

Specific water management facilitated rice-based phytoremediation of cadmium contaminated paddy fields

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Research Article

Keywords: Cadmium, Paddy field, Cd phytoextraction by high-accumulating rice, Specific water management

Posted Date: May 7th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9242360/v1>

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Version of Record: A version of this preprint was published at Plant and Soil on September 8th, 2026. See the published version at <https://doi.org/10.1007/s11104-026-09050-0>.

Abstract

Background & Aims

Reducing cadmium (Cd) contamination in paddy soils is critical for food security and soil remediation. To improve Cd phytoextraction efficiency by rice, this study developed a targeted water management strategy in a "rice-for-rice" system, aligning drainage duration with rice's critical Cd uptake periods.

Methods

A pot experiment with four water management treatments (CK, WMG1, WMG2, WMG3) and a two-year field trial with two rice cultivars (9311, Pokkali) and three water management (CK, FI, WM) were conducted in Cd-contaminated paddy soil. Soil and rice samples were collected at key stages.

Results

Pot results showed that water management significantly lowered soil pH (by 0.32) and raised Eh (by 350 mV), increasing DGT-labile Cd by 7.94-fold and greatly enhancing rice Cd accumulation, with WMG1 being the most effective. Drying-phase DGT-labile Cd was 61.70% higher on average than wetting phase in each irrigation cycle. Factor analysis confirmed water management regulated Cd content via Eh, pH, and bioavailable Cd. Field trials verified that water management enriched Fe/S-oxidizing bacteria, boosted Cd bioavailability, and increased Cd uptake by high-Cd-accumulating rice. Under "WM + Pokkali (high-Cd-accumulating rice)", rice extracted 474.56 g/ha/yr Cd, with theoretical and actual remediation efficiencies of 43.01% and 37.50%.

Conclusions

This strategy efficiently reduces Cd in moderately to heavily contaminated paddies without altering field properties or farming practices, offering a novel remediation approach.

Introduction

Cadmium (Cd) contamination in paddy soils has become a widespread environmental challenge, posing constraints on safe rice production and agricultural sustainability while seriously threatening the quality and safety of agricultural products. Globally, Cd-polluted paddy fields are predominantly distributed across parts of Asia, Europe, and the Americas, with contamination sources including industrial emissions, mining activities, and Cd-containing fertilizers (Hou et al., 2025). Total Cd content and its bioavailability in soils exhibit significant spatial variability, reflecting the extensive, heterogeneous, and persistent nature of Cd accumulation. Serving as a staple food for about half of the global population, rice has a greater ability to accumulate Cd than other cereal crops, with Cd concentrations in polished rice being approximately 2.3–8 times higher than those in other cereal grains (Shimbo et al., 2001; Song et al., 2017). The consumption of rice contaminated with Cd has been associated with severe adverse health outcomes in humans, such as chronic metal toxicity, nephrotoxicity, and carcinogenic potential. Consequently, the remediation of Cd contaminated paddy soil remains an urgent priority, representing a dual strategic imperative for ensuring food security and achieving ecological objectives of soil purification.

Over the past two decades, considerable advancements had been made in developing integrated technical frameworks for the safe utilization of Cd contaminated paddy soils. This framework primarily focused on the cultivation of rice varieties with low Cd accumulation potential, as well as the controlled irrigation practices and application of alkaline amendments, supplemented by soil passivation and foliar barrier control techniques. Notably, recent breakthroughs in low-Cd rice varieties have effectively enabled the safe production of large-scale rice under mild to moderate Cd contamination (Guan et al., 2025). Cd remains in the soil matrix, posing risks of lateral migration and potential accumulation in subsequent crops, making Cd reduction in contaminated paddy soils a persistent challenge. Moreover, for heavily Cd-contaminated soils, their inherent phytotoxicity severely impairs normal plant growth, rendering them unsuitable for the safe production of crops (Wang et al., 2021). Phytoremediation presents a cost-effective, environmentally friendly, and non-destructive in situ approach, especially for moderately to heavily contaminated fields. This method utilizes Cd hyperaccumulator plants that absorb and extract soil Cd, with subsequent removal via harvest at maturity. However, existing Cd-hyperaccumulators identified worldwide—such as *Noccaea caerulea* and *Sedum alfredii*—are adapted to upland conditions and are unsuitable for water-logged paddy environments. Moreover, long-term upland management in paddy fields would severely disrupt irrigation and drainage infrastructure, impair soil water retention, and require substantial economic investment to restore field facilities, rendering such plants impractical for most Cd-contaminated rice-growing regions. Rice plants, characterized by its strong Cd accumulation capacity, high adaptability to flooded conditions, and substantially greater biomass than conventional hyperaccumulators, holds potential as a soil Cd remediation plant. Moreover, it was well established that Cd accumulation varies substantially among rice genotypes (Duan et al., 2017; Mu et al., 2019), providing a substantial germplasm resource for screening high-Cd-accumulating lines tailored to paddy soil remediation. Our previous research had shown that high-Cd-accumulating rice varieties hold significant potential for reducing and remediating Cd in paddy soils (Liu et al., 2021a), with soil Cd removal efficiencies comparable to or even exceeding those of established Cd-hyperaccumulators such as *Sedum alfredii* and *Noccaea caerulea* (Xia et al., 2024, Yan et al., 2021).

To further enhance the efficiency of soil Cd extraction by rice, the core strategy lies in increasing soil Cd bioavailability, which serves as the fundamental prerequisite for promoting Cd uptake and accumulation in rice plants. Water management is not only an indispensable agronomic practice in rice cultivation but also the most widely adopted field management strategy for controlling Cd accumulation in rice through the regulation of soil Cd bioavailability (Honma et al., 2016). The underlying mechanism is that fluctuations in soil moisture can induce changes in soil pH, redox potential (Eh), and microbial community structure and function (Tao et al., 2025; Yin et al., 2024b), thereby altering the speciation and bioavailability of Cd in the soil, and ultimately influencing the

processes of Cd uptake and accumulation in rice plants (Liu et al., 2024). Studies have shown that the aerobic environment resulting from prolonged drainage in paddy soils can significantly enhance soil Cd availability, thereby substantially promoting Cd accumulation in rice (Yin et al., 2024a). This is attributed, on the one hand, to the decrease in soil pH under aerobic conditions, where H^+ competes with Cd^{2+} for adsorption sites, thereby facilitating Cd^{2+} desorption. On the other hand, drainage or aeration promotes the oxidation of CdS mediated by sulfur-oxidizing bacteria, releasing substantial amounts of Cd^{2+} and further increasing Cd bioavailability (Huang et al., 2023; Yang et al., 2024; Lin et al., 2021). Furthermore, the process of Cd uptake during the growth stages of rice is equally critical. Studies have shown that the grain-filling period is one of the most important stages for Cd accumulation in rice (Huang et al., 2022), and water demand during this stage is relatively low. Therefore, exploring water management practices that maximize soil Cd uptake by rice while ensuring normal rice growth is of great significance for enhancing the Cd extraction efficiency of rice as a remediation plant. However, current research on water management in Cd-contaminated paddy fields has primarily focused on ensuring the safe production of rice grains, with limited attention paid to actively regulating soil Cd availability through targeted management strategies to promote Cd uptake and accumulation in rice. The exploration of such strategies is expected to provide important theoretical support and practical pathways for the phytoextraction of Cd-contaminated soils using high-Cd-accumulating rice cultivars.

Therefore, this study proposes a novel approach for remediating Cd-contaminated paddy soils. This strategy follows the principle of "using rice to remediate paddy fields" and fully leverages the Cd accumulation capacity of rice plants while preserving the fundamental properties and structure of paddy soils. Therefore, we hypothesized that integrating water management with high-Cd-accumulating rice cultivars may significantly enhance the efficiency of soil Cd extraction. By selecting high-Cd-accumulating rice varieties and implementing water management practices that both target the activation of soil Cd and align with the Cd uptake patterns of rice, we systematically conducted remediation experiments in moderately to severely Cd-contaminated paddy fields. Through pot experiments, we investigated the dynamic changes in soil Cd bioavailability driven by different water management regimes and elucidated how water regime-induced alterations in soil Cd availability affect Cd uptake and accumulation in rice plants, as well as the resulting efficiency of soil Cd remediation. Then we systematically analyzed and identified the optimal water management strategy aimed at maximizing the efficiency of Cd remediation by rice. And the findings were further validated through field trials, which also examined the associated shifts in microbial community structure and function under the implemented water regimes. The findings of this research provide new perspectives into phytoremediation strategies tailored for Cd contaminated paddy fields. Moreover, these findings carry substantial implications for reducing of Cd in moderately to severely polluted paddy soils, which is of great significance in addressing the long-standing environmental challenges associated with Cd pollution in such agro-ecosystems.

Materials and methods

Pot experiment

The experimental design The tested soil was procured from the Jiacheng village, Yonghe town, Liuyang city, Hunan province. It was a paddy soil of 0–20 cm plough layer, derived from granite. The soil exhibited a pH value of 5.83, a total Cd content of 1.69 mg/kg, and a $CaCl_2$ -extractable Cd content of 0.44 mg/kg. The pollution of the paddy fields was caused by the mining of ores in the upstream area. The fundamental physical and chemical properties of the soil were presented in supporting information (Table S1). Upon collecting, the soil was air dried and sieved through a 20 - mesh nylon sieve for subsequent experiments.

The pot experiment was carried out in the greenhouse of the Hunan Academy of Agricultural Sciences. Polyethylene buckets were filled with 5 kg of soil samples and compacted to ensure the settlement and stabilization of the soil layer. Germinated seeds of the rice variety 9311 were sown in the pots, with 7 seeds per pot. After ten days, three rice seedlings with comparable growth status were selected and retained in each pot to serve as experimental seedlings. Before sowing, 2.3 g of base fertilizer (compound fertilizer with N: P_2O_5 : K_2O = 25:10:16) was applied to each pot, when the rice seedlings had turned green, added 1.0 g of fertilizer per pot. During the seedling stage, all treatments maintained soil moisture at 60% of field capacity. From the seedling stage to maturity, four distinct water management treatments were established: one conventional irrigation group (CK) and three specific water management groups (WMG, including WMG1, WMG2, WMG3), each with three replicates, as detailed in the supplementary information (Text S1). The different WMG treatments were designed to explore optimal regimes for maximizing soil drying duration to enhance soil oxidizability and thereby increase soil Cd bioavailability, under the premise of maintaining normal rice growth. The implementation schematic of these four water management treatments was illustrated in Fig. 1.

Sample collection and analysis During the period from rice tillering to maturity, soil pH and Eh were measured in situ using a portable handheld pH meter (LE438, Mettler-Toledo, Switzerland) and an Eh meter (LE501, Mettler-Toledo, Switzerland), respectively, at a frequency of every 2–4 days. Soil and rice plant samples were collected at key growth stages: tillering, booting, grain-filling, and maturity. Additionally, within each wet-dry cycle of every growth stage, soil samples were taken under both wet and dry conditions. Bioavailable Cd in soil was extracted using the diffusive gradients in thin-films (DGT) technique (ZrO-CA DC/F-Z-06, ZhongkeZhigan, China). Porewater was collected using rhizosphere porewater samplers. Rice plants were thoroughly cleaned, oven-dried to constant weight, and manually separated into roots, stems, leaves, and panicles, with each part weighed. Digestion of soil and plant samples and subsequent Cd concentration analysis followed the methods described by Liu et al. (2021b). The soil Cd speciation extraction during the rice maturity stage followed the method established by Hao et al. (2021). ICP-MS (ICAP Qc, Thermo Scientific, America) was employed to quantify the Cd levels in the samples.

Two-year field trial

The experimental design The experiment field situated in Yonghe Town, Liuyang City, Hunan Province (28°29'N, 113°89'E). The total Cd content in the soil of this experimental site was 0.79 mg/kg. The regional environmental characteristics and fundamental soil properties of the experimental plots were summarized in supplementary information (Table S2). In this experiment, two rice cultivars (9311 and Pokkali) were evaluated under three water management regimes—conventional practice (CK), continuous flooding (FI), and water management (WM)—resulting in a total of six treatments. The WM

regime was designed based on preliminary pot experiments, as detailed in the supplementary information (Text S2). Specifically: (1) CK + 9311 (CK9311), (2) CK + Pokkali (CKpok), (3) WM + 9311 (WM9311), (4) WM + Pokkali (WMPok), (5) FI + Pokkali (FIPok), and (6) FI + 9311 (FI9311). Field trials were conducted during the rice growing seasons from June to October 2024 and from June to September 2025, with three replicates per treatment, totaling 18 plots. Additionally, Cd levels in irrigation water and atmospheric deposition were monitored and recorded throughout the experimental period. The results confirmed no significant external Cd input in the study area, with detailed data presented in supplementary information (Table S3 and Table S4). Pesticide and fertilizer applications adhered to local management practices, maintaining consistency across all treatments.

Sample collection and analysis At the rice maturation stage, plant, rhizosphere soil, and non-rhizosphere soil were independently collected. To accurately determine the total Cd accumulation in rice, the plant samples collected in 2024 were separated into three parts: roots (underground), stems and leaves, and spikes (grains), and the dry biomass and Cd content of each part were measured. In 2025, the sampling protocol was refined: plant samples were divided into only two components-roots (underground) and shoots (aboveground)-for biomass determination and Cd content analysis. The collected soil samples were subjected to lyophilization using a freeze-dryer (SCIENTZ-12N, Scientz, China), followed by the removal of gravel, plant and animal debris, and sieving through a 10-mesh screen. The sample preparation and Cd content determination methods were consistent with those employed in the pot experiment.

Rhizosphere microbial sequencing and analysis Total DNA was extracted from soil samples collected during the grain-filling stage using the TGuide S96 Magnetic Universal DNA Kit (DP812, Tiangen, Beijing, China). The V3-V4 hypervariable regions of bacterial 16S rRNA genes were amplified with primers 338F (5'-ACTCCTACGGGAGGAGCA-3') and 806R (5'-GGACTACHVGGGTWTCTAAT-3'). Amplified libraries were sequenced on an Illumina NovaSeq 6000 platform (PE250). Detailed procedures for sequencing and bioinformatic analysis are provided in the supporting Information (Text S3).

Statistical analysis and computation

$$\text{The theoretical efficiency of rice in reducing soil cadmium content (\%)} = \frac{\text{The Cd accumulation content in rice plants (mg/ha)}}{(\text{Total soil Cd content} - \text{The screening value of soil Cd pollution risk}) \text{ (mg/kg)} * 5 * 1} * 100\%$$

$$\text{The actual remediation efficiencies of rice in reducing soil cadmium content (\%)} = \left(1 - \frac{\text{The Cd content of the soil after rice cultivation (mg/kg)}}{\text{The Cd content of the soil before rice cultivation (mg/kg)}}\right) * 100\%$$

The experimental data underwent rigorous statistical analysis utilizing the SPSS 19.0 statistical software package. Graphical visualizations were meticulously generated via the Origin 2021 software, and charts were crafted using Office 2021. To ascertain statistical significance at the $p < 0.05$ threshold, a one-way analysis of variance grounded in Duncan's test was employed.

Results

The impact on soil pH and Eh under specific water management regimes

Under WMG treatments, the average Eh values of WMG1, WMG2, and WMG3 throughout the water management period were all positive, being 292.17 mV, 281.73 mV, and 242.54 mV respectively. Both pH and Eh showed fluctuating increases. Due to the different soil wetting and drying cycles in WMG2 and WMG3 treatments, their pH and Eh fluctuation cycles were also different. In the WMG1 treatment, soil pH significantly decreased from 6.74 to 6.47, while Eh increased from 277 mV to 302 mV, rising by 0.23 and 136 mV respectively compared to the initial values.

Under CK practices, the soil pH exhibited a continuous increase during the initial period with prolonged flooding, reaching a maximum value of 7.19. Subsequently, the pH began to decline during the mid-to-late stages of rice maturation, ultimately stabilizing at 6.99 (Fig. 2). The soil Eh remained relatively stable from the tillering stage to the grain filling stage, with an average value of -164 mV. Upon drainage initiation during the maturation stage, the Eh experienced a significant increase, rising by 319 mV compared to the initial value, and reaching a maximum of 152 mV.

Variation of Cd in soil under specific water management regimes

Soil DGT-Cd

The soil managed under WMG exhibited a markedly higher DGT-Cd level compared to the CK treatment. Throughout the growth period, the average DGT-Cd content in CK soils was 0.08 µg/kg, while in WMG-managed soils it reached 0.67 µg/kg, representing a 7.94-fold increase. By the maturity stage, DGT-Cd in CK soils increased to 0.27 µg/kg as the fields were drained, yet remained significantly lower than in the WMG1 treatment. Across all water regimes, DGT-Cd levels peaked during the tillering stage, with an average value of 1.05 µg/kg and gradually declined over time to 0.45 µg/kg at maturity. No significant differences in DGT-Cd content were observed between WMG2 and WMG3 treatments across most growth stages, except during the grain-filling period when WMG3 exhibited higher DGT-Cd than WMG2. Comparison between WMG1 and WMG2 revealed that post-filling drainage significantly increased soil DGT-Cd to 0.65 µg/kg, which was 44.62% higher than under continued alternate wetting and drying (Fig. 3a).

Within individual wet-dry cycles, DGT-Cd levels were consistently higher under drained conditions than under wet conditions. The difference between drained and wet states diminished as the frequency of wet-dry cycles increased. During the tillering stage, DGT-Cd in WMG-managed soils was on average 61.70% higher in the drained phase than in the wet phase. By maturity, this difference narrowed to only 11.15% (Fig. 3b).

Cd in soil pore water

Throughout the rice growth period, soil porewater Cd concentrations under WMG treatments were consistent and significantly higher than those under CK treatment. Across all treatments, porewater Cd levels peaked during the heading stage, with the highest value (7.88 µg/L) observed in the WMG3 treatment (Fig. 3c). At the tillering and heading stages, no significant differences in porewater Cd were detected among the water management groups. During the grain-filling stage, porewater Cd under WMG3 reached 3.44 µg/L, which was 2.08% higher than that under WMG2. By maturity, porewater Cd in WMG3 was 0.17 µg/L, exceeding the WMG2 level by 30.77%.

Cd fractionation of soil

The WMG measures exerted a marked influence on the concentrations of Cd fractions in mature paddy soils (Fig. 3d). Compared to the original soil sampled collected from pot experiments, water management practices, including the CK treatment, brought about considerable growth in the exchangeable fraction (F1) portion, with an increment of 5.75%. In comparison to CK, the residual fraction (F5) under WMG treatment decreased by experiencing an average reduction of 3.67%. Among them, the WMG1 treatment showed a particularly pronounced decrease in residual Cd, reaching 5.17%, whereas the content of exchangeable Cd increased by 5.32%.

Fluctuation of Cd content in diverse tissues of rice

During the rice growth period, the Cd contents in all plant tissues under WMG treatments were significantly elevated compared to the CK practice. In the WMG1 treatment, mean Cd concentrations in roots, stems, leaves, and spikes reached 29.96 mg/kg, 8.35 mg/kg, 3.73 mg/kg, and 5.51 mg/kg, respectively, representing increases of 7.41, 16.90, 11.40, and 19.41-fold relative to CK. In contrast, Cd concentrations did not differ significantly among the three WM treatments (Fig. 4).

Overall, the highest Cd concentrations were observed at maturity. However, distinct patterns of Cd uptake and translocation emerged between CK and WMG treatments over the growth cycle. Under CK, Cd concentrations in all plant organs increased progressively with growth stage, peaking at maturity. Under WMG treatments, root and stem Cd concentrations reached relatively high levels by the heading-flowering stage and remained elevated through grain-filling and maturity, with no significant further increase after heading. Leaf Cd concentrations peaked at maturity, whereas spike Cd peaked during grain-filling and declined slightly thereafter. Compared with CK, the WMG strategy designed to activate soil Cd significantly altered Cd translocation patterns: Cd transfer from roots to stems increased by 2.93-fold, while transfer from stems to leaves decreased by 0.69-fold, and translocation from leaves to spikes rose by 1.87-fold. No significant differences in Cd partitioning were observed among the three WMGs. Notably, leaves and spikes exhibited distinct Cd-accumulation dynamics during maturity and grain-filling, respectively.

Cd accumulation in rice under specific water management regimes

Cd partitioning among different organs of rice plants

The Cd accumulation in various parts of rice plants exhibited a continuous increase throughout the growth period, with the accumulation pattern consistently showing root > stem > leaf > spike across different growth stages (supplementary information Figure S1). The WMG treatment demonstrated highly significant differences in Cd accumulation compared to the CK management, with WMG1 treatment showing the highest Cd accumulation. At maturity, the Cd accumulation levels in WMG1 treated plants reached 777.49 µg/hill (root), 612.49 µg/hill (stem), 221.20 µg/hill (leaf), and 109.28 (spike) µg/hill, significantly surpassing other treatments. The total Cd accumulation in WMG2 and WMG3 treatments were 1568.05 and 1658.91 µg/hill respectively, with no significant difference between these two treatments.

Analysis of daily accumulation rates of Cd in rice tissues

The daily Cd accumulation rate in rice was calculated as the total Cd accumulated in plant tissues during a given growth stage divided by the duration of that stage. Under the CK treatment, Cd accumulation in different rice tissues remained relatively uniform throughout the growth cycle, with the highest daily accumulation rates occurring at maturity. The ranking of Cd accumulation across tissues followed: root > stem > leaf > spike. Specifically, daily Cd accumulation rates in roots, stems, leaves, and spikes were 1.04 µg/day, 1.31 µg/day, 0.43 µg/day, and 0.42 µg/day, respectively.

In contrast, under WMG management, the principal periods of Cd accumulation were the heading-flowering and grain-filling stages. Maximum daily Cd accumulation rates in roots and leaves were observed during heading-flowering stages, whereas stems and spikes peaked during grain-filling stages (Fig. 5a). During heading-flowering stages, daily Cd accumulation rates followed the order root > stem > leaf > spike, with mean values of 13.43 µg/day, 9.12 µg/day, 3.43 µg/day, and 0.50 µg/day, respectively, corresponding to 59.09, 116.84, 169.39, and 18.68 times increases compared to CK. In the grain-filling stage, the ranking shifted to stem > root > spike > leaf, with average rates of 10.42 µg/day, 7.89 µg/day, 6.15 µg/day, and 0.93 µg/day, respectively. These values represented 2.95, 9.75, 47.82, and 6.94 times elevations relative to CK.

Factors influencing on Cd accumulation in rice

Principal component analysis (PCA) was conducted on 12 key variables associated with Cd uptake and accumulation in rice to assess the influence of different water-management regimes on Cd accumulation (Fig. 5b). The PCA results showed a clear separation between the CK and the three water-management groups (WMG1, WMG2, and WMG3), whereas no significant separation was observed among the three water management groups. The first principal component (PC1) was strongly positively correlated with DGT-Cd, porewater Cd, Eh, aerial part Cd accumulation, and whole-plant Cd

accumulation, while soil pH exhibited a strong negative correlation with PC1. The second principal component (PC2) was positively correlated with soil Cd fractions F3 and F4 but negatively correlated with fractions F1 and F2.

Field-scale validation of the influence of water management on driving Cd accumulation in rice plants

Two years of field trials confirmed that the water management strategy optimized based on pot experiments, when combined with high-Cd-accumulating rice cultivars, significantly enhanced the depletion of soil Cd by rice and thereby effectively reduced soil Cd content. The improved water management (WM) comprised two phases: from the post-transplanting seedling recovery stage to the late grain-filling stage, alternating wetting and drying cycles were implemented—during each drying phase, the soil was allowed to develop visible cracks while ensuring normal rice growth; during each flooding phase, a 1–2 cm surface water layer was maintained before the next drying cycle commenced. From the late grain-filling stage to maturity, continuous drainage was applied until rice reached maturity.

In the 2024 trial, under WM treatment, Cd concentrations in stems and leaves of cultivars 9311 and Pokkali were 2.31-fold and 1.96-fold higher, respectively, than those in CK. Similarly, grain Cd concentrations increased by 2.44-fold in 9311 and 1.63-fold in Pokkali, while root Cd concentrations reached 0.90-fold and 1.60-fold of the CK values, respectively (Fig. 6a). Notably, Pokkali exhibited a significantly greater capacity for soil Cd uptake compared to 9311. Consequently, the combined WM + Pokkali treatment yielded the highest Cd extraction from soil. Under WM conditions, Pokkali achieved shoot and total plant (root + shoot) Cd accumulations of 2.64 mg/plant and 2.85 mg/plant, respectively (Fig. 6b). Based on an average rice planting density of 180,000 plants/ha, the shoots and the entire plant of Pokkali could extract 474.56 g/ha and 512.76 g/ha of Cd from the soil per single cropping season (Fig. 6c), with soil Cd remediation efficiencies of 43.01% and 46.51%, respectively. Comparative analysis of non-rhizosphere soil Cd content revealed that under the WM+Pokkali model, the total soil Cd content decreased from 0.80 mg/kg to 0.50 mg/kg (Fig. 6d), representing a 37.50% reduction in Cd content. Results from the 2025 trial further demonstrated that WM treatment promoted Cd accumulation in both aboveground and belowground parts. Compared with CK, Cd concentrations in the shoots of Pokkali and 9311 increased by 3.17- and 14.64-fold, respectively (Fig. 6e), and total Cd accumulation in shoots increased by 2.55- and 7.37-fold, respectively (Fig. 6f).

Differences in rhizosphere microbial communities as affected by water management and cultivar

Water management was the primary factor shaping the rhizosphere bacterial community, accounting for approximately 27% of the total variation along the first principal coordinate (PCoA1), a finding supported by PERMANOVA ($R^2=0.31$, $P < 0.001$). In contrast, rice cultivars explained a smaller proportion of the variation (about 10.2%) in the bacterial community (Fig. 7a). At the phylum level, significant differences in rhizosphere bacterial abundance were observed under different water regimes (Fig. 7b). The most dominant phyla were Proteobacteria (23–28%) and Acidobacteria (19–32%). The relative abundance of Acidobacteria increased progressively as soil moisture decreased (WM < CK < FI) in both cultivars. Specifically, under WM treatment, the relative abundance of Acidobacteria in Pokkali rhizosphere was 14% and 70% higher than in CK and FI treatments, respectively. Similarly, in cultivar 9311, WM treatment resulted in 18% and 35% higher Acidobacteria abundance compared to CK and FI. Notably, Pokkali harbored a higher relative abundance of Acidobacteria than 9311, with WMpok showing a 12% increase over WM9311. Concurrently, the relative abundances of iron- and sulfur-reducing bacteria (Bacteroidota, Firmicutes, and Desulfobacterota) decreased with reduced soil moisture. In Pokkali, these phyla declined by 93–96%, 235–447%, and 107–127%, respectively, while in 9311, the decreases were 56–68%, 87–163%, and 126–136%. At the genus level, *Candidatus_Koribacter* and *Candidatus_Solibacter* (both belonging to Acidobacteria) significantly increased in abundance under lower soil moisture. However, their relative abundances in CK and WM treatments were lower in Pokkali rhizosphere compared to 9311 (Fig. 7c). Linear discriminant analysis effect size (LEfSe) further confirmed that WMpok rhizosphere at the grain-filling stage was enriched with a significantly higher abundance of *Candidatus_Koribacter* compared to other treatments (Fig. 7d). Moreover, correlation analysis revealed a significant positive relationship between total Cd accumulation in plants and the abundance of *Candidatus_Koribacter* ($R^2 = 0.37$, $P < 0.001$).

Response of microbial community functions to water management and cultivar

BugBase phenotype prediction revealed that the WM treatment significantly increased the relative abundance of aerobic bacteria in the rhizosphere of both rice cultivars, with increments of 6–8% compared to the CK and 13–29% compared to FI (Fig. 8a). Conversely, the relative abundance of anaerobic bacteria decreased by 6–10% relative to CK and by 46–58% relative to FI (Fig. 8b). Consistent with these findings, FAPROTAX-based functional prediction indicated that, compared to FI and CK treatments, WM enriched rhizosphere microbial functions related to sulfur and iron oxidation-including dark sulfide oxidation, dark thiosulfate oxidation, and dark iron oxidation-while substantially suppressing functions associated with sulfur and iron reduction, such as respiration of sulfur compounds and iron respiration (Fig. 8b). In contrast, no significant differences in microbial functional profiles were observed between the two rice cultivars.

Discussions

Water management enhancing soil Cd activity with low pH and high Eh conditions

Soil pH and Eh are widely recognized as critical electrochemical parameters that respond dynamically to flooding, drainage, and alternating wet-dry cycles (Sahrawat, 2015). During repeated flooding and drainage events, soil pH and Eh undergoes periodic fluctuations, which substantially influence the mobility, bioavailability, and chemical speciation of heavy metals in soil (Biswash et al., 2024; Hira et al., 2025; Honma et al., 2016; Huang et al., 2025; Liu et al., 2025; Luis et al., 2025). As noted by Yao (2022), soil Eh and pH collectively govern Cd solubility and bioavailability. This relationship is supported by Pearson correlation analyses, which have shown that exchangeable Cd is significantly correlated with soil pH and Eh (Xu et al., 2021). Principal component analysis

further indicated that variation in rice Cd content under different irrigation regimes was largely explained by differences in soil Cd availability, Eh, and pH (Fig. 5b). The underlying mechanisms can be summarized as follows: First, during drainage periods, oxidation of Fe²⁺ and Mn²⁺ releases protons (e.g., O₂ + 2Fe²⁺ + 4H₂O → 2Fe(OH)₃ + 2H⁺; O₂ + 2Mn²⁺ + 2H₂O → 2MnO₂ + 4H⁺) (Ding et al., 2019), lowering soil pH and modifying pH-dependent surface charges, thereby enhancing Cd solubility and mobilization (Wang et al., 2019). Concurrently, soil drying promotes macropore and crack formation, facilitating oxygen infiltration and raising Eh. The resulting oxidative conditions convert insoluble CdS into soluble Cd²⁺ and SO₄²⁻ (Zhang et al., 2025), while accelerated Fe/Mn-mineral oxidation further mobilizes sorbed or co-precipitated Cd. Second, repeated wetting-drying cycles enlarge and deepen soil pores, improving hydraulic connectivity between surface and subsurface layers. This structural change enhances the release of Cd from subsurface horizons and promotes its uptake by rice roots. For instance, in a typical drying interval during the tillering stage, DGT-labile Cd increased from 0.65 mg/kg under moist conditions to 1.05 mg/kg after drainage—a 60.21% rise.

In the pot experiment of this study, the average soil pH under WMG treatments throughout the entire growth period was 0.24 units lower than that under conventional management, while the average Eh was 339.16 mV higher, reaching 272.15 mV. This significantly promoted the activation of soil Cd under WMG treatments. Compared with CK, the soil available Cd content (measured by DGT) under WMG treatments increased by 794.44%. Furthermore, the average soil Eh throughout the growth period was significantly higher in WMG1 and WMG2 than in WMG3, indicating that extending the drainage duration significantly enhances soil oxidizability. More notably, the DGT-labile Cd content during the maturation period was significantly higher in WMG1 than in WMG2, with an increase of 52% (Fig. 3a). This was primarily attributed to the sustained drainage and soil drying environment maintained under WMG1 from the late grain-filling stage to maturity, which significantly enhanced soil Cd activation. This further promoted soil Cd accumulation in rice during the critical Cd uptake period from the late grain-filling stage to maturity under the WMG1 treatment (Huang et al., 2022), ultimately resulting in the highest Cd content in rice under WMG1 (Fig. 4).

Water management driving key microorganisms to active Cd in soil

Alternating flooding and drainage induce pronounced redox fluctuations that significantly reshape microbial community composition and metabolic activity. In this study, water management, rather than rice cultivar, was identified as the primary driver of rhizosphere microbial structure. By modulating the soil redox environment, water management regulates key microbial redox processes that govern Cd behavior in paddy soils (Lin et al., 2019; Zhang et al., 2024b). Specifically, compared to CK and FI treatments, WM significantly increased the relative abundance of Acidobacteria (Fig. 7). This phylum has been reported to correlate positively with bioavailable and acid-soluble Cd fractions and can influence Cd bioavailability through multiple pathways (Pan et al., 2020; Zhang et al., 2022). First, Acidobacteria are active participants in sulfide-mineral oxidation, a process that can promote the dissolution of Cd-bearing precipitates (Li et al., 2024). Second, members of this phylum contribute to iron cycling by accelerating the dissolution of iron oxides, thereby mobilizing adsorbed or co-precipitated Cd and enhancing its bioavailability (Li et al., 2022; Suhadolnik et al., 2021). Notably, we observed a marked enrichment of the genus *Candidatus Koribacter* (within Acidobacteria) in the WMpok rhizosphere (Fig. 7c, d). Its relative abundance showed a strong positive correlation with total plant Cd accumulation (Fig. 7e). The underlying mechanism likely involves the capacity of *Candidatus Koribacter* to drive sulfide and ferrous-iron oxidation. This activity not only enhances soil acidification, releasing Cd sorbed on or co-precipitated with iron oxides, but also oxidizes insoluble CdS to more soluble CdSO₄, collectively increasing Cd mobility and promoting plant uptake (Wang et al., 2018; Zhang et al., 2024a). Consistent with this mobilization pattern, WM treatment significantly reduced the relative abundance of S-/Fe-reducing bacterial phyla (e.g., Bacteroidota, Firmicutes, and Desulfobacterota), thereby diminishing microbial sulfate reduction and Cd immobilization as sulfides, which further contributed to elevated Cd availability. BugBase phenotypic prediction and FAPROTAX functional profiling supported these observations, showing that WM-managed rhizosphere soils were enriched in functional genes associated with sulfide oxidation (*dark_sulfide_oxidation*, *dark_thiosulfate_oxidation*) and iron oxidation (*dark_iron_oxidation*)—processes that collectively promote Cd mobilization in paddy soils.

Coupling critical Cd uptake period with water management to maximize soil Cd bioavailability and enhance Cd uptake in rice

Water management is widely recognized as an effective strategy for regulating Cd uptake and accumulation in rice plants (Li et al., 2022). Compared with continuous flooding or moist conditions, aerobic soil conditions generally enhance Cd bioavailability and subsequently promote Cd uptake by rice (Li and Xu, 2017; Rizwan et al., 2018). Studies have shown that alternating wetting and drying (AWD) during the early reproductive stage significantly increases grain Cd concentration, and that continuous AWD across multiple growth stages is more effective in promoting Cd accumulation in rice than water management applied during a single stage (Carrizo et al., 2022). The results of the present study are consistent with these findings. All three WMG treatments significantly extended the duration of aerobic drainage and thereby substantially enhanced Cd accumulation in rice, with the average Cd content in the WMG being significantly higher than that in the CK (Fig. S1). Among all treatments, WMG1 exhibited the highest Cd accumulation, exceeding that of CK, WMG2, and WMG3 by 404.5%, 9.7%, and 3.7%, respectively. Regarding treatment design, the difference between WMG1 and WMG2 lay solely in the soil moisture status from the late grain-filling stage to maturity (drainage in WMG1 vs. continuous AWD in WMG2), while the difference between WMG2 and WMG3 was reflected in the frequency of wet–dry cycles (1–2 days vs. 2–3 days). Huang et al. (2022) reported that the grain-filling stage to maturity is a critical period for Cd uptake in rice, and that maximizing soil Cd bioavailability during this phase significantly enhances Cd accumulation in rice. This finding is highly consistent with the maximized Cd extraction achieved by the WMG1 treatment in this study. In summary, the key strategy for promoting Cd accumulation in rice through water management consists of two aspects. First, from the seedling recovery stage to the early grain-filling stage, drainage duration should be extended as much as possible while ensuring normal rice growth. Second, during the late grain-filling stage to maturity, a critical period characterized by low water demand and high Cd uptake potential in rice, a water management regime featuring continuous drainage and soil drying should be implemented. This strategy, by maximizing soil Cd bioavailability from the seedling recovery stage to the early grain-filling stage while ensuring normal rice growth, and by targeted enhancement of soil Cd availability during critical growth stages for Cd uptake in rice, this approach is more effective in promoting Cd accumulation in rice than merely increasing the frequency of wet–dry cycles. Two years of field trials also validated the effectiveness of the strategy of extending drainage duration to maximize the reduction of soil Eh and increase soil pH, thereby enhancing soil Cd availability and subsequently promoting Cd depletion from soil by rice.

The potential of high-Cd-accumulation rice to remediate Cd pollution in paddy fields activated by targeted water management

Given the dual pressures of limited arable land per capita and the risks posed by Cd contamination in rice, current management of Cd-polluted paddy fields commonly relies on a “safe production coupled with remediation” approach—simultaneously aiming to secure grain safety and reduce soil Cd content (Chi et al., 2024; Deng et al., 2023; Kang et al., 2021; Li et al., 2024; Wang et al., 2025a; Wang et al., 2025b). However, such integrated strategies still struggle to meet grain-Cd standards in moderately to heavily contaminated fields and to achieve effective remediation in strictly regulated paddies. Moreover, continuous Cd inputs from atmospheric deposition, irrigation water, and agricultural amendments can exacerbate soil Cd accumulation. Therefore, reducing the total Cd pool in paddy soils represents a fundamental step toward controlling the Cd mass balance and enabling long-term remediation.

Rice has been identified as a promising candidate for phytoremediation (Shao et al., 2017; Takahashi et al., 2016; Yan et al., 2021; He et al., 2020). For example, a field trial conducted by Yan et al. (2021) demonstrated the feasibility of depleting available Cd in paddy soils using rice plants. By removing the entire mature rice plant (including roots), the Cd concentration in polished rice in the subsequent season decreased by 24%. Moreover, cultivating the cultivar ‘Akita 110’ reduced soil Cd content by 15.5%, while two consecutive years of planting the high-Cd-accumulating indica cultivar ‘Choukokoku’ significantly enhanced the Cd depletion capacity of rice, leading to a 38% reduction in total soil Cd content (Murakami et al., 2009). This phenomenon demonstrates that, compared with conventional rice cultivars, high-Cd-accumulating rice cultivars are more suitable for use as Cd phytoremediation plants. Our field trial results also confirmed this, as the soil Cd concentration under the WM+Pokkali regime was significantly reduced by 8% compared to that under the WM + 9311 regime. These findings demonstrate that selecting high-Cd-accumulating rice cultivars, combined with maximizing drainage duration based on the Cd uptake characteristics of different rice growth stages while ensuring normal rice growth, is key to improving the efficiency of rice-based phytoremediation.

In this study, pot experiments showed that a water management strategy combining the characteristics of rice Cd uptake periods with maximizing the duration of drainage and soil drying, while ensuring normal rice growth, increased soil Cd removal efficiency from 4.91% to 23.73%. Under field conditions, the improved optimal water management regime for enhancing Cd uptake achieved theoretical and actual soil Cd removal efficiencies of 43.04% and 37.9%, respectively. By comparison, typical Cd-hyperaccumulators reported in China, such as *Sedum alfredii* and *Sedum plumbizincicola*, generally exhibit Cd removal efficiencies of only about 27.6% per growing season (Fan et al., 2019). Other high-Cd-accumulating plants like *Noccaea caerulea* are further constrained by low biomass, demanding agronomic management, and limited regional adaptability (Milner and Kochian, 2008; Zhao et al., 2003). In contrast, rice offers the advantages of high biomass production, well-established cultivation techniques, and high farmer acceptance, making it a more practical and scalable candidate for the phytoremediation of Cd-contaminated paddy soils. Therefore, integrating selected high-Cd-accumulating rice cultivars with water management practices aimed at enhancing Cd mobilization can significantly improve the efficiency of rice-based phytoremediation, providing an agriculturally feasible and scalable strategy for remediating Cd-contaminated paddy systems. However, it is worth noting that the rice grain produced under this model does not meet food safety standards. Therefore, it is recommended that the government establish corresponding policies to strictly prevent the remediation-derived rice from entering the market, develop safe disposal protocols for Cd-containing biomass, further optimize technical parameters and strengthen extension efforts, and provide appropriate economic compensation to farmers, thereby achieving synergies between remediation benefits and ecological safety.

Conclusions

This study evaluated the synergistic effect of integrating water management with high-Cd-accumulating rice cultivars on enhancing soil Cd extraction efficiency by rice through pot and field trials. The experimental results demonstrated that the WMG1 treatment maximized the duration of soil drainage, thereby lowering soil pH and increasing Eh, which maintained the soil in a persistently high-oxidation state and increased the abundance of Fe/S-oxidizing bacteria. These changes significantly elevated soil bioavailable Cd content and subsequently enhanced Cd accumulation in rice plants. Field trials further confirmed that WM coupled with the high-Cd-accumulating cultivar Pokkali, effectively strengthened the capacity of rice to extract Cd from contaminated paddy soils. Under the condition of complete aboveground biomass removal, Pokkali achieved a Cd extraction amount of 474.56 g/ha per single cropping season, corresponding to theoretical and actual soil Cd remediation efficiencies of 46.79% and 37.50%, respectively.

In summary, this study demonstrates that selecting high-Cd-accumulating rice cultivars in combination with the following water management regime can maximize soil Cd activation and enhance Cd extraction efficiency by rice, leveraging the high Cd accumulation characteristic of rice from the grain-filling stage to maturity: from the post-transplanting seedling recovery stage to the late grain-filling stage, alternating wetting and drying cycles are implemented—during each drying phase, the soil is allowed to develop visible cracks while ensuring normal rice growth; during each flooding phase, a 1–2 cm surface water layer is maintained before the next drying cycle commences; from the late grain-filling stage to maturity, continuous drainage is applied until rice reaches maturity. This technical approach requires no alteration of the inherent properties or structure of paddy fields, nor changes to conventional farming practices, while offering the advantages of high efficiency, low cost, operational simplicity (strong farmer operability), and ease of large-scale promotion. It is suitable for efficient Cd reduction in moderately to heavily Cd-contaminated paddy soils.

Declarations

CRedit authorship contribution statement

Xuefei Yin: Data curation, Writing-original draft. **Rui Huang:** Writing-original draft, Investigation, Formal analysis. **Saihua Liu:** Conceptualization, Funding acquisition, Methodology, Writing-original draft & review & editing. **Jie Chen:** Investigation, Formal analysis. **Xionghui Ji:** Methodology, Conceptualization.

Declaration of competing interest

The authors declare no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was financially supported by the Science and Technology Innovation Program of Hunan Province (2024RC3241), the National Key Research and Development Program of China (2023YFD1703000), the National Natural Science Foundation of China (U22A20606).

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Figures

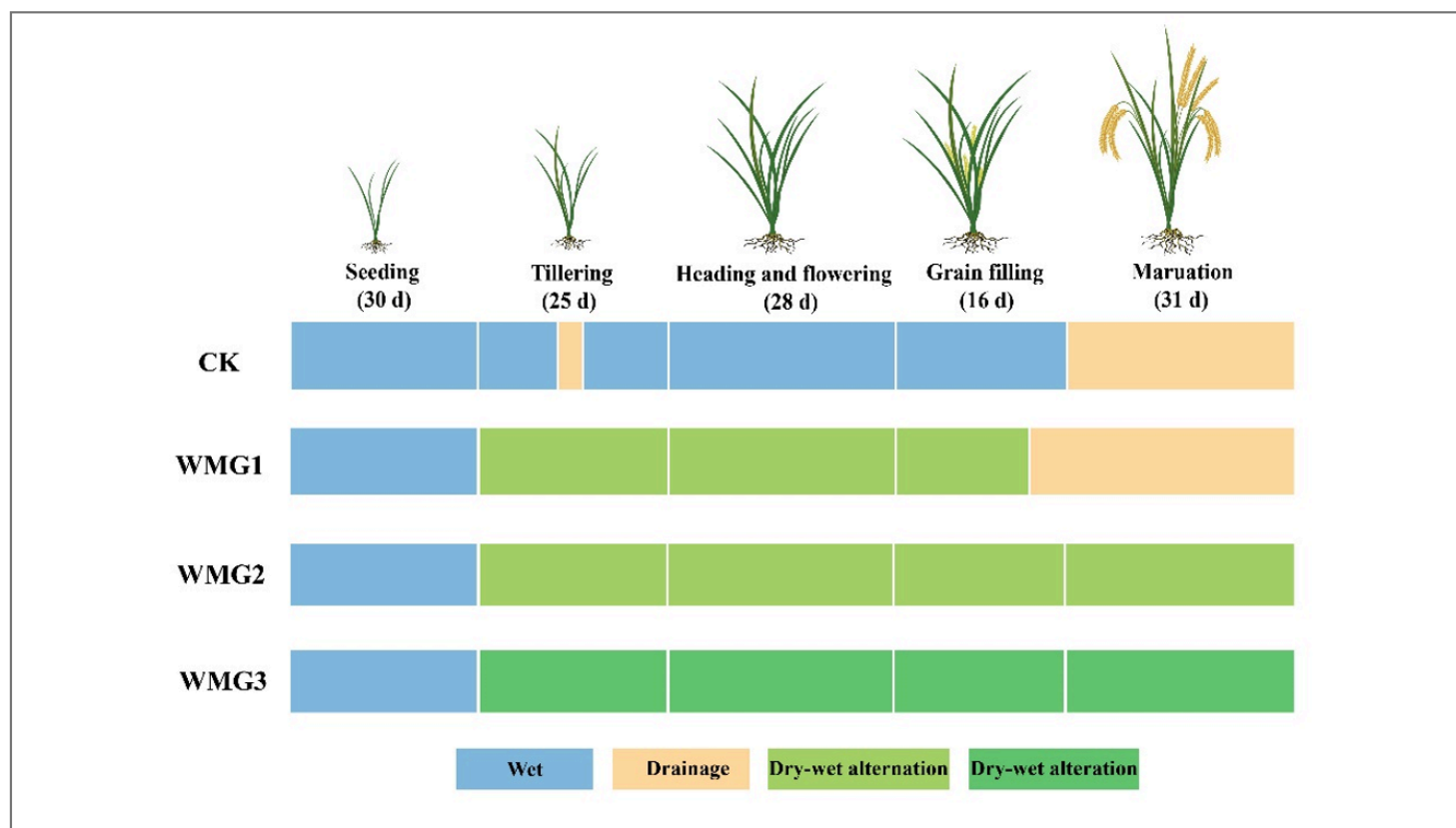


Figure 1

The schematic diagram illustrating the implementation of the specific water management treatments applied in the pot experiment.

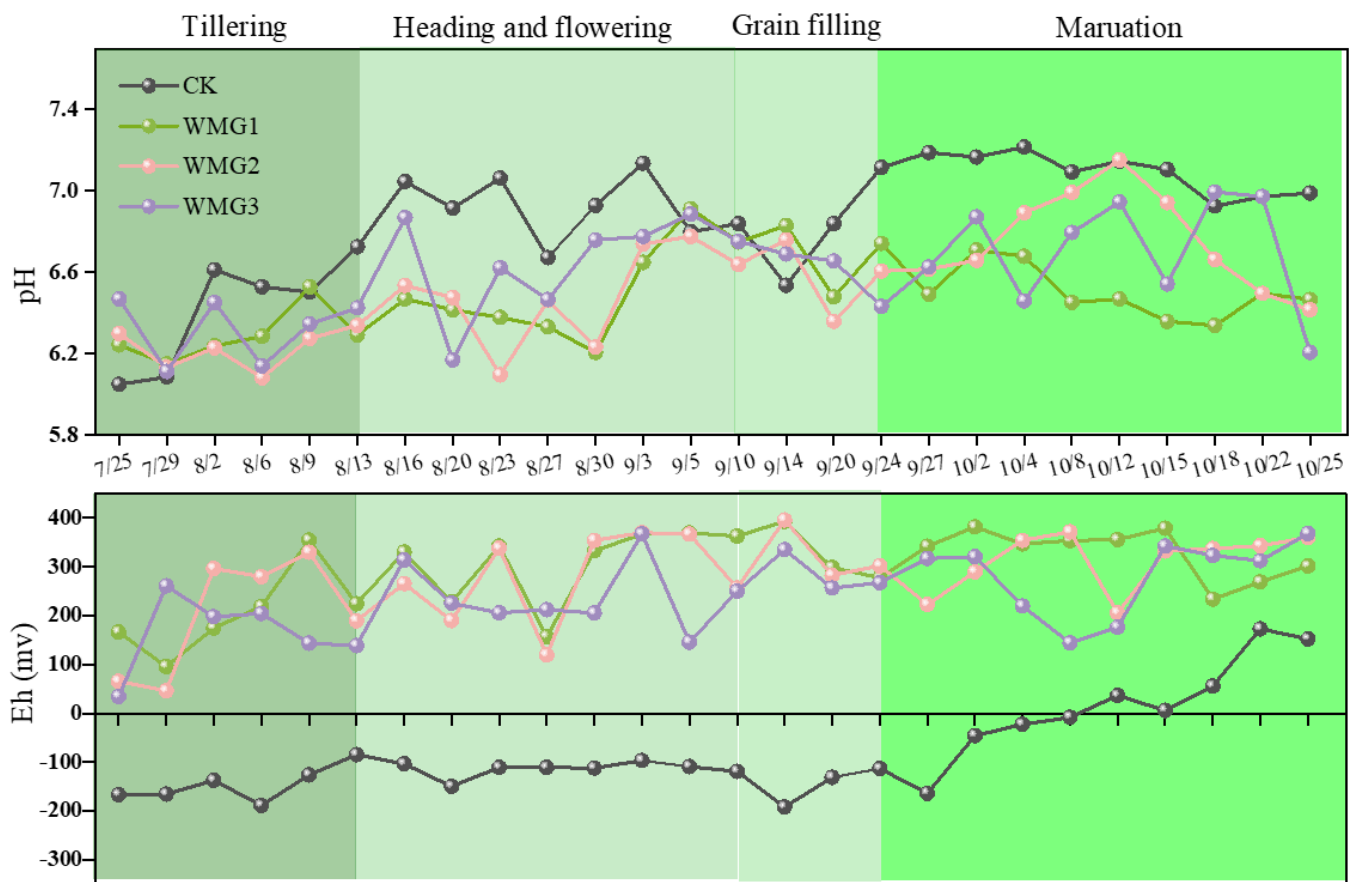


Figure 2

Changes in soil pH and Eh during different growth stages of rice under specific water management practices.

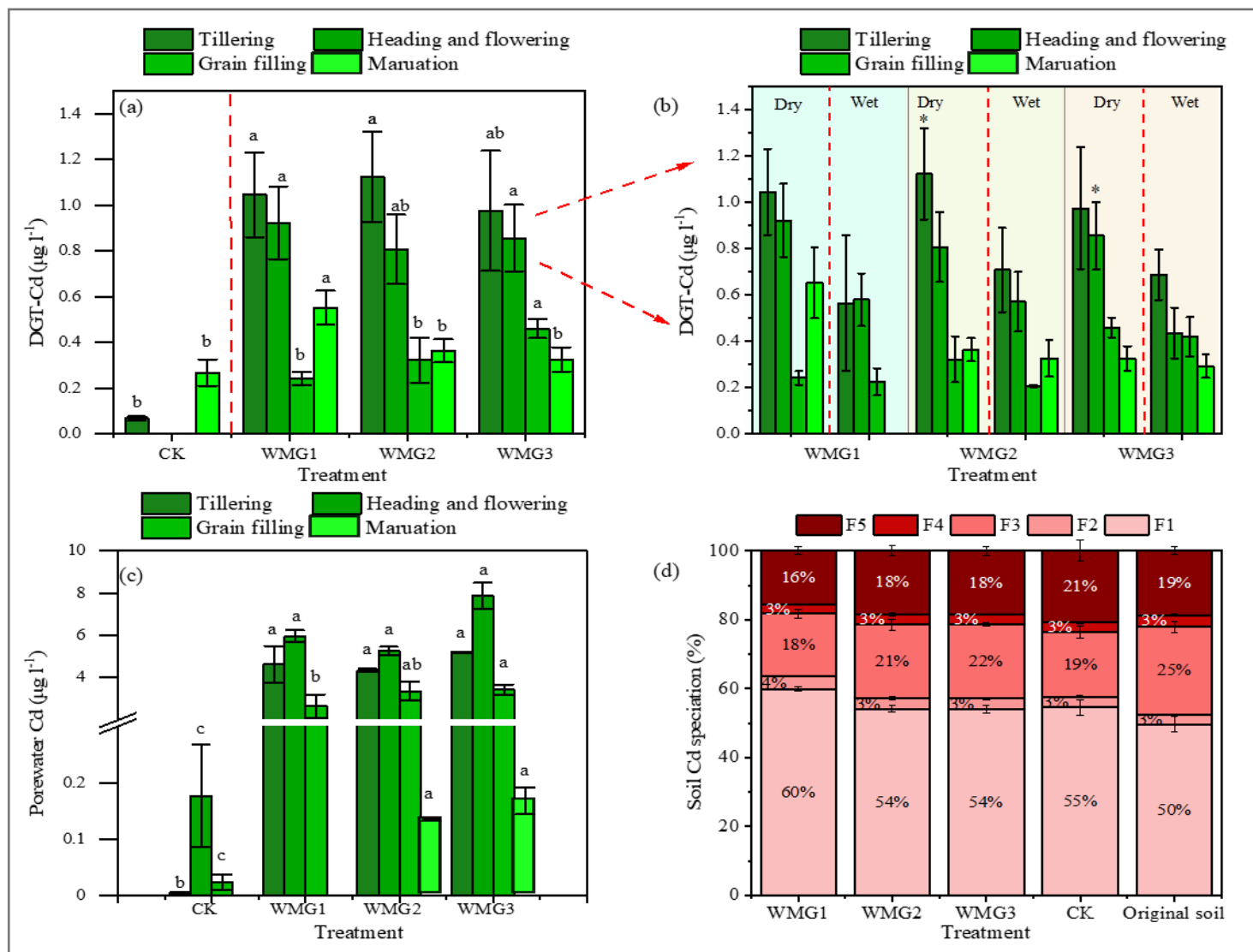


Figure 3

The influence of water management on cadmium of the soil during the four growth stages of rice (a, soil DGT-Cd content; b, soil DGT-Cd content under one dry-wet alternation cycle, dry referred to the soil sample taken when the soil naturally dries, wet referred to the soil sample taken when the soil was rehydrated to reach a moisture content of 40%-45% after drying; C, cadmium content in soil porewater; D, cadmium fractions of the soil at the rice maturity stage). Different letters and * indicated differences at $P < 0.05$ among treatments.

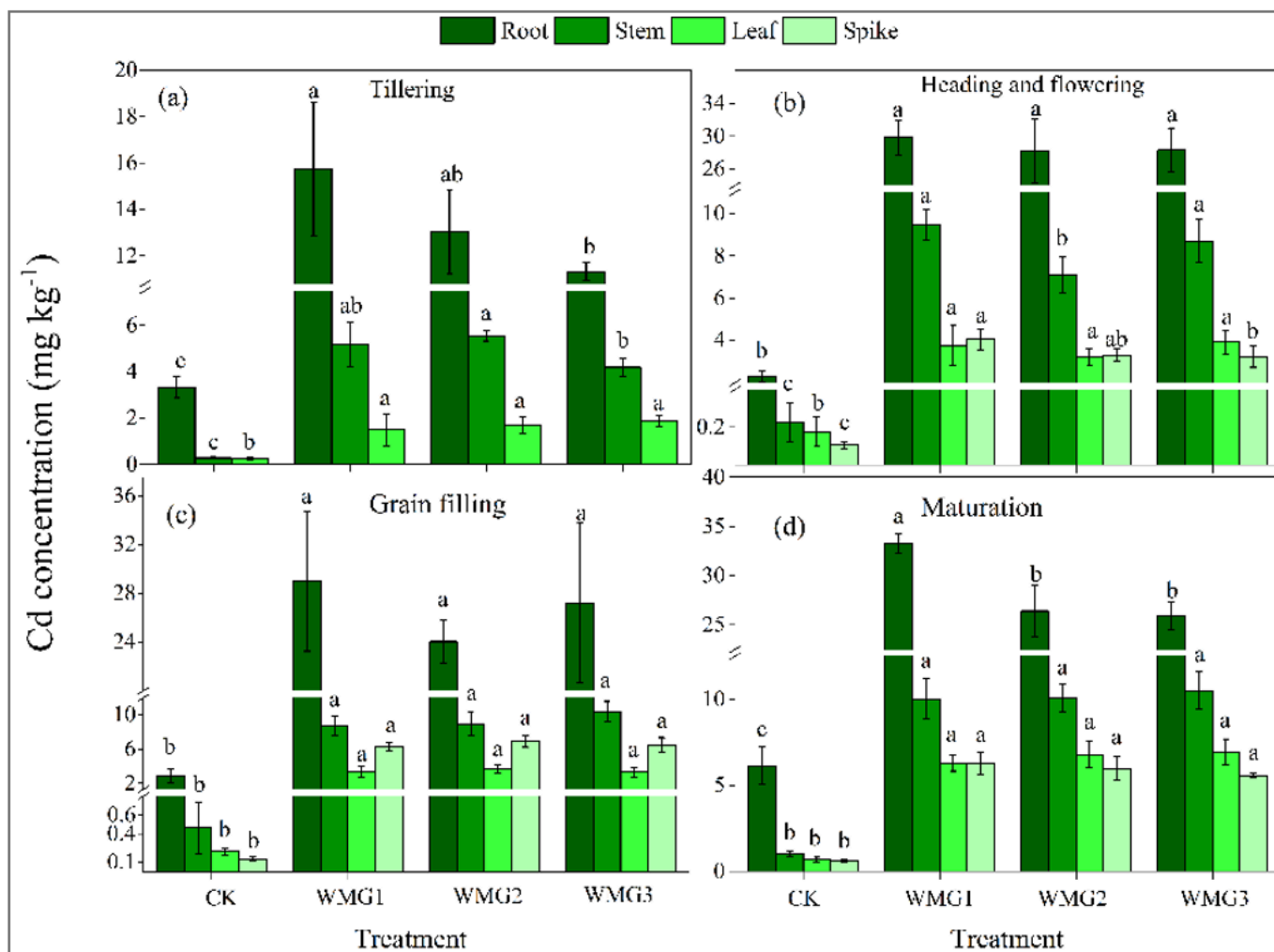


Figure 4
Cadmium content in different tissues of rice during four growth stages under specific water management practices. Different letters indicate differences at $P < 0.05$ among treatments.

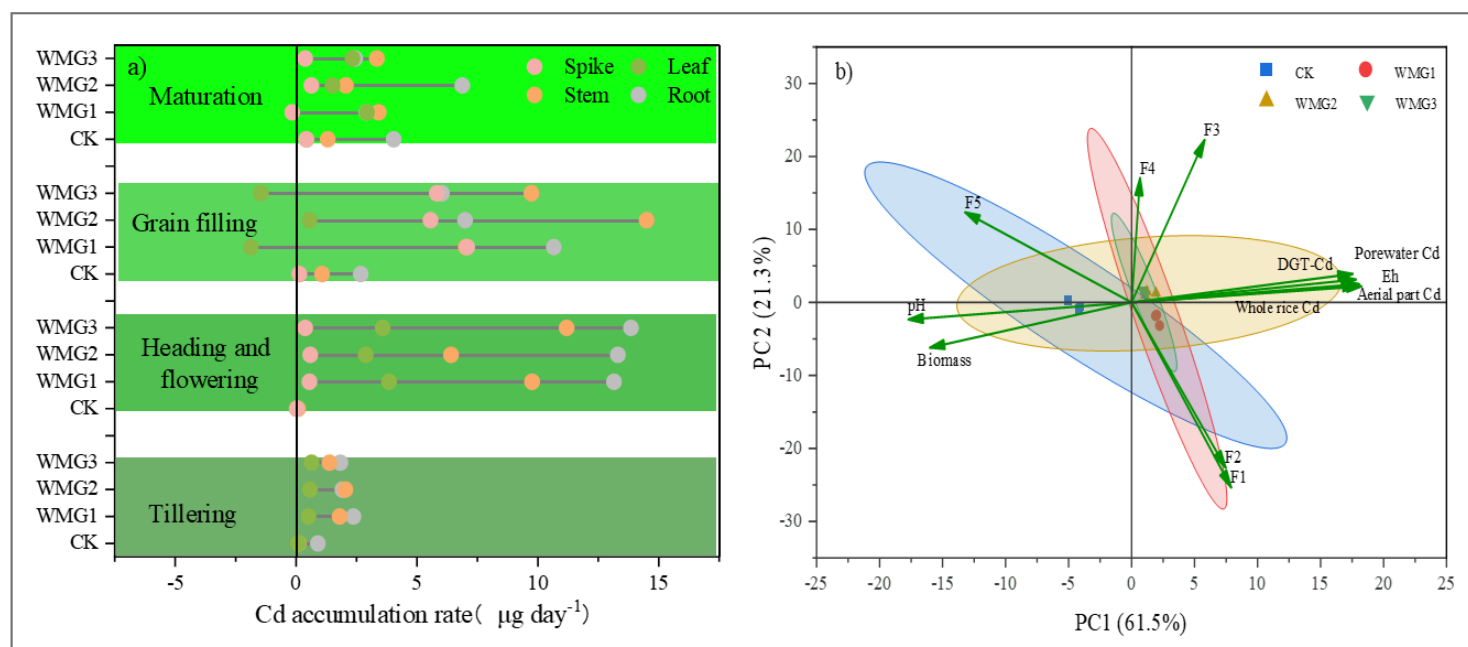


Figure 5

Influence of water management on cadmium accumulation in rice(a)the daily accumulation rates of cadmium in different parts of rice (root, stem, leaf and spike) during four growth stages under various water management practices; b, Principal component analysis of the effects of water management on cadmium accumulation in rice).

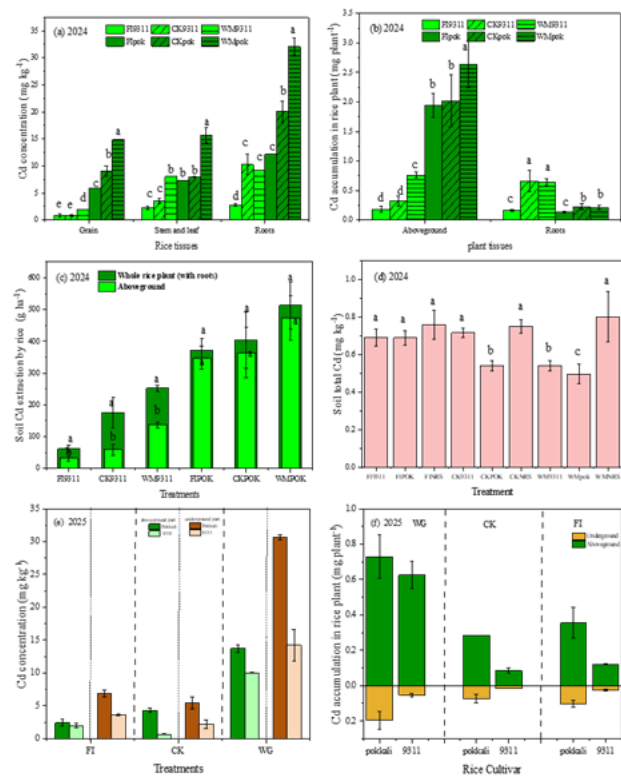


Figure 6

Changes in soil cadmium content, cadmium content and accumulation in rice, and cadmium extraction amount in rice under different water management conditions in field experiments (a, cadmium content in various rice organs, mg/kg; b, cadmium accumulation in roots and aboveground parts of rice, mg/plant; c, cadmium extraction amount from soil by rice, g/ha; d, total cadmium content in soil after rice harvest, mg/kg; NRS refers to non-root zone soil without rice cultivation e, cadmium content in aboveground and underground parts of rice, mg/kg; f, cadmium accumulation in aboveground and underground parts of rice, mg/plant). Different letters indicate differences at P < 0.05 among treatments.

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