Toxic Metals in a Paddy Field System: A Review

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Abstract: The threat of toxic metals to food security and human health has become a high-priority issue in recent decades. As the world’s main food crop source, the safe cultivation of rice has been the focus of much research, particularly the restoration of toxic metals in paddy fields. Therefore, in this paper, we focus on the effects of toxic metals on rice, as well as the removal or repair methods of toxic metals in paddy fields. We also provide a detailed discussion of the sources and monitoring methods of toxic metals pollution, the current toxic metal removal, and remediation methods in paddy fields. Finally, several important research issues related to toxic metals in paddy field systems are proposed for future work. The review has an important guiding role for the future of heavy metal remediation in paddy fields, safe production of rice, green ecological fish culture, and human food security and health.

Keywords: toxic metals; health risk; paddy field; bioremediation; rice–fish co-culture system

1. Introduction

Metals are typically classified as non-essential and essential metals. Non-essential metals (mercury (Hg), cadmium (Cd), lead (Pb), etc.) have no proven biological purpose, and their toxicity is a function of their concentration. In contrast, essential metals (iron (Fe), zinc (Zn), copper (Cu), etc.) have known biological effects, and toxicity occurs when the metal is metabolically deficient or at a high concentration [1]. In general, any metal or metalloid that is not used in the basic metabolism or is not biodegradable is considered a heavy metal [2]. Heavy metals are defined as those elements with a density greater than 5 g/cm³ and an atomic number greater than 20, and include 53 metals [2] (gold (Au), silver (Ag), Cu, etc.). Despite being a metalloid element, arsenic (As) is listed as a heavy metal due to its multiple properties, similar to heavy metals. Heavy metals can be divided into toxic (e.g., Cd), precious (e.g., Au), and radionuclide (e.g., Uranium, U) metals [3]. The term “heavy metal” is considered meaningless at worst and imprecise at best [4,5]; this paper replaces it with “toxic metal” in later descriptions. When the intake of toxic metals exceeds a certain amount, it will do serious harm to humans’ kidneys, nervous system, and fertility, and even cause cancer and death [6–8]. In China, Hg, Cd, Pb, chromium (Cr), and As are commonly known as the “five poisons” [9]. Numerous toxic metals (TM) (Cd, Pb, Hg, As, etc.) have been identified as non-essential elements for bodily functions [10] and have been included in the top 20 list of hazardous substances [11]. Therefore, the toxicity, and maximum allowable value of TMs in food and other related issues has been the focus of much attention.

Rice is an extremely important food crop, not only in China but also across the world, with a global cultivation area reaching 145 million hectares. The principle rice-producing areas are distributed in East, South, and Southeast Asia, followed by Mediterranean coastal countries, the United States and Brazil [12]. At present, more than half of the world’s population relies on rice for their calorie intake [13], and thus a decline in rice yield will have a significant global impact. By 2050, the growth in population and acceleration of
urbanization will require each rice-producing hectare to feed at least 43 people, compared to the current value of 27 people per hectare [14]. Kaur et al. [15] predicted that rice production would need to increase by at least 40% by 2050 to ensure food security. Rice quality is particularly important due to the key role rice plays in the global diet. High-quality rice produced by artificial breeding has been observed to have therapeutic and preventive effects on several human diseases [16]. In addition to nutrients, the phytochemicals present in rice can play a biological role, with antioxidant, anticancer, anti-diabetic, and anti-inflammatory effects [17]. However, poor-quality rice can have a negative impact on human health, causing dizziness, thoracic stuffiness, nausea, vomiting, abdominal discomfort, etc. [18]. Therefore, ensuring the high quality and yield of rice is of great significance.

In 2020, a total of 720–811 million people worldwide were facing hunger, and nearly one-third of the global population (2.37 billion) were not able to get enough food [19]. The yield and quality of rice have been the subject of much interest. TM pollution not only reduces the quality and yield of rice, but also endangers human health and even causes death. The ecological cultivation of aquatic animals and plants has recently attracted the attention of scholars and governments, with its vigorous promotion and active application in practice by farmers. This has consequently improved the quality and yield of agricultural products as well as their taste and safety. An in-depth understanding of the relationships between TMs and rice, and their corresponding removal methods are important prerequisites for effectively improving the food safety of rice. To achieve this goal, in the current paper, we first introduce the effects of TMs on rice. Then, the sources, monitoring methods and measuring instruments of TM pollution, as well as the measures employed to remove TMs and reduce their bioavailability in paddy fields, are discussed in detail. Finally, the research trends and challenges of TM removal or remediation in paddy fields are introduced.

2. Effects of TMs on Rice

The relationships between TMs and the growth, development, metabolism, and nutrient composition of rice have been the subject of extensive research (Figure 1). As trace elements, the presence of TMs can have both positive and negative effects on organisms. Low TM concentrations can promote the metabolic activities of organisms and vice versa for high concentrations [20]. TM stress has been observed to have a significant effect on agronomic rice traits, including panicle number per plant, filled grain per panicle, 1000-grain weight, and grain yield per plant [21–25]. In addition, TM stress exerts a great impact on the molecular and gene level of rice, inducing changes of a higher complexity compared to those of the agronomic traits, which are mainly related to the physiological metabolism, variations in enzymes, and the regulation of gene expression [26,27]. Such examples are internal factors that affect the growth and development of rice. Thus, increasing our understanding of the TM mechanisms affecting rice is essential for the prevention and control of TMs.

2.1. Effects of TMs on Apparent Indexes and Body Composition of Rice

Highly available Zn concentrations in the soil not only result in rice chlorosis and inhibit plant growth but also reduce Fe concentrations in rice plant shoots to the level considered deficient [28]. Moreover, Cd can prevent the transformation of starch, affect seed germination by inhibiting amylase activity [29], and reduce the chlorophyll content of rice, thus affecting photosynthesis [23,30]. Hg can inhibit germination and seedling growth by damaging the embryo, while Pb destroys endosperm starch solubilization by inhibiting \( \alpha \)-amylase activity, and obstructs seed germination and seedling growth [31]. Ni can affect the H-ATpase activity and lipid composition of rice cell membranes [32] and reduce the content of ions (Na, K, and Ca), photosynthetic pigments (chlorophyll and carotenoids), total protein, and organic nitrogen in seedlings [33]. The down-regulation of key metabolic enzymes with excessive Cu, such as \( \alpha \)-amylase or enolase, not only affects the starvation absorption of water by seeds, but also leads to the failure of the reserve mobilization process [26]. Lanthanum (La) shoot contents exceeding the toxicity value result in a decline
in plant growth and chlorophyll a/b, while peroxidase activity, cell membrane permeability, and proline content in the leaves increase [34–37]. Tables S1 and S2 report more effects of TMs on the apparent indexes and body composition of rice [38–52].

2.2. Effects of TMs on the Gene Expression of Rice

Genetic diversity is an important intrinsic factor determining the TM content in rice grains. The TM uptake of different cultivars is varied; for example, Cd-tolerant rice has a certain tolerance to Cd stress [53]. Metal exposure can result in the up- or downregulation of some genes/miRNAs in rice [54] and can consequently alter the corresponding physiological, biochemical, and metabolic properties. Furthermore, TMs can induce the expression of genes involved in numerous biological processes in rice [26,55–57], such as signal transduction, ion transport and binding, stress responses, metabolism, etc. However, the expression of genes can also affect the impact of TMs on rice (Table 1). The interaction between genes and TMs is highly complex, and more research is required to clarify the underlying mechanisms.

Figure 1. The relationships between toxic metals and the growth, development, metabolism, and nutrient composition of rice.
Table 1. Toxic metal-related genes.

| Gene/Protein          | Function                                                                                                                                                                                                 | References       |
|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| OsHMA1, OsHMA2, OsHMA3, OsHMA4, OsHMA5 | involves the transfer of toxic metals and reduces toxic metals concentrations in rice grains provides tolerance for toxic metals and other abiotic stresses | [55,57–59]       |
| OsGSTL2               | contributes to toxic metal, drought and salt tolerance in rice plants reduces cytosolic Cd concentration by promoting the secretion of Cd into the extracellular space and chelating Cd in the cytosol | [60]             |
| OsLEA4                | 
| CAL1                  | 
| MTP11                 | Mn tolerance via intracellular Mn compartmentalization promotes the redistribution of Cu from old leaves to developing tissues and seeds, as well as the root-to-shoot Cu translocation in rice | [62]             |
| OsATX1                | promotes rice multiple stress tolerance induces As volatilization and methylation, thus reducing As content in grains | [63]             |
| OsMTs                 | 
| WaarsM                | 
| OsMRLK                | promotes rice development and multiple stress tolerance alleviates the oxidative stress of Cd and Zn, decrease the translocation and accumulation of Cd to grains enhances the content of Zn and Fe in polished rice contributes to the uptake of Cd and Mn in rice | [64,65,66,67,68,69] |

2.3. Effects of TMs with Types and Forms on Rice

The impacts of TMs on rice vary according to the types and forms of TMs, while the same TM can also have different effects on rice. When the concentration of TMs reaches a certain level, it can completely inhibit the germination and growth of rice. For example, high levels of Hg and Pb can inhibit rice germination and seedling growth [21,22], and different types of As can have similar effects [49,70]. The roots of rice are more sensitive to TMs compared to shoots [70]. The regularity effect of TMs on an enzyme is a function of the TM type. For example, Pb, Hg, Cd, and Zn can decrease the superoxide dismutase activity of rice [23,43,45,46], while the opposite has been reported for Cd and Pb [44,47]. Peroxidase is more sensitive to Pb and Cd stress than superoxide dismutase [71]. See Tables S1 and S2 for more information. Therefore, the relationship between TMs and the physiological and biochemical indexes of rice is highly complex and requires verification.

3. TM Sources in Paddy Fields

TM sources originate from both natural and man-made sources. Natural sources include parent rock weathering [72], volcanic activity [73], and atmospheric deposition [74], etc. Anthropogenic sources refer to pollutants discharged into the environment via human activities, such as industrial emissions [75], pesticides, and chemical fertilizer residues [76], domestic wastewater [77], etc. Anthropogenic activity is the principal source of TMs in paddy fields. In particular, the concentration of TMs in industrialized areas is generally higher than that in non-industrialized areas [78]. The diffusion of TMs from the source to the surrounding areas typically depends on pollution sources, the geochemical status [79], and the surface runoff [80]. Moreover, TMs in the atmospheric phase are transferred to paddy fields via atmospheric deposition. In particular, wet atmospheric deposition of TMs...
is positively correlated with rainfall depth, while dry deposition is positively correlated with the number of dry days [81]. Sediments are a secondary pollution source of TMs, greatly threatening the safety of aquatic ecosystems. The accumulation or release of TMs in sediments to water bodies depends on the physical, chemical, and biological conditions of the sediment-water interface, such as changes in salinity and pH, biological disturbances, tidal currents, and floods [82].

4. TM Monitoring Methods

In view of the importance of food security and the crucial role of rice products in the human diet, TM monitoring and corresponding risk assessments are particularly important. Numerous methods have been developed to investigate the effects of TM pollution in rice paddy fields. Currently, the most popular methods are those using models based on advanced science and technology, for example, the back propagation neural-network [83], time-spectrum feature space [84], and World Food Study (WOFOST) models [85]. Brus et al. [86] employed a multiple linear model to successfully predict the content of TMs in rice grains. The generalized dynamic fuzzy neural network model combines spectral indices with environmental parameters to predict TM concentrations (Cu and Cd), outperforming adaptive-network-based fuzzy interference systems, back-propagation (BP) neural network models, and regression models [87]. Furthermore, the field-scale TM assessment model improves the monitoring of TM stress from its predecessor, the generalized dynamic fuzzy neural network model [88]. Compared with traditional methods (toxicity characteristic leaching, diethylenetriaminepentaacetic acid extraction, and HCl extraction), field capacity-derived soil solution extraction can successfully predict the total Cd content of rice from the tillering to mature stages [89]. The development of science and technology has permitted the gradual application of remote sensing technology to the TM monitoring of crops, for example, the collection of biochemical and hyperspectral data. The coupling of these two data types can be adopted for TM monitoring, indicating the relationship between the TM content in the soil and the cell structure and chlorophyll content in rice canopies or leaves [90,91]. Optical remote sensing typically monitors the internal structure, color, and additional characteristics of crop cells, while microwave techniques focus on the geometric characteristics and morphology of cells. Combining these two technologies can build a robust monitoring model for TM stress in rice, and can also be used to investigate a variety of environmental stresses [92]. The WOFOST model is the most suitable model for the application of remote sensing technology in this field. In particular, integrating remote sensing technology and statistical methods with the world food research model can greatly improve the accurate monitoring of crop TM stress.

5. TM Measuring Instruments

For TMs, most exist in nature at natural concentrations, which are relatively low and difficult to detect. However, TMs will be enriched into the human body via food, soil, water, air, and other means, resulting in the destruction of normal human physiological metabolism and a serious impact on human health. Therefore, in order to clarify the TM pollution existing in the current living and ecological environment, it is necessary to do a good job of TM detection with the help of various analytical instruments.

At present, the instruments for the determination of TMs mainly include atomic absorption spectrometer, inductively coupled plasma spectrometer, atomic fluorescence spectrometer, inductively coupled plasma mass spectrometer, voltammetric analyzer, etc. Because of its sensitivity, accuracy, and simplicity, atomic absorption spectrometers have been widely used in the analysis of TMs in agriculture, food, and environmental monitoring [93–95], etc. An inductively coupled plasma spectrometer can detect multiple elements (metal elements and non-metallic elements) in the sample [96,97], and its sensitivity is relatively high. Compared with atomic absorption spectrometry, an inductively coupled plasma spectrometer is suitable for the determination of more than three samples at the same time. Atomic fluorescence spectrometers have the advantages of low price, low
detection cost, low detection limit and high sensitivity [98–100]. It is easier to popularize than other detection instruments. Inductively coupled plasma mass spectrometry has good detection limit, scanning ability, and relatively high sensitivity; moreover, it can determine multiple elements at the same time and can determine and identify isotopes [101,102]. However, compared with other analytical instruments, the detection cost of inductively coupled plasma mass spectrometers is relatively high, and the detection limit of some elements is limited. A voltammetric analyzer can have a better detection effect for the monitoring of trace metals [103,104]. It can have a certain sensitivity and precision for the determination of TMs in some substances by means of dissolution analysis, so the accuracy of the final monitoring results is relatively high. It is relatively simple to use and is an important analytical instrument in trace analysis.

6. Remediation of TMs from Paddy Fields

Reducing TM content in rice has been the focus of much research, typically via enhancing the stability of pollutants in the soil, reducing soil surface pollutant concentrations, modifying the ability of rice to absorb and transport TMs, and so on. Studies on reducing plant available TMs in the environment generally concentrate on soil remediation techniques: turnover and dilution, in situ stabilization via chemical improvers, and bioremediation [105].

6.1. Remediation of TMs with Soil Amendments

6.1.1. Metal Soil Amendments

At present, the majority of relevant research is directed toward soil amendments due to their rapid and efficient effects. In particular, soil amendments are a class of compounds containing Ca, Fe, etc. TM adsorption by soil amendments occurs via physical adsorption, surface complexation, and ion exchange [106], which convert TMs to non-biousable forms [107]. The bioavailability of TMs in soil is the result of the interaction of organic matter, ions, redox conditions, and soil pH [108]. Soil pH exerts a great influence on TM content in rice; for example, the optimal pH for the adsorption of Ni (II) and Cu (II) is 6 and 5, respectively [109]. pH levels in paddy fields can be increased by applying liming and red mud [106,110]. As well as impacting pH levels, red mud also improves the microbial composition in paddy fields and increases the activity of urease, acid phosphatase, and catalase in the soil [110]. Fe exhibits high bioavailability and does not exert adverse effects on rice quality and yield [111]. Adding Fe to paddy fields can reduce the absorption of TMs by rice and increase the elemental contents of Fe, Cu, Mn in rice grains, and Zn in rice plants [112]. Moreover, the application of Fe-containing materials can effectively reduce the concentration of As in soil solutions and rice grains, with zero-valent Fe demonstrated to be particularly powerful. Makino et al. [113] attributed this to the formation of arsenic sulfide. Moreover, Yu et al. [114] determined a significant positive correlation between As and Fe, suggesting that Fe-containing amendments may have an indirect influence on the fractionation of soil As and biological effects to ease the As for rice. The application of metals or additional complexes can enhance the amount of iron plaque, which is composed of crystallized and amorphous iron oxides, hydroxides, etc. [115], on the root surface [116]. This technique can also enhance the interception of TMs by rice roots.

6.1.2. Non-Metallic Soil Amendments

Non-metallic soil amendments are mainly compounds containing silicon (Si), organic matter, etc. Si soil amendments have been the focus of much research due to their ability to actively induce the molecular expression of Cd tolerance in rice leaves. The addition of Si to paddy fields can reduce the As and Cd content in rice, alleviate abiotic stress, and increase rice yields, while also significantly improving the uptake of N, P, and K by rice [117]. Immobilized metals are typically bound in soil organic matter components and exist as an organic binding state [118], thus facilitating research on organic soil amendments. Common biochar contains straw, hull, etc. [119,120]. Biochar can effectively fix TMs and reduce their
bioavailability and mobility in soil [118]. Moreover, biochar can directly or indirectly affect indigenous microorganisms by changing the physical and chemical properties and TM content of sediments [121]. However, biochar has also been reported to induce oxidative stress in rice [122], and thus any potential negative effects of biochar must be considered in agricultural and environmental applications. Furthermore, the application of non-metallic elements (e.g., Se and S) can alleviate the toxic effects of TMs on rice [116,123].

6.1.3. Nanoscale Soil Amendments

Nanoscale soil amendments have recently been the focus of much research, achieving promising results. For example, Nano-Si has a positive impact on the yield and growth of rice in polymetallic contaminated soil and can reduce TM content in grains [124]. Moreover, CuO nanoparticles have been reported to accelerate the arrival of the rice heading stage, shorten the plant life cycle, and reduce As accumulation in grains [125]. Biochar nanoparticles have a high adsorption affinity for Cd, thus reducing the toxicity of Cd in rice. This is particularly true for biochar nanoparticles prepared under high temperature conditions, manifested as increased biomass, root activity, and chlorophyll content in rice plants [122]. However, the toxicity and outcome of co-existing metals with nanoparticles remain unclear. The negative impact exerted by CuO nanoparticles on plant growth is more significant than that of bulk particles [126]. High ZnO nanoparticle concentrations are able to enhance the content of bioavailable Cd in rhizosphere soil. The addition of ZnO nanoparticles at high concentrations to soil containing low levels of Cd can significantly promote Cd accumulation in rice [127].

6.1.4. Composite Soil Amendments

Multiple TMs are typically present in paddy fields; thus, applying composite soil amendments rather than a single component is required. The Cd bioavailability in the rhizosphere of rice can decrease by 92–100% from the tillering stage to maturity via the application of Ca-Si-rich composite minerals. In addition, Si deposition on the rice root cross-section has been observed to significantly increase following the application of a Ca-Si-rich composite mineral treatment, which consequently enhances the storage of Cd in roots and reduces the translocation of Cd from the root to the shoot [128]. Sulfur and iron-modified biochar amendments can significantly increase the amount of iron plaque on the root surface, facilitating the transition of Cd to binding states (such as Fe-Mn oxide) and reducing Cd concentration in contaminated soil and rice grains [116]. The combined application of biochar and lime reduces Pb availability in soil and Pb accumulation in brown rice at a greater rate compared to the corresponding single applications [129]. Furthermore, integrating ferric oxide and calcium sulfate into a single amendment can effectively reduce the bioavailability of Pb and Cd in soil and the content of Cd, As, and Pb in rice grains [130]. Moreover, Honma et al. [131] demonstrated the ability of prolonged flooding with short-range-order iron hydroxide and rainfed management combined with converter furnace slag to reduce both the Cd and As uptake of rice.

6.2. Bioremediation of TMs

Bioremediation is a low-cost technique that has a limited impact on the environment, and includes phytoremediation, microbial remediation, animal remediation, etc. Crop rotation and intercropping are common TM remediation methods that can effectively ensure the safety and yield of rice and restore metal-contaminated soil [107,132,133], with examples including wheat-rice rotation, oilseed rape-rice rotation, rice-water spinach intercropping, etc. The composition and sources of environmental microbiota play a key role in the health and productivity management of sustainable agriculture. The application of microorganisms to paddy fields contaminated with TMs is a newly developed remediation method. Scholars have identified a reduction in TMs with resistant bacteria in rice grains and have highlighted the potential of bioremediation for contaminated soil. For example, Cd transporters (OsHMA2 and OsNramp5) in rice roots can experience down-regulation
following inoculation with *Stenotrophomonas maltophilia*. This may be an internal factor affecting Cd content in rice [134]. Lin et al. [135] determined *Stenotrophomonas acidaminiphila, Pseudomonas aeruginosa, and Delftia tsuruhatensis* to be Cd tolerant, effectively reducing the enrichment of Cd in rice grains. In particular, *P. aeruginosa* is considered to be a multi-metal-resistant bacterium. Animal remediation technology refers to the absorption, transfer, or degradation of TMs through the food chain of soil animals, and research in this field is relatively limited. The backbone of animal remediation is microbial remediation [136]. For example, earthworms have the ability to alter the structure and permeability of soil, and form the basis of the most commonly used remediation method for TM-contaminated soil.

6.3. Field Management

Water management approaches are easy to operate and are commonly adopted. For example, continuous culture flooding is an effective method for reducing TM content in rice grains [137], yet it has an increased risk of As accumulation [113]. In addition, the aerobic conditions created by the release of water [138] in aerobic treatments can increase Cd concentrations [139]. Flooding in paddy fields may cause sulfide mineral precipitation, significantly reducing trace metal solubility [140], as well as the affinity for metals in the rhizosphere and iron plaque on the root surface [137]. Although the drying-wetting cycles of soil promote the release of metals into the water, Honma et al. [141] determined that intermittent irrigation (3-day flooding and 5-day no-flooding) can simultaneously reduce the accumulation of As and Cd in grains. Current research on the combined benefits of intermittent and aerobic irrigation demonstrates the ability of intermittent irrigation to reduce the Cd content in grains and increase rice yields [142].

6.4. Planting Methods and Varieties

Furthermore, the cultivation, season, and variety of rice may affect the relationship between rice and TMs during the production process. Deng et al. [143] demonstrated greater Cd and Pb contents in brown rice, straw, and roots via the direct seeding method compared with manual transplanting and seedling throwing. Farooq and Zhu [144] and Yi et al. [145] determined that early and late planting of rice impacted the Cd content in white rice. Differences in rice varieties are attributed to gene differences. Under low and moderate soil Cd pollution, japonica rice cultivars are more suitable than indica rice [146]. Dry season varieties are more tolerant to arsenite or arsenate than rainy season varieties [147]. Studies have also reduced the toxicity of TMs to rice by inserting or removing certain genes via genetic engineering and cross breeding [57,61,65,68]. For example, low Cd accumulation may reduce Cd absorption by inhibiting the bioavailability of Cd in the rhizosphere or by decreasing Cd transport [148]. Thus, the genotype, environment, and their interaction are considered the most significant factors affecting the TM content in rice grains.

7. Recent Trends and Challenges

The importance of rice to human beings and TMs may cause great harm to human beings through bioaccumulation, which will lead to research on TMs in rice fields becoming a hot issue. The relevant research on the treatment of TM pollution in paddy fields around the world mainly includes: (1) changing the existing state of TMs in soil, making them fixed or stable, and then reducing the activity of TMs; (2) changing the planting system to reduce the absorption of TMs by rice; (3) extracting TMs from rice fields, so as to reduce the concentration of TMs in rice fields. Since 2011, the number of papers published in the field of TM remediation in paddy fields has increased rapidly. These studies mainly focused on five TMs: Cd, Pb, As, Cu, and Zn, which indirectly showed that rice fields around the world were mainly polluted by these heavy metals. In addition, there was also a small amount of research on rare earth metals. Among these research hotspots, the remediation and treatment of Cd pollution in paddy fields was the main, and the passivation remediation fixation/stabilization technology was the most. However, the best effect of reducing Cd was the planting of low-accumulation Cd varieties, which could reach 74.50% [149].
It is very difficult to completely remove TMs from rice fields. At present, scholars mainly focus on passivating TMs, reducing their activity, and reducing their absorption by rice. In addition, at present, most of the treatment technologies of TM pollution in rice fields are still in the stage of laboratory or field experiment and demonstration, and there are few real engineering applications, so they have great market potential in the future. In order to realize the simultaneous production and repair activities, we can develop environment-friendly, long-lasting, and high-efficiency passivators for moderate and mild TM pollution; for severe pollution, the combination of soil elution technology and passivation remediation technology or phytoremediation technology can be used; for microbial remediation, especially the screening and cultivation of microbial strains, further research is needed. Due to the differences in soil properties, there are few universal technologies that can be popularized in a large area. Therefore, it is particularly important to develop efficient and lasting comprehensive prevention and control technology for toxic metal pollution in paddy fields according to local conditions.

8. Conclusions

TMs may affect human growth and development, physiological metabolism, etc., and may cause diseases and even death. TMs enter the food chain via organisms located at the bottom of the food chain, and their concentration and toxicity are subsequently amplified as they move further up the food chain. Consuming a certain amount of food contaminated by TMs can threaten an individual’s health. Thus, humans (who are at the top of the food chain) face great health risks, as they risk TM exposure principally through food intake. Rice is more important than fish in terms of the risk of metal exposure in the human diet, and arsenic requires particular attention. Grain crops (e.g., rice) that grow on soil/water polluted by TMs not only experience a reduction in yield and quality but also enrich a large amount of TMs. To reduce the threat of TMs to human health, measures must be taken from the source. In particular, uncontaminated soil and water bodies can guarantee the production of healthy food, which is key to human health. Therefore, the research and exploration of the technical methods of heavy metal removal or remediation in rice fields is of great significance to human food safety and health.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/toxics10050249/s1, Table S1: Effects of toxic metals on the apparent indexes and body composition of rice (Promote/Increase). Table S2: Effects of toxic metals on the apparent indexes and body composition of rice (Inhibit/Reduce).

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References

1. Sfakianakis, D.; Renieri, E.; Kentouri, M.; Tsatsakis, A. Effect of heavy metals on fish larvae deformities: A review. Environ. Res. 2015, 137, 246–253. [CrossRef] [PubMed]

2. Guevara-Garcia, A.A.; Juárez, K.; Herrera-Estrella, L.R. Heavy metal adaptation. In eLS Encyclopedia of Life Sciences; John Wiley & Sons, Ltd.: Chichester, UK, 2017; pp. 1–9.

3. Wang, J.; Chen, C. Biosorbents for heavy metals removal and their future. Biotechnol. Adv. 2009, 27, 195–226. [CrossRef] [PubMed]

4. Duffus, J.H. “Heavy metals” a meaningless term? (IUPAC Technical Report). Pure Appl. Chem. 2002, 74, 793–807. Erratum in Pure Appl. Chem. 2002, 75, 1357. [CrossRef]

5. Pourret, O.; Bollinger, J.C. ‘Heavy metals’—what to do now: To use or not to use? (Letter to the Editor). Sci. Total Environ. 2018, 610, 419–420. [CrossRef] [PubMed]

6. Dickman, M.; Leung, K.; Koo, L. Mercury in Human Hair and Fish: Is there a Hong Kong Male Subfertility Connection? Mar. Pollut. Bull. 1999, 39, 352–356. [CrossRef]

7. Bandara, J.M.R.S.; Wijewardena, H.V.P.; Liyanage, J.; Upul, M.A.; Bandara, J.M.U.A. Chronic renal failure in Sri Lanka caused by elevated dietary cadmium: Trojan horse of the green revolution. Toxicol. Lett. 2010, 198, 33–39. [CrossRef]

8. Yu, X.-D.; Yan, C.-H.; Chen, C. Biosorbents for heavy metals removal and their future. Water Air Soil Pollut. 2007, 186, 39, 352–356. [CrossRef]

9. Jin, X. How many lands have been filled with poison—Investigation on soil heavy metal pollution in China. Environ. Educ. 2015, 6, 4–9. (In Chinese)

10. Rai, P.K.; Lee, S.S.; Zhang, M.; Tsang, Y.F.; Kim, K.-H. Heavy metals in food crops: Health risks, fate, mechanisms, and management. Environ. Int. 2019, 125, 365–385. [CrossRef]

11. ATSDR. Toxicological Profile for Barium; U.S. Department of Health and Human Services, Public Health Service: Atlanta, GA, USA, 2007.

12. Liu, S. A brief analysis of the rice production Status in the world and China. Xin Nongye 2020, 20, 14–16. (In Chinese)

13. CGIAR. The Global Staple. 2021. Available online: http://ricepedia.org/rice-as-food/the-global-staple-rice-consumers. (accessed on 3 March 2021).

14. Hibberd, J.M.; Sheehy, J.E.; Langdale, J.A. Using C4 photosynthesis to increase the yield of rice—rationale and feasibility. Curr. Opin. Plant Biol. 2008, 11, 228–231. [CrossRef] [PubMed]

15. Kaur, R.; Bhunia, R.K.; Rajam, M.V. MicroRNAs as potential targets for improving rice yield via plant architecture modulation: Recent studies and future perspectives. J. Biosci. 2020, 45, 116. [CrossRef] [PubMed]

16. Jung, J.; Choi, H.-Y.; Huy, N.-X.; Park, H.; Kim, H.H.; Yang, M.-S.; Kang, S.-H.; Kim, D.-I.; Kim, N.-S. Production of recombinant human acid β-glucosidase with high mannose-type N-glycans in rice nmt1 mutant for potential treatment of Gaucher disease. Protein Expr. Purif. 2019, 158, 81–88. [CrossRef]

17. Verma, D.K.; Srivastava, P.P. Bioactive compounds of rice (Oryza sativa L.): Review on paradigm and its potential benefit in human health. Trends Food Sci. Technol. 2020, 97, 355–365. [CrossRef]

18. Wang, Z.G.; Feng, J.N.; Tong, Z. Human toxicosis caused by moldy rice contaminated with fusarium and T-2 toxin. Biomed. Environ. Sci. 1993, 6, 65. [PubMed]

19. FAO. The State of Food Security and Nutrition in the World. 2021. Available online: https://www.fao.org/publications/sofi/en. (accessed on 5 April 2022).

20. Mahmood, T.; Islam, K.R.; Muhammad, S. Toxic effects of heavy metals on early growth and tolerance of cereal crops. Pak. J. Bot. 2007, 39, 451.

21. Mishra, A.; Choudhuri, M.A. Amelioration of lead and mercury effects on germination and rice seedling growth by antioxidants. Biol. Plant. 1998, 41, 469–473. [CrossRef]

22. Mishra, A.; Choudhuri, M.A. Monitoring of Phytotoxicity of Lead and Mercury from Germination and Early Seedling Growth Indices in Two Rice Cultivars. Water Air Soil Pollut. 1999, 114, 339–346. [CrossRef]

23. Hassan, M.J.; Shao, G.; Zhang, G. Influence of Cadmium Toxicity on Growth and Antioxidant Enzyme Activity in Rice Cultivars with Different Grain Cadmium Accumulation. J. Plant Nutr. 2005, 28, 1259–1270. [CrossRef]

24. He, J.; Ren, Y. Effect of Cadmium on Seed Germination, Seedling Growth and Amylolytic Activity of Rice. Acta Agri-Cult. Borosli-Sin. 2008, 23, 131–134.

25. Ashraf, U.; Hussain, S.; Anjum, S.A.; Abbas, F.; Tanveer, M.; Noor, M.A.; Tang, X. Alterations in growth, oxidative damage, and metal uptake of five aromatic rice cultivars under lead toxicity. Plant Physiol. Biochem. 2017, 115, 461–471. [CrossRef]

26. Ahsan, N.; Lee, D.-G.; Lee, S.-H.; Kang, K.Y.; Lee, J.J.; Kim, P.J.; Yoon, H.-S.; Kim, J.-S.; Lee, B.-H. Excess copper induced physiological and proteomic changes in germinating rice seeds. Chemosphere 2007, 67, 1182–1193. [CrossRef] [PubMed]

27. Ashraf, U.; Kanu, A.S.; Deng, Q.; Mo, Z.; Pan, S.; Tian, H.; Tang, X. Lead (Pb) Toxicity; Physio-Biochemical Mechanisms, Grain Yield, Quality, and Pb Distribution Proportions in Scented Rice. Front. Plant Sci. 2017, 8, 259. [CrossRef] [PubMed]

28. Silva, M.L.D.S.; Vitti, G.C.; Trevizam, A.R. Heavy metal toxicity in rice and soybean plants cultivated in contaminated soil. Rev. Ceres 2014, 61, 248–254. [CrossRef]

29. He, J.-Y.; Chen, Y.-F.; Zhu, C.; Jiang, D. Effects of Cadmium Stress on Seed Germination, Seedling Growth and Seed Amylase Activities in Rice (Oryza sativa). Rice Sci. 2008, 15, 319–325. [CrossRef]
30. Rascio, N.; Vecchia, F.D.; La Rocca, N.; Barbato, R.; Pagliano, C.; Raviolo, M.; Gonnelli, C.; Gabrieilli, R. Metal accumulation and damage in rice (cv. Vialone nano) seedlings exposed to cadmium. *Environ. Exp. Bot.* 2008, 62, 267–278. [CrossRef]

31. Gautam, M.; Sengar, R.S.; Chaudhary, R.; Sengar, K.; Garg, S. Possible cause of inhibition of seed germination in two rice cultivars by heavy metals Pb(NO₃)₂ and HgCl₂. *Toxicol. Environ. Chem.* 2010, 92, 1111–1119. [CrossRef]

32. Ross, R.; Cook, D.T.; Martinez-Cortina, C.; Picazo, I. Nickel and Cadmium-related Changes in Growth, Plasma Membrane Lipid Composition, ATPase Hydrolytic Activity and Proton-pumping of Rice (*Oryza sativa* L. cv. Bahia) Shoots. *J. Exp. Bot.* 1992, 43, 1475–1481. [CrossRef]

33. Jamil, M.; Zeb, S.; Anees, M.; Roohi, A.; Ahmed, I.; Rehman, S.U.; Rha, E.S. Role of Actinobacteria in Phytoremediation of Nickel Contaminated Soil Cultivated with Rice. *Int. J. Phytoremediation*. 2014, 16, 554–571. [CrossRef]

34. Huang, F.; Wen, X.-H.; Cai, Y.-X.; Cai, K.-Z. Silicon-Mediated Enhancement of Heavy Metal Tolerance in Rice at Different Growth Stages. *J. Plant Nutr. Soil Sci.* 2015, 178, 907–911. [CrossRef]

35. Liu, D.; Wang, X. Lanthanum regulates the reactive oxygen species in the roots of rice seedlings. *Plant Soil Environ.* 2015, 61, 196–200. [CrossRef]

36. Liu, D.; Zheng, S.; Wang, X. Lanthanum regulates the reactive oxygen species in the roots of rice seedlings. *Sci. Rep.* 2016, 6, 31860. [CrossRef] [PubMed]

37. Liu, D.; Li, M.; Yang, J. Effects of different forms of antimony on rice during the period of germination and growth and antimony concentration in rice tissue. *Sci. Total Environ.* 1999, 243–244, 149–155. [CrossRef]

38. Abedin, J.; Cresser, M.S.; Meharg, A.A.; Feldmann, J.; Cotter-Howells, J. Arsenic Accumulation and Metabolism in Rice (*Oryza sativa* L.). *Environ. Sci. Technol.* 2002, 36, 962–968. [CrossRef]

39. Nautiyal, N.; Chatterjee, C.; Sharma, C. Copper stress affects grain filling in rice. *Commun. Soil Sci. Plant Anal.* 1999, 30, 1625–1632. [CrossRef]

40. Marin, A.R.; Pezeshki, S.R.; Masschelen, P.H.; Choi, H.S. Effect of dimethylarsenic acid (DMAA) on growth, tissue arsenic, and photosynthesis of rice plants. *J. Plant Nutr.* 1993, 16, 865–880. [CrossRef]

41. Wang, L.; Liu, B.; Wang, Y.; Qin, Y.; Zhou, Y.; Qian, H. Influence and interaction of iron and lead on seed germination in upland rice. *Plant Soil 2020*, 455, 187–202. [CrossRef]

42. Mishra, A.; Choudhuri, M. Effects of Salicylic Acid on Heavy Metal-Induced Membrane Deterioration Mediated by Lipoxygenase in Rice. *Biocatal. Biotransform.* 1999, 42, 409–415. [CrossRef]

43. Ashraf, U.; Tang, X. Yield and quality responses, plant metabolism and metal distribution pattern in aromatic rice under lead (Pb) toxicity. *Chemosphere 2017*, 176, 141–155. [CrossRef]

44. Huang, F.; Wen, X.-H.; Cai, Y.-X.; Cai, K.-Z. Silicon-Mediated Enhancement of Heavy Metal Tolerance in Rice at Different Growth Stages. *Int. J. Environ. Res. Public Health*. 2018, 15, 2193. [CrossRef] [PubMed]

45. Kanu, A.S.; Ashraf, U.; Mo, Z.; Sabir, S.-U.; Baggie, I.; Charley, C.S.; Tang, X. Calcium amendment improved the performance of fragrant rice and reduced metal uptake under cadmium toxicity. *Environ. Sci. Pollut. Res.* 2019, 26, 24748–24757. [CrossRef] [PubMed]

46. Wang, L.; Liu, B.; Wang, Y.; Qin, Y.; Zhou, Y.; Qian, H. Influence and interaction of iron and lead on seed germination in upland rice. *Plant Soil Environ.* 2015, 61, 196–200. [CrossRef]

47. Huang, D.-F.; Xi, L.-L.; Yang, L.-N.; Wang, Z.-Q.; Yang, J.-C. Comparison of Agronomic and Physiological Traits of Rice Genotypes Differing in Cadmium-Tolerance. *Acta Agron. Sin.* 2008, 34, 809–817. [CrossRef]

48. Fan, X.; Wen, X.; Huang, F.; Cai, Y.; Cai, K. Effects of silicon on morphology, ultrastructure and exudates of rice root under heavy metal stress. *Acta Physiol. Plant.* 2016, 38, 19. [CrossRef]

49. Begum, M.; Mondal, S. Relative Toxicity of Arsenate and Arsenite on Early Seedling Growth and Photosynthetic Pigments of Rice. *Curr. J. Appl. Sci. Technol*. 2019, 33, 1–5. [CrossRef]

50. Farooq, H.; Asghar, H.N.; Khan, M.Y.; Saleem-Mand, Z.A. Auxin-mediated growth of rice in cadmium-contaminated soil. *Turk. J. Agric. For.* 2015, 39, 272–276. [CrossRef]

51. Rehman, M.Z.U.; Rizwan, M.; Rauf, A.; Ayub, M.A.; Ali, S.; Qayyum, M.F.; Naeem, A.; Sanaullah, M. Split application of silicon in cadmium (Cd) spiked alkaline soil plays a vital role in decreasing Cd accumulation in rice (*Oryza sativa* L.) grains. *Chemosphere 2019*, 226, 454–462. [CrossRef]

52. Moya, J.L.; Ros, R.; Picazo, I. Influence of cadmium and nickel on growth, net photosynthesis and carbohydrate distribution in rice plants. *Photosynth. Res.* 1993, 36, 75–80. [CrossRef]

53. Cao, F.; Cai, Y.; Liu, L.; Zhang, M.; He, X.; Zhang, G.; Wu, F. Differences in photosynthesis, yield and grain cadmium accumulation as affected by exogenous glutathione and glutathione in the two rice genotypes. *Plant Growth Regul.* 2015, 75, 715–723. [CrossRef]

54. Ding, Y.; Wang, Y.; Jiang, Z.; Wang, F.; Jiang, Q.; Sun, J.; Chen, Z.; Zhu, C. MicroRNA268 Overexpression Affects Rice Seedling Growth under Cadmium Stress. *J. Agric. Food Chem.* 2017, 65, 5860–5867. [CrossRef]

55. Takahashi, R.; Bashir, K.; Ishimaru, Y.; Nishizawa, N.K.; Nakanishi, H. The role of heavy-metal ATPases, HMAs, in zinc and cadmium transport in rice. *Plant Signal. Behav.* 2012, 7, 1605–1607. [CrossRef] [PubMed]

56. Luo, J.-S.; Huang, J.; Zeng, D.-L.; Peng, J.-S.; Zhang, G.-B.; Ma, H.-L.; Guan, Y.; Yi, H.-Y.; Fu, Y.-L.; Han, B.; et al. A defensin-like protein drives cadmium efflux and allocation in rice. *Nat. Commun.* 2018, 9, 645. [CrossRef] [PubMed]
57. Tian, S.; Liang, S.; Qiao, K.; Wang, F.; Zhang, Y.; Chai, T. Co-expression of multiple heavy metal transporters changes the translocation, accumulation, and potential oxidative stress of Cd and Zn in rice (Oryza sativa). J. Hazard. Mater. 2019, 380, 120853. [CrossRef] [PubMed]

58. Deng, F.; Yamaji, N.; Xia, J.; Ma, J.F. A Member of the Heavy Metal P-Type ATPase OsHMA5 Is Involved in Xylem Loading of Copper in Rice. Plant Physiol. 2013, 163, 1355–1362. [CrossRef]

59. Huang, X.; Deng, F.; Yamaji, N.; Pinson, S.R.; Fujii-Kashino, M.; Danku, J.; Douglas, A.; Guerinot, M.L.; Salt, D.E.; Ma, J.F. A heavy metal P-type ATPase OsHMA4 prevents copper accumulation in rice grain. Nat. Commun. 2016, 7, 12138. [CrossRef]

60. Kumar, S.; Asif, M.H.; Chakraborty, D.; Tripathi, R.D.; Dubey, R.S.; Trivedi, P.K. Expression of a rice Lambda class of glutathione S-transferase, OsGSTL2, in Arabidopsis provides tolerance to heavy metal and other abiotic stresses. J. Hazard. Mater. 2013, 248–249, 228–237. [CrossRef]

61. Hu, T.; Zhu, S.; Tan, L.; Qi, W.; He, S.; Wang, G. Overexpression of OsLEA4 enhances drought, high salt and heavy metal stress tolerance in transgenic rice (Oryza sativa L.). Environ. Exp. Bot. 2016, 123, 68–77. [CrossRef]

62. Tsumenitsu, Y.; Yenga, M.; Okada, T.; Yamaji, N.; Ma, J.F.; Miyazaki, A.; Kato, S.-I.; Iwasaki, K.; Ueno, D. A member of cation diffusion facilitator family, MTP11, is required for manganese tolerance and high fertility in rice. Planta 2018, 248, 231–241. [CrossRef]

63. Zhang, Y.; Chen, K.; Zhao, F.-J.; Sun, C.; Jin, C.; Shi, Y.; Sun, Y.; Li, Y.; Yang, M.; Jing, X.; et al. OsATX1 Interacts with Heavy Metal P1B-Type ATPases and Affects Copper Transport and Distribution. Plant Physiol. 2018, 178, 329–344. [CrossRef]

64. Kim, Y.-O.; Kang, H. Heavy metal resistance in rice (Oryza sativa) and Arabidopsis thaliana. Biosci. Biotechnol. Biochem. 2018, 82, 1656–1665. [CrossRef]

65. Verma, S.; Verma, P.; Meher, A.K.; Bansiwal, A.K.; Tripathi, R.D.; Chakraborty, D. A novel fungal arsenic methyltransferase, WaarsM reduces grain arsenic methylation in transgenic rice (Oryza sativa L.). J. Hazard. Mater. 2018, 344, 626–634. [CrossRef] [PubMed]

66. Jeng, X.-Q.; Shalmani, A.; Zhou, M.-R.; Shi, P.-T.; Muhammad, I.; Shi, Y.; Sharif, R.; Li, W.-Q.; Liu, W.-T.; Chen, K.-M. Genome-Wide Identification of Malecin/Malecin-Like Domain Containing Protein Family Genes in Rice and Their Expression Regulation Under Various Hormones, Abiotic Stresses, and Heavy Metal Treatments. J. Plant Growth Regul. 2019, 39, 492–506. [CrossRef]

67. Che, J.; Yokosho, K.; Yamaji, N.; Ma, J.F. A Vacuolar Phytosiderophore Transporter Alters Iron and Zinc Accumulation in Polished Rice Grains. Plant Physiol. 2019, 181, 276–288. [CrossRef] [PubMed]

68. Wang, T.; Li, Y.; Fu, Y.; Xie, H.; Song, S.; Qiu, M.; Wen, J.; Chen, M.; Chen, G.; Tian, Y.; et al. Mutation at Different Sites of Metal Transporter Gene OsNRAMP5 Affects Cd Accumulation and Related Agronomic Traits in Rice (Oryza sativa L.). Front. Plant Sci. 2019, 10, 1081. [CrossRef]

69. Chang, J.; Huang, S.; Yamaji, N.; Zhang, W.; Ma, J.F.; Zhao, F. OsNRAMP1 transporter contributes to cadmium and manganese uptake in rice. Plant Cell Environ. 2020, 43, 2476–2491. [CrossRef]

70. Moulick, D.; Ghosh, D.; Santra, S.C. Evaluation of effectiveness of seed priming with selenium in rice during germination under arsenic stress. Plant Physiol. Biochem. 2016, 109, 571–578. [CrossRef]

71. Wang, Y.; Xiao, L.; Li, S.; Guo, Y.; Cai, X. Effects of Compound Pollution of Pb and Cd on Soil and Physiological and Biochemical Characteristics of Rice Leaves. Chin. Agr. Sci. Bull. 2010, 26, 369–373. [CrossRef]

72. Barzegar, R.; Moghaddam, A.A.; Soltani, S.; Fijani, E.; Tziritis, E.; Kazemian, N. Heavy Metal(loids) in the Groundwater of Shabestar Area (NW Iran): Source Identification and Health Risk Assessment. Environ. Exp. Bot. 2019, 160, 217–227. [CrossRef]

73. Mariyanto, M.; Amir, M.F.; Utama, W.; Hamdan, A.M.; Bijaksana, S.; Pratama, A.; Yunginger, R.; Sudarningsih, S. Heavy metal contents and magnetic properties of surface sediments in volcanic and tropical environment from Brantas River, Jawa Timur Province, Indonesia. Sci. Total Environ. 2019, 675, 632–641. [CrossRef]

74. Zhou, J.; Du, B.; Liu, H.; Cui, H.; Zhang, W.; Fan, X.; Cui, J.; Zhou, J. The bioavailability and contribution of the newly deposited heavy metals (copper and lead) from atmosphere to rice (Oryza sativa L.). J. Hazard. Mater. 2020, 384, 121285. [CrossRef]

75. Luo, L.; Mei, K.; Qu, L.; Zhang, C.; Chen, H.; Wang, S.; Di, D.; Huang, H.; Wang, Z.; Xia, F.; et al. Assessment of the Geographical Detector Method for investigating heavy metal source apportionment in an urban watershed of Eastern China. Sci. Total Environ. 2019, 653, 714–722. [CrossRef] [PubMed]

76. Atafar, Z.; Mesdaghinia, A.; Nouri, J.; Homoae, M.; Yunesian, M.; Ahmadimoghadam, M.; Mahvi, A.H. Effect of fertilizer application on soil heavy metal concentration. Environ. Monit. Assess. 2010, 160, 83–89. [CrossRef] [PubMed]

77. Gassama, U.M.; Bin Puteh, A.; Abd-Halim, M.R.; Kargbo, B. Influence of municipal wastewater on rice seed germination, seedling performance, nutrient uptake, and chlorophyll content. J. Crop Sci. Biotechnol. 2015, 18, 9–19. [CrossRef]

78. Bussan, D.; Harris, A.; Douvrin, C. Monitoring of selected trace elements in sediments of heavily industrialized areas in Calcasieu Parish, Louisiana, United States by inductively coupled plasma-optical emission spectroscopy (ICP-OES). Microchem. J. 2019, 144, 51–55. [CrossRef]

79. Ning, L.; Liyuan, Y.; Jirui, D.; Xugui, P. Heavy metal pollution in surface water of Linglong gold mining area, China. Procedia Environ. Sci. 2011, 10, 914–917. [CrossRef]

80. Ignataviˇcius, G.; Valskys, V.; Bulskaya, I.; Palilus, D.; Zigmontien˙e, A.; Satk ¯unas, J. Heavy metal contamination in surface runoff waters of the urban area of Vilnius, Lithuania. Estonian J. Earth Sci. 2017, 66, 13. [CrossRef]

81. Liu, A.; Ma, Y.; Gunawardena, J.M.; Egodawatta, P.; Ayoko, G.A.; Goonetilleke, A. Heavy metals transport pathways: The importance of atmospheric pollution contributing to stormwater pollution. Ecotoxicol. Environ. Safe 2018, 164, 966–703. [CrossRef]
82. Birch, G.; Taylor, S.; Matthai, C. Small-scale spatial and temporal variation in the concentration of heavy metals in aquatic sediments: A review and some new concepts. *Environ. Pollut.* 2001, 113, 357–372. [CrossRef]

83. Liu, M.; Liu, X.; Li, M.; Fang, M.; Chi, W. Neural-network model for estimating leaf chlorophyll concentration in rice under stress from heavy metals using four spectral indices. *Biosyst. Eng.* 2010, 106, 223–233. [CrossRef]

84. Liu, M.; Liu, X.; Zhang, B.; Ding, C. Regional heavy metal pollution in crops by integrating physiological function variability with spatio-temporal stability using multi-temporal thermal remote sensing. *Int. J. Appl. Earth Obs. Geoinf.* 2016, 51, 91–102. [CrossRef]

85. Zhao, S.; Qian, X.; Liu, X.; Xu, Z. Finding the Key Periods for Assimilating HJ-1A/B CCD Data and the WOFOST Model to Evaluate Heavy Metal Stress in Rice. *Sensors* 2018, 18, 1230. [CrossRef] [PubMed]

86. Brus, D.J.; Li, Z.; Song, J.; Koopmans, G.F.; Temminghoff, E.J.M.; Yin, X.; Yao, C.; Zhang, H.; Luo, Y.; Japenga, J. Predictions of Spatially Averaged Cadmium Contents in Rice Grains in the Fuyang Valley, PR China. *J. Environ. Qual.* 2009, 38, 1126–1136. [CrossRef] [PubMed]

87. Liu, M.; Liu, X.; Li, J.; Li, T. Estimating regional heavy metal concentrations in rice by scaling up a field-scale heavy metal assessment model. *Int. J. Appl. Earth Obs.* 2012, 19, 12–23. [CrossRef]

88. Chen, Q.; Peng, P.-Q.; Long, J.; Li, X.-Y.; Ding, X.; Hou, H.-B.; Liao, B.-H. Cadmium phytoavailability evaluation in rice-soil system using a field capacity-derived soil solution extraction: An entire growth period study in subtropical China. *Soil Tillage Res.* 2019, 194, 104315. [CrossRef]

89. Shi, T.; Liu, H.; Wang, J.; Chen, Y.; Fei, T.; Wu, G. Monitoring Arsenic Contamination in Agricultural Soils with Reflectance Spectroscopy of Rice Plants. *Environ. Sci. Technol.* 2014, 48, 6264–6272. [CrossRef]

90. Shi, T.; Wang, J.; Chen, Y.; Wu, G. Improving the prediction of arsenic contents in agricultural soils by combining the reflectance spectroscopy of soils and rice plants. *Int. J. Appl. Earth Obs.* 2016, 52, 95–103. [CrossRef]

91. Li, X.; Li, L.; Liu, X. Collaborative inversion heavy metal stress in rice by using two-dimensional spectral feature space based on HJ-1 A HSI and radarsat-2 SAR remote sensing data. *Int. J. Appl. Earth Obs. Geoinf.* 2019, 78, 39–52. [CrossRef]

92. Abrham, F.; Gholap, A.V. Analysis of heavy metal concentration in some vegetables using atomic absorption spectroscopy. *Pollut. Bull.* 2021, 7, 205–216. [CrossRef]

93. Ay, E.; Tekin, Z.; Özdoğan, N.; Bakirdere, S. Zirconium Nanoparticles Based Vortex Assisted Ligandless Dispersive Solid Phase Extraction for Trace Determination of Lead in Domestic Wastewater using Flame Atomic Absorption Spectrophotometry. *Bull. Environ. Contam. Toxicol.* 2022, 108, 324–330. [CrossRef]

94. Goodarzi, L.; Bayatlo, M.R.; Chalavi, S.; Nojavan, S.; Rahmani, T.; Azimi, S.B. Selective extraction and determination of Cr(VI) in food samples based on tandem electromembrane extraction followed by electrothermal atomic absorption spectrometry. *Food Chem.* 2022, 373, 131442. [CrossRef] [PubMed]

95. Castiñeira, M.D.M.; Brandt, R.; Jakubowski, N.; Andersson, J.T. Changes of the Metal Composition in German White Wines through the Winemaking Process. A Study of 63 Elements by Inductively Coupled Plasma—Mass Spectrometry. *J. Agric. Food Chem.* 2004, 52, 2953–2961. [CrossRef] [PubMed]

96. Fu, L.; Xie, H.; Huang, J.; Chen, L. Determination of the Non-metallic Elements in Herbal Tea by Inductively Coupled Plasma Tandem Mass Spectrometry. *Biol. Trace Element Res.* 2021, 179, 769–778. [CrossRef] [PubMed]

97. Bloom, N.; Fitzgerald, W.F. Determination of volatile mercury species at the picogram level by low-temperature gas chromatography with cold-vapour atomic fluorescence detection. *Anal. Chim. Acta* 1988, 208, 151–161. [CrossRef]

98. Gómez-Arizo, J.L.; Lorenzo, F.; García-Barrera, T. Comparative study of atomic fluorescence spectroscopy and inductively coupled plasma mass spectrometry for mercury and arsenic multispeciation. *Anal. Bioanal. Chem.* 2005, 382, 485–492. [CrossRef]

99. Musil, S.; Matoušek, T.; Currier, J.M.; Stáblo, M.; Dédina, J. Speciation Analysis of Arsenic by Selective Hydride Generation-Cryotrapping-Atomic Spectrometry with Flame-in-Gas-Shield Atomizer: Achieving Extremely Low Detection Limits with Inexpensive Instrumentation. *Anal. Chem.* 2014, 86, 10422–10428. [CrossRef]

100. Tang, X.; Qian, Y.; Guo, Y.; Wei, N.; Li, Y.; Yao, J.; Wang, G.; Ma, J.; Liu, W. Analysis of atmospheric pollutant metals by laser ablation inductively coupled plasma mass spectrometry with a radial line-scan dried-droplet approach. *Spectrochim. Acta Part B At. Spectros.* 2017, 138, 18–22. [CrossRef]

101. Peyneau, P.-E. Poisson process modelling of spike occurrence in single particle inductively coupled plasma mass spectrometry time scans for very dilute nanoparticle dispersions. *Spectrochim. Acta Part B At. Spectros.* 2021, 178, 106126. [CrossRef]

102. Valenta, P.; Sipos, L.; Kramer, I.; Krumpen, P.; Rützel, H. An automatic voltammetric analyzer for the simultaneous determination of toxic trace metals in water. *Z. Anal. Bioanal. Chem.* 1982, 312, 101–108. [CrossRef]

103. Clark, B.R.; DePaoli, D.W.; McTaggart, D.R.; Patton, B.D. An on-line voltammetric analyzer for trace metals in wastewater. *Anal. Chim. Acta* 1998, 315, 13–20. [CrossRef]

104. Hseu, Z.-Y.; Su, S.-W.; Lai, H.-Y.; Guo, H.-Y.; Chen, T.-C.; Chen, Z.-S. Remediation techniques and heavy metal uptake by different rice varieties in metal-contaminated soils of Taiwan: New aspects for food safety regulation and sustainable agriculture. *Soil Sci. Plant Nutr.* 2010, 56, 31–52. [CrossRef] [PubMed]

105. Li, H.; Liu, Y.; Luo, Z.; Zhou, Y.; Hou, D.; Mao, Q.; Zhi, D.; Zhang, J.; Yang, Y.; Luo, L. Effect of RM-based-passivator for the remediation of two kinds of Cd polluted paddy soils and mechanism of Cd(II) adsorption. *Environ. Technol.* 2019, 42, 1623–1633. [CrossRef] [PubMed]
107. Yang, X.; Zhang, W.; Qin, J.; Zhang, X.; Li, H. Role of passivators for Cd alleviation in rice-water spinach intercropping system. *Ecotoxicol. Environ. Safe* 2020, 205, 111321. [CrossRef] [PubMed]

108. Daulta, R.; Sridevi, T.; Garg, V.K. Spatial distribution of heavy metals in rice grains, rice husk, and arable soil, their bioaccumulation and associated health risks in Haryana, India. *Toxin Res.* 2020, 40, 859–871. [CrossRef]

109. Yildirim, A.; Baran, M.F.; Acay, H. Kinetic and isotherm investigation into the removal of heavy metals using a fungal-extract-based bio-nanosorbent. *Environ. Technol. Innov.* 2020, 20, 101076. [CrossRef]

110. Fan, M.; Luo, L.; Liao, Y.; Tian, J.; Hu, B. Effect of Application on Different Amount of Red Mud on Rice Yield and Soil Bio-logical Properties in Cd-contaminated Paddy Soil. *J. Soil. Water Conserv.* 2011, 6, 39. [CrossRef]

111. Trijatmiko, K.; Dueñas, C.; Tsakirpaloglou, N.; Torrizo, L.; Arines, F.M.; Adeva, C.; Balindong, J.; Oliva, N.; Sapos, M.V.; Borrero, J.; et al. Biofortified indica rice attains iron and zinc nutrition dietary targets in the field. *Sci. Rep.* 2016, 6, 19792. [CrossRef]

112. Shao, G.; Chen, M.; Wang, D.; Xu, C.; Mou, R.; Cao, Z.; Zhang, X. Using iron fertilizer to control Cd accumulation in rice plants: A new promising technology. *Sci. China Ser. C Life Sci.* 2008, 51, 245–253. [CrossRef]

113. Makino, T.; Nakamura, K.; Katou, H.; Ishikawa, S.; Ito, M.; Honma, T.; Sano, S.; Matsumoto, S.; et al. Simultaneous decrease of arsenic and cadmium in rice (*Oryza sativa L.*) plants cultivated under submerged field conditions by the application of iron-bearing materials. *Soil Sci. Plant Nutr.* 2016, 62, 340–348. [CrossRef]

114. Yu, H.-Y.; Wang, X.; Li, F.; Li, B.; Liu, C.; Wang, Q.; Lei, J. Arsenic mobility and bioavailability in paddy soil under iron compound amendments at different growth stages of rice. *Environ. Pollut.* 2017, 224, 136–147. [CrossRef]

115. Chen, C.C.; Dixon, J.B.; Turner, F.T. Iron Coatings on Rice Roots: Mineralogy and Quantity Influencing Factors. *Sci. Total Environ.* 2017, 592, 126–138. [CrossRef] [PubMed]

116. Rajendran, M.; Shi, L.; Wu, C.; Li, W.C.; An, W.; Liu, Z.; Xue, S. Effect of sulfur and sulfur-iron modified biochar on cadmium availability and transfer in the soil–rice system. *Chemosphere* 2019, 222, 314–322. [CrossRef] [PubMed]

117. Cuong, T.X.; Ullah, H.; Datta, A.; Hanh, T.C. Effects of Silicon-Based Fertilizer on Growth, Yield and Nutrient Uptake of Rice in Tropical Zone of Vietnam. *Rice Sci.* 2017, 24, 283–290. [CrossRef]

118. Lu, K.; Yang, X.; Gielen, G.; Bolan, N.; Ok, Y.S.; Niazi, N.K.; Xu, S.; Yuan, G.; Chen, X.; Zhang, X.; et al. Effect of bamboo and rice straw biomass on the mobility and redistribution of heavy metals (Cd, Cu, Pb and Zn) in contaminated soil. *J. Environ. Manag.* 2017, 186, 285–292. [CrossRef]

119. Yin, D.; Wang, X.; Peng, B.; Tan, C.; Ma, L.Q. Effect of biochar and Fe-biochar on Cd and As mobility and transfer in soil–rice system. *Chemosphere* 2017, 186, 928–937. [CrossRef]

120. Xing, Y.; Wang, X.; Shaheen, S.M.; Feng, X.; Chen, Z.; Zhang, H.; Rinklebe, J. Mitigation of mercury accumulation in rice using rice hull-derived biochar as soil amendment: A field investigation. *J. Hazard. Mater.* 2020, 388, 121477. [CrossRef]

121. Huang, D.; Liu, L.; Zeng, G.; Xu, P.; Huang, C.; Deng, L.; Wang, R.; Wan, J. The effects of rice straw biochar on indigenous microbial community and enzymes activity in heavy metal-contaminated sediment. *Chemosphere* 2017, 174, 545–553. [CrossRef]

122. Yue, L.; Lian, F.; Han, Y.; Bao, Q.; Wang, Z.; Xing, B. The effect of biochar nanoparticles on rice plant growth and the uptake of heavy metals: Implications for agricultural benefits and potential risk. *Sci. Total Environ.* 2019, 656, 9–18. [CrossRef]

123. Farooq, M.U.; Tang, Z.; Zheng, T.; Asghar, M.A.; Zeng, R.; Su, Y.; Li, H.H.; Liang, Y.; Zhang, Y.; Ye, X.; et al. Cross-Talk between Cadmium and Selenium at Elevated Cadmium Stress Determines the Fate of Selenium Uptake in Rice. *Biomolecules* 2019, 9, 247. [CrossRef]

124. Wang, S.; Wang, F.; Gao, S.; Wang, X. Heavy Metal Accumulation in Different Rice Cultivars as Influenced by Foliar Application of Nano-silicon. *Water Air Soil Pollut.* 2016, 227, 228. [CrossRef]

125. Liu, J.; Simms, M.; Song, S.; King, R.S.; Cobb, G.P. Physiological Effects of Copper Oxide Nanoparticles and Arsenic on the Growth and Life Cycle of Rice (*Oryza sativa japonica* ‘Koshihikari’). *Environ. Sci. Technol.* 2018, 52, 13728–13737. [CrossRef] [PubMed]

126. Peng, C.; Xu, C.; Liu, Q.; Sun, L.; Luo, Y.; Shi, J. Fate and Transformation of CuO Nanoparticles in the Soil–Rice System during the Life Cycle of Rice Plants. *Environ. Sci. Technol.* 2017, 51, 4907–4917. [CrossRef] [PubMed]

127. Zhang, W.; Long, J.; Li, J.; Zhang, M.; Xiao, G.; Ye, X.; Chang, W.; Zeng, H. Impact of ZnO nanoparticles on Cd toxicity and bioaccumulation in rice (*Oryza sativa L.*). *Environ. Pollut. Sci.* 2019, 26, 23119–23128. [CrossRef] [PubMed]

128. Zhang, Y.; Wang, X.; Ji, X.; Liu, Y.; Lin, Z.; Lin, Z.; Xiao, S.; Peng, B.; Tan, C.; Zhang, X. Effect of a novel Ca-Si composite mineral on Cd bioavailability, transport and accumulation in paddy soil–rice system. *J. Environ. Manag.* 2019, 233, 802–811. [CrossRef]

129. Li, H.; Xu, H.; Zhou, S.; Yu, Y.; Li, H.; Zhou, C.; Chen, Y.; Li, Y.; Wang, M.; Wang, G. Distribution and transformation of lead in rice plants grown in contaminated soil amended with biochar and lime. *Ecotoxicol. Environ. Safe* 2018, 165, 589–596. [CrossRef] [PubMed]

130. Zhai, W.; Zhao, W.; Yuan, H.; Guo, T.; Hashmi, M.Z.; Liu, X.; Tang, X. Reduced Cd, Pb, and As accumulation in rice (*Oryza sativa L.*) by a combined amendment of calcium sulfate and ferric oxide. *Environ. Sci. Pollut. Res.* 2020, 27, 1348–1358. [CrossRef]

131. Honma, T.; Ohba, H.; Kaneko, A.; Nakamura, K.; Makino, T.; Katou, H. Effects of soil amendments on arsenic and cadmium uptake by rice plants (*Oryza sativa L.* cv. Koshihikari) under different water management practices. *Soil Sci. Plant Nutr.* 2016, 62, 349–356. [CrossRef]

132. Zhou, Y.; Jia, Z.; Wang, J.; Chen, L.; Zou, M.; Li, Y.; Zhou, S. Heavy metal distribution, relationship and prediction in a wheat–rice rotation system. *Geoderma* 2019, 354, 113886. [CrossRef]
133. Huang, S.; Rao, G.; Ashraf, U.; He, L.; Zhang, Z.; Zhang, H.; Mo, Z.; Pan, S.; Tang, X. Application of inorganic passivators reduced Cd contents in brown rice in oilseed rape-rice rotation under Cd contaminated soil. Chemosphere 2020, 259, 127404. [CrossRef]

134. Zhou, J.; Li, P.; Meng, D.; Gu, Y.; Zheng, Z.; Yin, H.; Zhou, Q.; Li, J. Isolation, characterization and inoculation of Cd tolerant rice endophytes and their impacts on rice under Cd contaminated environment. Environ. Pollut. 2020, 260, 113990. [CrossRef]

135. Lin, X.; Mou, R.; Cao, Z.; Xu, P.; Wu, X.; Zhu, Z.; Chen, M. Characterization of cadmium-resistant bacteria and their potential for reducing accumulation of cadmium in rice grains. Sci. Total Environ. 2016, 569-570, 97–104. [CrossRef] [PubMed]

136. Tang, X.; Ni, Y. Review of Remediation Technologies for Cadmium in soil. E3S Web Conf. 2021, 233, 01037. [CrossRef]

137. Zhang, Q.; Chen, H.; Huang, D.; Xu, C.; Zhu, H.; Zhu, Q. Water managements limit heavy metal accumulation in rice: Dual effects of iron-plaque formation and microbial communities. Sci. Total Environ. 2019, 687, 790–799. [CrossRef] [PubMed]

138. Nakanishi, H.; Ogawa, I.; Ishimaru, Y.; Mori, S.; Nishizawa, N.K. Iron deficiency enhances cadmium uptake and translocation mediated by the Fe^{2+} transporters OsIRT1 and OsIRT2 in rice. Soil Sci. Plant Nutr. 2006, 52, 464–469. [CrossRef]

139. Arao, T.; Kawasaki, A.; Baba, K.; Mori, S.; Matsumoto, S. Effects of Water Management on Cadmium and Arsenic Accumulation and Dimethylarsinic Acid Concentrations in Japanese Rice. Environ. Sci. Technol. 2009, 43, 9361–9367. [CrossRef]

140. Pan, Y.; Koopmans, G.F.; Bonten, L.T.C.; Song, J.; Luo, Y.; Temminghoff, E.J.M.; Comans, R.N.J. Temporal variability in trace metal solubility in a paddy soil not reflected in uptake by rice (Oryza sativa L.). Environ. Geochem. Health 2016, 38, 1355–1372. [CrossRef] [PubMed]

141. Honma, T.; Ohba, H.; Kaneko-Kadokura, A.; Makino, T.; Nakamura, K.; Katou, H. Optimal Soil Eh, pH, and Water Management for Simultaneously Minimizing Arsenic and Cadmium Concentrations in Rice Grains. Environ. Sci. Technol. 2016, 50, 4178–4185. [CrossRef]

142. Ishfaq, M.; Farooq, M.; Zulfiqar, U.; Hussain, S.; Akbar, N.; Nawaz, A.; Anjum, S.A. Alternate wetting and drying: A water-saving and ecofriendly rice production system. Agric. Water Manag. 2020, 241, 106363. [CrossRef]

143. Deng, X.; Yang, Y.; Zeng, H.; Chen, Y.; Zeng, Q. Variations in iron plaque, root morphology and metal bioavailability response to seedling establishment methods and their impacts on Cd and Pb accumulation and translocation in rice (Oryza sativa L.). J. Hazard. Mater. 2020, 384, 121343. [CrossRef]

144. Farooq, M.U.; Zhu, J. The paradox in accumulation behavior of cadmium and selenium at different planting times in rice. Environ. Sci. Pollut. Res. 2019, 26, 22421–22430. [CrossRef]

145. Yi, Y.K.; Zhou, Z.B.; Chen, G.H. Effects of soil pH on growth and grain cadmium content in rice. J. Agro-Environ. Sci. 2017, 36, 428–436.

146. Chen, H.; Yang, Y.; Ye, Y.; Tao, L.; Fu, X.; Liu, B.; Wu, Y. Differences in cadmium accumulation between indica and japonica rice cultivars in the reproductive stage. Ecotoxicol. Environ. Safe 2019, 186, 109795. [CrossRef] [PubMed]

147. Abedin, M.J.; Meharg, A.A. Relative toxicity of arsenite and arsenate on germination and early seedling growth of rice (Oryza sativa L.). Plant Soil 2002, 243, 57–66. [CrossRef]

148. Songmei, L.; Jie, J.; Yang, L.; Jun, M.; Shouling, X.; Yuanyuan, T.; Youfa, L.; Qingyao, S.; Jianzhong, H. Characterization and Evaluation of OsLCT1 and OsNramp5 Mutants Generated Through CRISPR/Cas9-Mediated Mutagenesis for Breeding Low Cd Rice. Rice Sci. 2019, 26, 88–97. [CrossRef]

149. Du, Z.; Su, D. Bibliometric analysis of the effects of heavy metal pollution remediation technologies on paddy fields. J. Agro-Environ. Sci. 2018, 37, 2409–2417.