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*Review Article*

# Organic Amendment-Assisted Phytoremediation of Heavy Metals-Contaminated Paddy Soils

**Khoirunnisaa' Kamaluddin Aniisah* and Osumanu Haruna Ahmed**

*Faculty of Agriculture, Universiti Islam Sultan Sharif Ali (UNISSA), Sinaut Campus, KM33 Jalan Tutong, Kampong Sinaut, TB1741 Tutong, Brunei Darussalam*

## ABSTRACT

Paddy soils are increasingly threatened by heavy metal contamination from the overuse of agrochemicals, industrial emissions, and wastewater irrigation because these challenges pose risks to food safety, crop productivity, and environmental quality. High costs, environmental trade-offs, or low effectiveness under flooded paddy conditions often limit the use of conventional remediation techniques. This review examines the synergistic potential of organic amendment-assisted phytoremediation (OAAP) as a sustainable approach for detoxifying paddy soils contaminated with heavy metals. This approach combines plant-based remediation with the application of organic amendments to enhance the bioavailability of heavy metals, support plant growth and development, and restore soil health. We selected eight studies from the literature published between 2005 and 2025 using strict inclusion criteria. The reviewed studies demonstrate that OAAP significantly improves heavy metals uptake by hyperaccumulator plants by enhancing soil organic matter, microbial activity, and enzymatic functions. The mechanisms identified include chelation, rhizosphere acidification, activation of antioxidative enzymes, and shifts in microbial communities. However, post-remediation concerns such as safe biomass disposal and long-term soil health remain underexplored. Although OAAP demonstrates strong potential in controlled settings, field-scale validations and comprehensive risk assessments are essential for broader adoption. This review highlights OAAP's promise as a nature-based and low-input strategy for rehabilitating heavy metal-contaminated paddy soils, aligning with the goals of sustainable agriculture.

*Keywords:* Bioavailability, circular agriculture, food safety, nature-based remediation, soil restoration, sustainable rice farming

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*E-mail addresses*:
aniisahkhoirun.kamaluddin@gmail.com (Khoirunnisaa' Kamaluddin Aniisah)
ahmedosumanu0@gmail.com (Osumanu Haruna Ahmed)
* Corresponding author

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## INTRODUCTION

Paddy soils are anthropogenic wetland soils developed for rice cultivation in bunded and levelled fields, where the soil is intentionally flooded and puddled under water-saturated conditions (Liu et al., 2021; Witt & Haefele, 2005). As of 2023, paddy cultivation covered approximately 168 million hectares worldwide (Shahbandeh, 2025). This hectarage is the backbone of the global rice production, a cereal crop which serves as a staple food for more than 50% of the world's population (Wang et al., 2024). However, these agroecosystems are increasingly threatened by different pollutants arising from agricultural and anthropogenic activities. Chemical contamination from commercial fertilisers, organic manures, pesticides, herbicides, and untreated wastewater irrigation has significantly degraded paddy soil quality (Nuruzzaman, 2025). This degradation could jeopardise paddy grain yield and food safety and disrupt critical soil functions such as nutrient cycling and microbial balance. Furthermore, polluted paddy soils may increase environmental risks by promoting contaminants' movement into downstream water bodies and into human and animal food chains (Akram et al., 2018).

Among the various pollutants affecting paddy systems, heavy metals stand out because they are persistent and hazardous. For example, cadmium (Cd), arsenic (As), and mercury (Hg), primarily introduced through industrial emissions and the excessive use of agrochemicals, have become a significant concern in paddy farms. At toxic levels, these heavy metals degrade soil health, diminish crop productivity, and compromise food safety (Tang et al., 2020; Wang et al., 2024). Excessive Cd accumulation in rice from contaminated paddy soils may be transferred to the food chain and cause health issues, such as lung cancer and renal tubular dysfunction, thus necessitating its mitigation (Rasin et al., 2025; Wang et al., 2024). Similarly, although arsenic is not an essential element for humans, chronic arsenic intake through rice consumption beyond safe limits damages the kidneys, lungs, and liver (Zheng et al., 2019). Moreover, methylated Hg, which forms under anaerobic soil conditions that are typical of flooded paddy fields, may also bioaccumulate in the food chain, posing health risks including nervous, respiratory, and cardiovascular disorders to humans (Charkiewicz et al., 2025; Zhou et al., 2023).

Paddy soils are vulnerable due to their periodic flooding and fluctuating redox conditions, a process which enhances the mobility and uptake of certain heavy metals by rice plants. These challenges call for effective, sustainable, and locally adaptable remediation strategies to restore paddy soil health in a manner which safeguards food systems. Conventional mitigation strategies include intermittent irrigation, soil passivation using inorganic or organic amendments, phytoremediation, leaching, electrokinetic remediation, and selecting low-accumulation rice cultivars (Chen et al., 2022; Hu et al., 2013; Zhao et al., 2022). Although each of these methods possesses certain advantages, they have some limitations. For example, intermittent irrigation reduces methane emissions, but this practice inadvertently increases As and Cd uptake because of redox-driven changes in heavy metal solubility (Cui et al., 2025). Soil passivation and phytoremediation are slow or ineffective for composite pollution. Moreover, many conventional approaches lack adaptability to different soil types and climatic conditions, and in some cases, trade-offs arise where alleviating one contaminant exacerbates another (Cui et al., 2025).

Considering the challenges in paddy soil remediation, more sustainable and environmentally friendly approaches are gaining attention, particularly the use of organic amendments and phytoremediation. Although organic amendments, such as compost and biochar, have been widely used to improve soil properties and immobilise contaminants, their effectiveness in enhancing overall heavy metal removal remains limited (Wang et al., 2024; Zhou et al., 2023). Similarly, although phytoremediation is cost-effective and environmentally friendly, its performance is often constrained by the low bioavailability of heavy metals in soils (Tang et al., 2020; Wang, 2024).

To address the afore-stated limitations, the integration of organic amendments with phytoremediation, hereafter referred to as organic amendment-assisted phytoremediation (OAAP), has emerged. Organic amendment-assisted phytoremediation leverages the synergy between organic amendments and plant-based remediation processes, which may include the extraction of heavy metals by hyperaccumulators, microbial stimulation in the rhizosphere, or contaminant immobilisation in the root zone of plants. Through these mechanisms, OAAP can improve heavy metals' bioavailability, support plant growth, and regulate microbial activity to improve remediation efficiency (Li et al., 2020; Tang et al., 2020; Zhou et al., 2023). Previous reviews have commonly examined phytoremediation or organic amendments separately across broad contaminated soil systems (Anggraini et al., 2025; Ghani et al., 2022; Gao et al., 2023; Sharma et al., 2023). In contrast, this review focuses specifically on their integrated use in paddy soils, where flooding and redox fluctuations strongly influence heavy metals mobility, plant uptake, and remediation outcomes (Cui et al., 2025). Its novelty lies in synthesising paddy-specific OAAP evidence on heavy metals removal, soil health restoration, post-remediation soil reuse, biomass fate, and food safety. To this end, this review critically synthesises the literature on OAAP for paddy soil remediation by examining the approaches used, evaluating their reported outcomes, and identifying research gaps that must be addressed to support its practical implementation in sustainable paddy soil management.

## MATERIALS AND METHODS

### Data Collection and Screening

We conducted this systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021) to ensure a transparent and replicable methodology. We performed a comprehensive search on 23 February 2025 using search engines such as Scopus, ScienceDirect, Google Scholar, and AGRICOLA, limiting the search to peer-reviewed journal articles published between 2005 and 2025, and including only articles written in English. To capture a wide range of the literature on OAAP in paddy soils, general and specific search terms were used. These included “organic amendment assisted phytoremediation paddy” and Boolean combinations such as “organic AND amendment AND assisted AND phytoremediation AND paddy.” We also conducted targeted searches using amendment-specific phrases, including “biochar assisted phytoremediation AND paddy” and “compost assisted phytoremediation AND paddy.”

The initial search yielded 461 records. After removing 33 duplicates, we retained 428 unique records for screening. Title and abstract screening resulted in the exclusion of 407 studies that did not meet the review criteria, primarily because of a lack of relevance to OAAP or a focus outside of paddy soil systems. The remaining full-text articles were assessed against predefined inclusion and exclusion criteria, detailed in the following section. The whole process of identification, screening, and selection is summarised in Figure 1.

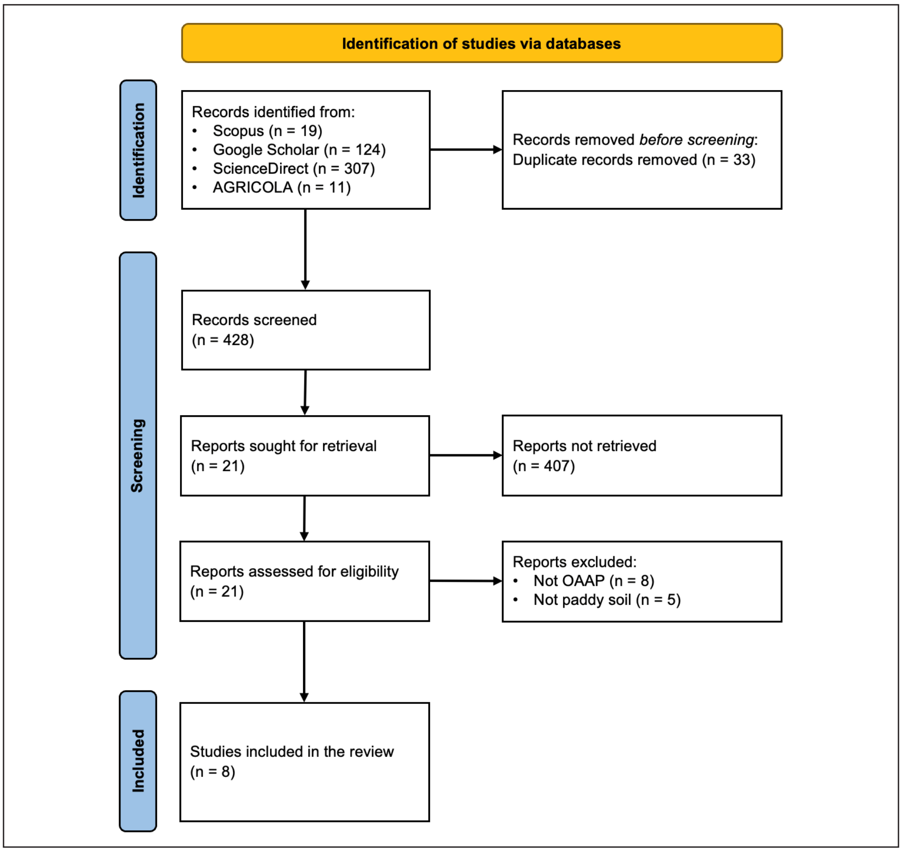

*Figure 1.* An amended PRISMA 2020 flow diagram illustrating the identification, screening, and inclusion process for studies on organic amendment-assisted phytoremediation (OAAP) in paddy soils

## Inclusion and Exclusion Criteria

To determine eligibility for this review, three inclusion criteria were applied. Firstly, studies which focus specifically on the remediation of paddy soils. Secondly, studies which explicitly integrated both organic amendments and phytoremediation were considered. Thirdly, eligible studies were required to assess outcomes such as contaminant reduction, plant heavy metal uptake, or soil quality improvement resulting from the combined treatment. Following title and abstract screening, we reviewed 21 full-text articles and excluded 11 full-text articles because they investigated only one OAAP component (Either organic amendment or phytoremediation), using non-organic amendments, or focusing on non-paddy soil systems. Ultimately, eight studies fulfilled all inclusion criteria and were selected for in-depth analysis. The selected eight studies are summarised in Table 1, which presents the source journal, the number of relevant articles from each journal, and the titles of the included publications.

Table 1
*Source journals and titles of articles included in the systematic review on organic amendment-assisted phytoremediation in paddy soils*

| Journal | No. of Articles | Article Title | Authors |
|---|---|---|---|
| Environmental Science and Pollution Research | 1 | Biochar-assisted phytoextraction of arsenic in soil using *Pteris vittata* L. | Zheng et al. (2019) |
| Environmental Technology & Innovation | 1 | Biochar assists phytoremediation of cadmium by regulation of rhizosphere microbiome in paddy fields | Wang et al. (2024) |
| International Journal of Phytoremediation | 2 | Phytoextraction of copper from contaminated soil by *Elsholtzia splendens* as affected by EDTA, citric acid, and compost | Yang et al. (2005) |
| | | Impacts of bamboo biochar on the phytoremediation potential of *Salix psammophila* grown in multi-metal contaminated soil | Li et al. (2020) |
| Journal of Environmental Management | 1 | Application potential of biofertiliser-assisted *Pennisetum giganteum* in safe utilisation of mercury-contaminated paddy fields | Zhou et al. (2023) |
| Journal of Environmental Science and Health | 1 | Copper phytoavailability and uptake by *Elsholtzia splendens* from contaminated soil as affected by soil amendments | Peng et al. (2005) |
| Plant Soil | 1 | The efficiency of Cd phytoextraction by *S. plumbizincicola* increased with the addition of rice straw to polluted soils: the role of particulate organic matter | Zhou et al. (2018) |
| Sustainability | 1 | Biochelator-assisted phytoremediation for cadmium (Cd) pollution in paddy fields | Wang et al. (2021) |

### Data Analysis

The selected studies were analysed qualitatively to extract relevant information on OAAP in paddy soils. For each study, key data were compiled, including the source journal, article title, publication year, and primary research focus. Additional information was recorded on the type of organic amendment used, the phytoremediator species employed, the targeted heavy metal contaminants, and the reported outcomes related to metal uptake, contaminant removal, and improvements in soil quality. Data were organised to compare the interaction between amendment type and phytoremediator, the effectiveness of the remediation approach, and any effects on soil properties or metal bioavailability. Studies that discussed the role of chemical, biological, or physiological mechanisms in enhancing phytoremediation were also noted for later discussion. Due to variability in experimental designs, soil types, contaminant profiles, and data reporting formats, a quantitative meta-analysis was not conducted. Instead, a narrative synthesis approach was used to highlight shared findings, differences, and methodological gaps. The results are presented and subsequently discussed in detail, supported by a summary table (Table 2) that outlines the key findings of each study.

## RESULTS AND DISCUSSION

### Organic Amendment-assisted Phytoremediation Approaches in Paddy Soils

Among the different phytoremediation approaches applied in paddy soils, phytoextraction was the most frequently adopted approach in the reviewed studies. This process involves the use of hyperaccumulator plants, which are capable of absorbing soluble heavy metals through their roots and translocating them to aboveground tissues, which are later harvested for contaminant removal. Phytoextraction is valued for its simplicity, cost-effectiveness, and potential for biomass valorisation, particularly when combined with organic amendments that enhance heavy metal availability and plant health (Awad et al., 2021; Li et al., 2020).

Several combinations of organic amendments and hyperaccumulator species have been used to remediate heavy metal-contaminated paddy soils. We classified the organic amendments used into five categories: agricultural wastes, composts, biochars, biochelators, and biofertilisers. Table 2 summarises these approaches by outlining the type of organic amendment, the phytoremediator, the target pollutant, and the key findings, including improvements in heavy metal uptake, plant performance, and soil conditions. Altogether, these combinations reflect the diversity and adaptability of OAAP approaches across different paddy soil systems.

Table 2
*Summary of key findings from the selected papers on organic amendment-assisted phytoremediation of paddy soils contaminated with heavy metals*

| No. | Organic Amendment | Phytoremediator | Pollutant | Key Findings | Reference |
|---|---|---|---|---|---|
| 1 | Compost | *Elsholtzia splendens* | Copper (Cu) | Increased water-extractable Cu by shifting Cu into more bioavailable exchangeable and organic-bound forms.<br>Resulted in a 3.6-fold increase in Cu extraction.<br>Enhanced shoot Cu accumulation in *E. splendens*, especially in paddy soils.<br>Compost was more effective in paddy soils than in mined soils.<br>Demonstrated suitability of *E. splendens* for Cu phytoextraction when paired with compost. | Yang et al. (2005) |
| 2 | Manure | *Elsholtzia splendens* | Cu | Increased water-exchangeable Cu in contaminated paddy soil.<br>Stimulated Cu uptake and shoot biomass in *E. splendens*.<br>Mechanisms involved rhizospheric acidification and DOM chelation.<br>Highlighted the Cu tolerance, high biomass, and accumulation potential of *E. splendens*.<br>Manure at appropriate rates significantly improved Cu bioavailability and phytoextraction efficiency. | Peng et al. (2005) |
| 3 | Rice straw | *Sedum plumbizincicola* | Cd | Increased Cd uptake by 14.3-20.7% in the first harvest, and this positive effect was sustained across four cropping cycles.<br>Significantly raised soil POM mass.<br>Enhanced oxidizable Cd fractions and Cd bioavailability within POM pools.<br>Improved availability of N, P, and K, supporting plant growth and biomass production.<br>Cd concentrations in POM fractions decreased after repeated phytoextraction. | Zhou et al. (2018) |

Table 2 (*continued*)

| No. | Organic Amendment | Phytoremediator | Pollutant | Key Findings | Reference |
|---|---|---|---|---|---|
| 4 | Rice straw-derived biochar | *Pteris vittata* L. | As | Alkaline biochar raised soil pH, mobilising As and increasing its bioavailability.<br>Biochar amendment (1-5%) significantly enhanced As accumulation in *P. vittata* after 40 days.<br>DGT measurements indicated active root uptake and spatial As redistribution.<br>Rates >1% posed a risk of As leaching, highlighting the need for rate optimisation.<br>Biochar used had negligible As content, preventing secondary contamination. | Zheng et al. (2019) |
| 5 | Bamboo-derived biochar | *Salix psammophila* | Cd, Zinc (Zn), Cu, and lead (Pb) | Increased soil organic matter and nutrient availability yet reduced bioavailable metal fractions.<br>Enhanced accumulation of Cd, Zn, and Cu in *S. psammophila*.<br>Optimal BBC dose (1-5%) supported plant growth; 7% suppressed biomass.<br>Improved bioconcentration and translocation factors for Cd and Zn.<br>Demonstrated potential for cost-effective, eco-friendly in situ remediation using fast-growing willow species. | Li et al. (2020) |
| 6 | Biochelators (Humic acid and rhamnolipid) | *Iris sibirica* L. | Cd | HA and RL treatments improved growth, Cd uptake, and stress tolerance in *I. sibirica* under Cd-contaminated conditions.<br>HA increased dry weights of leaves (3 mg $L^{-1}$), stems (7 mg $L^{-1}$), and roots at optimal doses.<br>HA reduced Cd accumulation in plant tissues, indicating immobilisation.<br>RL enhanced Cd accumulation in stems and roots, indicating increased phytoavailability.<br>RL also elevated SOD, POD, and CAT activities, improving antioxidative stress response. | Wang et al. (2021) |

Table 2 (*continued*)

| No. | Organic Amendment | Phytoremediator | Pollutant | Key Findings | Reference |
|---|---|---|---|---|---|
| 7 | Biofertiliser (*Bacillus*-inoculated distiller's grain) | *Pennisetum giganteum* | Hg | Inoculation with Hg-resistant *Bacillus* sp. increased soil *Bacillus* abundance by 157.12%.<br>Enabled removal of 27.52% of water-soluble Hg *via* microbial volatilisation and adsorption.<br>Reduced THg in plant tissues by 48-94%, depending on organ.<br>Significantly lowered MeHg concentrations across plant parts.<br>Biofertiliser-assisted *P. giganteum* cultivation generated fourfold higher income than traditional rice planting. | Zhou et al. (2023) |
| 8 | Moss-derived biochar | *Solanum nigrum* and *Echinochloa crus-galli* | Cd | Porous biochar structure (~4.79 nm) provided binding sites and habitat for beneficial microbes.<br>Improved Cd removal rate from 11-15% to 23-35% after 60 days.<br>Increased bacterial abundance from ~2.26-2.76 × $10^6$ to 3.89-4.78 × $10^6$ cells $g^{-1}$ soil.<br>Enhanced organic matter and enzyme activities, supporting soil fertility and plant health.<br>Enriched stress-tolerant, biofilm-forming bacteria that remodelled the rhizosphere and improved Cd tolerance. | Wang et al. (2024) |

*Note.* DOM = dissolved organic matter; POM = particulate organic matter; DGT = diffusive gradients in thin films; HA = humic acid; RL = rhamnolipid; SOD = superoxide dismutase; POD = peroxidase; CAT = catalase; THg = total mercury; MeHg = methylmercury

## Mechanisms Underpinning Organic Amendment-Assisted Phytoremediation

Organic amendments influence the mobility of heavy metals, plant uptake, and soil functionality through a combination of chemical, biological, and physiological processes. These mechanisms play a role in enhancing the bioavailability of target heavy metals, thereby improving plant health and soil microbial dynamics, and ultimately facilitating more efficient and sustainable phytoremediation. The key mechanisms identified in the reviewed studies are subsequently discussed based on their contributions to the availability of heavy metals, plant performance, and soil restoration (Figure 2).

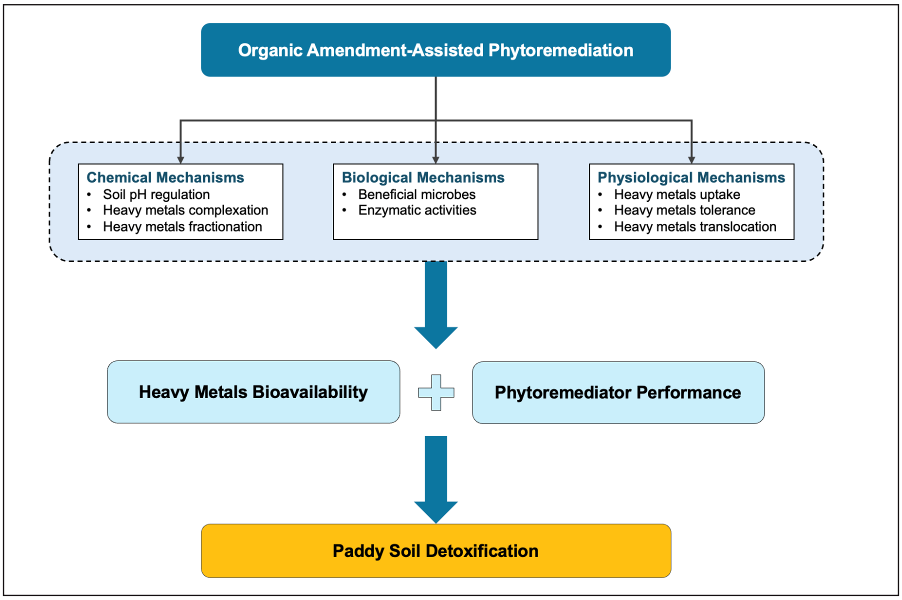

*Figure 2.* A summary of the three primary mechanisms governing organic amendment-assisted phytoremediation for detoxifying heavy metals-contaminated paddy soils

### *Enhancement of Heavy Metal Bioavailability*

Organic amendments influence the speciation, solubility, and distribution of heavy metals in paddy soils, thereby directly affecting their bioavailability to plants. For example, Yang et al. (2005) found that the application of compost (5% w/w) significantly increased the water-extractable and exchangeable fractions of Cu, resulting in a 3.6-fold increase in Cu phytoextraction by *Elsholtzia splendens.* Similarly, organic manure enhanced Cu bioavailability by stimulating rhizospheric acidification and promoting chelation with dissolved organic matter, both of which increased Cu mobility and uptake (Peng et al., 2005). These effects are attributed to the presence of functional groups such as carboxyl and hydroxyl moieties on organic matter surfaces, which complex with metal ions and shift them into more available fractions (Sabir et al., 2015; Wiszniewska et al., 2016).

For Cd, rice straw amendment elevated particulate organic matter pools and increased oxidizable Cd fractions. Thus, maintaining high Cd bioavailability and supporting uptake by *Sedum plumbizincicola* across four cropping cycles (Zhou et al., 2018). In As-contaminated soils, rice straw-derived biochar increased soil pH, and this shifts As into more labile forms, enhancing As accumulation in *Pteris vittata*. However, higher application rates (>1%) pose a potential leaching risk (Zheng et al., 2019). Likewise, bamboo-derived biochar (BBC) demonstrated a dual role, namely reducing the soluble fractions of Cd, Zn, Cu, and Pb, yet supporting their accumulation in *Salix psammophila* through improved bioconcentration and translocation (Li et al., 2020). These findings demonstrate that whereas some amendments mobilise heavy metals to facilitate uptake, others immobilise excess bioavailable fractions to reduce phytotoxicity. Hence, suggesting the importance of both dose and metal type.

Further evidence demonstrates that biochelators, such as humic acids (HAs) and rhamnolipid (RL), modulate heavy metal bioavailability in contrasting ways. Humic acids reduced Cd uptake in *Iris sibirica* by immobilising free Cd ions in the rhizosphere, whereas RL increased Cd accumulation in stems and roots, likely by enhancing Cd solubility (Wang et al., 2021). These outcomes illustrate how the same amendment class can induce opposing effects depending on formulation and target heavy metal, thus underscoring the context-specific nature of OAAP strategies. Overall, OAAP-enhanced heavy metals bioavailability is governed by mechanisms such as pH regulation, heavy metal complexation, chelation, and redistribution of heavy metal fractions, all of which vary with the type and composition of the organic amendment used.

### *Improvement of Phytoremediator Plant Performance*

Organic amendments play a pivotal role in enhancing plant performance under heavy metal stress. This is essential for successful phytoremediation. The reviewed studies reported improvements in biomass, heavy metal translocation efficiency, nutrient uptake, and stress tolerance across various OAAP systems. For example, *Elsholtzia splendens*, which is reputed for its high tolerance to Cu and biomass, exhibited significantly enhanced growth and Cu accumulation when treated with compost or organic manure, particularly through improved nutrient availability and reduced metal toxicity (Peng et al., 2005; Yang et al., 2005). In a long-term study, rice straw amendment supported biomass production and sustained Cd uptake in *Sedum plumbizincicola* over four consecutive cropping cycles, demonstrating the potential of OAAP to deliver durable physiological improvements (Zhou et al., 2018). Similarly, BBC improved the accumulation of Cd, Zn, and Cu in *Salix psammophila* through enhancing bioconcentration and translocation factors. However, excessive BBC application (7%) suppresses plant growth, highlighting the importance of optimising amendment dosage (Li et al., 2020). In *Pteris vittata*, rice straw-derived biochar increased As translocation to aboveground parts through increasing soil pH and enhancing uptake mechanisms (Zheng et al., 2019).

Beyond uptake and biomass, OAAP enhances the phytoremediator plant's tolerance to oxidative stress. In *Iris sibirica*, the HAs application improved nutrient uptake and increased the dry weights of leaves, stems, and roots, whereas the RL treatment activated antioxidant defence enzymes, such as superoxide dismutase, peroxidase, and catalase, and this enables the plant to cope with Cd-induced stress (Wang et al., 2021). These findings suggest that organic amendments can modulate physiological responses such as photosynthesis, root growth, metal transport, and defence enzyme activities, all of which contribute to enhanced remediation performance.

In a field application of biofertiliser derived from *Bacillus*-inoculated distiller's grains, *Pennisetum giganteum* exhibited vigorous growth and a marked reduction in Hg accumulation in the plant tissues (Zhou et al., 2023). This biofertiliser-assisted *P. giganteum* cultivation system generated economic returns, approximately four times higher than those from traditional rice cultivation on Hg-contaminated paddy fields, reflecting both improved physiological health and enhanced agronomic viability (Zhou et al., 2023). Generally, these studies demonstrate that organic amendments enhance plant performance by mitigating heavy metal toxicity, reducing phytotoxic stress, stimulating growth parameters, and promoting metal translocation, which are key attributes that underpin the effectiveness of phytoremediation.

### ***Restoration of Paddy Soil Health***

Besides facilitating the removal of heavy metals and promoting plant growth, organic amendments play a crucial role in restoring soil health through enhancing microbial dynamics, enzymatic activities, organic matter content, and nutrient cycling. These biological improvements are essential for maintaining remediation outcomes and restoring long-term soil functionality in paddy cultivation. For example, the application of moss-derived biochar increased soil organic matter, microbial biomass, and enzyme activities, such as urease, acid phosphatase, and catalase. These are among the indicators of improved soil fertility and biological function (Wang et al., 2024). The same study reported a significant increase in rhizosphere bacterial populations, from approximately 2.26-2.76 $\times 10^6$ to 3.89-4.78 $\times 10^6$ cells $g^{-1}$ of soil, alongside an enrichment of stress-tolerant and biofilm-forming bacteria that remodelled the rhizosphere and promoted Cd tolerance and removal. Similarly, the use of a biofertiliser comprising *Bacillus*-inoculated distiller's grains significantly increased the abundance of Hg-resistant *Bacillus* spp. It enabled microbial volatilisation and adsorption of Hg, resulting in reduced Hg accumulation in *Pennisetum giganteum* tissues (Zhou et al., 2023). These biological activities may reduce pollutant load and contribute to soil microbial reconditioning, an essential factor in post-remediation resilience.

Broader studies have also revealed that organic input such as compost, manure, and biochar foster shifts in microbial community structure, favouring taxa that are capable of either solubilising metals to support phytoextraction or immobilising them through transformation processes (Duan et al., 2022; Hussain et al., 2021; Wiszniewska et al., 2016). In several cases, enhanced microbial activity coincided with improved soil enzyme activities and better root-soil interactions, indirectly supporting plant health and remediation efficiency. Collectively, studies reviewed in this present paper highlight that

OAAP contributes to contaminant reduction, alongside the biological recovery of soil systems through enhanced microbial functioning, organic matter enrichment, and improved biochemical processes, thereby supporting sustainable land use post-remediation.

## Safe Use of Treated Paddy Soils

Successful remediation extends beyond contaminant removal; it must also ensure that the remediated paddy soil is safe for sustainable rice production, especially in systems where soil quality directly influences rice safety and consequently, regional food security. Although OAAP has shown promising results in lowering extractable heavy metal fractions and improving soil fertility, the long-term safety of planting edible crops, particularly rice, on remediated soils remains uncertain. For example, Wang et al. (2024) demonstrated that moss biochar-assisted phytoremediation significantly reduced soil Cd concentrations and improved enzyme activity and organic matter content, indicating enhanced soil quality. However, the study did not evaluate the implications of these changes on paddy productivity or rice grain heavy metal content. Similarly, Zhou et al. (2023) reported successful Hg reduction in paddy soils using biofertiliser-assisted *Pennisetum giganteum*, but the reuse potential of the remediated soil for food crop cultivation was not assessed. These findings highlight a recurring limitation in OAAP research: although heavy metal extraction efficiency is well-documented, the post-remediation suitability of soils for food production, especially in terms of residual bioavailable heavy metal fractions and food safety thresholds, remains underexplored.

The study by Tamma et al. (2025) revealed limited focus on the post-remediation suitability of soils for food crop production, underscoring the importance of moving beyond contaminant removal to address the long-term usability of the remediated soils. Although some OAAP strategies have demonstrated effectiveness in reducing total heavy metal concentrations and enhancing soil quality, many studies neglect the issue of whether these improvements translate into safe conditions for growing food crops such as rice. This is important because the residual bioavailable heavy metals may still threaten crop safety, particularly when left unassessed. This is problematic in paddy systems, where heavy metal uptake by rice plants can lead to food chain contamination. Tamma et al. (2025) argue that evaluating soil recovery based solely on reduced metal content or improved fertility is insufficient. Instead, they recommend a more rigorous assessment framework that includes testing for plant-available metal fractions, potential for heavy metal re-accumulation in edible tissues, and alignment with established food safety benchmarks. Furthermore, it is also essential to integrate such assessments into national guidelines to support safe agricultural reuse and protect human health. By broadening the scope of OAAP evaluations, future applications can better ensure that detoxified soils are genuinely fit for sustainable food production, especially in regions where rice is a dietary staple and a cornerstone of food security. Hence, comprehensive post-remediation evaluations, including assessments of heavy metal bioavailability, re-accumulation risk, and crop safety, are needed to support the long-term viability of OAAP in food systems in ensuring healthy crop growth without compromising food quality.

## Fate of Post-Remediation Biomass

Evaluating the post-remediation fate involves assessing residual heavy metal concentrations and potential risks of recontamination. Hyperaccumulator biomass harvested after phytoextraction may contain elevated levels of heavy metals, thus making disposal or reuse a potential environmental concern. Therefore, different routes such as added value products, biofuels, composting under monitored conditions, or regulated disposal must be considered to prevent secondary contamination.

The harvested biomass from hyperaccumulator plants represents a critical post-remediation concern, particularly when edible or fast-growing species are used. These plants often contain high levels of accumulated heavy metals in their aerial parts, rendering them unsuitable for direct consumption or composting without proper safeguards. Wang et al. (2021) found that *Iris sibirica* L. accumulated over 1000 mg kg$^{-1}$ of Cd in roots and stems when assisted by rhamnolipid, a level exceeding the Tolerable Weekly Intake for adults, which is 0.4-0.5 mg per week, or 60-70 µg per day, as recommended by the Joint FAO/WHO Expert Committee on Food Additives (JECFA) (Charkiewicz et al., 2023). Similarly, Zhou et al. (2023) observed substantial Hg concentrations in *Pennisetum giganteum* tissues after biofertiliser-assisted remediation, including 93.72% reduction in stem total Hg, indicating that biomass management must be approached with caution. One valorisation option is biochar production, which may stabilise heavy metal contents to enable the material to be reused in non-edible applications. However, even biochar must comply with the maximum permissible concentration (MPC) limits for heavy metals before being applied to soil. Table 3 presents the MPC values for several heavy metals

Table 3
*Maximum permissible concentration (MPC) for selected heavy metals in paddy soils*

| Heavy Metal | MPC (mg kg$^{-1}$) | Country | Reference |
|---|---|---|---|
| Hg | 1.0 | China | Du et al. (2021) |
| Cd | 1.5 | China | Ji et al. (2012) |
| As | 14 | India | Mandal et al. (2023) |
| Pb | 50 | China | Wang et al. (2023) |
| Cu | 100 | Pakistan | Khan et al. (2024) |
| Zn | 200 | Pakistan | Khan et al. (2024) |

(As, Cd, Hg, Pb) which threaten paddy plants and food safety when their concentrations exceed the allowable limit, including micronutrients such as Cu and Zn, which become phytotoxic at elevated levels. Alternatively, Ionata et al. (2024) suggest that biomass derived from phytoremediation can be valorised into renewable biofuels, such as bioethanol, biodiesel, and biogas, through biochemical and thermochemical conversion processes. For example, *Pteris vittata* biomass has been utilised as a feedstock for bioethanol and biogas production following As phytoremediation. The biomass was pretreated with ultrapure water and sodium hydroxide, and a subsequent ethanol-assisted anaerobic digestion which enables recovery of energy-rich products while managing As-containing residues.

Ultimately, the responsible handling of post-remediation biomass is important to safeguard environmental and food system integrity. Whether through valorisation into safe, non-edible applications or carefully regulated disposal, post-remediation strategies must ensure that the benefits of phytoremediation are not undermined by unintended pathways of heavy metal re-entry into the ecosystem.

## Comparative Sustainability and Economic Viability of Organic Amendment-assisted Phytoremediation and Conventional Remediation Strategies

Organic amendment-assisted phytoremediation aligns well with the goals of sustainable agriculture by promoting waste reutilisation, improving soil health, and reducing environmental risks associated with conventional remediation practices. For example, rice straw, which is often burned in paddy-producing regions, was repurposed as an organic amendment to enhance Cd uptake by *Sedum plumbizincicola*, demonstrating how crop residues can be converted into valuable remediation inputs (Zhou et al., 2018). Similarly, the use of manure and compost supports nutrient recycling and minimises synthetic fertiliser dependence (Peng et al., 2005; Yang et al., 2005). Meanwhile, biochar application improves long-term soil structure, water retention, and carbon sequestration potential (Li et al., 2020; Wang et al., 2024; Zheng et al., 2019). Moreover, the integration of biochelators and biofertilisers further enhances microbial diversity and rhizosphere health, promoting a self-reinforcing system of soil regeneration (Wang et al., 2021; Zhou et al., 2023). These attributes make OAAP a nature-based, low-input alternative to conventional lime-based treatments, which often require repeated application and can lead to long-term soil degradation if mismanaged.

Compared with conventional remediation technologies, OAAP provides a broader sustainability function by combining contaminant removal with soil health restoration. Conventional approaches such as water management, passivation, and low-accumulation rice cultivars can reduce metal mobility, crop uptake, or exposure risk, but they may not necessarily restore contaminated paddy soils through contaminant removal and biological soil recovery. For instance, water management regulates As and Cd availability through redox changes, but its effects are contaminant-specific: flooding may reduce Cd availability through sulfide precipitation, whereas drying may reduce As availability but increase Cd release through CdS oxidation, making simultaneous As and Cd control difficult under field conditions (Cui et al., 2025). Passivation can effectively reduce metal bioavailability and grain accumulation, as shown by Zhao et al. (2022), who reported lower DTPA-extractable Cd, Cr, and Pb in soil and reduced metal accumulation in rice grains after applying multi-component passivators. However, passivation immobilises metals rather than removing them. Furthermore, low-accumulation rice cultivars represent a food-chain risk mitigation strategy instead of a soil remediation method. They can reduce heavy metals transfer into rice grains, but they mainly manage plant uptake and grain accumulation instead of treating the contaminated soil itself (Hu et al., 2013). Phytoremediation alone is environmentally friendly, but its performance is often limited by low metal bioavailability, slow removal rates, and poor growth of non-hyperaccumulators under metal stress; these limitations explain why assisted strategies using organic amendments have been explored to improve plant-based remediation (Tang et al., 2020; Wiszniewska et al., 2016).

In contrast, OAAP integrates plant-based metal uptake with organic amendment-driven improvements in nutrient supply, microbial activity, organic matter status, and soil biochemical functioning. Several reviewed studies reported measurable improvements in metal uptake, contaminant removal, phytoremediator performance, and soil biological activity under OAAP treatments (Wang et al., 2024; Yang et al., 2005; Zhou et al., 2018; Zhou et al., 2023). However, these outcomes cannot be directly normalised against the conventional methods because the studies differed in contaminant type, remediation endpoint, plant species, amendment type, and experimental duration. Therefore, OAAP is viewed as a soil-restorative strategy that can complement conventional remediation technologies where long-term sustainability and practical affordability are priorities.

From an economic perspective, the use of readily available agricultural wastes such as manure, rice straw, and biochar feedstocks reduces material costs, making OAAP more accessible to resource-limited farming communities. For example, Zhou et al. (2023) reported that biofertiliser-assisted *Pennisetum giganteum* cultivation remediated Hg-contaminated paddy soil and generated income four times higher than traditional rice farming on the same land, highlighting the dual benefits of land rehabilitation and biomass utilisation. Despite these advantages, certain limitations must be addressed. For example, labour-intensive biomass management, variability in amendment quality, and the lack of standardised application guidelines may limit scalability. Additionally, upfront investment in amendment production, such as biochar kilns or composting infrastructure, could pose a barrier for smallholder farmers without institutional support. To this end, comprehensive cost-benefit analyses and policy incentives will be essential to establish OAAP as a viable alternative for large-scale adoption in paddy systems.

## Implications and Future Directions

The findings of this present review highlight the potential of OAAP as a sustainable approach for remediating heavy metal-contaminated paddy soils. The studies elucidate that organic amendments can enhance heavy metal uptake by hyperaccumulator plants, besides contributing to long-term improvements in soil quality and microbial health. These dual benefits position OAAP as a nature-based solution that aligns with the goals of sustainable agriculture and circular economy frameworks. Furthermore, the successful use of locally available organic wastes such as rice straw, manure, and compost underscores their practicality in resource-constrained agricultural systems. As paddy cultivation remains central to food security in many countries, the adoption of OAAP strategies may serve as an important step toward improving degraded soils, besides minimising environmental impacts.

However, several gaps and limitations in current OAAP research were also identified. Most of the studies were conducted at pot-scale or under controlled conditions, limiting their applicability to field scenarios. Long-term impacts, crop productivity outcomes, and the potential for residual heavy metal accumulation in subsequent cropping cycles remain underexplored. Moreover, the post-remediation management of phytoremediation biomass, particularly for species that accumulate substantial heavy metal concentrations, requires further investigation to ensure that these materials do not become secondary sources of contamination. This is especially relevant for species such as *Solanum nigrum* and *Pennisetum giganteum*, which are known to be used as food or forage in certain contexts. The potential for heavy metals to enter the food chain *via* consumption or animal feed poses significant health and environmental risks if biomass is not properly evaluated and managed. In addition, mechanisms involving soil-plant-microbe interactions under fluctuating field conditions such as flooding, drainage, or pH shifts are still poorly understood. Future studies should prioritise field-scale validation, multi-season trials, and comprehensive assessments of both agronomic outcomes and environmental safety, to advance OAAP toward practical, large-scale implementation.

## CONCLUSION

Organic amendment-assisted phytoremediation presents a sustainable approach for remediating heavy metal-contaminated paddy soils, besides improving soil health and fertility. This review demonstrates that integrating organic amendments with hyperaccumulator plants can enhance heavy metals bioavailability, promote plant growth, and support beneficial microbial activity, which are factors that are essential for effective phytoremediation. However, the success of OAAP is site-specific, influenced by soil properties, contaminant types, and amendment selection. In spite of the encouraging outcomes, the limited number of studies, most of which are pot-based, restricts the generalizability of current findings. Current studies rarely examine long-term soil health, paddy productivity, and food safety. Moreover, the post-remediation fate of contaminated biomass and the economic feasibility of OAAP require further investigation. Future research should prioritise field-scale validation, assess multi-season impacts, and develop standardised procedures for amendment application and biomass management. Addressing these gaps will be essential to advancing OAAP as a viable, scalable solution for sustainable paddy soil management.

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## DECLARATION ON THE USE OF AI-ASSISTED TOOLS

The authors declare that the manuscript was prepared by the authors. The conception of the review, literature search, article screening, data interpretation, critical synthesis, conclusions, and final approval of the manuscript were undertaken by the authors. Artificial Intelligence-assisted tools were used only for language polishing, grammar checking, and improving sentence clarity.

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