



REVIEW ARTICLE

Microbial enhancement of *Sesbania sesban* (L.) Merr. for efficient heavy metal phytoremediation and soil restoration in crop systems

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Abstract

This review explores the multifaceted role of *Sesbania sesban* (L.) Merr. in improving soil health and boosting agricultural productivity. Soil degradation driven by unsustainable practices and nutrient depletion continues to threaten global food security. As a nitrogen-fixing legume, *S. sesban* offers a sustainable solution by enhancing soil's physical, chemical and biological properties. It improves soil structure, increases nutrient content and stimulates microbial activity. In rice cultivation, the species serves as an effective green manure, significantly enhancing grain yield by improving nitrogen availability and organic matter content. Its symbiotic associations with rhizobia such as *Mesorhizobium*, *Rhizobium* and *Sinorhizobium* facilitate biological nitrogen fixation. Additionally, the plant growth-promoting rhizobacteria (PGPR) associated with *Sesbania* enhance nutrient uptake, produce phytohormones and suppresses phytopathogens, further supporting plant growth. Beyond its agricultural benefits, *S. sesban* shows strong phytoremediation potential, effectively removing heavy metals like cadmium, lead and chromium from contaminated soils and wastewater. Its diverse phytochemical profile also contributes to antioxidant, antimicrobial and anti-inflammatory activities, highlighting its medicinal value. With its rich nutritional and therapeutic properties, *S. sesban* emerges as an asset for sustainable agriculture and holistic environmental management.

Keywords: bioremediation; heavy metals; rhizobacteria; *Sesbania sesban*

Introduction

The rising global population represents a critical determinant influencing both food production and consumption patterns. The increasing demographic pressure, combined with the finite availability of arable land, poses a substantial constraint in meeting the growing food demand and ensuring an equitable supply (1). Maintaining the quality of food grain production without compromising soil productivity and fertility remains a persistent challenge in contemporary agriculture. The extensive reliance on chemical fertilisers, pesticides and fungicides has become a conventional practice, often regarded as an immediate solution to achieving higher crop yields (2). However, such indiscriminate applications accelerate the depletion of soil fertility and structure rather than enhancing them, resulting in long-term degradation of agroecosystems and adverse nutritional outcomes in human populations (3). This phenomenon is particularly pronounced in rice cultivation systems, where chemical usage frequently exceeds threshold limits, leading to detrimental effects on soil health. In this context, the integration of green manuring practices has emerged as an ecologically sustainable approach to improve soil fertility and crop productivity. Members of the family Leguminosae, employed as

green manure crops, have demonstrated their capacity to fulfil a substantial proportion of nitrogen (N) demand while simultaneously enriching the soil organic matter pool, thereby maintaining long-term fertility and sustainability (4).

Plant growth-promoting rhizobacteria (PGPR) play a pivotal role in supporting sustainable agriculture through the production of phyto regulators, phytohormones and diverse secondary metabolites that facilitate nutrient availability and bioremediation. Endophytic bacteria, residing asymptotically within the internal plant tissues, are particularly abundant in leguminous species and serve as critical agents in promoting plant growth and stress tolerance (5). These endophytes enhance plant development by suppressing phytopathogenic microorganisms, synthesising bioactive compounds and alleviating the toxic effects of environmental contaminants such as heavy metals. Their ability to colonise root tissues and the rhizospheric environment allows them to contribute effectively to bioremediation and sustainable agricultural productivity. Consequently, endophytic microorganisms and PGPR represent eco-friendly alternatives to conventional agrochemicals, functioning as biofertilisers that optimise crop yield and minimise environmental contamination (6). Heavy metals, including cadmium (Cd), lead (Pb),

arsenic (As), mercury (Hg) and chromium (Cr), constitute a major class of persistent environmental contaminants with significant ecological and public health implications. These elements enter agricultural soils through multiple anthropogenic pathways, such as industrial effluent discharge, irrigation with contaminated wastewater, intensive use of chemical fertilisers and pesticides, atmospheric deposition from vehicular emissions, mining activities and sewage sludge application (7, 8). Once introduced into the soil matrix, heavy metals exhibit prolonged persistence due to their non-biodegradable nature and high affinity for soil colloids. They interfere with essential physiological processes in plants, including nutrient uptake, photosynthesis and enzymatic functioning, ultimately leading to reduced growth, chlorosis and yield decline. Furthermore, the bioaccumulation and biomagnification of heavy metals through the food chain pose severe health hazards to humans and animals, manifesting as renal dysfunction, neurological impairments, hepatic toxicity and potential carcinogenic effects (9).

Leguminous plants are widely used as green manures due to their nitrogen-fixing capacity and high nitrogen content in foliage (Table 1). Studies have shown that *Leucaena leucocephala* (Lam.) de Wit, when cultivated along rice field bunds, produced approximately 250 g m⁻² of dry leaf biomass per season, contributing around 10 g N m⁻². Incorporation of these leaves as green manure increased rice grain yield to 220 g m⁻², outperforming half-dose nitrogen fertilisation (4.3 g N m⁻²) by 75 g m⁻² (18). However, because bunds often serve as farm pathways, this approach is less practical for farmers. A more feasible alternative is the direct integration of leguminous crops within rice fields before planting, which also provides the added advantage of weed suppression (19). Among green manure species, the *Sesbania* genus holds significant promise. *Sesbania rostrata* Bremek. & Oberm. has been reported to fix up to 27 g N m⁻² (20), while Indian studies indicate that *S. aculeata* and *S. speciosa* can enhance rice yields beyond those achieved with 9.0 g N m⁻² of applied nitrogen (21). Screening trials have further shown that *S. cannabina* can produce up to 1700 g m⁻² of dry biomass containing 24.5 g N m⁻² within 98 days (9).

Sesbania species, belonging to the family Fabaceae, are typically fast-growing shrubs or small trees characterised by pinnate leaves, papilionaceous flowers and elongated pods (21). Among these, *S. sesban* is the most widely recognised for its adaptability and

agronomic value. Notably, certain species such as *S. rostrata* can form both root and stem nodules, conferring a distinct advantage in nitrogen fixation (22). These species are distributed widely across tropical and subtropical regions of Africa, Asia and the Americas, thriving in moist alluvial soils near riverbanks, floodplains and wetlands (23). *Sesbania grandiflora*, native to Southeast Asia and *S. sesban*, common in Africa and South Asia, are extensively utilised for fodder, green manure and agroforestry applications (24, 25). Incorporating *Sesbania* species as green manure significantly enhances soil physical, chemical and biological properties. Physically, it improves soil structure, aggregate stability and water retention by 18–25 % (26). Chemically, it enriches soil organic carbon, balances pH and increases the availability of key nutrients such as nitrogen (N), phosphorus (P) and potassium (K) through decomposition and microbial activity (27). Biologically, *Sesbania* promotes microbial biomass, enzyme activity (urease and phosphatase) and earthworm populations, leading to improved nutrient cycling and soil respiration (28). Collectively, these characteristics establish *Sesbania* as a highly effective green manure species for enhancing soil fertility and supporting sustainable crop production (Table 2).

Role of *Sesbania sesban* in crop cultivation

Sesbania sesban plays a crucial role in broader crop cultivation systems due to its adaptability and multifunctional benefits. As a fast-growing leguminous shrub, it is widely utilised in intercropping, agroforestry and soil-restoration programs. Its deep-rooted system improves soil structure, prevents erosion and facilitates nutrient cycling (29). When used as green manure or cover crop, *S. sesban* enhances organic matter content, increases cation exchange capacity and supports beneficial soil microorganisms. Additionally, its capacity to fix atmospheric nitrogen not only reduces dependence on synthetic fertilisers but also provides a sustainable nutrient input for subsequent crops (30). Beyond soil improvement, *S. sesban* serves as an excellent source of livestock fodder and contributes to the diversification of farming systems, thereby enhancing resilience and promoting ecological stability in tropical agroecosystems (31).

Intercropping and relay cropping strategies with rice have also been extensively explored to enhance productivity, resource efficiency and sustainability in rice-based farming systems.

Table 1. Comparative overview of *Sesbania*-based agronomic applications: Benefits, nutrient profiles and decomposition rates

Agronomic practice	Use/potential benefit	Composition rate (%)	Decomposition rate	Reference
Green manure	Improves soil fertility and enhances organic matter	2.5–3.2 % N, 0.5–0.7 % P, 1.5–2.0 % K	60–70 % biomass decomposition within 4–6 weeks	(10)
Nitrogen fixation	Biological nitrogen fixation (BNF) and enhances soil N availability	80–150 kg N/ha/year	Continuous mineralisation over cropping cycle	(11)
Soil erosion control	Dense canopy reduces erosion and increases soil stability	5.5 % lignin, 10–12 % cellulose	Moderate decomposition over 8–12 weeks	(12)
Livestock fodder	High-protein feed for ruminants	22–27 % crude protein, 12 % crude fiber	Digestibility rate ~65 % in livestock	(13)
Agroforestry component	Provides shade, biomass and ecosystem services	12–18 t/ha biomass yield	Decomposition varies with incorporation method	(14)
Carbon sequestration	Increases soil carbon stocks and reduces atmospheric CO ₂	45–50 % organic carbon in biomass	Long-term sequestration (5–10 years)	(15)
Soil microbial activity enhancement	Supports beneficial microbes for soil health	8–10 % root exudates promote microbial growth	Rapid microbial turnover within 2–4 weeks	(16)
Heavy metal phytoremediation	Absorbs Cd, Pb and Ni from polluted soils	Cd: 3.2 mg/kg, Pb: 5.6 mg/kg, Ni: 2.1 mg/kg	Phytoextraction efficiency 50–70 % within one cropping cycle	(17)

Table 2. Enhancing soil properties through *Sesbania* species: physical, chemical and biological perspectives

Soil property	Impact of <i>Sesbania</i> species	Mitigation	Reference
Physical properties			
Soil texture	Improves soil structure and aggregation due to organic matter addition from decomposing biomass	25–30 % increase in soil aggregate stability	(18)
Bulk density	Reduces bulk density, enhancing soil porosity and aeration	Decreases from 1.35 g/cm ³ to 1.20 g/cm ³ in <i>Sesbania</i> -amended soil	(17)
Water holding capacity	Increases due to high organic matter content and improved soil structure	Increases by 18–25 % compared to control soils	(19)
Infiltration rate	Enhances water infiltration by reducing surface crusting and compaction	Improves by 30–40 % after <i>Sesbania</i> biomass incorporation	(20)
Chemical properties			
Soil pH	Balances soil pH through organic acid production during decomposition	pH shifts from 5.5 to 6.2 in acidic soils and from 8.2 to 7.5 in alkaline soils	(17)
Organic carbon	Increases due to high biomass contribution, enhancing soil fertility	Organic carbon increases by 1.2–2.0 %	(18)
Nitrogen (N)	Enhances nitrogen levels due to biological nitrogen fixation by <i>Sesbania</i> roots	Adds 80–150 kg N/ha/year to soil	(19)
Phosphorus (P)	Improves phosphorus availability through organic matter decomposition and microbial activity	Available P increases by 12–18 %	(20)
Potassium (K)	Increases due to the release of K from decomposed plant residues	Exchangeable K increases by 15–22 %	(17)
Biological properties			
Microbial biomass	Enhances microbial activity by providing a nutrient-rich environment	Microbial biomass carbon increases by 20–30 %	(18)
Enzyme activity	Increases enzyme activities such as urease, phosphatase and dehydrogenase, indicating improved soil health	Urease activity increases by 25 %, phosphatase by 18 % and dehydrogenase by 30 %	(19)
Earthworm population	Promotes earthworm activity, aiding in organic matter decomposition and nutrient cycling	Earthworm density increases by 40–50 % in <i>Sesbania</i> -treated soils	(17)
Soil respiration	Increases CO ₂ release due to enhanced microbial decomposition of organic material	Soil respiration rate increases by 35–45 %	(20)

Intercropping involves growing rice alongside compatible legumes such as *S. sesban*, *Vigna radiata* L. or *Cajanus cajan* (L.) Huth, which improve nitrogen availability through biological nitrogen fixation, suppress weeds and enhance system resilience (32). Studies indicate that legume intercropping can significantly increase land-use efficiency and soil health, resulting in higher grain yields compared to monocropping (17). Relay cropping, on the other hand, entails sowing a secondary crop before harvesting the primary rice crop to ensure continuous land cover and nutrient utilisation. For instance, incorporating *S. rostrata* in a relay system before rice transplanting enhances soil nitrogen levels, thereby promoting better rice growth and yield (33). Relay cropping with pulses such as lentil (*Lens culinaris* Medik.) or chickpea (*Cicer arietinum* L.) has similarly improved soil fertility while providing additional economic benefits to farmers (34). Together, these integrated approaches optimise resource use, enhance soil health and strengthen the sustainability of rice-based agricultural systems.

Nitrogen-fixing green manure crops, including *S. rostrata*, *Sesbania speciosa* Taub. ex Engl. and *Sesbania aculeata* Pers., were cultivated in rice fields during the dry season to assess their biomass production, nodule formation, nitrogenase activity and accumulation of organic carbon, nitrogen, phosphorus and micronutrients. Following their growth, the fresh biomass of these legumes, along with fertiliser nitrogen, was incorporated into rice fields to evaluate their effects on crop performance. Among the studied species, *S. rostrata* and *S. aculeata* produced greater biomass than *S. speciosa* by the 50th day of growth. Notably, *S. rostrata* developed a higher number of nodules on its stem than

on its roots and these stem nodules exhibited superior nitrogenase activity. In terms of nutrient accumulation, *S. rostrata* contained a higher nitrogen concentration and greater micronutrient content compared to *S. aculeata* and *S. speciosa*. The incorporation of *S. rostrata* and *S. aculeata* biomass, combined with fertiliser nitrogen at a rate of 60 kg N ha⁻¹, resulted in a significant increase in rice grain yield, underscoring their potential as effective green manure sources for improving soil fertility and crop productivity (35).

Comparative studies on rice yield improvement have highlighted the effectiveness of *S. sesban* as a green manure in enhancing soil fertility and crop productivity. Incorporation of *S. sesban* biomass into rice fields has been shown to substantially increase grain yield through improvements in soil nitrogen availability and organic matter content (36). Trials comparing *S. sesban* with other green manure species revealed that rice yield was notably higher in *S. sesban*-amended fields, attributed to its rapid decomposition and high nitrogen-release rate (37). Furthermore, *S. sesban* enhances soil microbial activity and micronutrient availability, contributing to overall improvements in crop growth and yield (38). These findings establish *S. sesban* as a valuable nitrogen-fixing species for sustainable rice cultivation, particularly in nutrient-depleted soils.

Rhizosphere and the function of plant growth-promoting rhizobacteria in enhancing sustainable crop production

Various species of *Sesbania* exhibit diverse symbiotic relationships with rhizobia. *Sesbania sesban* is known to associate with *Mesorhizobium*, *Rhizobium*, *Sinorhizobium* and *Allorhizobium* (39).

Similarly, *S. cannabina* forms symbiotic partnerships with *Ensifer*, *Rhizobium*, *Agrobacterium* and *Sinorhizobium* (30). Likewise, *S. bispona* establishes associations with *Rhizobium*, *Escherichia coli*, *Pseudomonas fluorescens* and *Burkholderia* species (40). *Sesbania rostrata* harbours *Azorhizobium* and *Sinorhizobium* (41), while *Sesbania virgata* (Cav.) Poir. primarily interacts with *Azorhizobium* (42). Additionally, *S. punicea* has been reported to support *Mesorhizobium* (43). These symbiotic associations play a crucial role in biological nitrogen fixation, enhancing soil fertility and promoting sustainable agriculture. The term "rhizosphere" describing it as the specialised zone of soil surrounding plant roots (44). This microenvironment harbours a diverse array of microorganisms, including bacteria, fungi, algae and protozoa, which play a pivotal role in plant-microbe interactions (45). Functionally, the rhizosphere serves as a biologically active region enriched with essential nutrients that support plant growth and development. It is an approximately 1 mm-thick zone around the root system, where root exudates significantly influence the biological and chemical composition of the soil. These exudates, comprising various phytochemicals of low and high molecular weight, mediate interactions between plant roots and associated microbial communities. The composition of these exudates is influenced by plant species, developmental stages, cultivars and environmental factors such as soil pH and temperature (46).

Species within the *Sesbania* genus have demonstrated a remarkable ability to accumulate nitrogen-rich biomass, making them effective biofertilisers that enhance soil fertility. These plants contribute to soil enrichment by facilitating biological nitrogen fixation (BNF) through their symbiotic association with rhizobia (47). Moreover, *Sesbania* species improve soil structure and nutrient cycling, thereby playing a crucial role in sustainable land management (48). Root-associated bacteria, known as PGPR, establish synergistic relationships with plant roots, fostering plant growth and development through various mechanisms.

The concept of PGPR referring to a group of beneficial microbes, including *Rhizobium*, *Azorhizobium*, *Bradyrhizobium*, *Mesorhizobium* and *Pseudomonas*, that function as biofertilisers (49). The colonisation of these bacteria in the rhizosphere is influenced by soil pH, nutrient availability and root exudates. The PGPR engage in two primary forms of interaction with host plants: (i) endophytic, residing within plant tissues and (ii) rhizospheric, thriving in the surrounding soil. These microbes contribute to soil fertility by enhancing symbiotic interactions, increasing root surface area, augmenting nutrient availability and promoting nitrogen fixation. Previous studies introduced two additional terminologies: (i) Plant growth-promoting bacteria (PGPB), which is analogous to PGPR and (ii) Biocontrol plant growth-promoting bacteria (Biocontrol-PGPB), which specifically aids in plant disease resistance (50). The PGPB not only promote plant health but also provide protection against

abiotic and biotic stresses. These symbiotic bacteria play a significant role in sustainable agriculture, particularly in saline soils, where they enhance salt tolerance and plant resilience (51).

The excessive reliance on chemical fertilisers has led to significant environmental degradation, adversely affecting soil structure, microbial diversity and overall ecosystem health. Additionally, the rising costs of synthetic fertilisers pose economic challenges for farmers. Thus, the adoption of biofertilisers, including PGPR, presents an eco-friendly alternative to chemical inputs, ensuring long-term agricultural sustainability (52). The PGPR facilitate rapid colonisation of the rhizosphere and provide both direct and indirect benefits to plants. Direct mechanisms include enhancing nutrient uptake, mineral solubilisation, phytohormone production (Indole-3-acetic acid (IAA), gibberellic acid (GA) and cytokinin (CK)) and nitrogen fixation (Table 3). Indirect mechanisms involve phytopathogen suppression, induced systemic resistance (ISR), production of antagonistic compounds like hydrogen cyanide (HCN) and secretion of lytic enzymes (53, 54).

Research has demonstrated that PGPR isolated from *Sesbania* species exhibit a wide range of plant-beneficial traits. *Sesbania sesban* rhizosphere has been found to harbour nitrogen-fixing bacteria such as *Azotobacter* spp. (*A. chroococcum* and *A. vinelandii*) and *Rhizobium sesbani*, which significantly improve plant growth, chlorophyll content and nitrogen assimilation. Field studies have reported that *S. sesban* can fix approximately 0.05–0.06 g Nb in waterlogged soils and 0.12–0.13 g Nb in arid conditions, with nitrogen fixation estimates reaching up to 140000 plants per hectare. This species can generate up to 12 tonnes of biomass (fresh weight) per hectare within 45 days, making it an excellent green manure candidate (55). Additionally, *S. sesban* plays a crucial role in phytoremediation by removing heavy metals from contaminated soils and improving nutrient uptake from wastewater, thereby enhancing wetland system productivity (56). Furthermore, rhizosphere bacteria contribute to soil rehabilitation through bio-assisted phytoremediation, helping to degrade toxic pesticides in an eco-friendly manner (57).

The rhizosphere is classified into three zones: (i) endorhizosphere, (ii) rhizoplane and (iii) ectorhizosphere, each playing a unique role in microbial interactions and nutrient cycling (58). Studies indicate that *Sesbania* root nodulating bacteria (*Rhizobia*) not only establish symbiotic associations with legumes but also benefit non-leguminous crops by improving growth and yield (59). Certain soil bacteria thrive within or around plant tissues, actively supporting plant growth-promoting activities (60). Furthermore, research by Sridevi and Mallaiah (61) identified 26 IAA-producing bacterial strains from the root nodules of *S. sesban*, all of which were classified as *Rhizobium*. Of these, five isolates exhibited maximum IAA production, emphasizing the significant role of indigenous microbes

Table 3. Role of endophytic bacteria in nitrogen fixation and phytohormone production

Endophytic bacteria	Host plant	Nitrogen fixation	Phytohormones	Reference
<i>Rhizobium</i> spp.	Legumes (<i>Sesbania sesban</i> , <i>Glycine max</i>)	Symbiotic nitrogen fixation	Indole-3-acetic acid (IAA)	(26)
<i>Azospirillum</i> spp.	Cereals (<i>Zea mays</i> , <i>Oryza sativa</i>)	Associative nitrogen fixation	IAA, Gibberellins (GA)	(41)
<i>Herbaspirillum</i> spp.	Sugarcane and rice	Endophytic nitrogen fixation	IAA, Cytokinins (CK)	(42)
<i>Burkholderia</i> spp.	Rice and maize	Free-living and endophytic nitrogen fixation	IAA, Abscissic acid (ABA)	(43)
<i>Pseudomonas fluorescens</i>	Various crops	Enhances nutrient uptake	IAA, Siderophores	(44)

in enhancing plant growth. These beneficial microorganisms also contribute to biodegradation processes, effectively breaking down toxic compounds in contaminated soils and offering a sustainable approach to environmental remediation (62).

The PGPR hold immense potential in promoting soil fertility, enhancing crop productivity and ensuring environmental sustainability. Their dual role as biofertilisers and bioremediators positions them as key players in the transition towards eco-friendly agricultural practices. The integration of *Sesbania* species into farming systems not only improves soil nitrogen content but also contributes to land restoration and climate resilience. Future research should focus on optimising microbial consortia to maximise the efficiency of PGPR-based biofertilisers for diverse agroecosystems.

Sesbania sesban as an eco-friendly agent for heavy metal remediation: Mechanisms and field applications

Heavy metal contamination in agricultural soils is a critical environmental concern, adversely impacting soil microbial communities, nutrient cycling and crop productivity (Table 4 and 5). Anthropogenic activities such as industrial effluents, mining operations, excessive fertiliser use and wastewater irrigation have led to elevated concentrations of toxic metals, including cadmium (Cd), lead (Pb), arsenic (As) and chromium (Cr) in agricultural lands (68, 69). These metals exhibit long persistence in soil matrices, leading to bioaccumulation in crops and posing serious health risks through the food chain (40). Traditional remediation techniques

such as excavation and soil washing are cost-intensive and ecologically disruptive, necessitating the adoption of sustainable alternatives like phytoremediation (41). Phytoremediation employs hyperaccumulator plants to extract, stabilise, or filter heavy metals from contaminated environments (69). *Sesbania sesban*, a fast-growing, nitrogen-fixing legume with an extensive root system, has shown high efficiency in multiple phytoremediation mechanisms. It functions through phytoextraction, wherein metals such as Cd, Pb and Zn are absorbed from the soil and translocated into aerial tissues, reducing metal bioavailability (70). In phytostabilisation, *S. sesban* reduces metal mobility through root exudation and organic matter deposition, forming stable metal complexes within the rhizosphere (71). Additionally, rhizofiltration enables *S. sesban* to absorb and adsorb heavy metals from contaminated water, making it effective for wastewater treatment (72). Its association with arbuscular mycorrhizal fungi and rhizobia further enhances metal immobilisation and mitigates metal toxicity by altering soil microbial diversity and enzymatic activity (72). Empirical studies have demonstrated the efficiency of *S. sesban* in metal-contaminated environments. A field study in mining-impacted soils reported a 45–60 % reduction in Cd and Zn levels after multiple cropping cycles, with *S. sesban* accumulating up to 2350 mg/kg of Cd in its biomass (65). Similarly, it was found that *S. sesban* effectively reduced Pb mobility by 35 %, coupled with a significant increase in microbial biomass and enzyme activity (6). In wastewater treatment applications, *S. sesban* was shown to remove up to 78 % of Cr (VI)

Table 4. Potential of microbial interactions in bioremediation and stress tolerance

Microbial group	Mechanism of bioremediation	Stress tolerance role	Reference
<i>Pseudomonas spp.</i>	Degradation of organic pollutants, hydrocarbon degradation	Induced systemic resistance (ISR), drought tolerance	(63)
<i>Rhizobium spp.</i>	Heavy metal sequestration, nitrogen fixation	Enhances salinity and drought tolerance	(63)
<i>Azospirillum spp.</i>	Phytoremediation enhancement, nitrogen fixation	Produces ACC deaminase to reduce ethylene stress	(64)
<i>Bacillus spp.</i>	Biosorption of heavy metals (Pb, Cd, As)	Enhances plant root growth under stress	(65)
<i>Mycorrhizal fungi</i>	Soil stabilization, bioaccumulation of heavy metals	Improves water and nutrient uptake under drought stress	(65)

Table 5. Heavy metal contamination in agricultural soils, its impact and phytoremediation mechanisms

Heavy metal	Source of contamination	Contamination level (mg/kg or %) in agricultural soils	Impact on soil and plants	Phytoremediation mechanism	Reference
Lead (Pb)	Industrial waste, vehicular emissions, phosphate fertilisers	50–300 mg/kg (above 100 mg/kg toxic)	Reduces microbial activity, inhibits seed germination, affects plant growth	Phytoextraction (<i>Brassica juncea</i>) removes 5.3 mg/kg Pb per cycle; Phytostabilization (<i>Vetiveria zizanioides</i>) reduces Pb mobility by 65 %	(65)
Cadmium (Cd)	Mining, pesticides, phosphate fertilisers	1–30 mg/kg (above 3 mg/kg toxic)	Toxic to roots, disrupts nutrient uptake, affects plant metabolism	Phytoextraction (<i>Helianthus annuus</i>) removes 0.8 mg/kg Cd per cycle; Rhizofiltration (<i>Eichhornia crassipes</i>) reduces Cd by 80 % in wastewater	(66)
Arsenic (As)	Groundwater contamination, pesticides, industrial discharge	5–50 mg/kg (above 20 mg/kg toxic)	Disrupts photosynthesis, inhibits enzyme activity, bioaccumulates in crops	Phytostabilization (<i>Pteris vittata</i>) reduces As bioavailability by 50 %; Rhizofiltration (<i>Lemna minor</i>) removes up to 75 % As from water	(58)
Mercury (Hg)	Industrial discharge, fungicides, mining activities	0.01–2 mg/kg (above 0.3 mg/kg toxic)	Reduces soil fertility, disrupts microbial diversity, toxic to crops	Rhizofiltration (<i>Typha latifolia</i>) removes 60 % Hg from contaminated water; Phytoextraction (<i>Brassica napus</i>) accumulates 2.4 mg/kg Hg	(66)
Chromium (Cr)	Tannery waste, electroplating industries, fertilisers	10–150 mg/kg (above 50 mg/kg toxic)	Affects root elongation, reduces plant biomass, toxic to beneficial microbes	Phytostabilization (<i>Populus deltoides</i>) reduces Cr mobility by 45 %; Phytoextraction (<i>Salix spp.</i>) accumulates 8.5 mg/kg Cr	(67)
Nickel (Ni)	Sewage sludge, industrial effluents, fossil fuel combustion	10–100 mg/kg (above 50 mg/kg toxic)	Alters chlorophyll synthesis, reduces seed germination and growth	Phytoextraction (<i>Alyssum murale</i>) removes 10.2 mg/kg Ni per cycle; Phytostabilization (<i>Vetiveria zizanioides</i>) reduces Ni leaching by 55 %	(66)

from industrial effluents within a 14-day period (63). Despite its high phytoremediation potential, biomass management strategies such as controlled harvesting and metal recovery remain crucial to prevent secondary contamination. Further research on genetic modifications and microbial-assisted remediation could enhance *S. sesban* efficiency in large-scale applications, reinforcing its role in sustainable pollution mitigation (72).

Sesbania phytochemistry and pharmacological activities

In sub-Saharan Africa, *S. sesban* is widely utilised for medicinal, agricultural and environmental purposes, including land restoration, livestock feed and wood production (73). The species possesses rich phytochemical diversity, contributing to its antioxidant, antimicrobial, antiviral, anthelmintic, anti-inflammatory and antidiabetic properties (66, 74). Studies have shown that ethanolic and methanolic extracts of *S. sesban* leaves exhibit strong free radical scavenging activity, primarily due to bioactive compounds such as anthocyanins, phenols and flavonoids (74). Antimicrobial assays revealed effective inhibition of Gram-positive bacteria (*Staphylococcus aureus*, *Staphylococcus sophyticus*), while bark and flower extracts displayed broad-spectrum antibacterial and antifungal activity against pathogens like *Fusarium oxysporum* and *Curvularia lunata* (71, 75). Crude saponin extracts also demonstrated significant anti-inflammatory effects, reducing carrageenan-induced oedema by up to 59 % in *in vivo* studies (76). These findings highlight *S. sesban* as a potent natural source of antimicrobial and anti-inflammatory agents.

Sesbania grandiflora (L.) Poir. and *Sesbania cannabina* (Retz.) Poir. are also notable for their agricultural and medicinal values. *Sesbania grandiflora*, a fast-growing nitrogen-fixing tree, is utilised for fodder, green manure, timber and traditional medicine. It contains diuretic, purgative, hepatoprotective and antimicrobial properties and is employed in treating fever, stomatitis and respiratory disorders. Similarly, *S. cannabina* (syn. *S. aculeata*) is used in folk medicine for wound healing, skin infections and parasitic ailments, with its leaf tea showing antimicrobial and anthelmintic activity.

Nutritionally, *Sesbania* species are rich in proteins, amino acids, vitamins and minerals—*S. javanica* contains up to 41 % protein and *S. grandiflora* provides 145 mg/100 g vitamin C and 666 mg/100 g calcium. The genus is also a valuable source of secondary metabolites such as betulinic acid, medicarpin, oleanolic acid glucuronide and stigmaterol, contributing to its cardioprotective, hypolipidemic, anticancer and analgesic properties (8, 60, 75). Agriculturally, several *Sesbania* species are extensively used as green manure and soil improvers, enhancing nitrogen content and overall soil fertility. Their rapid biomass accumulation and nitrogen-fixing ability make them integral to sustainable agro-ecological practices. Some species provide fibre (*S. bispinosa*) and aid in pollution control. However, certain *Sesbania* species can act as weeds or pest hosts and excessive seed intake may be toxic to livestock. Despite these limitations, the genus *Sesbania* remains a vital resource linking agricultural productivity, environmental sustainability and ethnomedicine.

Ecological and environmental significance

Soil salinisation is a major factor limiting agricultural production and sustainable agricultural development in arid and semi-arid zones and poses a serious threat to the ecological environment (70–76). It is noteworthy that there is already more than 1.1×10^9 hm² of salinised land in the world and this figure is increasing year by year. There are

three primary approaches to mitigating soil salinisation: engineering, chemical and biological remediation strategies. However, engineering-based methods that rely on the principles of water-salt movement are not resource-efficient, particularly in regions facing water scarcity. One effective technique for controlling soil salinisation is gravel mulching, which helps prevent secondary salinisation by reducing salt accumulation on the soil surface. Researchers demonstrated that gravel mulching significantly lowers soil salinity (74). Additionally, incorporation of straw into the soil resulted in a desalination rate of 53 %, with reductions in Na⁺ and Cl⁻ ions by 52.7 % and 51.9 %, respectively (75). Organic amendments, such as manure, improve saline soils by influencing the movement of soluble salts and water-soluble ions, effectively reducing surface soil salinity (75, 76). Application of organic fertilisers plays a crucial role in slowing down the process of soil salinization (74–77). Furthermore, halophytic crops contribute to soil desalination through their physiological mechanisms, including salt uptake and secretion via root infiltration, helping to lower soil salinity levels (78). While existing research confirms the effectiveness of these strategies, further studies are urgently required to evaluate their potential across different soil salinity conditions.

Sesbania species, particularly *S. sesban*, play a crucial role in biodiversity conservation and agroforestry due to their adaptability, nitrogen-fixing ability and multi-functional applications. As fast-growing leguminous trees, they enhance soil fertility by fixing atmospheric nitrogen through symbiosis with *Rhizobium* bacteria, thus improving soil health and supporting diverse plant communities (79). Their deep root systems contribute to soil stabilisation, reducing erosion and promoting sustainable land use in degraded ecosystems (8). Moreover, *Sesbania* serves as a habitat and food source for various pollinators and beneficial insects, contributing to ecological balance (80). In agroforestry systems, *S. sesban* is widely used as a shade tree, windbreak and fodder source, supporting integrated farming approaches that enhance productivity while maintaining biodiversity (80). Additionally, its application in alley cropping and silvopastoral systems demonstrates its potential in sustainable agriculture and climate-resilient farming. Given these benefits, further research is essential to optimise *Sesbania* utilisation in agroforestry models tailored to diverse environmental conditions.

Challenges and constraints in the adoption of green manure legumes in rice-based cropping systems

In lowland rice-based cropping systems, relatively few green manure legumes are commonly cultivated. In the cool tropics of Asia (such as China and Japan), the predominant post-rice green manure species is *Astragalus sinicus* L. (81), whereas in the Americas, vetches and clovers are more frequently utilised (82). In contrast, in the warmer tropical regions, legumes are rarely cultivated exclusively for soil enhancement. Instead, species such as *Indigofera tinctoria* in Asia and *Calopogonium* spp. in Africa (10) are occasionally employed. Additionally, forage legumes such as *Stylosanthes*, *Desmodium* and *Clitoria* spp. are more commonly integrated into cropping systems, particularly in South America (11).

Despite the proven agronomic and ecological benefits of green manure legumes, several challenges hinder their widespread adoption in rice-based cropping systems. The primary constraints include limited awareness among farmers, inadequate availability of quality seeds and labor-intensive incorporation practices. In many regions, short turnaround times between rice crops leave insufficient

periods for green manure growth and decomposition. Economic considerations also deter adoption, as farmers often prioritise immediate cash returns from cereal or cash crops over soil-restorative legumes. Additionally, uncertainties about climatic variability, water availability and pest or disease susceptibility further limit the consistent cultivation of green manure species such as *S. rostrata* and *S. cannabina*. Institutional challenges such as weak extension networks and lack of integration in national agricultural policies exacerbate the problem, preventing the scaling of these sustainable practices.

Rice green manure applications, *S. cannabina* is among the most widely utilised species across the warm tropics of Africa and Asia. One notable green manure species, *S. rostrata*, originally from West Africa, has undergone extensive research and is now recommended for use in both Asia and Africa. Since its introduction to Asia around a decade ago, the crop has been widely adopted and is currently cultivated on approximately 500,000 hectares in the Delta and Central Plain regions of Myanmar (12–16). Other *Sesbania* species, such as *S. sesban* and *S. speciosa*, have more localized significance (83). For instance, *Sesbania speciosa*, which is cultivated in Thailand, serves a dual purpose by producing nutrient-rich biomass and edible flowers (84). In addition to *Sesbania* species, certain stem-nodulating legumes, such as *Aeschynomene afraspera* and *Aeschynomene nilotica*, have only recently been domesticated (85). However, their usage remains largely confined to research stations and demonstration farms rather than widespread agricultural implementation. Meanwhile, other legume-based green manure species, such as *Aeschynomene indica*, have been recognised as regionally important but are yet to be adopted on a large scale (86). This overview underscores the strategic role of green manure species in sustainable rice production and highlights the need for further research and extension efforts to optimise their adoption and effectiveness in diverse agro-climatic regions.

Looking ahead, the prospects for green manure legumes are promising with the integration of modern technologies and policy support (87). Advances in biotechnology and microbial inoculant development can enhance nitrogen fixation efficiency and stress resilience in legume species. Breeding programs focusing on short-duration, high-biomass and multi-purpose cultivars could make green manure crops more compatible with intensive rice systems. Moreover, incorporating digital tools for soil fertility mapping, coupled with farmer training and incentive-based schemes, can accelerate adoption. Climate-smart agriculture initiatives and sustainable intensification approach further position legumes such as *S. sesban* as central to future soil health management. Collaborative research, participatory extension models and region-specific adaptation strategies will be essential to realize the full potential of green manure legumes in enhancing productivity, resilience and environmental sustainability in rice-based agroecosystems

Conclusion

Sesbania sesban demonstrates potential in enhancing soil health, improving crop productivity and advancing sustainable farming systems. Its incorporation as a green manure improves soil structure, lowers bulk density and increases water-holding capacity, facilitating better root growth and moisture retention. Chemically, it enriches soil organic matter, enhances nitrogen content through biological fixation and improves the availability of phosphorus and potassium.

Biologically, *Sesbania sesban* boosts microbial biomass, enzyme activity and earthworm populations, creating a more resilient and fertile soil ecosystem. Beyond agronomic benefits, its antimicrobial, antifungal and anti-inflammatory properties add further value to agricultural and medicinal applications. Despite these advantages, adoption of *Sesbania sesban* remains limited due to a lack of awareness and policy support. Future research should prioritise long-term field evaluations, cost-benefit analyses and integration with other sustainable practices such as conservation and organic farming. Strengthening institutional frameworks, providing farmer incentives and promoting its inclusion in sustainable agriculture programs are essential for scaling its impact. By mainstreaming *Sesbania sesban* into climate-resilient agricultural systems, it can play a pivotal role in restoring soil fertility, improving food security and mitigating the adverse effects of climate change marking a crucial step toward a more sustainable and resilient agricultural future.

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Authors' contributions

APM and MP carried out the conceptualisation and methodology of the study. APM, MP and CKS contributed to the writing of the manuscript. SD, CKS and CP were involved in reviewing and editing. Tables were prepared by APM and MP. All authors read and approved the final manuscript.

Compliance with ethical standards

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