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Review

A review of amendments for simultaneously reducing Cd and As availability in paddy soils and rice grain based on meta-analysis

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ABSTRACT

Arsenic (As) and cadmium (Cd) accumulation in rice grains is a global food safety issue, and various methods and materials have been used to remove or reduce As and Cd in agricultural soils and rice grains. Despite the availability of synthesized materials capable of simultaneous As and Cd reduction from soil and rice grains, the contributions, efficiency, and main ingredients of the materials for As and Cd immobilization remain unclear. The present study first summarized the biogeochemistry of As and Cd in paddy soils and their transfer in the soil-food-human continuum. We also reviewed a series of reported inorganic and organic materials for simultaneous immobilization of As and Cd in paddy soils, and their reduction efficiency of As and Cd bioavailability were listed and compared. Based on the abovementioned materials, the study conducted a meta-analysis of 38 articles with 2565 observations to quantify the impacts of materials on simultaneous As and Cd reduction from soil and rice grains. Meta-analysis results showed that combining organic and inorganic amendments corresponded to effect sizes of −62.3% and −67.8% on As and Cd accumulation in rice grains, while the effect sizes on As and Cd reduction in paddy soils were −44.2% and −46.2%, respectively. Application of Fe based materials significantly ($P < 0.05$) reduced As (−54.2%) and Cd (−74.9%), accounting for the highest immobilization efficiency of As and Cd in rice grain among all the reviewed materials, outweighing S, Mn, P, Si, and Ca based materials. Moreover, precipitation, surface complexation, ion exchange, and electrostatic attraction mechanisms were involved in the co-immobilization tactics. The present study underlines the application of combined organic and inorganic amendments in simultaneous As and Cd immobilization. It also highlighted that employing Fe-incorporated biochar material may be a potential strategy for co-mitigating As and Cd pollution in paddy soils and accumulation in rice grains.

1. Introduction

Arsenic (As) and cadmium (Cd) present significant risks to both the environment and human health due to their toxic and carcinogenic properties (Zwolak, 2020). What makes them particularly insidious is their lack of odor and taste, which allows them to enter the food chain, primarily through rice, without immediate detection (Zhao and Wang, 2020). Swallowing or inhaling substances, such as Cd in both organic and inorganic forms, can result in acute or chronic poisoning. Prolonged exposure can cause adverse effects such as cancer and dysfunction of multiple organ systems, including the neurological, respiratory, cardiovascular, skeletal, and urinary systems. Two examples are Itai-Itai disease and chronic arsenicosis (Balali-Mood et al., 2021; Palma-Lara et al., 2020). As and Cd enter the agricultural system through various pathways, including natural geochemical processes, mining activities, pesticide application, contamination of groundwater and irrigation waters, and fertilizer (Alengebawy et al., 2021; Dixit et al., 2015). Agricultural soil pollution by As and Cd is now a burning problem on a global environmental scale, threatening the yield quantity and quality of farm products as well as human health. Hou et al. (2020) reported that

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16.1% of agricultural soils of the studied sampling sites exceeded environmental quality standards (GB15618-1995). Hou et al. (2020) emphasized the importance of the United Nations call to action. In many parts of Asia, soil and rice grains have elevated levels of As and Cd. In some regions of Asia, inorganic As levels in rice grains exceed the limits set by the World Health Organization (200 μg kg^{-1}) (Carey et al., 2020; Chen and Zhao, 2023). In Europe, rice tends to have lower levels of inorganic As than in other regions, but some samples still exceed the European Union infant formula limit of 100 μg kg-1. In America, especially South America, inorganic As content is generally elevated, with slight geographical variation. Similarly, in some West African countries such as Nigeria and Ghana, As and Cd levels in rice grains may exceed legal limits (Carey et al., 2020). This highlights the global prevalence and severity of As and Cd accumulation in rice soils and grains, which poses significant risks to food safety and human health, particularly in rice-consuming populations.

Rice plants are considered sensitive to As and Cd and, therefore, can accumulate higher levels of As and Cd in their grains and thus enter human food (Ma et al., 2020). The increased sensitivity of rice plants to As and Cd is attributed to their unique characteristics and growth environment (Ma et al., 2020; Nakanishi et al., 2006). The flooded rice fields create an anaerobic environment that increases the mobility and bioavailability of arsenic in the soil, making it easily accessible for root uptake. Rice plants have highly efficient uptake mechanisms and a large root surface area with dense root hairs, specifically intended to maximize nutrient and water absorption from the flooded soil (Khanam et al., 2020). Unfortunately, this efficiency also applies to As and Cd, allowing them to be readily absorbed and transported into the plant (Deng et al., 2021; Meeinkuirt et al., 2019). Specific proteins and transporters within the rice plant support the movement of these metals within its tissues, further contributing to their accumulation (Latowski et al., 2018). Despite being commonly found in rice, As and Cd do not provide any advantages to the plant and instead impede its growth. When present in high concentrations, these metals cause significant destruction to the biology of rice. Arsenic interferes with the functioning of root cell membranes, blocking the absorption of water and nutrients.

On the other hand, Cd disturbs photosynthesis and enzyme activity, severely impacting the plant's ability to produce energy. As a result of this chain of destructive effects, the growth of the rice plant is stunted, leading to lower yields and, in extreme cases, even crop death (Li et al., 2022b). Treating agricultural land contaminated with Cd and As poses particular difficulties because efficient tactics for addressing one metal can occasionally affect the availability of the other metal. Safe soil conditions require a complex balancing act because, for example, increasing soil pH to reduce As mobility can inadvertently increase Cd mobility (Hou et al., 2020; Vardhan et al., 2019).

Various materials, including biochar, Mn oxides, Fe oxides, nanoparticles, Zn oxides, Si, and even some clays, show promise in the field of Cd and As remediation, but their effectiveness varies greatly (Huang et al., 2024; Suda and Makino, 2016). How As and Cd occur, the properties of the contaminated soil and the particular type of material play a role in this divergence. This variability makes it challenging to create an understandable solution, preventing these materials from being widely used in practice. Numerous studies have explored the simultaneous immobilization of As and Cd using different physical and chemical methods (Bashir et al., 2019; Lin et al., 2024). Recent meta-analyses have extensively examined the removal of As and Cd individually by various amendment materials. These studies have shown significant progress in understanding the mechanisms and effectiveness of specific changes in reducing As and Cd bioavailability. However, there is a notable gap in research addressing simultaneous reduction of both pollutants, particularly in paddy soils. While many studies examine the simultaneous removal of As and Cd in paddy soils, there is a lack of more comprehensive meta-analyses and systematic reviews that explicitly focus on this topic. Such analysis will help develop novel materials to immobilize As and Cd in paddy soils.

Therefore, the present study aimed to (1) summarize the biogeochemistry of As and Cd in paddy soils and their transfer into the soil-food-human continuum; (2) review the currently reported amendment materials applied in As and Cd mitigation in paddy soils (3) analyze and compare the As and Cd co-mitigation efficiency of different amendment materials and their application strategies based on meta-analysis and (4) discussing the future focus on the co-immobilization of As and Cd in agricultural soils. The materials and methods applied to this study are attached as supplementary material (SI) submitted along with this manuscript.

2. Biogeochemistry of As and Cd in paddy soils and their transfer in the soil-food-human continuum

Paddy soils undergo fluctuating flooding and drainage cycles, resulting in alternating aerobic and anaerobic conditions (Wang et al., 2022c). This dynamic environment influences the mobility and bioavailability of As and Cd, with Cd maintaining high bioavailability due to its strong affinity for soil particles (Riaz et al., 2021). Flooding increases pH, favoring the release of bound As from soil particles, while drying introduces oxygen, converting mobile As to less bioavailable forms (Fig. 1). Conversely, Cd's mobility increases during drying because of competition with elements like Fe, but subsequent flooding can trap it again in less available forms. Under low redox potential (Eh), As (V) is reduced to more mobile As (III) through microbial activity or reaction with FeS, facilitating plant uptake. However, under high Eh conditions, As (III) is oxidized to less mobile As (V), reducing plant uptake. Redox fluctuations also affect As sorption/desorption behavior, with As (V) exhibiting stronger sorption to Fe oxides and clays under oxidizing conditions. At the same time, As (III) desorbs under reducing conditions, increasing mobility.

Under flooded soil conditions, the pH shifts to an alkaline range, increasing the mobility of As but reducing mobility of Cd. NO_3 reduction processes yieldNO_2^- and Fe^{2+}, which facilitates the reduction of As(V) to its more mobile and toxic form As(III) (Fang et al., 2021). Dissolved organic matter forms complexes with As and Cd, increasing mobility. The microbial reduction of SO_4^{2-} to S^{2-}/HS^- leads to less mobile CdS molecules precipitation. As the soil dries out, pH decreased to a more acidic value, reducing the mobility of As but increasing mobility of Cd. Fe transformations are crucial in this phase, with oxidation of Fe(II) to Fe(III) allowing co-precipitation with As to form minerals such as Fe–As oxides and As effectively immobilized (Yin et al., 2024).

According to Zhao and Wang (2020), the uptake of As and Cd from the soil into the root cell occurs mainly via membrane transporters (Fig. 2). As and Cd elements hitchhike on these transporters and enter the cell because their physicochemical properties are like those of the essential aspects, and membrane transporters often have incomplete substrate selectivity. It mainly occurs in the grain in the form of inorganic As and dimethylarsinic acid (Zhao et al., 2009), while Cd also occurs in inorganic forms such as Cd^{2+} and CdS (Li et al., 2017). Genetic factors and mechanisms are the critical parameters for absorption and distribution in rice that regulate transport. An important player, OsNRAMP5, is a crucial factor for As influx through the root plasma membrane. This transporter, which has a higher affinity for As than Cd, is pivotal in determining As accumulation in rice grains (Chang et al., 2022).

Interestingly, its expression is modulated by both As exposure and Fe deficiency, indicating complex regulatory networks (Zhao and Wang, 2020). In contrast, OsABCC1, an ATP-binding cassette transporter, actively secretes Cd from root cells, acting as a first line of defense against Cd toxicity (Upadhyaya et al., 2023). Gui et al. (2024) reported that OsABCC1, OsPCS1, and OsHMA3 genes play a crucial role in Cd detoxification in roots by converting them into less toxic forms and sequestering them in vacuoles. Notably, differences in the expression and activity of these transporters and genes contribute to the observed variations in As and Cd accumulation between rice cultivars,

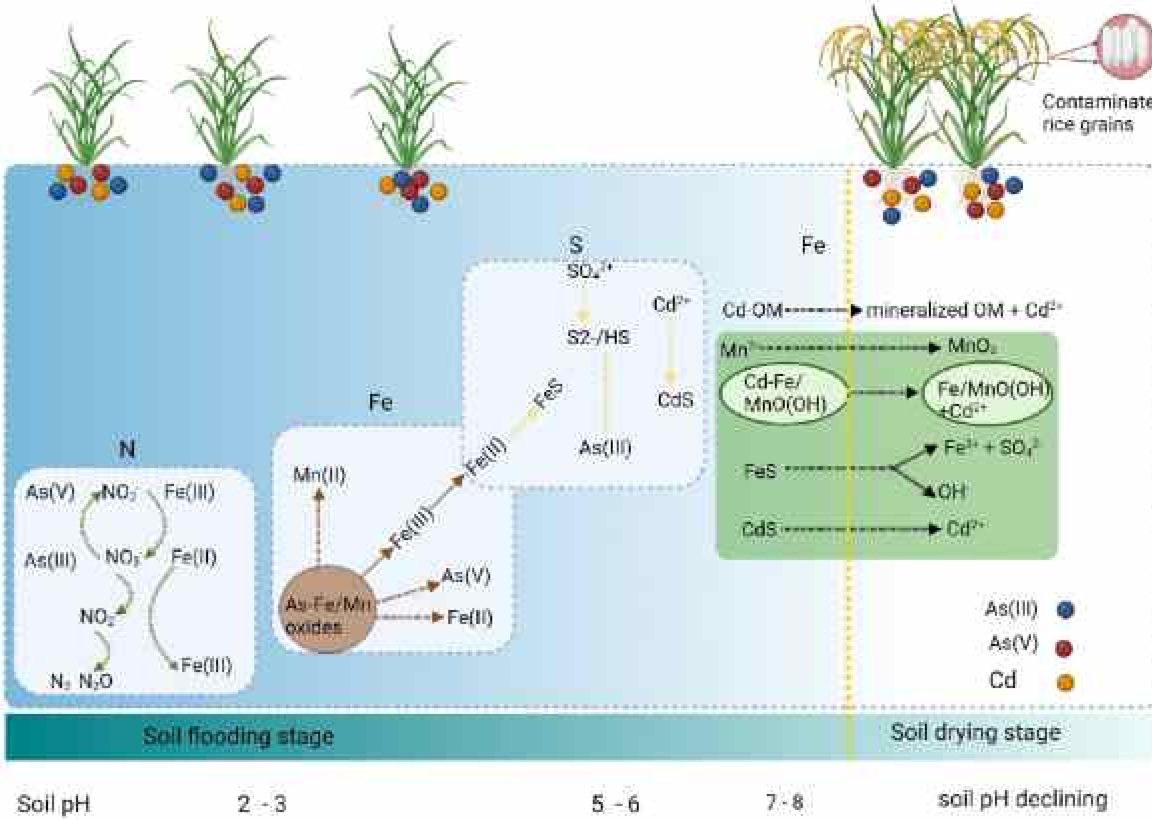

Fig. 1. A systematic illustration showcasing the biogeochemical processes that govern the solubility of As and Cd in soil, as well as their subsequent accumulation in rice, throughout the flooding and drying phases.

highlighting the potential for breeding or genetic engineering approaches (Chaudhary et al., 2024; Raghuvanshi et al., 2023). Further research to investigate the regulatory networks that control these key players and their interaction with environmental factors is crucial for developing effective strategies to minimize As and Cd transfer in rice and ultimately protect human health. Ahad et al. (2022) identified OsNIP3.1, a silicon transporter that plays a role in Cd uptake and translocation, highlighting potential opportunities for breeding or genetic modification.

3. Performance of the reported materials in As and Cd co-immobilization in paddy soils

3.1. Inorganic materials

3.1.1. Zero-valent Fe materials

Studies showed that zero-valent Fe materials (ZVI) have remarkably influenced the simultaneous immobilization of As and Cd in rice grains (Suda and Makino, 2016). According to a study by Mlangeni et al. (2020), applying ZVI decreased 32% and 51% in both As and Cd contents, respectively, in rice grains. In the study by Sun et al. (2024), sepiolite-based nanoscale ZVI (S-nZVI) was used to mitigate the accumulation of As and Cd in rice grains and soil. The study revealed a substantial reduction in As and Cd concentrations in rice grains, ranging from 46.18% to 68.13% for As and 24.26%–57.16% for Cd after application. The application of S-nZVI resulted in a significant decrease in the concentrations of Cd and As in the soil pore water, with reductions in Cd ranging from 8.23% to 86.70% and in As between 5.69% and 82.03% (Table 1).

Furthermore, S-nZVI facilitated the conversion of chemical speciation of Cd and As into immobile fractions, thereby reducing their availability to rice plants. Adding S-nZVI caused soil pH to improve and redox potential (Eh) to decrease. In the study of zeolite-supported nanoscale ZVI (Z-nZVI) for immobilization of Cd and As in agricultural soils (He et al., 2022; Li et al., 2020), it was demonstrated that remarkable Cd and As removal efficiencies were achieved in both aqueous solutions and soil samples, with the available metal (loid) concentrations decreasing by 10.2–96.8% via addition of Z-nZVI amendment at 30 g kg^{-1}. In the actual application, the aggregation of nZVI restricts its efficiency of immobilizing As/Cd when dosed to soil; therefore, encapsulation of nZVI in natural zeolite can effectively reduce aggregation and increase remediation efficiency (Li et al., 2020). The application of sulfide-ZVI (S-ZVI) showed a significant reduction of 79% in the phytoavailability of As and Cd after the S-ZVI amendment (Liu et al., 2023). ZVI was a viable and effective way to reduce As and Cd contamination with relatively high remediation efficiency.

3.1.2. Fe oxides

Fe oxides are standard components in soil, especially in tropical or subtropical areas (Kirsten et al., 2021). Fe is an effective soil conditioner that reduces As and Cd's presence through adsorption. Soil particles enriched with Fe oxides exhibit strong attraction to As and Cd ions, reducing their solubility and bioavailability for plant uptake. The chemical interactions between Fe and As/Cd culminate in their immobilization, thus reducing their availability in the soil matrix. As reported by Suda and Makino (2018), the application of Fe materials at 10 and 30 t ha^{-1} resulted in reduced As uptake by rice plants and lower total and inorganic As concentrations in rice grains. Yang et al. (2023) showed in their study that the introduction of modified ferrihydrite resulted in two benefits: the stabilization rates reached 94.66% and 95.52% for water-soluble As and Cd, respectively, and the immobilization efficiency significantly increased by 72.22 % or 25.30% for As and Cd, respectively. Similarly, another study reported that ferrihydrite reduced soil's total As content by 89%, mainly related to Fe/Al oxides (Zhang et al.,

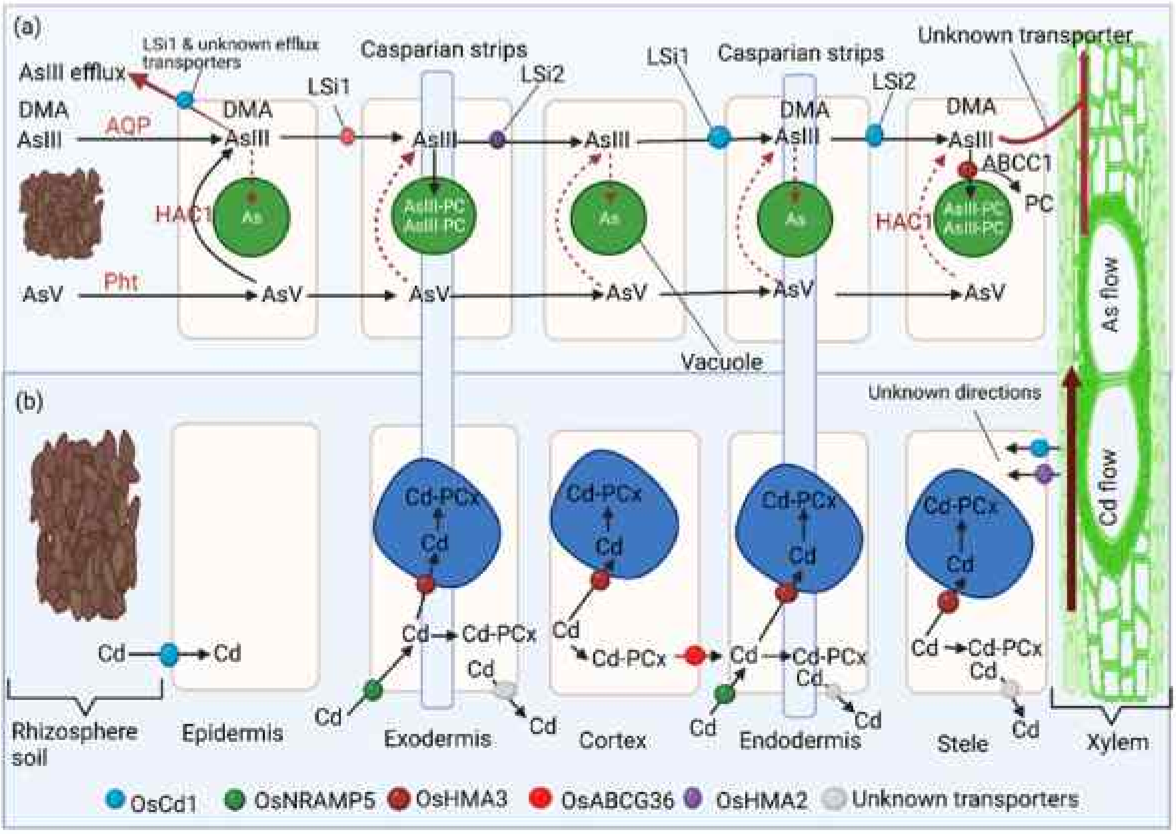

Fig. 2. Diagrammatical portrayal of (a) As(III) and As(V) uptake and As vacuolar sequestration in rice roots. As(III) and As(V) are taken up by rice roots via aquaporins (AQP) and phosphate transporters (Pht), respectively. As(V) is reduced to As(III) by arsenate reductase HAC1. As(III) influx transporter Lsi1 and As(III) efflux transporter Lsi2 are critical in As uptake and transport to the root xylem for translocation. As(III) can be chelated by phytochelatins (PC), and ABCC1 is an As (III)-PC complex transporter that localizes to the vacuolar membrane and transports As into root vacuoles for sequestration. Lsi1 and other unknown transporters mediate As(III) efflux. An unknown transporter is involved in As(III) xylem loading. (b)Schematic diagram of Cd uptake, efflux, vacuolar sequestration, and loading into xylem in rice the root through Cd vacuolar sequestration. Cd is absorbed by root cells from the soil, which OsCd1, OsNRAMP1, OsHMA3, and OsHMA2 mediate. After entering root cells, Cd can be transported into the vacuole by OsHMA3 for sequestration. There are unknown transporters involved in Cd1 xylem loading. There are unknown directions for OsCd1 and OsHMA2. Based on (Zhao and Wang, 2020) improvements.

2022a).

3.1.3. Binary metal oxides

Mn and Fe oxides can adsorb cationic elements, and As, depending on pH and redox conditions, has different adsorption capacities and behaviors. These oxides can oxidize As to less soluble As, thereby affecting the solubility of As. The interaction between Mn/Fe oxides and trace elements in soil systems enhances the ability of these oxides to act as crucial components for the fate and transport of As, Cd, and other trace elements in the environment (Suda and Makino, 2016). In another study by Lin et al. (2020), Fe–Mn binary oxides were investigated as soil amendments. The study concludes that Fe–Mn application significantly reduces the total concentrations of As and Cd in rice grains, husks, straws, and roots. In particular, 0.60 wt% Fe–Mn treatment shows the most effective reduction, with As and Cd content in rice grains decreasing by 42.42% and 36.49%, respectively. Researchers investigated Fe/Fe–Mn modified sepiolite materials to reduce As and Cd, and notably, these materials reduced both Cd (by 57% and 87%, respectively) and As content (by 30% and 25%, respectively) in brown rice. The mechanism was probably due to the Fe and Mn oxides in the sepiolite attracting and binding the Cd and As in the soil, preventing the rice from taking them up (Zhou et al., 2022).

3.1.4. Si materials

Si minerals are essential in immobilizing heavy metals in the soil matrix. The results of a meta-analysis study suggest that applying Si significantly positively impacts the reduction of toxicity and accumulation of As and Cd in cereal crops. Si supplementation reduced shoot As and Cd accumulation by 24.1% and 31.9%, respectively (Huang et al., 2024). Similarly, various Si fertilizers significantly reduced Cd from rice grains compared to As and increased crop yield (Sun et al., 2021). According to Wei et al. (2021), using Si-rich materials, especially in combination with limestone, has a synergistic effect on reducing Cd accumulation in rice grains. Using Si-rich materials in the study resulted in a 16–68% reduction in grain As content and a 30–56% reduction in grain Cd content.

Furthermore, combining Si-rich materials with gypsum was more efficient in reducing the accumulation of arsenic in rice grains. The use of bentonite materials was demonstrated to reduce the concentrations of As and Cd in the shoots of Brassica chinensis L. by 4.05% and 32.5% of exchangeable As and Cd, by 36.2% and 64.6%, respectively. The main mechanisms involved were ion exchange and adsorption, while As was made immobile by the precipitation of Ca and Mg (He et al., 2020). In another case, Wang et al. (2021a) used Si oxide nanoparticles (SiO_2 NPs) to reduce the uptake of As and Cd in rice tissue, observing a significant decrease in the accumulation of these heavy metals compared to the control group. Specifically, at a concentration of 500 mg kg^{-1} SiO_2 NPs, there was a 29% reduction in As uptake and a 68% reduction in Cd uptake in rice sprouts, highlighting the potential of SiO_2 NPs to mitigate heavy metal contamination in rice plants. The underlying mechanism involves the formation of silica bodies in the cell walls of rice roots through the addition of SiO_2 NPs (Rias et al., 2023), which inhibit the

Table 1
The reported inorganic materials capable of simultaneous immobilization of As and Cd in soils and rice grains.

Material types	Main mechanism	Pollutant	As removal efficiency (%)		Cd removal efficiency (%)		Reference
			From soil	From rice grain	From soil	From rice grain	
Iron oxide (Fe_2O_3) is coated with modified hairs (MHs), with $CaCO_3$ as the base amendment.	Adsorption (fungal hyphae and nano-hydroxyapatites attract As and Cd), complexation (where Iron oxide accelerates the formation of iron plaque to reduce As and Cd)	As and Cd	67	81	60	46	Ullah et al. (2020) 10.3390/agronomy10030359
Sepiolite-supported nanoscale zero-valent iron	Combined effects of adsorption, reduction, chemical transformation, and immobilization.	As and Cd	43.86	40.71	47.46	57.15	Sun et al. (2024) org/10.1016/j.eti.2024.103540
Calcium silicate fertilizer	Surface complexation, adsorption, precipitation, and oxidation	As and Cd	–	69	–	55.1	Sun et al. (2021) org/10.1007/s11368-020-02725-w
Fe–Mn binary oxide	Adsorption, precipitation, oxidation, and reduction	As and Cd	65.63	65.63	52.98	52.98	Lin et al. (2020) org/10.1525/elementa.2020.094
Fly ash and steel slag	Formation of complexes and precipitates with Ca, Si, Mn, and Zn with As and Cd	As and Cd	21.85	45.4	57.75	37.4	Chi et al. (2022) org/10.1016/j.geoderma.2022.115879
Natural iron-based desulfurization material	Complexation and co-precipitation ($Cd(OH)_2$ as a product), ion exchange (Fe^{2+} from Cd^{2+}) mechanisms	As and Cd	53.9	33.3–42.7	88.95	26.4–51.6	Peng et al. (2022) org/10.1016/j.scitotenv.2021.152603
Iron/iron-manganese modified sepiolite	Adsorption, Co-precipitation, Oxidation of As(III) to As(V), and Sequestration in the iron plaque	As and Cd	57	27.5	89.5	72	Zhou et al. (2022) org/10.1016/j.scitotenv.2021.152189
CaO + Fe_2CO_3	Metals can bind to the surface of the CaO + Fe_2CO_3 through surface complexation and ion exchange.	As and Cd		26.19		2.43	Yang et al. (2021) org/10.1016/j.jhazmat.2021.125837
Titanium gypsum (TG)	In ion exchange, the positively charged ions in TG (such as calcium and titanium) exchange places with the negatively charged heavy metal ions.	As and Cd	36.0	35.2	35.2	38	Zhao et al. (2009) org/10.1016/j.envpol.2019.113790
Nano iron oxide (Fe_2O_3)	Increased Fe in iron plaques on the root surface aided in lowering As and Cd co-precipitation, adsorption, and oxidation	As and Cd	32.17	14	50.96	4	Li et al., (2022a) org/10.3390/nano 12,081,311
Zero-valent iron	Through ion exchange, oxidation, and precipitation mechanisms	As and Cd	–	98	–	Decreased Cd	Makino et al. (2016) org/10.1080/00,380,768.2016.1203731
Zero valent iron	Through ion exchange, oxidation, and precipitation mechanisms	As and Cd	–	32	–	51	Mlangeni et al. (2020) org/10.1016/j.scitotenv.2019.134696

passive uptake of As and Cd.

3.1.5. Industrial by-products

When coal dust is burned in thermal power plants, fly ash is produced, an industrial by-product. Using fly ash and steel slag significantly reduces the bioavailable concentrations of As and Cd in the soil and their accumulation in rice grains (Singh et al., 2016). Observations show that steel slag minimizes the accumulation of As and Cd in rice grains by 35.8%, 30.3%, 43.4%, and 51.8%, respectively. Similarly, fly ash reduced As by 34.2%, 19.3%, and Cd by 31.4% and 39.0%, respectively, in two varieties (TY998 and HY638). Consequently, applying steel slag and subsequent fly ash reduces the accumulation of Cd, As, and iAs in rice grains (Chi et al., 2022). After using the Fe-based desulfurization material, an industrial by-product that adsorbed SO_2 from the sintering flue gas, the results indicated a reduction in rice grain Cd by 51–80% and a decline in iAs by 37.5–40%. Likewise, the application decreased soil available Cd by 89–90% and As by 38–70% (Feng et al., 2022). In the study of Xu et al. (2021), the application of modified fly ash significantly reduced the Cd content, and the content of bioavailable fractions in Guanzhong and Hunan soils decreased by 40.5% and 53.2%, respectively. The reuse of slag materials has positive effects on metal immobilization in acidic soils. The use of powdered slag in both amounts resulted in significantly lower Cd concentration in rice tissue, 82.6–92.9%, compared to the control (Ning et al., 2016). According to He et al. (2020), steel slag significantly decreased soluble concentrations of Cd in pore water for remediating co-contaminated paddy soils. Applying steel slag reduced total plant Cd concentrations in rice tissues by 48–78% at both stages. According to Chen et al. (2022), adding iron-modified fly ash considerably affects the soil's immobilization of As and Cd. The results showed that fly ash-nZVI was the most effective supplement for the simultaneous immobilization of As and Cd. Iron-modified fly ash reduced the concentration of available As by 30.02–38.09% and Cd by 37.74–52.18%. This indicates that steel slag and fly ash represent favorable potential for remediating As and Cd-contaminated paddy soils. Mg slag significantly increased soil pH in the field study conducted on paddy soils. As a result of the changes induced by S-nZVI addition, the soil became less conducive to the bioavailability of As and Cd. Consequently, the Cd content of rice grains increased by 77%, while the As content decreased by 21%. Mg can directly interact with As and Cd ions on the slag surface to form stable complexes. Mg-containing materials generally reduce the buildup of As and Cd in rice plants (Zhang et al., 2022b).

3.1.6. Liming materials

Liming has been reported to increase As bioavailability due to increased competition from –OH for anion sorption sites on Fe (hydr) oxides (Li et al., 2021). Lime is an abundant and valuable material, inexpensive and natural, and easy to work with, making it an attractive and cost-effective option for removing heavy metals from soil. For the simultaneous mitigation of As and Cd accumulation in rice, lime significantly impacted the reduction of As and Cd in rice under continuous flooding and alternating humidification and drying conditions (Wei et al., 2021). According to Yu et al. (2023), the ability of lime to immobilize both As and Cd in flooded paddy soils depends on the availability of pore water Fe. At higher pH values, dissolved organic carbon competes with As for sorption sites on Fe (hydr)oxides, thereby limiting As immobilization. The results of this study provide better insight into the effectiveness of soil liming for As and Cd co-contamination in paddy soils. In the survey conducted by Bi et al. (2020), the use of oyster shells, composed predominantly of calcium carbonate ($CaCO_3$), showed significant effectiveness. The addition of oyster shell calcined at 800 °C at a dosage of 2.0% to soil contaminated with Cd and As resulted in a considerable reduction of 98% in Cd content in the edible part of the vegetable Bak Choi and, at the same time, a 73% reduction in As content.

3.1.7. Phosphate and sulfate containing materials

Materials containing anions such as phosphates and sulfates can immobilize heavy metals. They can bind to the metals and form insoluble compounds, trapping them in the soil and preventing them from dissolving and contamination. Huang et al. (2016) found that phosphate rock materials, including phosphate rock activated with oxalic acid, were most effective in reducing exchangeable Cd content in soil by 47%. Applying phosphate materials to contaminated soils effectively immobilizes Cd by reducing its mobility and converting its chemical speciation from more labile fractions to more stable fractions. Sulfate containing additives have been reported to be a promising technique for mitigating heavy metal contamination in rice because they can form complexes with As and Cd. According to Yan et al. (2022), the microbial sulfate induced the formation of As-sulfide minerals, Cd-sulfide minerals, and Fe-sulfide minerals, thereby limiting the transfer of As and Cd from the non-rhizosphere to the plant root. Using sulfate better affected contaminated soils with high-concentration As and low-sulfate backgrounds. Cao et al. (2020) demonstrated that with the application of sulfate containing amendments, bioavailable Cd and As were immobilized by 85.0% and 80.1%, respectively, converting the bioavailable Pb, Cd, and As into insoluble mercaptometal compounds (CdS) and less soluble $FeAsO_4$. The findings revealed that the application of sulfate containing material significantly reduced As and Cd levels in rice seedlings because of reduced As and Cd bioavailability in the rhizosphere soil rather than the iron plaque.

3.2. Organic materials

3.2.1. Modified biochar

Biochar has been widely used in the remediation of As- or Cd-contaminated water and soil due to its high specific surface area with abundant pore structure and functional groups. Biochar has a great deal of potential for remediating Cd-contaminated soils, as evidenced by the 92% reduction in Cd from the soil when using multiply modified biochar (Wang et al., 2021b). Ren et al. (2021) observed that applying biochar reduced the effect of Cd stress by decreasing the Cd content in plant leaves by 45.05%. In another study, amendments of hybrid ash/biochar biocomposites decreased extractable Cd by 77.9%–96.1% and 52.4%–70.7% in two hybrid rice cultivars (ZJZ17) and (HY518), respectively (Lei et al., 2020). The use of biochar in the remediation of contaminated soils is an essential topic of current research.

In actual practice, the application of biochar is restricted by a limited amount of surface functional group or low efficiency in treating both As and Cd contaminants; therefore, biochar was modified to enhance its performance in regulating As/Cd accumulation in rice grain and paddy soil (Islam et al., 2021). Numerous studies investigated the use of ZVI with biochar materials, and the results have demonstrated a significant impact on reducing As and Cd from rice grains (Qiao et al., 2019; Yang et al., 2021). Qiao JiangTao et al., 2018 reduced the buildup of Cd and As in rice by combining biochar with ZVI. In the mechanism, metals are adsorbed onto the biochar surface. At the same time, ZVI formed insoluble complexes with them, thus decreasing their bioavailability using this synergistic approach. When applying 1% ZVI-biochar amendment with a Fe loading ratio of 5% into the paddy soil, a noteworthy 93% reduction in Cd concentration and a 61% reduction in As concentration were achieved in rice grains. Similarly, Yang et al. (2022a) found that application of 1% nZVI-biochar reduced Cd and As accumulation in rice grains by 15.85–69.16% and 23.06–59.45%, respectively. It was observed that iron plaque acted as a barrier against As accumulation in rice, with higher As concentration immobilized on the iron plaque when treated with nZVI-biochar. According to Wang et al. (2020), $FeCl_3$-modified biochar made from corn straw demonstrated exceptional efficacy in rendering Cd and As inert in soil. $FeCl_3$-modified corn straw-derived biochar's surface oxygen-containing functional groups, can exchange cations through surface complexation. As and Cd were adsorbed by –COOH and –OH, which reduced 63.21% for As and 95.1% for Cd. A 10% $FeCl_3$-modified corn straw biochar dosage showed significant effectiveness in immobilization. These findings demonstrate the potential of $FeCl_3$-modified corn straw biochar as a material that holds great promise for simultaneously remediating soils contaminated with As and Cd. An adsorption experiment in an aqueous solution showed that hydroxyapatite, zeolite, and biochar materials (HZB) can adsorb and covalently bind Cd and As(V) via –OH, –COOH, -Si-O-Si and CO_3^{2-} groups, thereby promoting the in situ immobilization of Cd and As in the soil solution. Gu et al. (2019) applied HZB materials in a mass ratio of 2:1:2 to paddy soil with a dosage of 9000 kg ha^{-1}, reducing concentrations of Cd and inorganic As in brown rice to 0.18 and 0.16 mg kg^{-1}, respectively. Applying goethite-modified biochar to paddy rice concurrently lowers the accumulation of As and Cd. The findings demonstrated that adding 2% of goethite-modified biochar to the soil significantly reduced the amount of Cd and As in rice grains by 85 and 77 %, respectively (Irshad et al., 2022). Modifying Biochar with chemical elements has attracted considerable attention due to its proven effectiveness in reducing both As and Cd contents in paddy soils. Among the materials studied, Si-based biochars (Yang et al., 2023), biochar supported nZVI (Yang et al., 2021; Song et al., 2022), biochar supported sulfurized nZVI (Xu et al., 2024), Fe modified biochar (Pan et al., 2019), Ca and Fe enriched biochar (Islam et al., 2021), goethite-combined/modified biochar (Abdelrhman et al., 2022), Mg–Al modified biochar (Li et al., 2022a; Peng et al., 2023), successfully demonstrated simultaneous immobilization of As and Cd from paddy soils. Table 2 provides a comprehensive list of both organic and inorganic materials whose ability to simultaneously immobilize As and Cd in soils and rice grains has been documented.

3.2.2. Compost and manure

Organic matter such as manure, Compost, and manure can reduce As and Cd contamination in paddy soils. By binding to these metals, these materials make them less soluble and less accessible to rice plants to uptake. Observers noted that the application of chicken manure had little effect on total Cd and slightly reduced total As and inorganic As of rice grains at an application rate of 2.0%. Chicken manure is effective only when combined with other techniques (Liu et al., 2019).

4. Common mechanisms of As and Cd co-mitigation by materials

As and Cd are simultaneously immobilized by a complex method that depends on several variables, including the chemical forms of the metals, the composition of the immobilization matrix, and the surrounding setting (Yuan et al., 2017). First, the metals are adsorbed on the surface of the immobilization medium. Usually, this adsorption is followed by a series of chemical processes, resulting in more stable metal compounds that are less prone to detach from the matrix (Gankhurel et al., 2020). The type of immobilization matrix can have a significant impact on how well co-immobilization works. As and Cd can be adsorbed and immobilized more successfully in some matrices, including clays and hydrous oxides (Yang et al., 2022b). Environmental factors can also affect how well co-immobilization works. For example, the pH of the solution can affect how well the metals adhere to the matrix (Yu et al., 2023). As detailed in Fig. 3, several materials can simultaneously immobilize As and Cd through different processes.

4.1. Precipitation

The precipitation effect is essential in As and Cd immobilization in soil. When certain kinds of anions (hydroxide, carbonate, phosphate,

Table 2
The reported organic and inorganic materials capable of simultaneous immobilization of As and Cd in soils and rice grains.

Material types	Main mechanism	Pollutant	As removal efficiency (%)		Cd removal efficiency (%)		Reference
			From soil	From rice grain	From soil	From rice grain	
Zerovalent Iron and biochar	The ZVI can reduce the bioavailability of these metals by forming insoluble complexes, while the biochar can adsorb them onto its surface.	As and Cd	–	61	–	93	J.t. Qiao et al. (2018) org/10.1016/j. chemosphere.2017.12.081
Calcium enriched biochar	Adsorption: Under precipitation, calcium arsenate ($Ca_3(AsO_4)_2$) and cadmium carbonate ($CdCO_3$) is formed, and Ion exchange due to the presence of calcium ions (Ca^{2+})	As and Cd	27	60.75	71	85.65	Islam et al. (2021) 10.1016/j. chemosphere.2021.131102
Ferric trichloride ($FeCl_3$) modified corn-straw Biochar (FCB).	Surface complexation and cation exchange mechanisms where the surface oxygen-containing functional groups of FCB, such as –COOH and –OH, could adsorb As and Cd	As and Cd	74.57	63.21	50	95.1	Wang et al. (2020) 10.3390/ijerph17030827
Ferrous Ion and Biochar	Ferrous ions form complexes through oxidation and also react with As or Cd to form precipitates	As and Cd	33	75	23	80	Rong et al., (2019) 10.3390/app10010300
Woody peat + $Fe(NO_3)_3$	Formation of Fe plaques and poorly crystalline Fe oxides that bind to As and Cd	As and Cd		As decreased		Cd decreased	Wang et al. (2021a) org/10.1016/j. scitotenv.2018.08.387
Hydroxyapatite + zeolite + Biochar (HZB)	Complexation, whereby HZB could complex with Cd and As(V) via –OH, –COOH, -Si-O-Si, and CO_3^{2-} groups to generate carboxylates, silicates, and carbonates, facilitating Cd and As immobilization in soil solution.	As and Cd	37.25	Decreased by 28.6 in the soil	54.05	Decreased by 88.9 in the soil	Gu et al. (2019) org/10.1016/j. ecoenv.2019.01.003

etc.) exist in the soil solution upon amendment addition, cadmium can form precipitates, including $Cd(OH)_2$, $CdCO_3$, and $Cd_3(PO_4)_2$. In contrast, arsenic can be precipitated into forms such as AsS, $Fe_4(AsO_4)_2O_3$, $FeAsO_4$, etc (Ainiwaer et al., 2022; Feng et al., 2022). Several substances, such as iron oxides (FeO, Fe_2O_3, Fe_3O_4), hydroxides ($Fe(OH)_2$, $Fe(OH)_3$), and sulfides (FeS, FeS_2), can precipitate As and Cd out of solution. Other ions, such as calcium and magnesium, are generally present and aid in hastening this process (Li et al., 2022a). As Porter et al. (2004) demonstrated in arsenic, the precipitating agent, such as Fe or aluminum (Al), is added to the soil, and the reaction with As and Cd forms insoluble precipitates, which are then trapped in the soil. The mechanism for achieving this involves the following processes: $FeAsO_4$ and $Al(OH)_3$ are two complexes of insoluble precipitates formed when the precipitant combines with As and Cd. Once these precipitates are trapped in the soil, they become less available to plants (Cao et al., 2020). It has also been observed by Smieja-Król et al. (2015) that As and Cd can be immobilized by the development of metal sulfides in the presence of sulfide-producing microorganisms; on the other hand, As and Cd can also be immobilized by forming metal oxides in the presence of oxygen. As and Cd can be effectively immobilized in soil by the precipitation process. It is crucial to remember that the procedure is not entirely successful since it is a pH-dependent process (Wang et al., 2022b). Iron oxides such as FeO surfaces facilitate the direct coordination of As and Cd through electrostatic interactions and ligand exchange with surface hydroxyl groups (Fe–OH), forming inner-sphere complexes where the metal ions are directly bound to the Fe atom (Li et al., 2023).

4.2. Complexation

Surface complexation is another important mechanism for Cd and As immobilization in soil (Yu et al., 2023). It involves the stable complexation formation as a reaction between functional surface groups and Cd^{2+}, AsO_3^{3-}, and AsO_4^{3-} ions in the surrounding solutions (Hu et al., 2015). Surface complexation is characterized as a selective and irreversible process and thus is defined as the inner-sphere complexation (Bradl, 2004). Iron (II) oxide and Fe_3O_4 exhibit more diverse surface complexation mechanisms for As and Cd than FeO due to their varied surface structures and charge densities, potentially involving complexation pathways like edge-sharing and corner-sharing (Chowdhury, 2013). Contrasting Fe(II) and Fe(III) oxides, $Fe(OH)_2$ and $Fe(OH)_3$ interact with As and Cd through both inner-sphere complexation via covalent bonds and anion exchange, offering diverse binding mechanisms (Mustafa et al., 2013). FeS and FeS_2 exhibit distinct binding behavior towards As and Cd compared to Fe oxides and hydroxides, forming insoluble sulfides (As_2S_3 and CdS) through direct precipitation driven by covalent bonding between the metal cation and sulfur anion (Bostick and Fendorf, 2003). All the binding processes are pH, competing ions, and redox conditions dependents.

4.3. Ion exchange

Cd/As immobilization by ion exchange mechanism is the exchange between Cd/As ions and the anions/cations sorbed onto/included into soil components or amendments (Vejvodová et al., 2021). Ion exchange is considered a reversible process and tends to be affected by competing ions in the soil solutions (Serrano et al., 2009). Furthermore, a stoichiometric amount of exchangeable anions/cations will be released to the soil solution when Cd/As ions are adsorbed onto the material (Zhao et al., 2023). As and Cd can also sorb onto the surfaces of several substances, such as metal oxides, humic compounds, and clays. The material's surface charge and the metal ions' affinity for the surface frequently drive this process. A material (the adsorbate) adheres to the surface of another substance (the adsorbent) through the sorption process. For the adsorption of As and Cd, a solid with a large surface area, such as activated carbon, clay, or charcoal, is usually used as the adsorbent (Wang et al., 2022a). This is possible by changing the pH of the solution, the metal content, and the type of adsorbent.

4.4. Electrostatic attraction

The principle of the electrostatic attraction mechanism is as follows: for the inorganic materials such as clay minerals or metal oxide, the edge and surface M-O-H group can be protonated or deprotonated with pH variation of soil solution, leading to the variable charges on the materials (Ainiwaer et al., 2022). For organic materials, functional groups, including phenol, carboxylic, and amine groups, can adsorb or desorb

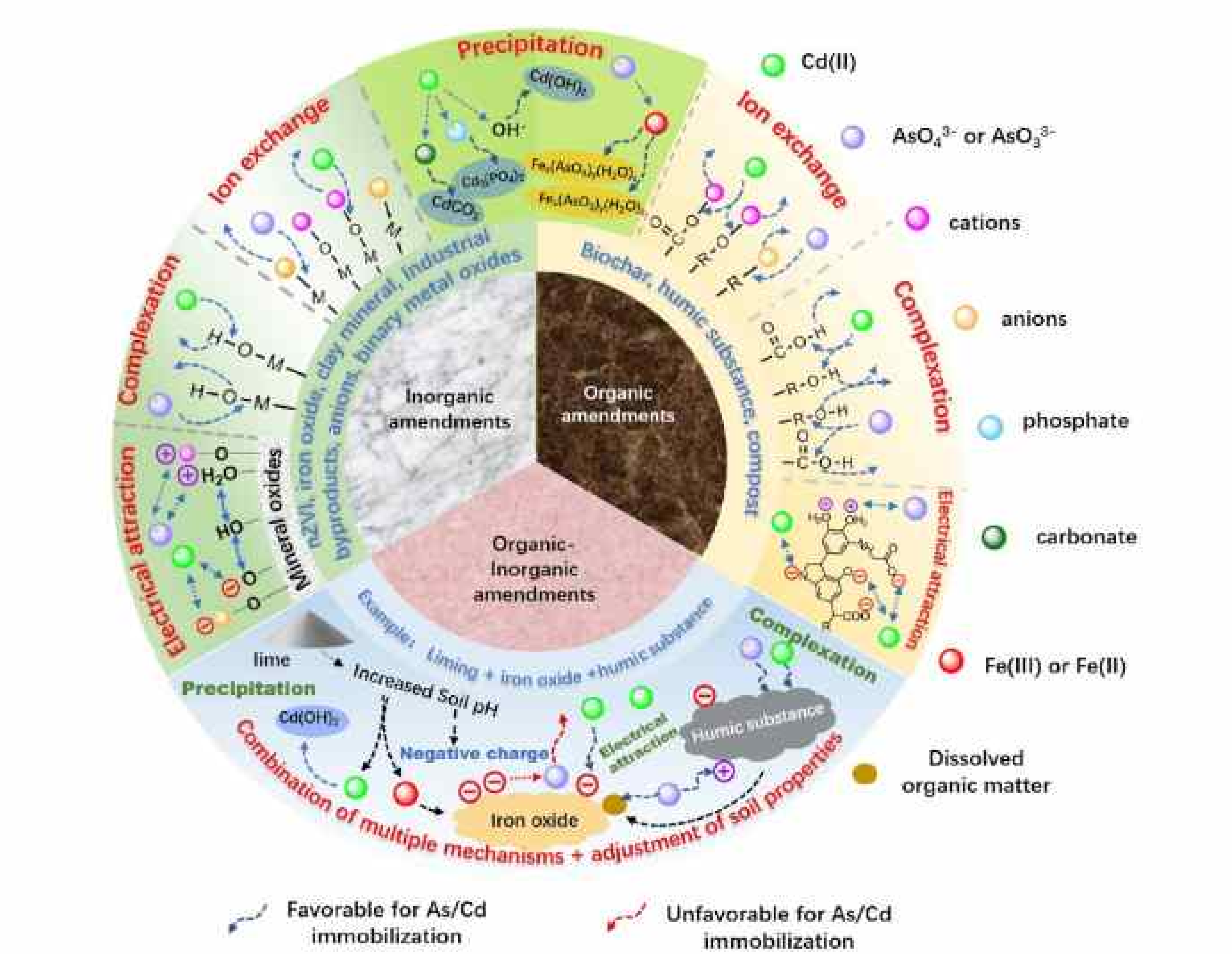

Fig. 3. This figure illustrates the various common chemical processes that inorganic (e. g., clay mineral, iron oxide, industrial by-products, and binary metal oxides), organic (e.g., biochar, humic substance, and compost), and organic-inorganic amendments (e.g., lime + iron oxide + humic substance) immobilize As/Cd in soil. Red and dotted arrows indicate favorable and unfavorable conditions for As/Cd immobilization, respectively.

anions/cations at different solution environments (pH, co-existing ions, etc), making the material's surface negative or positive charged and thus demonstrate electrostatic repulsive or attractive force toward Cd/As ions in soil solution (Lee et al., 2022; Lin et al., 2022). In the study on Cd adsorption onto vermiculite, reduction of surface negative charge denoted by zeta potential was revealed with increasing Cd uptake on vermiculite, indicating the vital role electrostatic interaction plays in enhancing Cd adsorption capacity (Padilla-Ortega et al., 2014). Another study carried out on As(V) removal by nZVI demonstrates that corrosion of the nZVI varied with the fluctuation of solution pH, implying the change of material's surface charge with pH variation and influence of electrostatic interaction on As(V) immobilization capacity (Wu et al., 2017).

5. Meta-analysis

5.1. *Effect sizes of inorganic and combined organic and inorganic materials on rice grain*

Twenty-four studies reported significant decreases in As and Cd from rice grains using different materials. Both organic and combined organic and inorganic materials showed negative effect sizes on As and Cd concentrations of rice grains. In our analysis, organic and inorganic amendments significantly negatively affected As and Cd in rice grains, accounting for the overall effect sizes of −62.3% and −67.8% for As and Cd reduction, respectively. For inorganic amendments, the overall effect sizes on As and Cd concentration decreasing in rice grains were −33.8% and −54.9% (Fig. 4), less efficient than the combined application of organic and inorganic amendments. Compared to inorganic materials alone, all materials in Fig. 4(b) and (d), representing combined organic and inorganic materials, exhibit an even more significant reduction in As and Cd by 84.3% and 23.4%, respectively. Similarly, a Tian et al. (2021) meta-analysis demonstrated that Fe-modified biochar enhanced the immobilization of As and Cd in paddy soils. This observation indicates that using a combination of inorganic and organic materials to remove As and Cd simultaneously from rice grains increases the efficiency of the materials.

Notably, Fe-containing materials are the main components that can immobilize both As and Cd from rice grains in both inorganic and combined organic and inorganic materials (Fig. 4). This is probably due to strong adsorption capacity compared to other elements (Qiao et al., 2018). Ferrous materials reduce As and Cd concentrations in rice grains, including nZVI, Fe oxides, and Fe-enriched biochar. Silicate-based materials generally show lower effectiveness in reducing As and Cd content in rice grains, except for iron biochar and silica. Furthermore, in all collection studies, Fe-containing materials significantly reduce Cd

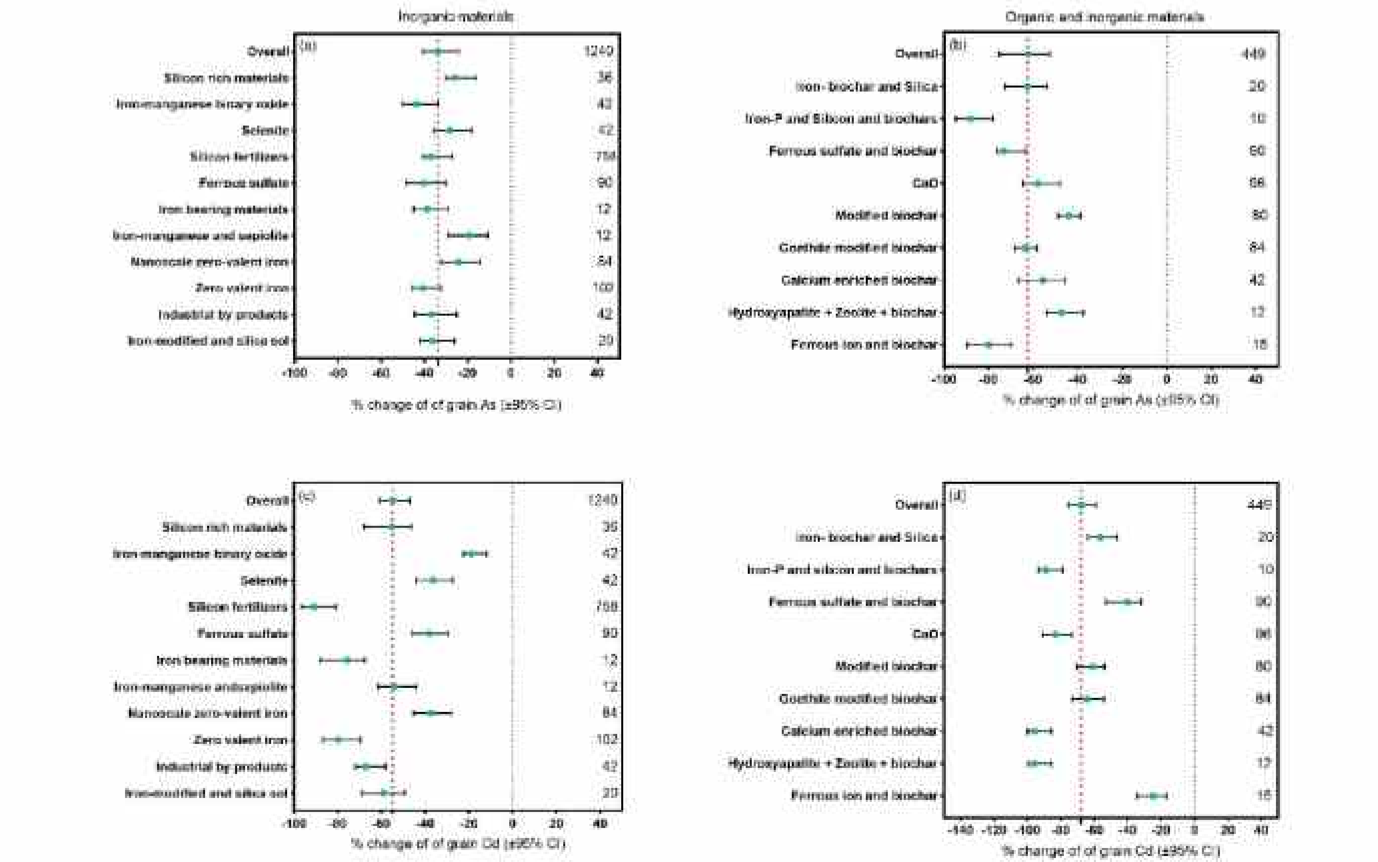

Fig. 4. Effect sizes of inorganic materials on changes in (a) As and (c) Cd concentrations and combined organic and inorganic materials on changes in (b) As and (d) Cd concentrations in rice grains. The red solid dots indicate the mean effect sizes (change percentages of the grain As and Cd under 95% confidence intervals (CIs). The 95% CI not crossing the zero line implies significant differences between the treatment and control groups. The numbers show the sample sizes.

compared to As in rice grains.

In addition, the combination of organic materials, mainly biochar, with inorganic materials (Fe oxides) reduces As and Cd concentrations more effectively than using organic or inorganic materials alone. Several meta-analysis studies have demonstrated that biochar is an effective amendment to remediate As and Cd-contaminated soils (Hu et al., 2020; Tian et al., 2021). Our analysis shows the quantitative contribution of inorganic and combined organic and inorganic additives to immobilizing As and Cd from rice grains. It suggests Fe as the main component of the inorganic ingredient for developing an effective additive for mitigating As and Cd from grains.

5.2. Effect sizes of combined organic and inorganic materials in the soil

Various remediation techniques have been investigated to reduce the concentrations of these toxic elements in the soil environment. Among these techniques, organic and inorganic materials have gained attention due to their potential to reduce As and Cd content in soil. Installing iron-containing materials has shown promising results in remediation efforts (Fang et al., 2021). This discussion examines the effectiveness of different materials, including inorganic, organic, and combined approaches, in mitigating As and Cd contamination in soil environments. Through a comparative analysis, the study sheds light on the superior remediation potential of combined organic and inorganic materials, particularly those containing iron. The results in Fig. 5 highlight the effectiveness of both inorganic and combined organic and inorganic materials in mitigating soil As and Cd concentrations.

In comparison, inorganic materials showed a notable reduction with an average of 32.6% for As and 41.9% for Cd; the combined organic and inorganic approach showed even greater effectiveness with an increase of 35.5% for As and 10.3% for Cd. The combined approach demonstrated superior remediation potential with an average reduction of 44.3% for As and 46.25% for Cd. Further analysis indicates that iron-containing materials are central to inorganic and combined changes. Among the inorganic additives, Fe-containing materials, such as ferrous sulfate, exogenous Fe, and Fe-based desulfurization materials, significantly reduced both As and Cd. Similarly, Fe-containing compounds such as ferrous and biochar additives, iron-modified biochar and silica sol additives, and iron phosphate and silicon-based biochar significantly reduced As and Cd concentrations. Similar to the abovementioned results by Pathy et al. (2023) and Viana et al. (2024), the combined utilization of biochar and phosphate rocks highlights the importance of sustainable agriculture and soil remediation practices. These results highlight the importance of incorporating organic and inorganic materials, particularly those containing Fe, for effective remediation of As and Cd contamination in soil environments.

5.3. Effect sizes of iron, calcium, silicon, manganese, and phosphorus based materials on the rice grain

We determined the influence of different elements in the materials used to remove As and Cd from rice grains by considering the material composition with the highest concentration. The results showed significant adverse effects of each element on the reduction of As and Cd. Based on the obtained datasets, the As and Cd accumulation changes in rice grains were notable variations, as illustrated in Fig. 6, and the meta-analysis assessed the mean effects. The application of Fe, S, Mn, P, Si, and Ca significantly ($P < 0.05$) reduced the accumulation of As and Cd in the rice grains, up to overall 42.4% (−54.2%, −46.1%, −43.8%, −42.2%, −40.3%, and −34.3%) and overall 52.1% (−74.9%,-51%,

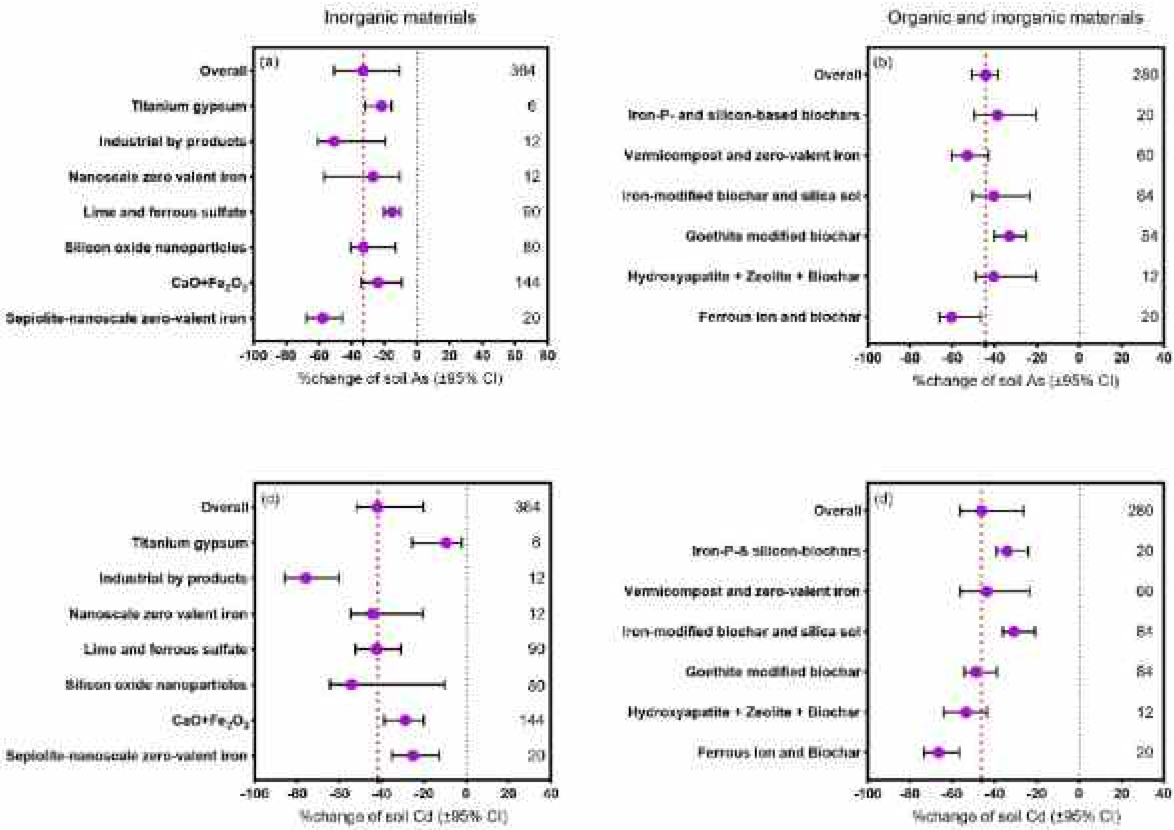

Fig. 5. Effect sizes of inorganic materials on the changes in (a) As and (c) Cd concentrations and combined organic and inorganic materials on the changes in (b) As and (d) Cd concentrations in the soils. The red dotted line indicates the mean effect sizes in the soil- As and Cd, respectively (change percentages of the grain As and Cd under 95% confidence intervals (CIs). The 95% CI not crossing the zero line implies significant differences between treatment and control groups. The numbers indicated the sample sizes.

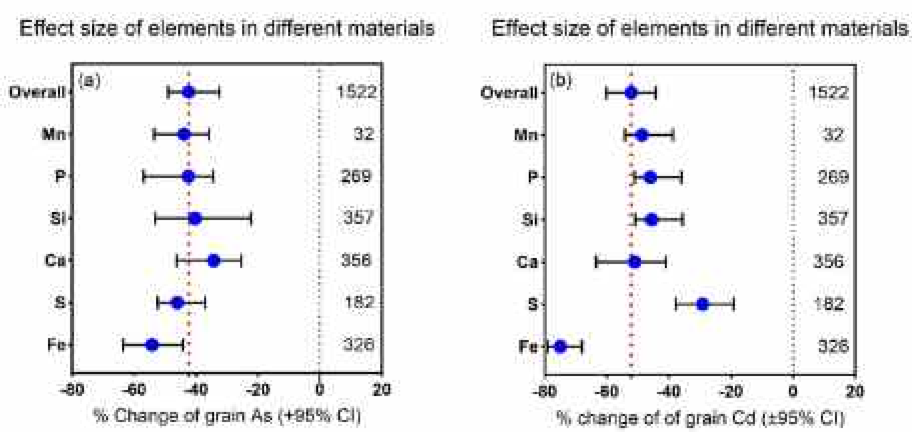

Fig. 6. Effect sizes of elements on the changes in (a) As and (b) Cd concentrations in rice grains. The red solid dots indicate the mean effect sizes (change percentages of the grain As and Cd under 95% confidence intervals (CIs). The 95% CI not crossing the zero line implies significant differences between treatment and control groups. The numbers showed the sample sizes.

−48.9%, −45.9%, −45.5%, and −29.1%) for Fe, Ca, Mn, P, Si, and S respectively. From meta-analysis, Fe-based materials negatively influenced As and Cd, reducing As concentration by −54.2% and Cd by −74.9%. Fe is a crucial component of the materials used to remediate paddy soil with As and Cd. Therefore, it can be concluded that Fe has a strong potential for simultaneously removing these pollutants. According to this meta-analysis, researchers find Fe an essential component of materials for remediating As and Cd-contaminated paddy soils.

The present study found that other elements present in the remediation materials contribute to the overall effectiveness of reducing As and Cd accumulation. Fe-containing materials consistently exhibit superior effectiveness in reducing both As and Cd despite variations in material composition. Silicate-based materials, excluding ferrous biochar and silica, generally demonstrate lower effectiveness. The results imply that Fe-based materials could offer a viable solution for treating paddy soil contaminated with As and Cd, especially when combined with organic elements like biochar. This approach could significantly impact agricultural practices where soil health and food safety are threatened by heavy metal contamination.

6. The future focus on As and Cd co-immobilization in agricultural soils

The present study analyzed the comparative efficiency and mechanisms of simultaneous reduction of As and Cd availability in paddy soils by applying various organic and inorganic materials. While research has made progress in understanding the effects of passivators, some critical areas still require additional investigation and improvement to establish efficient co-immobilization strategies. The areas for future research concentration highlighted in this study include.

i. *Customized nanomaterials* such as biochar composites, metal oxides, and zeolites, which have high surface area and specific properties, should be realized to improve the adsorption of As and Cd.
ii. *Functionalised biochars* are designed to possess tailored surface properties, including pH, porosity, and functional group contents. These changes aim to decrease As and Cd while increasing their selectivity and adsorption capacity for specific soil conditions.
iii. *Modeling and prediction tools:* Develop models and prediction tools to evaluate the long-term effectiveness of co-immobilization techniques, considering factors such as soil properties, climate conditions, and land use practices.
iv. *Molecular dynamics simulations:* Gain atomic-level insights into adsorption processes, including ion speciation, diffusion, and surface complexation, informing material design and optimization.
v. *Modify adsorbent characteristics:* Align adsorbent properties (such as pH, pore size, and surface charge) with individual soil attributes and contaminant compositions to achieve the best co-immobilization outcomes.
vi. *Formulate materials* to overcome challenges posed by other soil constituents, such as phosphates and carbonates, which may impede the adsorption of As and Cd due to competition.
vii. *Examine the involvement of microorganisms and microbial activities* in immobilizing As and Cd. This may include exploring microbial changes such as sulfate reduction or metal sulfide formation that lead to the formation of insoluble compounds.
viii. *Integration with carbon sequestration:* There is a growing interest in integrating contaminant immobilization techniques with carbon sequestration practices to address multiple environmental challenges simultaneously. Future research could focus on developing materials or strategies that mitigate As and Cd contamination, enhance soil carbon storage, and promote long-term soil health.

7. Conclusion and recommendation

Based on a meta-analysis, inorganic and combined organic-inorganic materials imposed adverse significant effects; more specifically, combined organic-inorganic materials had a more significant substantial effect. The study highlights the effectiveness of combined organic and inorganic approaches, especially those incorporating iron-containing materials, in mitigating As and Cd contamination in soil environments. Both organic and inorganic materials individually showed reductions in As and Cd concentrations, but the combined approach demonstrated even greater effectiveness. Iron emerged as a crucial component, significantly reducing As and Cd concentrations. Integrated strategies utilizing organic and inorganic materials, mainly those containing iron, are essential for practical remediation efforts targeting As and Cd-contaminated soil. In general, the innovative method should focus on combating the two pollutants together and restoring farmland for rice production. Combining inorganic materials with biochar is crucial in synthesizing materials capable of reducing As and Cd and improving paddy soil quality.

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CRediT authorship contribution statement

Frank Stephano Mabagala: Writing – original draft, Methodology, Formal analysis, Data curation. **Ting Zhang:** Software, Methodology, Investigation, Data curation. **Xibai Zeng:** Investigation, Data curation. **Chao He:** Writing – original draft, Investigation, Formal analysis. **Hong Shan:** Writing – review & editing, Formal analysis. **Cheng Qiu:** Investigation, Funding acquisition, Data curation. **Xue Gao:** Formal analysis, Data curation. **Nan Zhang:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Shiming Su:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.121661.

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