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Perspective

Managing metal(loid) contamination for safe rice production

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Abstract

Increasing contamination of rice paddies by toxic metal(loid)s from anthropogenic sources threatens food security and public health. In this Perspective, we outline the problem of metal(loid) contamination in paddy soils and propose an activity-centric framework for safeguarding rice production. Approximately 14–17% of croplands exceed safe thresholds for at least one toxic metal(loid), exposing 0.9–1.4 billion people to elevated ecological and health risks. Management strategies that reduce the total mass of toxic metal(loid)s in soils are useful for restoring sites with high metal(loid) concentrations. However, these approaches are expensive and interrupt crop production, making them poorly suited to most in-production rice paddies with low-to-moderate contamination. Activity-centric strategies aim to reduce metal(loid) bioavailability and plant uptake at the soil–water–root–grain continuum, offering a production-compatible alternative. An integrated risk management framework that bridges risk-informed implementation of technologies with localized policy governance to guide regional-scale metal(loid) management is proposed. Further research is needed to develop soil amendment materials and functional synthetic microbial communities that synergistically address metal(loid) contamination and actively contribute to overall soil health and resilience.

Sections

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Key points

- Toxic metal(loid)s from natural and anthropogenic sources lead to high metal(loid) concentrations in paddy soils in areas of southern and southeastern Asia, West Africa and parts of South America.

- The mobility and bioavailability of toxic metal(loid)s are controlled by redox interactions at the soil–water interface, iron plaque formation at the soil–root interface, and metal(loid) sequestration throughout the root-to-grain continuum.

- Total-mass reduction strategies, including physical soil replacement, chemical washing and phytoextraction, effectively lower the total concentration of metal(loid)s in heavily contaminated paddy soils, but they are not suitable for the vast expanses of working paddy fields, which have diffuse low-to-moderate contamination.

- Strategies applied throughout the entire rice growth cycle can reduce the movement of toxic metal(loid)s towards grains, for example, metal(loid) passivation during tillage, nutrient inputs to promote iron plaque formation during elongation, and using nanomaterials to reinforce physiological barriers at the flowering stage.

- We propose a framework covering the control of metal(loid) sources, risk assessment of metal(loid) contamination, risk-tailored implementation, sustainability assessment and supportive governance.

- Research priorities should include field experiments to validate the long-term stability of management strategies and the development of artificial intelligence-enabled tools for predicting the efficacy of different mitigation efforts.

Introduction

Rice is a staple crop that feeds nearly half of the population of the world, with a key role in achieving the Zero Hunger goal of the United Nations[1,2]. However, contamination of soil by toxic metal(loid)s, including metalloids such as arsenic (As), driven by increased agricultural production and industrial emissions is increasingly undermining crop safety and productivity[3,4]. Approximately 14–17% of croplands (~242 million ha) exceed safe thresholds for at least one toxic metal(loid), exposing 0.9–1.4 billion people to elevated ecological and health risks[5]. This contamination is particularly problematic in major rice-growing zones[6,7], especially in southern and southeastern Asia, where warm, flooded conditions enhance metal(loid) bioavailability and uptake by rice plants[8] (Fig. 1). In China, nearly 19% of agricultural soils have relatively high metal(loid) concentrations that surpass the risk screening values of the national soil quality standard (0.3 mg kg^{-1} for cadmium (Cd) and 30 mg kg^{-1} for As), threatening roughly 10 million tons of grain annually[9]. Therefore, effective, scalable risk management strategies are urgently needed to safeguard food security and public health.

Management technologies for safe rice production that are affordable, have minimal environmental impact, and can be integrated into the agricultural cycle without interrupting rice production are needed[10]. Historically, metal(loid) contamination in paddy soils has been managed using strategies adapted from brownfield or industrial site clean-ups, such as chemical leaching, physical removal and phytoextraction[11,12]. These approaches aim to reduce the total mass of metal(loid)s in soil. Although this strategy is justified for heavily contaminated sites, the high economic costs and disruption to ongoing agricultural production make such intensive measures unsuitable for the vast expanses of lightly to moderately contaminated paddy fields and/or remote rural areas. By contrast, activity-centric strategies prioritize reductions in metal(loid) bioavailability and mobility, limiting metal(loid) uptake by rice plants and enhancing food safety[4,13]. Such methods are minimally invasive, affordable and can be continuously operated to reduce risks without decreasing yield[14], offering a pragmatic balance between efficiency, agricultural productivity and economic feasibility.

Substantial efforts have been made to translate activity-centric strategies from laboratory investigations to field application[15,16]. By targeting key interfaces within the soil–water–root–grain continuum, activity-centric strategies can markedly reduce the bioavailability of toxic metal(loid)s[17,18]. However, variability in soil properties, agricultural practices and climate conditions can hinder consistent immobilization[19,20], and questions regarding the durability of existing technologies with global change remain. Moreover, management approaches for safe rice production must be embedded into broader agricultural practices and policy systems, adding an additional layer of complexity. Existing reviews have synthesized the biogeochemical processes of toxic metal(loid)s in paddy soils or catalogued available management technologies for safe rice production[21–30], focusing either on evaluating isolated technologies or on the biogeochemistry of individual metal(loid)s. An integrative framework that reorganizes existing knowledge around the control of metal(loid) activity across the soil–water–root–grain continuum and links it to scalable risk management and policy governance in rice paddies is, therefore, needed.

In this Perspective, we outline the problem of metal(loid) contamination in rice paddies and strategies for achieving sustainable rice safety and soil health. First, we discuss the sources and risks of metal(loid) contamination in soil and the key biogeochemical processes involved. We then consider the potential of activity-centric, multi-interface regulation as a strategy for lightly to moderately contaminated rice paddies. Building on this paradigm, we introduce an integrated risk management framework that connects the technical implementation of such strategies with localized policy instruments. Finally, we propose research directions to better understand and assess the long-term stability and scale-up feasibility of management approaches.

Metal(loid) occurrence in rice paddies

There is widespread accumulation of toxic metal(loid)s in paddy soils, with pronounced spatial heterogeneity across major rice-producing regions[5,31]. The bioavailability and associated health risks of toxic metal(loid)s in rice paddies, such as Cd, As, mercury (Hg), chromium (Cr), nickel (Ni) and lead (Pb), are determined by their chemical speciation and contributions from natural and anthropogenic sources. This section discusses the occurrence and biogeochemical behaviour of toxic metal(loid)s in paddy soils.

Sources and distribution

Toxic metal(loid)s in paddy soils originate from natural processes and anthropogenic activities, each contributing to distinct regional contamination profiles[24]. Natural sources include the weathering of metal(loid)-rich parent rocks and minerals, such as kolwezite ($Cd_2Cu(PO_4)_2{\cdot}2H_2O$), arsenopyrite (FeAsS), galena (PbS), cinnabar (HgS) and chromite ($FeCr_2O_4$), and atmospheric deposition from forest fires and volcanic eruptions[32,33]. By contrast, anthropogenic inputs arise from industrialization, notably mining, smelting, coal combustion and metal(loid) recycling, and agricultural practices such as the use of metal(loid)-laden irrigation water, straw, fertilizers and pesticides[5,8].

Hotspots occur in paddy soils wherein soil metal(loid) concentrations persistently exceed local agricultural safety standards[8,34]. These hotspots include areas in southern China, Bangladesh, northeastern India, Iran, Turkey, West Africa and parts of South America (Fig. 1a,b). In major rice-producing regions in Asia such as southern China and parts of Southeast Asia, the probability of toxic metal(loid) concentrations exceeding local standards is higher than in northeastern regions in China (Fig. 1c). These hotpots are often linked to the build-up of specific metal(loid)s from point sources. For instance, in mining-affected areas of southern China, paddy soil Cd concentrations frequently exceed 1.0 mg kg^{-1} (ref. 9). Cd exceedances in this region are also linked to atmospheric deposition[35], originating from multiple sources such as metal ore smelting, coal-fired power generation, and straw burning. In parts of Bangladesh and India, the long-term use of As-laden groundwater for irrigation has led to profound topsoil As enrichment, with peak concentrations beyond 100 mg kg^{-1} (ref. 36). Cr in Eastern Africa is primarily geogenic[37], and high levels of Pb in West Africa are found in areas with artisanal mining[38].

The uptake and translocation of metal(loid)s into rice grains lead to excessive accumulation in the edible parts, directly threatening food safety. Although most hulled rice in global commerce complies with international regulatory limits (Cd 200 μg kg^{-1} (ref. 39); inorganic As 150 μg kg^{-1} (ref. 40)), some samples from Bangladesh, Cambodia, China, India, Indonesia, Italy, Japan, the USA and Vietnam still exceed these safety thresholds[41,42] (Fig. 1d). Additionally, the maximum reported concentrations in grains from severely contaminated areas exceed safety limits by a substantial amount; for example, Cd and inorganic As grain concentrations of 4.0 mg kg^{-1} and 0.4 mg kg^{-1}, respectively, have been reported in some specific sites of Bangladesh, Japan, China and Cambodia[41,42], exceeding safety thresholds by a factor of 20 and 3, respectively. Thus, there is an urgent need for targeted monitoring and region-specific management strategies to reduce metal(loid) uptake in rice and safeguard public health in vulnerable populations.

Toxicity and human exposure risk

Consumption of rice is a major pathway for human exposure to toxic metal(loid)s, and even rice grains that meet national safety standards can pose chronic health risks[43]. Therefore, it is important to pay close attention to long-term, low-dose toxicity, particularly in children and other sensitive populations[44]. Together, Cd, Pb and As in rice grains account for over 80% of the health impacts associated with dietary metal(loid) exposure[45]. However, existing regulatory thresholds might not fully capture cumulative and lifelong exposure risks, which means that rice compliant with current standards can still contribute to adverse health outcomes, particularly in populations wherein rice is a major food source. Emerging regulations continue to broaden the scope of concern. For instance, Commission Regulation (EU) 2024/1987 will establish maximum levels of Ni in rice grain[46].

Toxic metal(loid)s in rice cause carcinogenic and non-carcinogenic effects[47,48]. Cd exposure, particularly from long-term dietary intake, is linked to pulmonary, cardiovascular and musculoskeletal disorders[48]. For As, the primary concern is inorganic As, with long-term ingestion increasing the risk of cancers, respiratory illness and diabetes[32]. Multiple factors, such as individual rice consumption rates, rice variety, metal(loid) speciation, contamination levels and variations in regulatory standards, shape health outcomes. In Japan, irrigation of rice paddies with water contaminated by mining activities led to elevated Cd levels in rice, ultimately causing the outbreak of Itai-itai disease[49], characterized by osteoporosis, kidney damage and skeletal deformities. Risk assessments in Thailand have identified elevated non-carcinogenic risks associated with Cd and As exposure from rice consumption[50,51], whereas carcinogenic and non-carcinogenic risks of Cr, Pb, Cd and As are substantial in Vietnam and Bangladesh[52].

Biogeochemical cycling

The biogeochemical behaviour of toxic metal(loid)s in paddy ecosystems comprises a network of complex and interconnected processes operating across multiple interfaces[53–55]. The alternating flooding and drainage cycles create dynamic shifts in redox conditions that govern metal(loid) transformation and transport pathways[56,57]. From initial mobilization at the soil–water interface to bioaccumulation in grains, metal(loid)s undergo continuous speciation changes influenced by soil conditions, microbial activities and plant physiological processes[27]. Therefore, the soil–water–root–grain continuum has an important influence on metal(loid) activity in rice paddies (Fig. 2a).

At the soil–water interface, flooding initiates a sequence of biogeochemical transformations that substantially alter metal(loid) mobility[58]. In this zone, Fe redox cycling coupled with proton consumption regulates Cd activity, and coupled cycling of Fe and natural organic matter has a dominant role in mediating As activity. The development of anoxic conditions during flooding triggers anaerobic microbial respiration, which uses alternative electron acceptors to oxygen, including nitrate, Fe(III) (oxyhydr)oxides, sulfate and arsenate (As(V))[59,60]. This redox cascade produces distinct effects on different metal(loid) species (Fig. 2b). The rise in pH during reducing conditions enhances the adsorption of cationic metal(loid)s such as Cd^{2+} and Pb^{2+} onto mineral surfaces, and the generation of sulfide promotes their precipitation as poorly soluble metal(loid) sulfides[61,62]. Simultaneously, the reductive dissolution of Fe(III) (oxyhydr)oxide minerals releases previously adsorbed or co-precipitated As and Cr oxyanions, increasing their concentration and bioavailability in pore water (that is, water contained in soil pores)[63,64].

During the drainage phase, oxygen re-enters the soil, triggering a pronounced shift in metal(loid) behaviour (Fig. 2). The oxidation of Fe(II) and sulfide minerals leads to a drop in pH, which mobilizes cationic metal(loid)s such as Cd^{2+}, Hg^{2+} and Pb^{2+} by decreasing their binding strength to soil colloids[65,66]. Conversely, the oxidation of arsenite (As(III)) to As(V) enhances its adsorption onto mineral surfaces, leading to a decline in its bioavailability[67,68]. Moreover, the oxidation of Fe(II) to Fe(III) promotes the formation of Fe (oxyhydr)oxides, increasing the sequestration of Cr.

At the soil–root interface, the rice rhizosphere represents a hotspot for biological activity. For example, root exudates, including organic acids, phenolics and mucilage, modify metal(loid) speciation through complexation, redox reactions, pH alteration and effects on microbial community structure[69,70]. Organic acids with low molecular weight can promote the dissolution of Fe oxyhydroxides in the rhizosphere, leading to the release of previously surface-bound toxic metal(loid)s[71], whereas higher molecular weight compounds often promote the immobilization of toxic metal(loid)s[72]. Additionally, rice roots release oxygen through radial oxygen loss, generating an oxidized zone that promotes the formation of a Fe plaque on root surfaces[73,74], which is primarily composed of ferrihydrite, lepidocrocite and goethite[75]. The Fe plaque formation process involves abiotically and microbially mediated Fe(II) oxidation. These Fe plaques develop

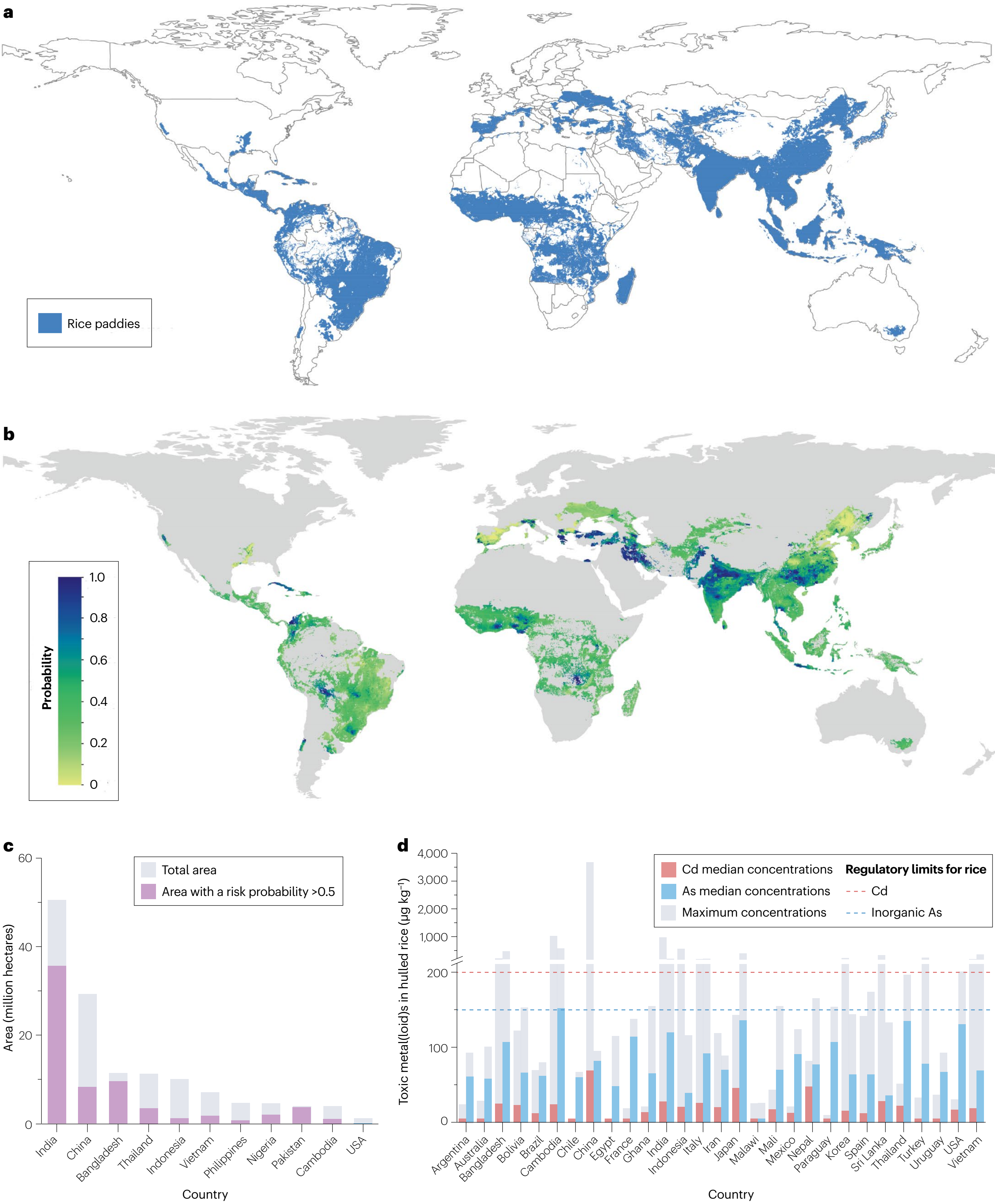

a
Rice paddies
b
Probability
1.0
0.8
0.6
0.4
0.2
0
c
Total area
Area with a risk probability >0.5
Area (million hectares)
60
40
20
0
India
China
Bangladesh
Thailand
Indonesia
Vietnam
Philippines
Nigeria
Pakistan
Cambodia
USA
Country
d
Cd median concentrations
As median concentrations
Maximum concentrations
Regulatory limits for rice
Cd
Inorganic As
Toxic metal(loid)s in hulled rice (μg kg⁻¹)
4,000
3,000
2,000
1,000
200
100
0
Argentina
Australia
Bangladesh
Bolivia
Brazil
Cambodia
Chile
China
Egypt
France
Ghana
India
Indonesia
Italy
Iran
Japan
Malawi
Mali
Mexico
Nepal
Paraguay
Korea
Spain
Sri Lanka
Thailand
Turkey
Uruguay
USA
Vietnam
Country

Fig. 1 | Global toxic metal(loid) contamination of paddy soils. a, Global spatial distribution of rice paddies in 2021(data from ref. 32). **b**, Global spatial patterns of the probability of toxic metal(loid) concentrations in paddy soils exceeding regional safety thresholds, derived from an Extremely Randomized Trees algorithm, trained on a climatic, topographic, geological and soil variables (data from refs. 5,31). Grey areas represent non-paddy regions. This map underestimates the possibility that legal thresholds for metal(loid)s are exceeded in rice grains because toxic metal(loid) limits in agricultural soils are much higher than those in food. **c**, Rice paddy total area in major rice-producing regions in 2024 (grey, derived from Food and Agriculture Organization (FAO) statistics) and the corresponding paddy area for which the probability of the metal(loid) concentration in soil exceeding the regional safety threshold is above 0.5 (purple, estimated by combining national rice paddy area statistics with the proportional estimates derived from spatial grids, wherein each grid cell represents the fraction of paddy area exceeding the threshold probability (>0.5) shown in panels **a** and **b**; these grid-cell fractions are then aggregated to estimate the total affected paddy area at the national scale[5,31]). **d**, Median (Cd, red; As, blue) and maximum (grey) concentrations of Cd and As in hulled rice in various rice-producing regions (data from refs. 41,42,213). Horizontal red and blue dashed lines represent the regulatory thresholds of Cd (ref. 39) and inorganic As (ref. 40) in rice, respectively. Toxic metal(loid) risks in paddy systems are unevenly distributed with hotspots in southern China, Bangladesh, northeastern India, Iran, Turkey, West Africa and parts of South America.

progressively throughout the root growth cycle of rice and sequester toxic metal(loid)s through adsorption and redox transformation[76,77]. Furthermore, redox dynamics at Fe plaques drive the oxidation of As(III) by reactive oxygen species (ROS)[78], producing As(V) which is favourable for adsorption on Fe plaques.

The transport systems involved in the uptake of toxic metal(loid)s by rice roots are also used to uptake essential nutrients. Divalent cations such as Cd(II), Pb(II) and Zn(II) are taken up mainly via metal transporters such as OsNRAMP1, OsIRT1, OsZIP1 and OsZIP9 (refs. 79,80), which primarily function in Fe, Mn and Zn acquisition. By contrast, the uptake of anionic species depends on their oxidation state. As(III), monomethylarsonic acid and dimethylarsinic acid enter root cells via silicic acid transporters OsLsi1 and OsLsi2 (ref. 81), whereas As(V), which is structurally analogous to phosphate, is taken up through members of the phosphate transporter family[82].

Once inside the plant, metal(loid)s are redistributed through a multistep translocation process involving root-to-shoot transport, xylem-to-phloem transfer and phloem-mediated delivery to grains[83]. During rice growth, Cd, Pb and As preferentially accumulate in leaves, wherein a substantial fraction is sequestered through complexation with phytochelatins in vacuoles for Cd and As, and/or immobilized on cell walls via carboxyl and hydroxyl groups for cationic metals[84,85]. In the flowering stage, metal(loid)s are mobilized from roots to nodes, which act as regulatory hubs that mediate xylem-to-phloem transfer towards panicles rather than leaves. During grain filling and maturation, metal(loid)s stored in leaves can be remobilized and redistributed to grains, substantially affecting final grain contamination levels[86].

Overall, understanding of metal(loid) dynamics across the soil–water–root–grain continuum provides essential principles for developing targeted strategies to reduce metal(loid) accumulation in rice grains while maintaining productivity.

Multi-interface activity regulation

The control of toxic metal(loid)s in rice paddies requires a balance between effectiveness, sustainability and economic feasibility. Activity-centric strategies focus on reducing metal(loid) bioavailability and mobility guided by the biogeochemical cycling of toxic metal(loid)s rather than aiming to reduce the total metal(loid) concentration. This section reviews the underlying principles and innovative strategies for multi-interface activity-centric regulation across the entire rice growth period in paddies (Fig. 3a).

Technology evolution

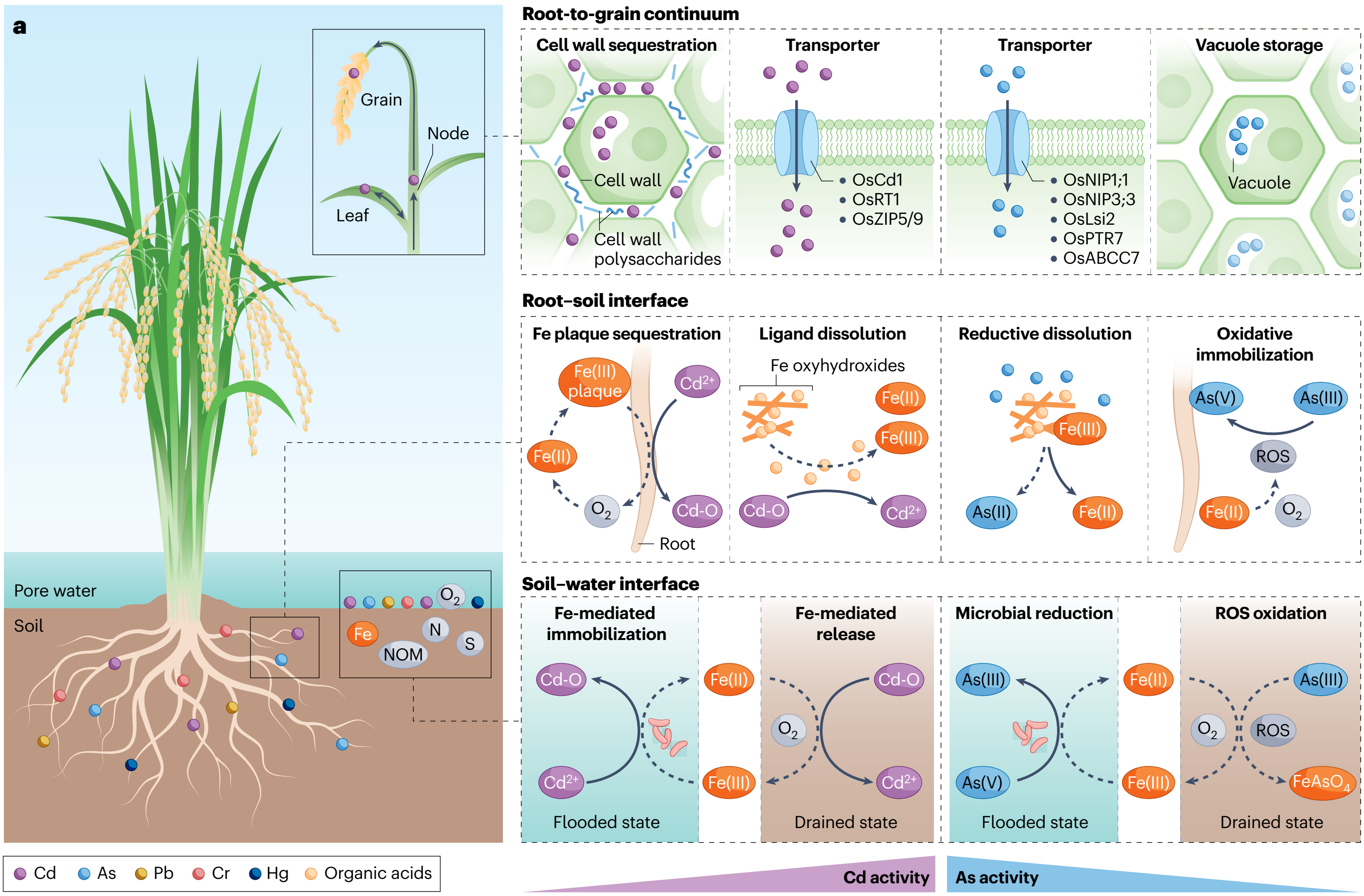
Remediation strategies, such as physical replacement, chemical washing and phytoextraction, aim to decrease the total mass of toxic metal(loid)s in soil. Physical remediation techniques, including soil replacement, soil dressing, deep plowing and magnetic separation, reduce metal(loid) occurrence through dilution or direct removal[87]. Chemical washing introduces leaching agents into contaminated soils to mobilize metal(loid)s through desorption, ion exchange or complexation, allowing the metal(loid)s to be separated from the soil solution[88,89]. Phytoextraction uses hyperaccumulator plants to uptake and concentrate metal(loid)s into harvestable biomass[90,91]. Each of these approaches can lower total soil metal(loid) concentrations and have been implemented in field settings[87].

Total mass reduction strategies are considered to be suitable for heavily contaminated paddy soils[92]. However, vast expanses of working paddy landscapes are characterized by diffuse, low-to-moderate contamination[5,31]. Mass reduction strategies are often time-consuming, costly and disruptive to soil structure, limiting their applicability in productive paddy systems. Therefore, an alternative approach that secures food safety while maintaining continuous production is needed. Activity-centric management approaches, which directly target the biogeochemical processes that control metal(loid) solubility, speciation and plant uptake across the soil–water–root interfaces, present a viable and pragmatic pathway (Box 1).

Soil metal(loid) activity regulation

The activity and bioavailability of toxic metal(loid)s at the soil–water interface are predominantly governed by their chemical speciation and valence states, which can be strategically managed through multiple approaches at the tillage state. Soil passivators can be applied to immobilize dissolved metal(loid)s through co-precipitation, complexation and ion exchange[93,94], sequestering metal(loid)s and reducing their bioavailability[93] (Fig. 3b). For example, the incorporation of alkaline materials such as limestone can increase soil pH and enhance metal(loid) precipitation and/or adsorption onto mineral surfaces[95]. Additionally, porous materials such as zeolite and clay minerals immobilize cationic metals through inner-sphere surface complexation[96,97] (that is, direct chemical bonds with sorbent). Passivation with limestone and sepiolite was reported to reduce concentrations of Cd and Pb in grains by 56–81% within the first season of a field experiment in southern China[98].

Carbon-based materials, such as biochar and humic substances[99], and Fe-based materials can also be used to stabilize metal(loid)s. Biochar modified by Fe, Mn or S, with abundant oxygen-containing functional groups, exhibits a strong affinity for multiple metal(loid)s. It effectively immobilizes As through strong chemical binding[100], Cd and Pb via strong electrostatic binding[101], and Hg through complexation with sulfur-functional groups[102]. These organic materials also promote the immobilization of metal(loid)s on soil minerals by



b

Metal(loid)	Flooded state: Fe	NOM	N	S	pH increase	Eh decrease	Drained state: Fe	NOM	N	S	pH decrease	Eh increase
Cd	–	–	–	–	–	–	+	+	+	+	+	+
As	+	+	+	+	+	+	–	–	–	–	–	–
Pb	–	–	–	–	–	–	+	+	+	+	+	+
Hg	–	–	–	–	–	–	+	+	+	+	+	+
Cr	+	+	+	+	+	+	–	–	–	–	–	–

Fig. 2 | Biogeochemical processes controlling the activity of toxic metal(loid)s in paddy soils. a, Transport and transformation of toxic metal(loid)s along the soil–root–grain continuum. The insets highlight processes that increase and decrease the activity of Cd and As at the soil–water interface, the root–soil interface, and the root–grain interface. Solid and dashed arrows are used to visually distinguish different processes. **b**, Left: a summary of the impact of the reduction of Fe(III), NOM, nitrate and sulfate; increased pH; and decreased redox potential (Eh) caused by anoxic conditions in the flooded state on the activity of metal(loid)s in paddy soils. Right: the same as on the left but for the impact of the oxidation of Fe(II), NOM, ammonium and sulfide; decreased pH; and increased Eh caused by oxic conditions in the drainage state. Redox-driven biogeochemical interactions have a key role in controlling metal(loid) activity in paddy soils. '+', increase; '–', decrease; NOM, natural organic matter; ROS, reactive oxygen species.

strengthening the binding between metal(loid)s and Fe (oxyhydr)oxide minerals and/or by lowering the nucleation energy barriers for Fe-metal(loid) co-precipitates[103,104]. Engineered Fe-based materials, such as zero-valent iron (ZVI), provide a highly reactive surface for metal(loid) immobilization. For example, ZVI oxidizes to form Fe(III) (oxyhydr)oxides, which immobilize metal(loid)s through strong chemical binding and hydrogen bonding[105].

Beyond material amendments, direct water management via alternative irrigation methods can be used to regulate the redox interface and metal(loid) bioavailability[106]. For example, replacing continuous flooding with intermittent or aerobic irrigation maintains higher soil redox potential, which can suppress the reductive dissolution of Fe (oxyhydr)oxide minerals and, thereby, limit the mobilization of As (refs. 107,108).

Microbial processes also regulate metal(loid) bioavailability. Under flooded, reducing conditions, microbial reduction of Fe(III) (oxyhydr)oxide minerals and As(V) increases the release of As(III)[68]. One approach to mitigate this mobilization of As is to apply granular activated carbon (that is, a porous carbon material with high adsorption capacity), which sequesters dissolved organic matter. This adsorption limits the electron shuttling capability of the dissolved organic matter, a mechanism that transfers electrons from microorganisms to As-bearing minerals, thereby suppressing the microbial reductive dissolution[109]. Conversely, Fe reduction promotes the immobilization of cationic metals. Some strategies enhance this process using electron shuttles, such as microbially produced phenazines and carbon materials, that facilitate the Fe(III)-to-Fe(II) redox transition[110,111]. Simultaneously, sulfate-reducing bacteria contribute to metal(loid) sequestration through precipitation of Cd, Hg and Pb as stable sulfides (Fig. 3b). This process can be accelerated by bioaugmentation with exogenous strains or endogenous activation of native communities[112,113]. For example, the addition of exogenous sulfate reduction strains decreased the concentration of available Cd by up to 40% in soils[114].

However, the translation of these microbial strategies from laboratory-based and greenhouse-based trials to large-scale

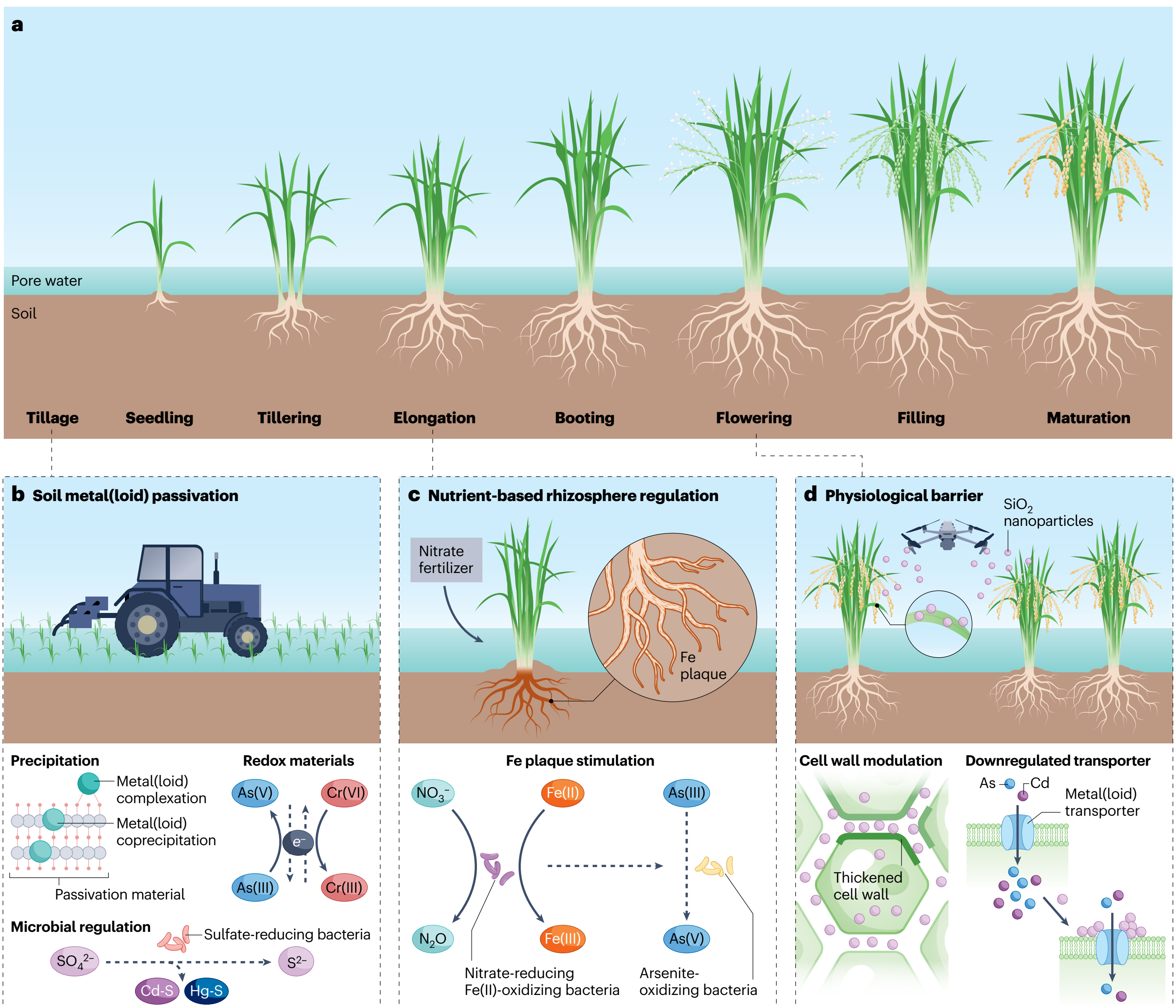


Fig. 3 | Activity-centric strategies for toxic metal(loid) management. **a**, The stages in the growth of rice plants. **b**, Metal(loid) precipitation induced by amendments; redox transformation mediated by reactive materials such as biochar; and microbial regulation target toxic metal(loid) passivation at soil–water interfaces during the tillage stage. **c**, In the rhizosphere, Fe plaque accumulation can be enhanced during the elongation stage by nutrient inputs such as nitrate, which might also promote biotic oxidation of As(III). **d**, At the flowering stage, physiological barriers are reinforced by nanomaterials (such as SiO_2 nanoparticles) that regulate metal(loid) transporter expression and strengthen cell wall architecture to reduce metal(loid) accumulation in grains. Controlling metal(loid) activity through coordinated, stage-specific interventions across key interfaces is central to mitigating metal(loid) accumulation in rice.

Box 1 | Activity-centric management

Activity-centric management approaches are increasingly being recognized as a more effective strategy for mitigating toxic metal(loid) risks than approaches based solely on total concentrations. These approaches focus on controlling the bioavailable fraction of metal(loid)s that directly governs plant uptake and food safety outcomes. This Box introduces bioavailability as the key concept in such approaches.

Bioavailability

Bioavailability refers to the fraction of total soil metal(loid)s accessible for uptake by rice roots and, therefore, governs the risk of transfer from soil to grain[217]. Bioavailability is not an intrinsic soil property but an emergent, dynamic outcome arising from interactions at the soil-solution–root interface. It is continuously reshaped by soil physicochemical conditions, rhizosphere biogeochemistry and water management practices, rather than being determined solely by bulk metal(loid) concentrations.

Governing factors

Soil physicochemical conditions

Multiple soil factors, including pH, Eh (redox potential), soil organic matter content and mineral composition, influence the bioavailability of metal(loid)s[218]. For example, pH strongly influences metal(loid) solubility and adsorption. Eh, which oscillates with flooding and drainage, controls the valence state and mobility of redox-sensitive elements such as As and Cd.

Metal(loid)-specific properties

The chemistry of the metal(loid) also influences its bioavailability[219]. Cationic metals compete with H^+ for sorption sites, and their bioavailability often increases with acidity. Arsenic exhibits valence-dependent behaviour: the reduced form As(III), prevalent under flooded conditions, is more mobile, toxic and bioavailable than As(V).

Bioavailability assessment

Bioavailability assessment often relies on chemical extraction[220,221]. These procedures use a sequence of reagents with increasing chemical strength to fractionate metal(loid)s into forms that approximately correspond to their availability. These operational extraction-based assessments underpin soil quality and contamination screening criteria in multiple national regulatory frameworks, including the Soil Protection Act of the Netherlands[222], the US Environmental Protection Agency's ecological soil screening levels[223], and China's Soil Environmental Quality Standard for Agricultural Land[170]. These methods use specific chemicals to simulate the desorption or dissolution processes that control metal(loid) release into soil solution and uptake by plants. However, the correlation between extracted metal(loid) concentration and actual plant uptake is highly variable and depends strongly on specific soil properties.

Multi-surface model (MSM)

Mechanistically based prediction approaches are emerging to overcome the limitations of empirical extractions. The MSM treats soil as a set of major reactive phases, including physiochemical factors, iron oxides, organic matter and clay minerals[224,225]. Using well-established adsorption models for each phase, the MSM calculates the speciation and partitioning of metal(loid)s in the soil solution based on fundamental soil chemistry data.

application faces important challenges. Exogenous microbial agents confront strong colonization resistance from native soil communities and face complex biotic interactions[115]. The long-term survival and efficacy of these agents without repeated inoculation are, therefore, uncertain. Future research across diverse paddy soil settings is required to better understand these challenges. Beyond the manipulation of individual microbial processes, the construction of functional synthetic microbial communities (SynComs) could enable the precise management of metal(loid) bioavailability in paddy soils[116,117]. Unlike single-strain inoculants, SynComs are designed consortia comprising multiple, interacting species that can perform complex, coordinated functions with increased ecological stability and resilience against the native soil microbiome[118,119]. This strategy might address the challenges of colonization resistance and functional persistence associated with single exogenous strains, offering a more robust and ecologically considerate approach to microbiome engineering[120,121].

The strategic regulation of redox-driven transformations can mitigate the toxicity of metal(loid)s such as As and Cr that have different bioavailability depending on their valence state. The availability of oxygen during drainage phases shifts the redox landscape, making the generation of ROS key for As(III) oxidation[122,123]. The production of ROS can be increased through natural biogeochemical cycles and engineered amendments. For example, inorganic–organic ligand pairs adsorbed on Fe(III) (oxyhydr)oxides catalyse Fenton-like reactions producing hydroxyl radicals (·OH) that oxidize As(III) (refs. 124,125). Additionally, biochar–ZVI composites promote the reduction of O_2 and subsequent As(III) oxidation through synergistic surface-catalytic effects[126,127]. Carbon-based materials with high electron storage capacity and abundant defects such as biochar and engineered porous carbon materials can enhance the activation of molecular oxygen, generating superoxide radicals that drive concurrent As(III) oxidation and Cr(VI) reduction[128,129] (Fig. 3b).

Microbial methylation and demethylation regulate the mobility and toxicity of metal(loid)s such as As and Hg. Specifically, As methylation, mediated by the *arsM* functional gene in microbial communities, converts inorganic As into volatile methylated species, providing a key detoxification pathway[130]. *arsM* expression can be activated by specific organic substrates, notably lignin-like and peptide-like organic matter to stimulate this process[131,132]. Additionally, bicarbonate addition promotes phototrophic methylators such as Oscillatoriales that release metabolites that support heterotrophic partners such as Chitinophagales, which together form cooperative microbial networks that amplify As methylation and reinforce rhizosphere resilience[133]. However, the regulation of As methylation must be carefully managed to avoid excess accumulation of methyl-arsenic, which can trigger straighthead disease, a disorder that causes spikelet sterility and substantial yield loss in rice[134]. By contrast, methylmercury (MeHg) is substantially more toxic than inorganic Hg. Demethylation strategies include activating ROS through Fenton-like reactions to decompose MeHg (ref. 135), using water management to suppress Hg-methylating microorganisms[136], and using microbial inoculation to cleave C–Hg bonds[137].

Although these strategies, including metal(loid) immobilization, redox regulation and (de)methylation control, show potential for managing metal(loid) activity, their practical implementation has been largely confined to laboratory, pot and small-scale field trials. Pot experiments often overestimate remediation efficiency compared to complex field environments with high heterogeneity across different sites. Therefore, translating these approaches into scalable and economically viable technologies for large-scale reduction of metal(loid) activity remains a key challenge for future research.

Rhizosphere modulation

The rice rhizosphere constitutes a dynamic microenvironment in which Fe plaque at the root interface serves as an important geochemical barrier for the sequestration and transformation of toxic metal(loid)s at the elongation stage of rice growth (Fig. 3c). There are multiple strategies that enhance metal(loid) sequestration in the rice rhizosphere by promoting Fe plaque formation.

The addition of specific fertilizers such as nitrogen, selenate, phosphate, sulfate and silicate can enhance Fe plaque formation by promoting microbial Fe(II) oxidation, Fe(III) precipitation and radial oxygen loss (that is, the release of oxygen by rice roots)[74,138]. For instance, nitrate addition couples Fe(II) oxidation to denitrification or dissimilatory nitrate reduction to ammonium by stimulating the oxidation of Fe(II) by nitrate-reducing bacteria, thereby linking Fe and N cycling. Furthermore, arsenite-oxidizing bacteria can use nitrate as an electron acceptor to oxidize asrenite to arsenate, directly linking nitrate reduction to As(III) oxidation[139,140]. Consequently, nitrate addition can simulate Fe plaque formation and enhance its ability to immobilize As. This approach decreased the total As content in rice grains by approximately 32% in a field trial in southern China[141].

Moreover, carbon-based and Fe-based materials are also used to promote Fe plaque formation. Carbon-based materials, including humic substances, biochar and woody peat, act as electron shuttles to Fe(III)-reducing bacteria, increasing the availability of Fe(II) for subsequent oxidation and mineral precipitation on root surfaces[142,143]. This enhanced Fe cycling drives the secondary formation of Fe minerals and localized Fenton-like reactions in oxygen-rich areas, generating ·OH that contribute to metal(loid) oxidation and immobilization[144,145]. Additionally, the application of Fe-based materials, such as ZVI, Fe(II) and Fe(III) salts, and Fe oxide nanoparticles, to paddy soils enriches the rice rhizosphere with labile Fe. This enhanced Fe pool promotes the oxidation and precipitation of Fe(II) on root surfaces, stimulating the formation of Fe plaques[74,146]. Furthermore, microbial activity also regulates Fe plaque formation and function. For example, microaerophilic Fe(II)-oxidizing bacteria that are abundant in paddy soils, such as species belonging to *Azospirillum*, *Magnetospirillum* and *Clostridium*, can be activated by organic carbon, accelerating Fe(II) oxidation and Fe plaque development[143,147].

Targeted approaches that selectively optimize Fe plaque structure and function in the root zone are still under development. The detoxification efficiency of Fe plaque is closely linked to its structure and composition. Structural defects in Fe(III) (oxyhydr)oxides serve as key active sites for metal(loid) adsorption, interfacial O_2 activation, and redox transformation of metal(loid)s[148,149]. Additionally, the presence of transition metals such as Cu or Mn within the plaque increases lattice disorder and facilitates efficient electron transfer, accelerating Fe(II)-mediated O_2 activation and the generation of ROS, which in turn enhance As(III) oxidation and Cr(VI) reduction[150,151]. These insights point to potential strategies to enhance the immobilization of toxic metal(loid)s by Fe plaque, for example, the targeted application of metal-doped fertilizers or irrigation with ion-amended water[150,151]. Additionally, scalable methods to fully leverage Fe plaque are being explored; for example, alternate wetting and drying can promote Fe(II) oxidation and enhance root plaque formation, thereby increasing metal(loid) sequestration at the rhizospshere[152]. Furthermore, similar to the soil process, SynComs could also be used to regulate the redox transformations of Fe(II) and toxic metal(loid)s in the rhizosphere and on root iron plaque, such as Fe(II) and As(III) oxidation, to limit metal(loid) mobility and uptake by rice[153].

Physiological barrier

The accumulation of toxic metal(loid)s in rice grains is governed by a series of physiological processes, including root uptake, xylem loading and intervascular transfer towards developing grains. Toxic metal(loid) s lack dedicated transport systems; therefore, they compete with essential nutrient elements for passage through shared transmembrane transporters[154]. This mechanistic understanding provides a basis for intervention strategies aimed at suppressing metal(loid) uptake and translocation at the flowering state (Fig. 3d).

Nutrient-based regulation represents a practical and agronomically viable approach to suppressing the uptake and translocation of metal(loid)s to rice grains. The application of Fe and Zn fertilizers downregulates the expression of metal transporter genes such as OsNRAMP5 and OsIRT1, which are major pathways for Cd uptake[80,155]. In field trials conducted in southern China, combined Zn fertilization and liming reduced Cd concentrations by 25–70% in grain while increasing plant photosynthetic efficiency and functional gene expression[156]. Additionally, silicon supplementation enhances the formation of silica–pectin complexes in the apoplast, which strengthen the binding of Cd and Pb in plant cell walls and decrease their mobility[85,157]. Silicate fertilizers also modulate the expression of aquaporin and phosphate transporter genes, inhibiting As uptake[158]. Field experiments in southern China demonstrated that silicon amendment can reduce the concentration of Cd and As in grain simultaneously by 50–70% and 20–30%, respectively[159].

Nanoparticle-based strategies offer a targeted and efficient way of altering metal(loid) transport pathways, by cooperatively regulating gene expression, cell wall structure and extracellular ROS level[160,161]. Foliar spraying of nano-silica, nano-selenium or Fe oxide nanozymes during the flowering stage suppresses the expression of key transporter genes such as OsLsi1 and OsNRAMP5, impeding the translocation of multiple metal(loid)s from roots to grains[162,163]. These nanomaterials also enhance the antioxidant defence system through catalytic redox reactions that eliminate extracellular ROS such as hydrogen peroxide and ·OH, which are often elevated under metal(loid) stress[164,165], thereby protecting cellular components from oxidative damage. Concurrently, they also promote the thickening of cell walls and increase pectin and hemicellulose content, reinforcing the apoplastic barrier for metal(loid) immobilization[17,166]. In field tests, foliar sprays of nano-silica hydrogels during the tillering and heading stages reduced the concentration of toxic metal(loid)s such as Cd and As in grain by 30–60% (ref. 167).

The integration of nutrient management and nanomaterial application demonstrates potential for reducing metal(loid) accumulation in grain, but there are constraints that limit the broader implementation of such approaches. Most examples of the success of these approaches are derived from controlled experiments performed in pots, which could amplify the positive impacts[158]. However, these experiments provide guidance for initial regional-scale screening and strategy design, and the few demonstrations in field trials confirm the mechanistic potential of these strategies under real agronomic conditions[167]. The high production costs of nanomaterials limit their cost effectiveness despite the low dosages required. This problem is being gradually addressed by advances in scalable synthesis and use of industrial by-products[157]. Additionally, the potential environmental risks must be considered; for example, nanoparticles entering soil–plant systems might affect microbial ecology or co-transport pollutants[168]. Therefore, comprehensive environmental risk assessment and large-scale, long-term field validation across diverse paddy environments remain essential before extensive applications.

Integrated risk management framework

Safeguarding sustainable production of rice that is safe for human consumption requires site-specific strategies that account for the pronounced spatial heterogeneity in metal(loid) speciation, contamination levels and soil properties[169]. Although various national approaches to managing the risk of toxic metal(loid)s in soils exist, a globally applicable framework specifically tailored to paddy systems remains lacking[170]. This section proposes an integrated risk management framework with a modular decision-making structure, built around metal(loid) flux and source control, risk-tailored implementation, sustainability evaluation and supportive governance. The design of the framework separates policy-level governance from technology-level implementation (Fig. 4), ensuring that its principles can be adapted to diverse institutional contexts.

Metal(loid) flux and source control

The control of toxic metal(loid) content and activities in rice paddies must be preceded by source identification and control because ongoing external inputs can compromise the efficacy of long-term management approaches. Early efforts to monitor toxic metal(loid) contamination in rice paddies were primarily based on bulk soil and water concentration measurements, but they lacked comprehensive analysis of input pathways, hindering accurate quantification of the metal(loid) fluxes

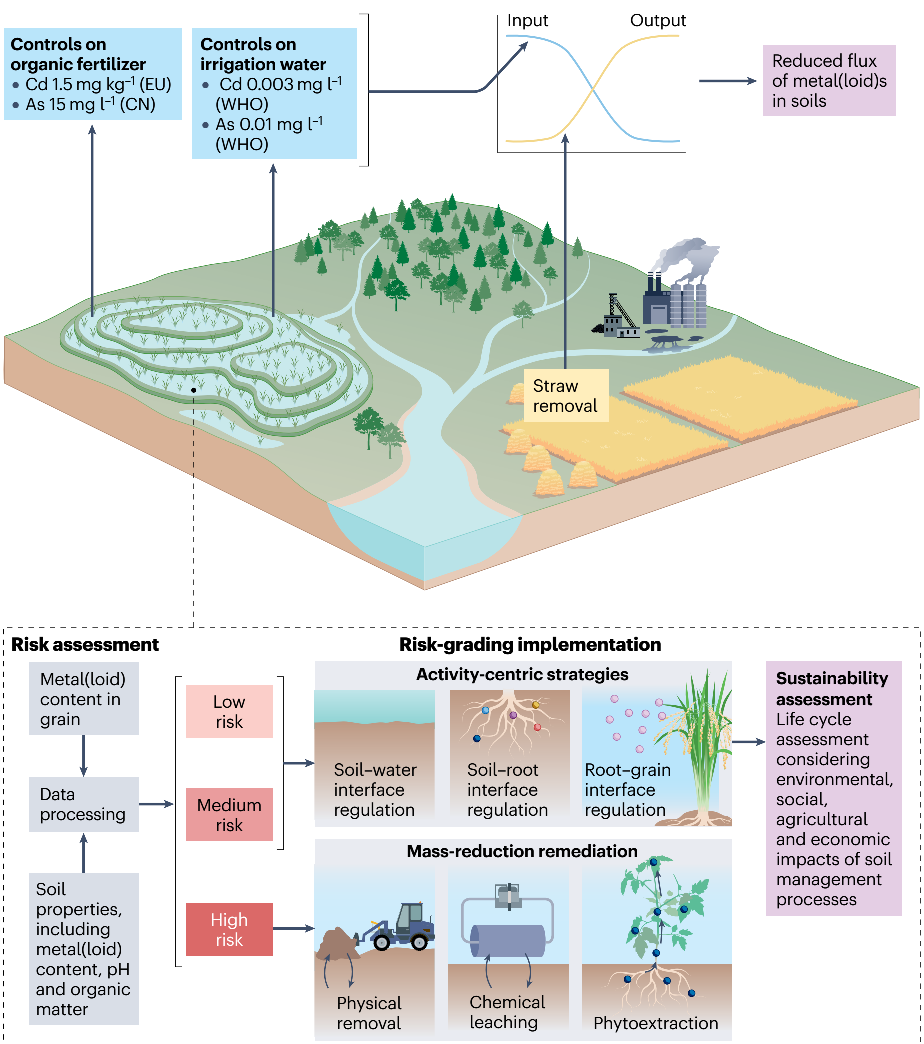


Fig. 4 | Integrated risk management framework. The regional-scale management framework for safe rice production combines the control of metal(loid) sources by imposing limits on metal(loid) concentrations in organic fertilizer and irrigation water and increasing straw removal; assessment of the regional risk of toxic metal(loid) contamination in paddy soils based on the concentration of metal(loid)s in soil and grain, and various soil properties; risk-informed technology implementation for regional metal(loid) management; and assessment of the sustainability of the management approach. The threshold values shown represent existing regulatory or guideline limits for Cd (EU regulations for fertilizers[214]) and As (Chinese (CN) standards for organic fertilizers)[215] in fertilizers and irrigation water (based on World Health Organization (WHO) guidelines for drinking water quality[216]). This framework prioritizes activity-centric regulation strategies in low-to-moderate risk sites to maintain agricultural productivity and reserves strategies focused on mass reduction for high-risk sites where regulatory thresholds are exceeded.

into and out of paddy systems[24]. These approaches often did not reliably attribute observed concentrations to specific sources, limiting their ability to resolve source–sink dynamics. Flux-based assessments are a robust alternative, integrating inputs from atmospheric deposition, irrigation water and agriculture, and output pathways to assess regional metal(loid) fluxes[171,172]. Tools such as the Weather Research and Forecasting model, coupled with Chemistry models and deep learning methods, have improved the spatial simulation of deposition fluxes and prediction of grain metal(loid) content[173], supporting high-resolution mapping of transport pathways[174]. Stable isotope tracing of Cd, Hg and Pb, combined with Bayesian mixing models, further enables source apportionment in complex systems[175–177]. However, monitoring systems continue to face several limitations, including insufficient spatial coverage and limited temporal resolution, which constrain the accuracy of flux estimation and source identification[178]. The integration of remote sensing and drone-based surveys with large-scale soil investigations would help to establish a more efficient and precise source tracing system.

Source control represents the primary defence against soil contamination, offering substantially lower costs than downstream management. The economic advantage of this approach is driving a shift from passive management of toxic metal(loid)s in soils via soil amendments and microbial agents towards proactive prevention of contamination. The integration of advanced monitoring and modelling methodologies enables the development of targeted intervention strategies. In regions characterized by high external inputs, the treatment of irrigation water through sedimentation and filtration systems effectively reduces metal(loid) loading[179,180]. Similarly, in industrial farming areas where atmospheric deposition constitutes a major external metal(loid) flux, emission control measures and deposition monitoring should be prioritized[181]. Additional measures, such as straw removal and stricter control of organic fertilizer inputs, can further limit the recycling and reintroduction of metal(loid)s within paddy systems. It is important to integrate these source-directed measures by systematically linking field-level management with regional emission control. Improved source control also requires the development of institutional synergies and integrated management frameworks that strengthen coordination between environmental impact assessment, land-use planning and ongoing contamination monitoring.

Risk-tailored implementation

Controlling the environmental and human health risk associated with toxic metal(loid)s in paddy soils, particularly their transfer to rice grains, requires a stratified strategy based on scientifically defined risk levels. Regulatory systems have evolved from uniform thresholds to classification-based frameworks that systematically incorporate metal(loid) content in soil and grain[182–184]. The framework proposes the use of a tiered risk assessment system, which integrates these concentrations with key soil properties, such as pH and organic matter, to classify paddy soils into different contamination grades based on the regional risk level. These classification criteria can be further refined by integrating additional parameters such as clay mineralogy, redox potential, Fe content and microbial community characteristics to improve the prediction of metal(loid) risk in rice production systems across heterogeneous landscapes.

In the proposed framework, remediation technologies for safe rice production are then selectively applied based on the risk categories. Soils with high metal(loid) risk often require intensive measures such as soil replacement or solidification to reduce total metal(loid) contents. After decreasing the metal(loid) content of the soil, these sites might be permitted to start agricultural production processes. By contrast, areas with low-to-medium risks benefit from activity-centric approaches, including immobilization and microbial agent amendments, water management and rhizosphere regulation, that reduce metal(loid) bioavailability with minimal disruption to food production[185]. In soils that are co-contaminated with elements exhibiting opposing redox sensitivities, such as As and Cd, the activity-centric strategies can be optimized through spatiotemporal decoupling[186]. This approach involves aligning water management approaches with the crop physiology stage and integrating complementary interventions. For example, multifunctional amendments can be used at the soil–root interface alongside foliar barriers to minimize overall risk without prioritizing one contaminant over the other.

Risk-based management practices for safe rice production should be progressively scaled based on effectiveness, from field-level pilots to regional implementation and eventually global application. To establish such an approach, a long-term monitoring system that tracks soil physicochemical properties, metal(loid) speciation and crop metal(loid) content is needed[185,187]. Such sustained monitoring is essential for evaluating the efficacy of management measures and identifying potential rebound risks to ensure that risk-tailored management approaches for safe rice production are adaptive and have long-term security.

Sustainability assessment

The sustainability of management strategies for toxic metal(loid)s in soils is crucial for ensuring lasting success in paddy soil management. The evaluation of soil safety management approaches has evolved from focusing solely on the efficiency of management approaches to encompassing multi-dimensional sustainability criteria[188]. Life cycle assessment (LCA) has been widely applied to evaluate the environmental impacts of management approaches throughout their entire life cycle, encompassing impacts on human health, ecosystems and resources[189]. Moreover, LCA approaches integrating social and economic dimensions have been further developed to support the sustainability assessment of different management strategies[190].

The framework proposes the use of a multi-criteria sustainability index to quantitatively compare different management strategies[191,192]. Such evaluations integrate environmental (using LCA to quantify ecological and health impacts), economic (analysing cost–effectiveness), social (assessing public acceptance and health safety), and agricultural (emphasizing soil functionality and grain safety)[11,193] sustainability. However, existing sustainability assessment models lack adequate indicators for critical soil health parameters, particularly those related to nutrient cycling, microbial community diversity, and soil ecological functions. Future efforts should incorporate these biological and biochemical metrics to better capture the long-term sustainability and ecological resilience of remediated paddy systems.

Standardization and policy-making

The shift of soil environmental management towards integrated lifecycle standardization systems[170] that coordinate standards across input control, soil management, crop production and post-harvest handling is anchored in legislative and policy tools. These tools vary by jurisdiction, but all of them aim to establish liability, set risk-based land-use categories, and mandate or guide action to address the safety of rice production[10,194]. Standards should span multiple tiers ranging from fundamental risk thresholds and technical guidelines for metal(loid) concentrations in soils and grains to effect-based evaluation protocols for remediation strategies. However, these criteria must be flexible and adaptive to account for regional variations in soil properties, climatic conditions and socioeconomic contexts.

The implementation of a risk management framework depends on diversified long-term funding. Large-scale strategies for safe management of paddy systems are critical for food security but can be difficult to achieve owing to the involvement of many fragmented smallholders[195]. For most countries, proactive, state-driven financing and policy coordination are indispensable for overcoming this challenge[170,196]. This top–down approach can establish monitoring infrastructure for tracking metal(loid) sources and concentrations in soils and rice grains, incentivize technology adoption, and de-risk private investment[197]. For example, China's dedicated special funds for controlling agricultural soil pollution have helped to launch large-scale, risk-based control and management programmes[198]. Furthermore, international financial institutions have a catalytic role in supporting such national efforts. The World Bank, for instance, provides concessional and low-interest loans to support risk management of toxic metal(loid)s in rice paddies in China[199]. Although public and international financing provide the foundation, leveraging public–private partnerships, blended finance and market-based instruments remain crucial for the scalability and long-term viability of an integrated risk management framework.

The framework is designed as a flexible decision logic rather than a prescriptive blueprint tied to any single context. In settings wherein landholdings are fragmented and agricultural extension systems are decentralized, the risk classification function could be exercised by regional cooperatives or local government bodies, with technology diffusion relying on community-based networks and participatory training programmes. In regions dominated by smallholder farming, international development programmes and public–private partnerships might have an important role in financing and implementing activity-centric remediation strategies, with a focus on affordable, low-tech interventions. Where regulatory infrastructure and monitoring capacity are less developed, the framework could initially prioritize establishing basic surveillance systems and building local technical capacity, with more sophisticated risk tiers, such as site-specific risk assessment, exposure-based thresholds and targeted management intervention, being implemented as institutional capacity matures.

Effective soil governance cannot be achieved without active public participation and societal engagement[200,201]. It is important to enhance farmers' awareness of metal(loid) risks and safe soil and crop management practices through training, to encourage community involvement in decision-making, and to strengthen information disclosure and public oversight mechanisms to ensure that environmental governance systems are transparent and inclusive. Substantial advances have been achieved in standard setting, funding and stakeholder engagement[202,203]. However, fully sustainable soil governance will require ongoing collaboration across governments, academia, enterprises and civil society to effectively translate policies into durable results.

Overall, the proposed integrated risk management framework offers a transferable logic for coordinating science, policy and practice in contaminated paddy fields. The modular integration of risk-based land classification, targeted technologies, sustainability evaluation and adaptive governance enables the framework to be used under diverse institutional arrangements. China's large-scale management of paddy soils supported by special funds of China and international financial institutions[199] demonstrates the viability of linking policy-driven risk boundaries with technology-driven solutions. The successful adaptation of this framework to other regions requires careful local calibration of policy instruments, standards and implementation pathways to align with specific governance structures, agricultural systems and socioeconomic contexts.

Summary and future perspectives

Effective and practical management of toxic metal(loid)s in rice paddies is fundamental to ensuring safe and sustainable food production. The uptake and translocation of metal(loid)s from soils into rice grains are a threat to human health. To address the problem of widespread soil contamination by metal(loid)s, management strategies are shifting from total-mass reduction to activity-centric control. A translational integrated risk management framework that links soil–root–grain mechanisms to risk-based land management, supportive policies and multi-stakeholder action is proposed. Moving forward, the challenges of long-term stability, scale-up feasibility and management of co-contaminated sites must be addressed through targeted research.

The long-term stability of control measures is essential for improving soil quality and achieving agricultural sustainability. Measures are often assessed based on metal(loid) immobilization over a few cropping cycles. Long-term evaluations (>10 years) of their efficacy, which remain rare, are important because performance is highly heterogeneous across regions owing to varying soil properties, climate and practices. The efficacy of interventions is dynamically challenged by inherent soil ageing processes that alter the buffering and retention capacity of the soil, including the transformation of Fe (oxyhydr) oxide minerals, alterations to soil organic matter, and changes in soil acidity. To address the issue of gradual passivation or deactivation of conventional amendments, future research should focus on developing reactive and regenerative materials, such as carbon-based materials with high electron storage capacity, that can be chemically or electrochemically recharged in situ. Field-based experiments that assess the persistence and functionality of existing and newly developed amendments are urgently needed.

Advancing multi-objective coordination in the context of climate change is equally crucial. Safe management of toxic metal(loid)s should be integrated into a broader strategy that simultaneously enhances soil quality, controls acidification, improves nutrient-use efficiency, supports biodiversity and mitigates greenhouse gas emissions[204,205]. Future work should prioritize the systematic evaluation of existing amendments and microbial consortia to maximize co-benefits. Additionally, the development of material–microbial composites capable of delivering coordinated outcomes should be explored. For microbial strategies, this evaluation must embed a safety-first framework, which entails establishing standard ecological risk assessment protocols and long-term monitoring to ensure that their deployment supports, rather than disrupts, soil biodiversity and ecosystem services. The goal is to achieve a synergy whereby pollution mitigation approaches actively contribute to overall soil health and resilience. Safe management efforts must account for co-occurring emerging pollutants, such as antibiotic resistance genes and microplastics, which interact synergistically with metal(loid)s[206]. Integrated solutions that concurrently mitigate metal(loid)s and emerging contaminants are needed.

Artificial intelligence offers potential to enhance the management of metal(loid)-contaminated rice paddies; however, most applications in this domain remain at an early stage[3,5]. At the micro-scale, machine learning has shown promise in materials science for predicting compound properties[207,208], suggesting possible applications for designing amendments, although direct validation in paddy systems is still lacking. Concurrently, artificial intelligence-driven analysis of multi-omics data has demonstrated value in controlled systems, such as laboratory microcosms and greenhouse experiments, enabling the identification of key microbial taxa and pathways underpinning metal(loid) transformation[209,210]. However, further developments are needed to enable its application to more complex field trial conditions. At the macro-scale, artificial intelligence-enabled models are increasingly being developed to integrate diverse environmental datasets to improve the prediction of metal(loid) distribution, transport and associated risks across landscapes[211,212]. However, large-scale deployment of artificial intelligence for forecasting the efficacy of soil management strategies and regional pollutant fluxes in rice paddies remains a research frontier rather than an established practice. Embedding these emerging tools into the integrated risk management framework could eventually support adaptive governance, provided that robust validation and capacity building in data infrastructure, technical expertise and institutional implementation accompany their development.

Gaps in policy and regulatory frameworks must be addressed to enable the sustainable management of toxic metal(loid)s in agricultural soils. Many regions still lack systematic baseline data, use inconsistent risk assessment methods, and have yet to establish coordinated cross-regional or international governance mechanisms. These gaps highlight the need for integrated frameworks that combine systematic data collection, standardized risk assessment, and coordinated governance across regions. Future efforts should focus on developing a multi-objective policy and standardization framework that accounts for carbon–nitrogen synergy, soil health and environmental well-being. Such a framework will make it possible to effectively align scientific insight, regulatory oversight and stakeholder participation to ensure long-term soil safety, enhance soil health, and secure sustainable rice production and food systems.

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Competing interests
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