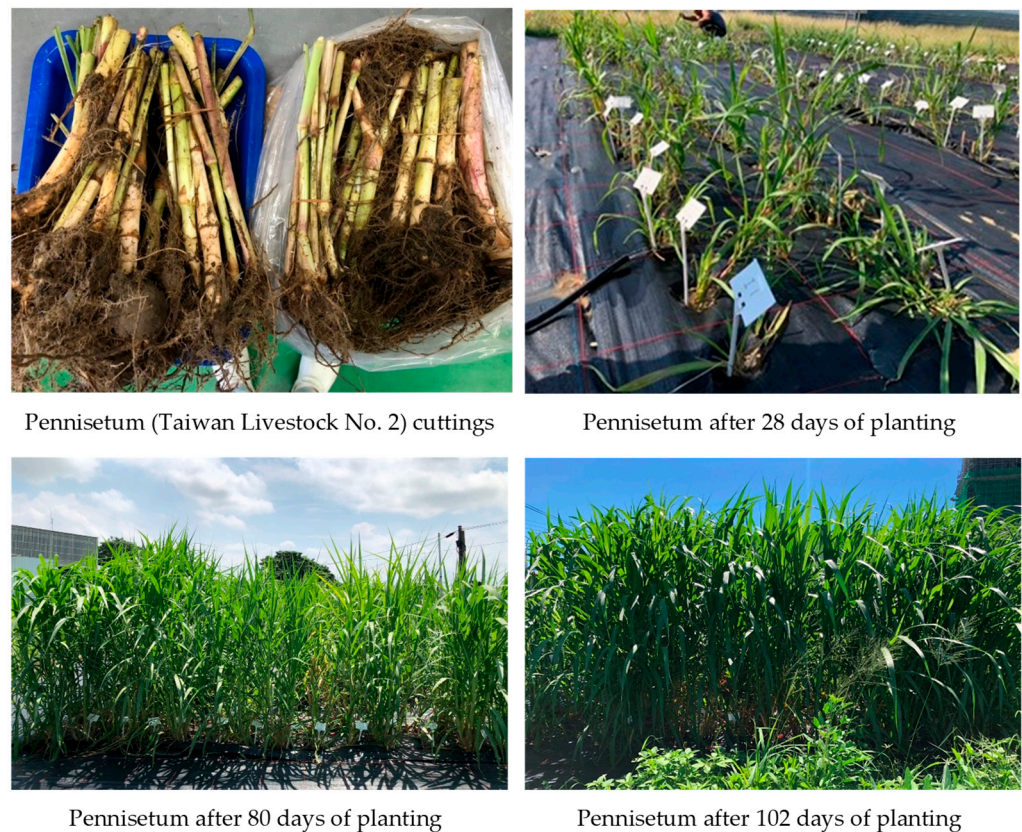


Figure 1. Planting Pennisetum and its growth.

When planting Pennisetum, the soil samples around each plant hole were collected to analyze the concentrations of copper and zinc. A total of 40 samples were taken from the farmland. Along with the soil concentration, the concentrations in plant roots, stems, and leaf mass were also analyzed.

The soil samples were treated using the aqua regia digestion method to extract and measure the concentrations of copper and zinc. An inductively coupled plasma spectrometer (ICP-OES) was used for the analysis. Soil properties, including soil texture, pH, conductivity, organic matter, and fertility, were also analyzed. The soil size was measured using the Baumann hydrometer method, and the texture was determined according to the soil texture triangle diagram of the USDA soil taxonomy.

Soil pH and conductivity were measured using electronic testers with electrodes. After mixing the soil and deionized water at a ratio of 1:5 (*w/v*), a pH meter and a conductivity meter were used to measure soil pH and conductivity. Soil organic matter was analyzed using the Walkey–Black wet oxidation method. In this method, a hot mixture of potassium dichromate ($K_2Cr_2O_7$) and concentrated sulfuric acid (H_2SO_4) is used to oxidize the organic matter in the soil. After measuring organic carbon concentration, it is converted into soil organic matter content. Soil fertility was measured using Menlike No. 3 extract by extracting available phosphorus, potassium, calcium, magnesium, iron, manganese, copper, and zinc and measuring their concentrations using an ICP-OES.

Statistical analysis was conducted using Statistical Product and Service Solutions (SPSS) software (IBM SPSS Statistics 22.0). The correlation coefficient (*r*) was used to examine the linear correlation between variables. A Pearson correlation coefficient was calculated using an equation of the common variation in two variables (*X* and *Y*) divided by their standard deviation. When the *r* value is close to 0, the correlation is weak, while an *r* close to 1 indicates a significant correlation.

3. Results and Discussion

3.1. Analysis Results

The farmland soil showed a heterogeneous distribution of soil composition due to the disposal of unknown waste in the past. The results of soil property analysis were shown in Table 1. Block A soil samples showed a higher sand content; Block B soil samples had a higher clay content as they consisted of a sandy clay loam; Block C and D soil samples were sandy loam. The pH values ranged from 7.32 to 7.91. Conductivity ranged from 238 to 749 $\mu\text{S}/\text{cm}$. The organic matter content was between 6.18 and 13.9%. The phosphorus content was in the range of 52.1–125.4 mg/kg; potassium was in the range of 86.8–205.1 mg/kg; calcium was in the range of 1220.0–1789.7 mg/kg; magnesium was in the range of 152.8–248.4 mg/kg; iron was in the range of 87.9–346.4 mg/kg; and manganese was in the range of 34.8–73.9 mg/kg. The contents of the fertility components generally were in an appropriate range for farming.

Table 1. Soil properties of samples in farmland.

Block	Particle Size Distribution (%)			Soil Texture	pH	Conductivity ($\mu\text{S}/\text{cm}$)	Organic Matter Content (%)
	Sand	Silt	Clay				
A	96	2	2	sandy soil	7.84	366.0	10.81
B	64	15	21	sandy clay loam	7.32	238.0	6.18
C	80	9	11	sandy loam	7.51	749.3	9.36
D	64	17	19	sandy loam	7.91	396.0	13.90
Block	Soil Fertility Elements (mg/kg)						
	Phosphorus	Potassium	Calcium	Magnesium	Iron	Manganese	
A	125.4	101.3	1351.0	248.4	182.4	73.9	
B	62.4	88.7	1220.0	152.8	346.4	40.3	
C	52.1	86.8	1250.3	240.3	146.4	70.6	
D	72.5	205.1	1789.7	224.9	87.9	34.8	

3.2. Correlation Analysis of Copper and Zinc Concentration in Soil and Plant Growth

The copper concentration in the soil samples ranged from 30.2 to 1082.3 mg/kg. The lowest zinc concentration was 200.2 mg/kg, while the highest was 3335.3 mg/kg. The tallest Pennisetum plant measured 287.0 cm, while the shortest stood at 140.0 cm. The copper concentrations in the rhizosphere soil were in the range of 211.5 and 568.2 mg/kg; the zinc concentrations were in the range of 1055.2 and 1872.4 mg/kg. The highest biomass of Pennisetum roots was 1744.0 g, and its soil copper and zinc concentrations were 172.4 and 889.4 mg/kg. The highest biomass yield in the shoots of Pennisetum was from the same plant with the highest root yield, which was 18,500 g. The distributions of soil copper and zinc concentrations in the plant rhizosphere, plant height, and growth mass are shown in Figure 2.

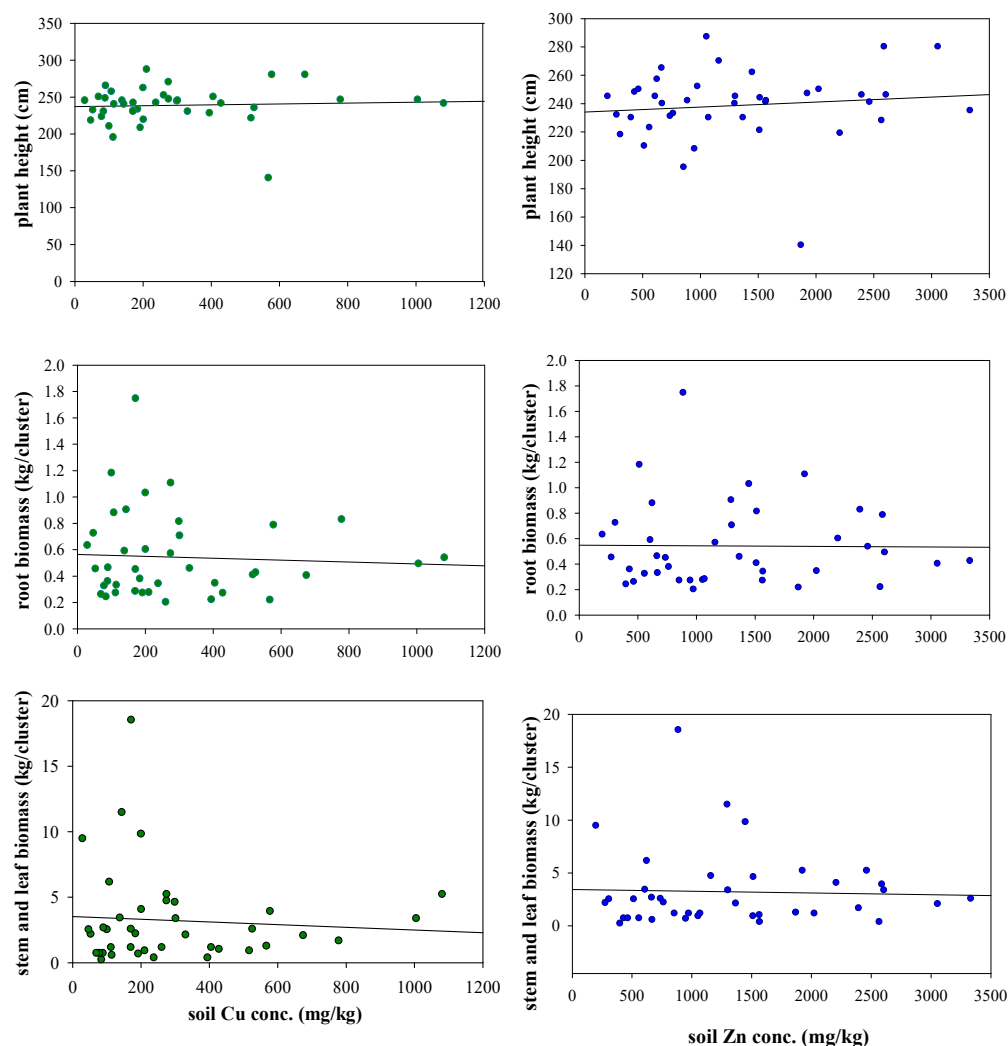


Figure 2. Correlation between soil copper and zinc concentrations and Pennisetum plant growth.

The Pennisetum plant height did not vary with soil copper and zinc concentrations. The correlation coefficient between the plant height and soil copper concentration was 0.061, indicating no significant correlation (Table 2). The correlation coefficient between plant height and soil zinc concentration was 0.116. The correlations between the biomass of the plant roots and stems and leaves and soil copper concentration were -0.056 and -0.072 , respectively. The correlations between the biomass of the root stems and leaves and soil zinc concentration were -0.072 and -0.038 . Pennisetum showed no significant correlation between soil copper and zinc concentrations and plant growth. Chen et al. planted Pennisetum in moderately cadmium-contaminated soil and found no remarkable plant growth inhibition at any stage [11].

Table 2. Correlation coefficients between soil Cu and Zn concentrations and the growth of Pennisetum.

Heavy Metal	Pennisetum					
	Height	Biomass		Cu and Zn Concentration		
		Root	Shoot	Root	Stem	Leaf
Cu	0.061	-0.056	-0.072	-0.021	0.262	0.078
Zn	0.116	-0.013	-0.038	0.333	0.076	0.204

3.3. Correlation Analysis of Copper and Zinc Concentrations in Soil and Parts of *Pennisetum*

The relationship between Cu and Zn concentrations in various parts of *Pennisetum* and soil Cu and Zn concentrations was explored (Figure 3). The highest Cu concentration in the roots was 346.1 mg/kg, while the lowest was 5.73 mg/kg. The corresponding soil copper concentrations were 115.9 and 30.2 mg/kg. The highest stem copper concentration was 2.43 mg/kg, the lowest was 0.82 mg/kg, and the corresponding soil copper concentrations were 568.2 and 526.6 mg/kg, respectively. The highest leaf copper concentration was 1.48 mg/kg, the lowest was 0.48 mg/kg, and the corresponding soil copper concentrations were 275.9 and 185.0 mg/kg, respectively. The highest zinc concentration in the roots was 312.0 mg/kg, the lowest was 33.3 mg/kg, and the corresponding soil zinc concentrations were 3058.1 mg/kg and 200.2 mg/kg, respectively. The highest zinc content in the stems was 34.3 mg/kg; the lowest was 12.0 mg/kg. The soil zinc contents were 1872.4 mg/kg and 309.3 mg/kg, respectively. The highest zinc content in the leaves was 11.2 mg/kg; the lowest was 3.58 mg/kg. The soil zinc contents were 1450.0 mg/kg and 766.0 mg/kg, respectively.

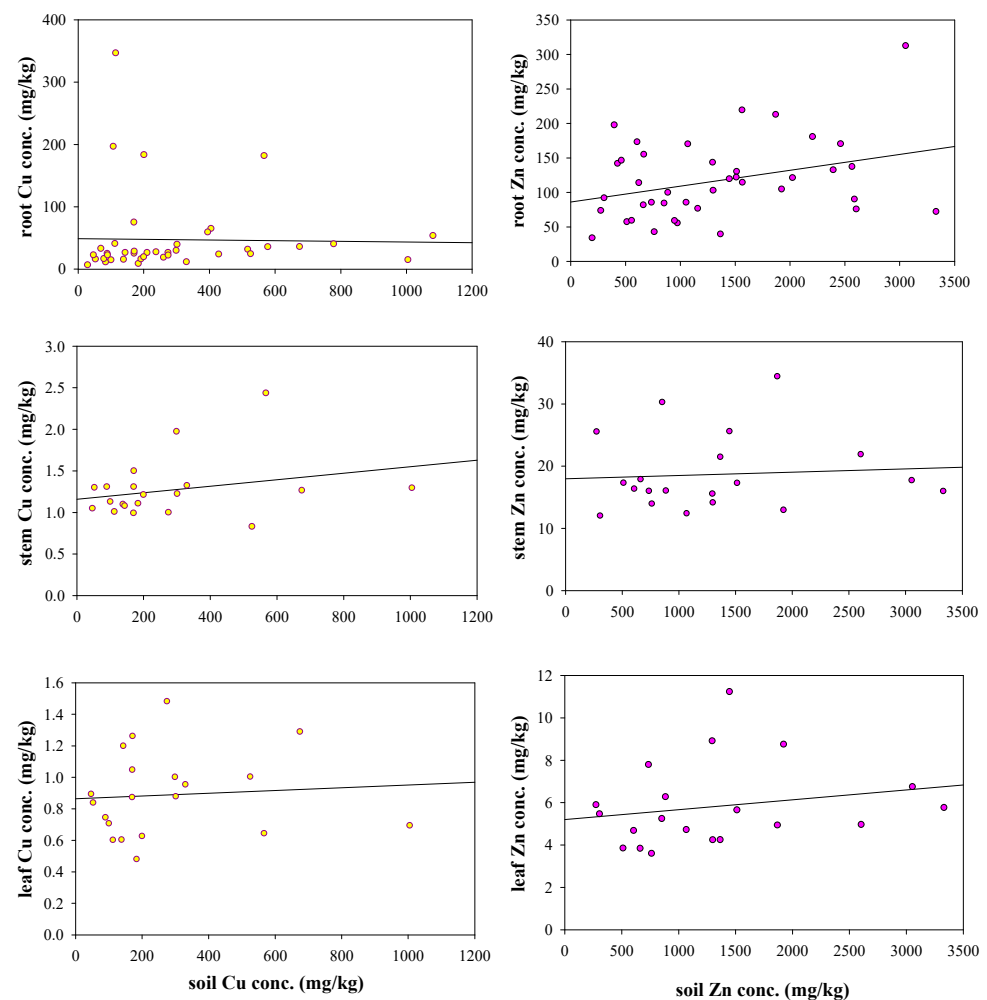


Figure 3. Correlation between soil copper and zinc concentrations and copper and zinc concentrations in various parts of *Pennisetum*.

The copper concentration in the stems and leaves of *Pennisetum* plants varied by approximately threefold, while the maximum difference in the roots was sixtyfold. Similarly, the maximum zinc concentrations in the stems and leaves varied threefold, while the maximum concentrations in the roots varied tenfold. The large difference in the concentration

in the roots indicated that the roots were not easily cleaned and did not retain soil. The correlation coefficient between the zinc concentrations in the roots of Pennisetum and in the soil was 0.333. The correlation coefficients of copper concentration in the stems and leaves and soil were 0.262 and 0.078; the correlation coefficients of zinc concentration in the stems and leaves and soil were 0.079 and 0.204. The soil copper and zinc concentrations did not correlate significantly with the plant parts.

3.4. Benefits of Pennisetum on Farmland

Copper and zinc are essential nutrients for animal growth. There are different standards for feeds for animals. In the National standard CNS 3027 of Taiwan, copper content for formulated feeds for livestock and poultry must be 35–150 ppm [12]. For zinc, the recommended content is 100–140 ppm [12]. According to the limit standards for homemade feed, the copper content must range from 25 to 60 ppm, while the zinc content must range from 100 to 130 ppm. The edible parts of Pennisetum are the stems and leaves. The highest zinc concentrations in this study were 34.3 mg/kg in the stems and 11.2 mg/kg in the leaves. The highest copper concentrations were 2.43 mg/kg in the stems and 1.48 mg/kg in the leaves. The copper and zinc concentrations in the stems and leaves of Pennisetum met the feed limit standards as shown in Table 3.

Table 3. Maximum concentration of copper and zinc in edible parts of Pennisetum and feed limit standards.

Feed Limit Standards		Copper (ppm)	Zinc (ppm)
CNS 3027 (Formulated feeds, for livestock and poultry)		35–150	100–140
Limit standards for self-made feed (ROC)		25–60	100–130
Pennisetum	Stem	2.43	34.3
	Leaf	1.48	11.2

Pennisetum can be used for the phytoremediation of copper- and zinc-polluted soil as it can provide about 1100 tons of shoots per hectare per year. The feed price is USD 0.04 per kilogram, and the annual income can be up to USD 0.4 million. The average carbon contents of the stems and leaves of Pennisetum are 40.53 and 42.89%. Combustion heat values are 16.31 and 17.25 KJ/g. By planting Pennisetum, 578.8 tons of carbon per hectare per year can be fixed, which is equivalent to 2124.2 tons of carbon dioxide. When used as fuel, Pennisetum provides 23,649 GJ as a biomass energy source.

4. Conclusions

Pennisetum activates farmland and provides production benefits in farmland polluted by copper and zinc. It can be used for the phytoremediation of polluted soil and the reduction in the cost of physical and chemical remediation and carbon emissions. In the growth process, Pennisetum absorbs carbon dioxide, and the harvested plants can be used as bioenergy. It captures carbon and is used as a green bioenergy source. Pennisetum is appropriate to be used for an eco-friendly and sustainable remediation strategy.

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References

1. Chen, Y.; Hu, L.; Liu, X.; Deng, Y.; Liu, M.; Xu, B.; Wang, M. Influences of king grass (*Pennisetum sinense* Roxb)-enhanced approaches for phytoextraction and microbial communities in multi-metal contaminated soil. *Geoderma* **2017**, *307*, 253–266. [[CrossRef](#)]
2. Sajimin, S.; Subiksa, I.G.M.; Krisnan, R.; Fanindi, A.; Hidayat, C.; Tresia, G.; Harmini, H.; Sutedi, E.; Pamungkas, F.A.; Herdiawan, I.; et al. Evaluating the productivity of five forages for the phytoremediation of heavy metal-contaminated land. *J. Water Land Dev.* **2024**, *63*, 158–167.
3. Hou, X.C.; Fan, X.F.; Wu, J.Y.; Zhu, Y.; Zhang, Y.X. Potentiality of herbaceous bioenergy plants in remediation of soil contaminated by heavy metals. *Chin. J. Grassl.* **2012**, *34*, 59–64.
4. Chen, X.; Tong, J.; Su, Y.; Xiao, L. *Pennisetum sinense*: A Potential Phytoremediation Plant for Chromium Deletion from Soil. *Sustainability* **2020**, *12*, 3651. [[CrossRef](#)]
5. Zou, W.; Cao, Z.; Wang, Y.; Jin, M.; Lin, M.Z. Intercropping of *Pennisetum sinense* with *Lolium perenne* improved phytoextraction of heavy metal from soil. *Restor. Ecol.* **2023**, *31*, e13702. [[CrossRef](#)]
6. Ko, C.H. *Using Energy Crops for Phytoremediation in the Heavy Metals Contaminated Soils with Different Fertilizer Treatments*; Environmental Protection Administration Research Project Report; Taiwan Environmental Protection Administration: Taipei, Taiwan, 2017.
7. Salam, A.K.; Hidayatullah, M.A.; Supriatin, S.; Yusnaini, S. The phytoextraction of copper and zinc by elephant grass (*Pennisetum purpureum*) from tropical soil 21 years after amendment with industrial waste containing heavy metals. *Earth Environ. Sci.* **2021**, *637*, 012044.
8. Zhou, Z.; Guo, Y.; Hu, L.; He, L.; Xu, B.; Huang, Z.; Wang, G.; Chen, Y. Potential use of king grass (*Pennisetum purpureum* Schumacher × *Pennisetum glaucum* (L.) R.Br.) for phytoextraction of cadmium from fields. *Environ. Sci. Pollut. Res.* **2020**, *27*, 35249–35260. [[CrossRef](#)] [[PubMed](#)]
9. Rahman, M.E.; Uddin, M.K.; Shamsuzzaman, S.M.; Mahmud, K.; Shukor, M.Y.A.; Ghani, S.S.A.; Nabayi, A.; Sadeq, B.M.; Chompa, S.S.; Akter, A.; et al. Potential use of *Pennisetum purpureum* for phytoremediation of arsenic in treatment sand: A phytotoxicity study. *Biocatal. Agric. Biotechnol.* **2024**, *60*, 103300. [[CrossRef](#)]
10. Osmama, N.A.; Roslana, A.M.; Ibrahim, M.F.; Hassana, M.A. Potential use of *Pennisetum purpureum* for phytoremediation and bioenergy production: A mini review. *AsPac J. Mol. Biol. Biotechnol.* **2020**, *28*, 14–26. [[CrossRef](#)]
11. Chen, C.; Wei, Z.; Hu, K.; Wu, Q.T. Phytoextraction and migration patterns of Cadmium in contaminated soils by *Pennisetum hybridum*. *Plants* **2023**, *12*, 2321. [[CrossRef](#)] [[PubMed](#)]
12. CNS 3027-2000; Formula feeds (For livestock and poultry). Bureau of Standards, Metrology and Inspection, M.O.E.A.: Taipei, Taiwan, 2000.

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