Recent advances in the bioremediation of arsenic-contaminated soils: a mini review

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Abstract:

The carcinogenic metalloid arsenic (As), owing to its persistent behavior in elevated levels in soils, aggravates environmental and human health concerns. The current strategies used in the As decontamination involve several physical and chemical approaches. However, it involves high cost and even leads to secondary pollution. Therefore, it is quite imperative to explore methods that can eradicate As menace from the environment in an eco-friendly, efficient, and cost-competitive way. Searching for such viable alternatives leads to the option of bioremediation technology by utilizing various microorganisms, green plants, enzymes or even their integrated methods. This review is intended to give scientific and technical details about recent advances in the bioremediation strategies of As in soil. It takes into purview the extent, toxicological manifestations, pathways of As exposure and exemplifies the substantive need of bioremediation technologies such as phytoremediation andbiosorption in a descriptive manner. Additionally, the paper looks into the wide potential of some plant growth promoting microorganisms (PGPMs) that improve plant growth on one hand and alleviate As toxicity on the other. Furthermore, it also makes a modest attempt to assimilate the use of nanoparticles, non-living biomass and transgenic crops which are the emerging alternative bioremediation technologies.

Introduction:

Arsenic (As), a toxic metalloid, has sparked worldwide concern. Its rising prevalence in biosphere (Sanyal, 2017) is alarming for environmental and human health (Mazumder et al., 2013), specifically as a tenacious category 1 human carcinogen (Menon et al., 2020). As may be found in the environment in both inorganic [arsine (As^{-3}), elemental As(0), As(III), and As(V)] and organic [dimethylarsinic acid (DMA), monomethylarsonic acid (MMA), trimethylarsine oxide (TMAO), arsenobetaine, etc] forms (Upadhyay et al., 2018). As pollution of groundwater in South and Southeast Asia is mostly caused by natural biogeochemical processes (Sengupta et al., 2021). In India and Bangladesh, the problem of As poisoning is more acute, with groundwater As concentrations in about 50% aquifers having > 2.50 mg/L, which is many magnitude greater than WHO recommended levels of 0.01 mg/L (Sanyal, 2017). Food crops, particularly paddy, grown with As-laden irrigation water are a potent source of As exposure to humans through soil-crop-food transfer.

Rice and rice based products are considered to be the leading source of As pollution for millions of people (Awasthi et al., 2017; Sengupta et al., 2022). In India and Bangladesh, daily consumption of rice is high around 68.2 and 173.3 kg person^{-1} year^{-1} respectively. Approximately 69.6% of the calorific intake is from rice in Bangladesh and for India it is 29.1% (Mandal et al. 2021; Sengupta et al. 2021).

Under anaerobic field conditions, the existence of As, mostly in the form of arsenite [As(III)] is transferred via over-expressed silicic acid transporters in rice (Srivastava et al., 2012). Other crops produced aerobically, such as wheat, maize, and Indian mustard, result in an excess of arsenate [As(V)]. Furthermore, As(V) is taken up and transported by phosphate transporters. Long-term exposure to As can have serious consequences for the functional integrity of human tissues and organs such as the intestinal system, liver, skin, kidney, nervous system, and so on. Animals also get impacted by As by ingestion of water and feed, and those can function as a origin of As to following species in the food chain (Datta et al., 2012). As poisoning affects plant growth and development, resulting in plant mortality or low crop production and quality, even curtailing yield by more than 30% in some cases (Bhattacharyya et al., 2021).

Arsenic pollution has sparked global interest, prompting the development of a number of physical and chemical cleanup techniques. The current available remediation approaches are mainly adsorption by using specific media, immobilization, modified coagulation along with filtration, precipitations, immobilizations, and complexation reactions (Lim et al., 2014). However, these mechanisms are costly and bear limited applicability among poorer section of the society. Further, these methods can also cause secondary pollution in the soil environment. This led to the search for alternative strategies. Microorganisms like *Aspergillus*, *Candida*, *Scopulariopsis*, *Penicillium*, *Fusarium*, and *Trichoderma* are among the fungi that may methylate inorganic As compounds to organic ones (Cullen and Reimer, 1989). Further, some microorganisms are resistant to arsine (AsH_3), monomethylarsine ($MeAsH_2$), dimethylarsine (Me_2AsH), and trimethylarsine (TMA) and have the ability to convert As into volatile arsine gases (Páez-Espino et al., 2009). Many microbes have the ability to resist the As and they also contain a special type of As resistant system, ars operon

(Laha et al., 2021). So the biological methods may be an alternative as they are the low cost and eco-friendly technique.

Simultaneously, the efficacy of plants for eliminating contaminants must be improved in order to harness phytoremediation potential, as it is an affordable solar-driven technique. As-resistant plant growth promoting microorganisms (PGPMs) might well be regarded as benign, minimal cost incurring, efficient and long-term biological agents for reducing As toxicity in plants and managing As accumulation in crops (Vejan et al., 2016). If appropriate PGPM-based techniques succeed, they will give further benefits in terms of diminished inorganic fertilizers use, economic savings, and environmental preservation.

Global status of As contamination and toxicological manifestations

Natural As pollution of groundwater has been recorded all over the world, with most of events occurring in the South Asian and South American zones (Mandal et al., 2021). Bangladesh, India, China, Nepal, Cambodia, Vietnam, Myanmar, Laos, Indonesia, the USA, are among the worst-affected countries (Bhattacharyya and Sengupta, 2020). Several studies show that high levels of As (0.5 to >4600 g/L) contamination in Bangladesh's shallow aquifers have a negative impact on public health (Shaji et al., 2021).

In India, groundwater is critical for meeting the water demands of numerous sectors, including household, industrial, and irrigational requirements. The alluvial tracts of Ganga and Brahmaputra rivers are the country's richest groundwater provinces. The Ganga is currently one of the earth’s most contaminated rivers, with levels of Cr, As, Cd, Pb, Cu and Hg, as well as pesticides and pathogenic bacteria, about >3000 times the World Health Organization's acceptable limit (WHO, 2011). Groundwater with high As levels (>10 µg/L) has been observed in ten Indian states; nonetheless, India's deeper aquifers (>100 m) are As free (Sanyal, 2017). As pollution in West Bengal's groundwater was first discovered in 1978, and roughly more than 50 million people are at danger in 12 districts and 111 blocks (Shaji et al., 2021).

The elevated level of As concentration in ground water is associated with human wellbeing. The formation of skin diseases, such as raindrop hypopigmentation, pigmentation, keratosis (palmer and plantar), and even dermatogical malignancies including basal cell carcinoma (BCC), squamous cell carcinoma (SCC), and Bowen's disease, is a key symptom of As toxicity. Surprisingly, only 15–20% of the population exhibits these symptoms. Research studies with human cancer cells unearthed different toxicological mechanisms with respect to skin-related outcomes and cancerous fates of bladder, lungs, liver etc (Sanyal, 2017). As research at the cellular level over the last decade has demonstrated that As changes the cellular gene expression motif, as well as cell cycle, epigenomic profile, telomere length, and other factors. DNA damage and repair mechanisms have been one of the most studied area of As poisoning in the last decade. The identification of genetic damage as a valid biomarker for As-triggered hazardous consequences has been demonstrated in both human and cell line studies. When compared to unexposed human participants, both chromosomal abnormalities and micronucleus were found to be highly related with As exposure and have exhibited a strong relationship to As toxicity (Upadhyay et al., 2018).

Remediation of As from the environment: the multi-faceted tools

As elimination mechanisms should connect certain basic technological criteria, together with hardiness, no additional environmental adverse effects, and ease of use. There are currently several procedures for decontaminating As from As-contaminated area, the physical, chemical, and biological techniques.

In the physical technique, the As content in soil can be lowered by combining polluted and unpolluted soils to achieve an allowable quantity of As dilution. Soil washing is one more treatment that belongs to physical methods, in which As-polluted soil is cleaned with various concentrations of chemicals such as nitric acid, phosphoric acid, sulfuric acid, and hydrogen bromide. The option of costly chemicals utilized for extractant is the limitation of the use of soil cleaning into smaller-scale actions (Mahimairaja et al., 2005).

Meanwhile, cement can immobilise soluble As(III) and has been effectively utilised to stabilise As-wealthy sludges, suggesting that it could be used to treat sludge from precipitative shifting units. The dumping of As-containing water treatment lavishes has been studied, with a specific focus on stabilisation/solidification (S/S) methods, for their suitability in managing As-bearing lavishes. The brine produced by the recovery of operated alumina filters is believed to speed up cement hydration in this process. Furthermore, because water solubility is the managing techniques of pollutant dissolution, additives (surfactants, cosolvents, etc.) have been employed to improve the abilities of soil flushing utilizing soapy solutions. In laboratory trials, the use of surfactant alone yields roughly 80–85% efficiency. Adsorption employing particular media, immobilisation, and altered coagulation with filtration, precipitations, immobilizations, and complexation reactions are among the currently available chemical remediation procedures. Coagulation with filtration is a cost-effective approach for removing As from polluted sources (Lim et al., 2014).

The stabilisation technique benefits from the creation of stable phases, such as insoluble $FeAsO_4$ and hydrous species of this compound, such as scorodite ($FeAsO_4.2H_2O$). Furthermore, because most of the contaminated area are polluted with numerous metal(loid)s, using selected stabilising amendments is a difficult operation. Another promising boost for the stabilising approach is nanosized oxides and Fe. Engineered oxide nanoparticles are promising materials for the remediation of soils polluted with inorganic contaminants due to their active and relatively high specified surface area (Waychunas et al., 2005).

Given the limits of traditional cleanup procedures, biological solutions involving bacteria could be investigated as a potential alternative mitigation strategy (Laha et al., 2021).

Bioremediation of soils polluted with inorganic or organic As carried in pesticides and hydrocarbons, has gained widespread acceptance in some areas. Despite the fact that bioremediation has significant drawbacks, it is gaining popularity for the reclamation of metal polluted soils because of its economic success. Two types of bioremediations are used: intrinsic and designed bioremediation. Intrinsic bioremediation is the breakdown of As by normally occurring microbes without human interfare, and this procedure is better suited to remediate soil with small levels of pollutants. Engineered bioremediation frequently relies on human intervention to optimise environmental conditions so as to increase the proliferation and activity of microbes living in the region. As a result, using a designed bioremediation approach in a heavily contaminated area is more advantageous (Mahimairaja et al., 2005). Absorption of As in the form of As(V) by phosphate transporters, uptake of As in the form of arsenite by aquaglyceroporins, conversion of arsenate to arsenite by arsenate reductases, and extrusion or sequestration of arsenite are the four mechanisms for As detoxification (Garbinski et al., 2019).

A microbial community vigorously oxidised As(III), resulting in a considerable drop in soluble As contents and a commensurate enhance in the As toxicity in the sediment downstream of the hydrothermal origin. *In situ* oxidation studies verified the existence of arsenite-oxidizing groups (aro A-like genes) in the structure. These findings suggest that microbe-involved As oxidation aid in the depletion of As content and stabilisation of As in the solid system, hence limiting the quantity of As carried downstream (Leiva et al., 2014).

Filtration, osmosis, adsorptions, and precipitations are among the physicochemical methods used to reduce As levels in water, while biological procedures involve phytoremediation or microbes assisted As decontamination (Singh et al., 2021). Biosorption and biomethylation are two essential processes in microorganisms' elimination of As from water. Biomethylation (by As(III) S-adenosylmethionine methyltransferase) has been identified as the most reliable biological method for eliminating As from aquatic media. The arsenite S-adenosylmethionine methyltransferase (ArsM) gene was recently introduced into the chromosome of *Pseudomonas putida* KT2440 for possible environmental As bioremediation as described by the first X-ray crystallographic structure (Lim et al., 2014; Gupta et al., 2020).

Microbes resistant to As

Microbes contain a special type of As resistant system. They contain ars operon which enable survival under As stress condition. The arsRDABC operon implicated in the As tolerance phenotype was found by the nucleotide sequence of the determinants from the *E. coli* R773 plasmid, and *Staphylococcal* plasmids pI258 and pSX267. ArsR, a metalloregulatory protein belonging to the SmtB/ArsR family, is encoded by the arsR gene. ArsR is a trans-acting transcriptional repressor protein that attaches to the ars operon promoter and aids in transcription (Ben et al., 2018). The arsC (reduction of arsenate to arsenite), arsR (transcriptional repressor), and arsB (may also be a component of the ArsAB arsenite-translocating ATPase, an ATP-driven efflux pump) genes make up the majority of detoxification operons. Furthermore, two additional genes (arsD-metallochaperone and arsA-ATPase) are found in several detoxifying operons. The metallochaperone ArsD binds cytosolic As(III) and transfers it to the efflux pump's ArsA subunit. Arsenate that enters the cell is converted to arsenite by the ArsC gene before being transported out by the ArsB gene in a normal procedure. As a result, the environment will be exposed to a more hazardous form of As . Microorganisms can also reduce arsenate to arsenite by a dissimilatory reduction pathway, which can occur in either a facultative or stringent anaerobe state, with arsenate functioning as the terminal electron acceptor. Those microbes having the capacity to eat other microorganisms, oxidise inorganic (sulphide and hydrogen) and organic (e.g., nitrous oxide) substances and use it as an electron donor (formate, aromatics, and lactase acetate) (Kabiraj et al., 2022).

Bacteria with As-toleration ability include *Acinetobacter*, *Rhodococcus*, *Agrobacterium*, *Staphylococcus*, *Thiobacillus*, *Escherichia*, *Achromobacter*, *Pseudomonas*, *Alcaligens*, *Microbacterium*, *Cupriavidus*, *Ochrobactrum*, *Desulfomicrobium*, *Fomitopsis pinicola*, *Fusarium oxysporum*, *Penicillium gladioli*, *Fucus gardneri*, *Bosea sp.*, *Psychrobacter sp.*, *Rhodobium*, *Bradyrhizobium*, *Sinorhizobium*, *and Clostridium* (Chandra and Banik, 2021).

Bioremediation as a potent weapon of alleviating As toxicity

Bioremediation, a procedure that utilises microbes to remove contaminants from soils, and phytoremediation, a method that involves plants to abolish heavy metals, are two biological approaches that are regarded successful for heavy metal remediation (Adams et al., 2015). Because of the extent and complexity of environmental issues by polluted soils, the fact that plant-based reclamation methods causes little environmental disruption, favours phytoremediation as the biggest profitable chances for As remediation (Susarla et al., 2002).

Global status of research initiatives in As bioremediation techniques

Various studies (Table 1) of biodegradation and bioremediation abilities involving specific microbes or plant have been published, with various levels of success (Elekwachi et al., 2014). However, little research into patterns and likely causes in the global use of these procedures has been uncovered. In 1996, Kinya and Kimberly looked into how many remediation companies and research institutes had adopted soil and groundwater cleanup processes, compared cleanup prices, and expressed thinking on the use of non-indigenous microbes for bioremediation (Kato et al., 1996). The previously recorded reports on the use of bioremediation method for remediation of contaminated zones is scarcely inspiring. Only 4 of the 391 polluted land sites addressed between 2000 and 2007 were treated with *in situ* bioremediation, according to the UK Environment Agency. Only two locations had *ex situ* bioremediation proposed, but it was never implemented. According to the US-EPA, out of 997 source-control-treatment programmes completed between 1982 and 2005, 240 were classed as "innovative technologies" with 60 *ex situ* and 53 *in situ* bioremediation operations accounting for a minor share (12%). Monitored Natural Attenuation (MNA), Bio-augmentation and Bio-stimulation are frequently used process (USEPA, 2007).

Mechanism of bioremediation

Bioremediation functions by reducing, detoxifying, degrading, mineralizing, or transforming more toxic metals into less harmful ones. Toxic waste is removed from a polluted environment using cleaning techniques. Bioremediation is extensively assumed in the degradation, eradication, immobilisation, of numerous chemical lavishes and physically toxic compounds from the neighbouring environment through microbes' all-encompassing and activity (Sharma, 2020). Figure 1 shows the different bioremediation measures that have been used till date.

Phytoremediation strategies

Phytoremediation of As requires the utilizations of green plants and associated rhizosphere dwelling microorganisms for complete elimination or stabilization or breakdown of contaminants from soil, sediment as well as surface and groundwater (Yadav et al. 2018; Wei et al. 2021). The different approaches for phytoremediation of As are phytoextraction, phytoexclusion, and phytostabilisation, wherein each of the techniques, has different set of mechanisms for creating pollutant-free environment (de Souza et al. 2019).

Phytoextraction

Phytoextraction aims to eliminate the pollutants from soil through plant uptake followed by translocation and accumulation into harvestable portion. Then, the harvestable biomass is incinerated and metals are extracted from the resulting ash content. *Pteris vittata* L. (Chinese brake fern) is the first reported As hyperaccumulator, having considerable ability to collect As efficiently from disturbed soils. Its unique metabolic properties, which include effective mobilization of As in the rhizosphere, efficient uptake by the roots, and translocation to the shoots, are largely responsible for its successful decontamination of As-contaminated soil. There are 11 Pteridaceae fern species have been discovered since the discovery of *P. vittata* (de Souza et al. 2019).

Mechanisms of As hyperaccumulation

The unique processes of As hyperaccumulation have been gradually unravelled based on a variety of investigations, and appear to require effective As mobilization in the rhizosphere, quick root uptake, and accelerated As transfer by *P. vittata*. Various characteristics set hyperaccumulator plants apart from regular or non-accumulator plants. The key mechanism separating hyperaccumulator plants from non-accumulator plants is the very quick transfer of As from the root to the aboveground portion, considerably stronger detoxifying ability, and higher As sequestration capacity in the aboveground part (Saxena and Misra, 2010).

Exudates from the roots are used to mobilize As

Arsenic solubilization in the rhizosphere has been demonstrated to be aided by root exudes and bacteria. *P. vittata* generate two times more diffused organic carbon (DOC) than the non-hyperaccumulating fern *Nephrolepis exaltata*. In comparison to *N. exaltata*, organic acids from root exudates caused three times or more greater mobilisation of As from unsolvable As minerals ($AlAsO_4$ and $FeAsO_4$) in an As-contaminated soil (Wang & Ma, 2015). In addition to root secretions, it has been demonstrated that As-tolerant bacteria from *P. vittata*'s rhizospheric zones (*Pseudomonas sp., Comamonas sp.,* and *Stenotrophomonas sp.*) may raise the As content in the absorption solution from 5 g/L to 5.04–7.37 mg/L by resolving insoluble $FeAsO_4$.

Mycorrhizal symbiosis

P. vittata colonized by a population of AMF accumulated 2–5 times more As than those without colonization in a greenhouse trial with total soil As of 100 mg kg^{-1}, with the increase becoming more pronounced with increasing soil P content (Wang and Ma, 2015).

Phytostabilization

Phytostabilization on the other hand, involves arresting of As through absorption and accumulation in the rhizospheric region. This low-cost process is particularly important in limiting the bioavailability as a whole and biomagnification in the food chain (Fernández et al., 2016). This technology stabilizes it in a particular environment and does not lead to the complete removal of pollutants which may trigger resurgence in future. Its potential can further be enhanced using amendments like compost, phosphates, bone mill, furnace slag, fly ash etc (Shackira and Puthur, 2019). Hammond et al. (2018) reported phytostabilization of As by *Prosopis juliflora* in compost-amended pyritic mine tailings. Kowitwiwat and Sampanpanish (2020) applied *Pennisetum purpureum* cv. Mott for phytostabilization of As in contaminated metalliferous mine site amended with cow-manure and acacia wood-derived biochar.

Indigenous tolerant species with low Translocation Factor (TF)

Native *Populus* and *Salix* could be used to phytostabilize As-contaminated areas, according to the discovery that trace metals were deposited primarily in woody roots (84–89%) with limited shoot translocation (Saxena and Misra, 2010). A 0.15-meter-thick layer of sand-filled soil was spread over a 0.7-meter-thick layer of ashes containing heavy metals in a polluted area (such as As, Cu, Zn etc.) to improve the uptake efficiency. Even with 16–92% lower tissue biomass than the control, 100% survival of native *Populus* and *Salix* was obtained following two years of soil improvement (such as blending with imported soils, ploughing, and fertilisation).

Legumes improve the substrate

Legumes with a high N-Fixation capacity and a robust root system can be employed as pioneering colonizer species to repair the substrate and revegetate the region in order to restore the nutritional condition of degraded areas with As pollution. Additionally, the majority of legume plants have a limited capacity to move their shoots (Vazquez et al., 2006).

Biochar and iron oxides

The metabolic behaviours of metals in soils are significantly impacted by biochar, a promising soil amendment. At a normal environmental pH, biochar with relatively high cation exchange capacity consistently exhibits adsorption capability toward metal cations but low binding ability for As species, regardless of the kind of feedstock and pyrolysis. In some circumstances, supplements like Fe oxides are required to reduce As pollution and threfore help plants survive. For example, As levels as high as 6670 and 56,600 mg kg^{-1} were found in two extremely polluted mining tailings in South Korea, resulting in substantial As toxicity in plants. Adding amorphous Fe with biochar precipitated most of the As bound to Fe, and thus further resulted in reduction of 70–80% accessible As (Wang and Ma, 2015).

Phosphorus

Phosphurus (P) more specifically pentavalent P is a chemical analog of As(V) and effectively competes with arsenate for binding sites in soils. Following P treatment, competitive anion exchange led to increased bioavailability and plant uptake of As. In a pot experiment with soil As at 0, 15, and 30 mg kg^{-1}, greater As buildup in both rice grain and straw was reported with lower grain production after P treatment of 50 mg/kg P (Hossain et al., 2009).

Organic matter

Due to the type of compost employed, the level of humification, and pH fluctuations, organic matter has inconsistent effects on As mobility as a complex mixture of varied components (Juwarkar et al., 2008; Lagerkvist et al., 2008; Shiralipour, 2002). For instance, in a greenhouse experiment, the treatment of municipal solid waste and biosolids compost led to a significant increase in soil soluble As from 5.7 to 7.1 mg/L. Application of orgnics, on the other hand, diminish As bioavailability in soils and therefore in plants, as hitherto showed for sesame (Sinha et al., 2011), wheat, and maize (Mandal et al., 2019a; 2019b), and vegetables (Bhattacharyya et al., 2021).

Mycorrhiza

Proper inoculates of As-tolerant mycorrhiza can serve as a practical way to give host-enhanced tolerance and boost Phyto stabilization by preferentially accumulating P over As(V). Mycorrhizal inoculation of *G. mosseae* enhanced plant P content by 50–200% using a compartmented cultivation system. Shoot As was reduced by 9%–30% in the presence of 1 and 205 mg kg^{-1} As (Wang & Ma, 2015).

Phytoexclusion

In As contaminated agricultural soils, it is impractical to use non-food crops for phytoextraction. Due to an effective silicon transport channel, rice, which feeds half of the world's population, accumulates As more quickly than other cereals, especially when it is flooded. This has led to widespread observations of elevated As levels in paddy rice, with As TF values frequently reaching unity. It is possible to remediate As-contaminated agricultural soils and lessen rice's uptake of As by using a variety of agronomic approaches and biotechnologies that have been developed to enhance food safety and agriculture sustainability (Zhao et al., 2010).

Water management

Water management can aid in reducing the mobilization of As brought on by the reductive dissolution of Fe hydroxides under anaerobic conditions since soil redox potential regulates As mobility and toxicity in paddy soils. When compared to conventional flooding farming, the availability and uptake of As by rice can be greatly reduced under aerobic conditions, even to the tune of 80% (Sengupta et al., 2021).

Silicon fertilization

According to Ma et al. (2008), rice easily absorbs As(III) through the Si transport system, which suggests that enhanced Si availability can decrease As transfer in the soil-rice system while also boosting grain output. Under Si fertilisation (20 g SiO_2 kg^{-1} soil) Despite a 1.5–2 fold higher As concentration in soil solution [with 78–100% As(III)], rice straw and grain had As concentrations that were 78% and 16% lower, respectively.

Arsenic sequestration by Fe plaque

In paddy rice and other aquatic species, As inflow into rice roots may be successfully reduced by the iron plaque that is produced on the root surface as a result of rhizosphere oxygenation due to its high capacity to store As(V). As concentrations in the rhizosphere soil solutions were noticeably reduced in a pot culture experiment with rice growing under flooded conditions, being 2.5-fold and 16-fold lower upon the amendment of amorphous iron at 0.1 and 0.5 percent as a result of enhanced As sequestration by Fe plaque (Ultra et al., 2009). The ability to control As inflow into rice roots by efficient As fixation by Fe plaque is higher in rice cultivars with higher root porosity and rate of radial O_2 loss because they release more O_2 to the rhizosphere.

Pre-treatment of As contaminated irrigating water/Phytofiltration

The heavy irrigation with groundwater contaminated with As is the main cause of the elevated levels of As in paddy soils in South and Southeast Asia. In addition to the above-mentioned strategies for lowering As contamination in the soil-rice system, it is crucial to use efficient methods for removing As from irrigation water. In both lab and pilot-scale studies, the As phytofiltration technique has been tried on As hyperaccumulators like *P. vittata*. Both *P. vittata* and *P. cretica*, another As hyperaccumulator, were able to reduce As to below the drinking water limit of 10 g/L in less than 24 hours, with baseline As(V) concentrations ranging from 20 to 200 g/L.

As concentration in the outflow was typically less than 2 g/L over the course of an 84-day demonstration in a pilot scale phytofiltration system, with starting As between 6.6 and 14 g/L and flow rate between 255 to 1900 L/day. Elless et al. (2005) found that the effectiveness of the As removal was unaffected by day length, light intensity, or humidity, demonstrating the high dependability of the technique. Therefore, in regions where As contamination is an issue, phytofiltration has the potential to lessen the buildup of As in agricultural soils by eliminating As from irrigation water (Wang & Ma., 2015).

Microbial remediation (biosorption, bioaccumulation, biotransformation etc.)

A low-cost and environmentally benign method of lowering the expense of heavy metal pollution removal is microbial bioremediation. In order for bacteria to withstand heavy metals, there are five primary mechanisms. 1) Extracellular barriers: Metal ions cannot enter the cell through the cell wall, plasma membrane, or capsule. 2) Active metal ion transport (efflux): P-type ATPases, CDF (Cation Diffusion Facilitator), and RND (Resistance, Nodulation, Cell Division) proteins work together to form a pathway to transport potentially dangerous metalloids from the cytoplasm. 3. Extracellular sequestration: this process involves the accumulation of metal ions in the periplasm, the outer membrane, or the complexation of metal ions by cellular components into insoluble compounds. 4) Intracellular sequestration: Metal resistance is based on the accumulation of metals in non-bioavailable forms inside the cytoplasm, preventing exposure to critical cellular components. This kind of metal resistance is demonstrated by the production of metalothionein by *Synechococcus* species and cysteine-rich proteins by *Pseudomonas* species. 5) Metal oxidation, including Cu and As, is another crucial detoxifying method (González Henao and Ghneim-Herrera, 2021).

Bio adsorption

Microbial Bio absorbent depends on the microbial species engaged in metal uptake, whether it is an active or passive process, or both. The passive uptake mechanism is generic to metal species, whereas the active process is a sluggish method that is dependent on cellular metabolism. Specific proteins, such as metallothioneins, form compounds with heavy metals throughout the active phase. Both active and passive processes can occur at the same time. In addition to chitosan and glucans, microbial species with high cell wall chitin content operate as an effective bio sorbent. Metal bio sorbents can also be found in the walls of fungus, yeasts, and algae. Gram-positive bacteria have a greater ability to attach metals than Gram-negative bacteria (Satyapal et al., 2016).

Bioaccumulation

Bioaccumulation is a heavy metal transport pathway that is energy-dependent. Ion pumps, ion channels, carrier mediated transport, endocytosis, and lipid permeability are all potential bioaccumulation pathways for heavy metal influx across bacterial membranes. Bioreporters for inorganic species in the environment have been made using genetically engineered microorganisms. These bioreporters are based on genetic constructs that combine an arsR operator and promoter sequence with the reporter gene sequence, such as luciferase, -galactose, an auto fluorescent protein, or cytochrome c peroxidase. The intracellular build-up of As by bacteria is preferred among the various probable As bioremediation processes. A mutant strain of *C. glutamicum* has been developed to accumulate As intracellularly (Satyapal et al., 2016).

Biotransformation

Biotransformation is a process of transfer of a metal from its toxic form to less toxic for or nontoxic form. Specific enzymes or respiratory chains in the bacteria are responsible for the redox transformation of As. These microbes can use As either as an electron donor or electronacceptor and thereby play a significant role in As detoxification mechanisms. A group of bacteria *(Pseudomonas sp, Burkholderia sp, Bacillus sp, Rhodobacter sp*.) are able to transfer arsenite (toxic form) to arsenate (less toxic form) (Laha et al., 2021). As(V) and

As(III) both can undergo chemical and or microbial oxidation-reduction and methylation reactions in soils and sediments and can adsorb on hydrous oxides of Fe, Al, and Mn. The most important natural attenuation process known for As(III) compounds is precipitation as As sulfide (As_2S_3). As(III) is more toxic and mobile in soils than As(V), and methylated species such as monomethylarsonic acid [MMAA, $CH_3AsO(OH)_2$] and dimethylarsinic acid [DMAA, $[(CH_3)_2AsO(OH)]$ are also mobile (Figure 3) . However, these methylated forms are volatile and unstable under oxidizing conditions and are cycled back into the soil environment in inorganic forms.

Bacterial metabolisms of As

The microbes have evolved several metabolic processes to counteract hazardous effects of As. According to certain theories, the enzyme arsenate reductase was not present during origin of life. When the environment turned reducing, microorganisms quickly evolved this enzyme. Bacterial As metabolism involves mainly four separate mechanisms, including reduction, oxidation, methylation, and demethylation (Ospino et al., 2019).

Arsenic is taken up by prokaryotes because of its molecular resemblance to the substrates of different membrane transporter proteins. $As(OH)_3$, which is formatively similar to glycerol, departs aqueous solution at physiological pH. AsIII and AsV, on the other hand, functions as a phosphate structural analogue and is taken up by membrane phosphate transporters. GlpF is an aquaglyceroprotein that helps AsIII pass the cell membrane (Kabiraj et al., 2022). Several microorganisms have GlpF homologies. Pit and Pst are phosphate transporter proteins that let AsV get into cells (Yang et al., 2012). Pst is a phosphate-specific transport system, whereas Pit is a universal transport system. Because of its configurational closeness to phosphate, arsenate is easily absorbed through the Pit transport system. Because Pst transports AsV inefficiently, microbial communities revealed to eleveted levels of arsenate express Pst solely to limit arsenate uptake. Arsenic is extruded by bacteria by two methods. The first is carrier-mediated efflux through an arsenite carrier protein, which is powered by the cell's membrane potential, and the second is arsenite-translocating ATPase (Yang et al., 2012).

In bacterial *ars* operon, ArsC enzyme plays key role in arsenate reduction and As resistance which is previously discussed. Bacterial transformation of As includes respiratory As(V) reduction and As(III) oxidation for autotrophic growth are called "arsenotrophy" (Oremland et al., 2009). The interconversion of As(V) and As(III) in arsenotrophy is catalyzed by one of the three enzymes of the dimethyl sulfoxide (DMSO) reductase family, arsenate reductase (ARR) and two distantly related arsenite oxidases, AIO and ARX (Ospino et al., 2019).

The arsM genes are directly involved in As methylation (Kabiraj et al.,2022). The methylation pathway proposed for prokaryotes (Stolz et al. 2006) is same with *Scopulariopsis brevicaulis* (Challenger,1945). It starts with As(V) and following a series of oxidative methylations by S-adenosylmethionine methyltransferases and reductive steps with glutathione and other thiol containing compounds to the end product TMAs, which is currently thought to be rather safe (Cullen and Bentley 2005). An overview of bacterial As metabolism are given in Figure 4.

Unveiling the importance of plant growth promoting microorganisms in As remediation

Arsenic resistance mechanisms in PGPB (Plant Growth Promoting Bacteria)

Microorganisms that can tolerate high levels of As have a variety of As-resistance systems that may be used in bioremediation procedures. Bacterial As-resistance pathways can be found in a variety of bacteria. Sequestration can be divided into two categories: intracellular and extracellular sequestration, as well as active sequestration. Biosorption and bioaccumulation are two effective strategies for extracellular and intracellular As sequestration, respectively. Due to their big surface-to-volume proportion and abundance of active chemisorption capacities, microbial cells are frequently considered as effective bio-sorbents (Sharma and Archana, 2016).

Biosorption is a physicochemical process which rummages heavy metals onto the surface of bacterial cells without using any energy. The toxicants have no impact on bacterial metabolism and have no toxic effects since they cannot enter the cell. Peptidoglycan and phosphate groups found in both gram-positive and gram-negative bacteria can behave as cationic and anionic binding sites. Extracellular polymeric substances (EPS), a large molecular mass bacterial secretory derivative that can also operate as a hazardous metal(loid) absorbent, are generally composed of mucopolysaccharides, polysaccharides, lipids, proteins, uronic acids, and humic substances (Sengupta and Dey, 2019).

The presence of acetamido, amine, sulfhydryl, carboxyl, and phosphodiester groups in proteins, as well as phosphate, hydroxyl, and polysaccharide groups, gives EPS a negative charge that promotes metal sequestration (Mukherjee et al., 2019). The energy-intensive, slow, and persistent process of bioaccumulation, in contrast, is how heavy metals build up inside the microbial cell after passing through ion pumps, ion channels, endocytosis, and lipid penetration. This, unlike biosorption, is a metabolism-dependent mechanism that has harmful effects on bacteria. The metal is likely rummaged inside the cell by cysteine-rich metallothionines (Mondal et al., 2021).

Biofilm development has also been observed among these PGPR. The biofilm structure is normally made up of EPS, proteins, and extracellular nucleic acids. Armendariz et al. (2015) and Vezza et al. (2020) found that it borders the cell populations across its surface, which additionally impede metal diffusion. By far the most researched method is active extrusion of the metal from the bacterial cell. Extrusion mediated by the ars operon (ArsB/ArsAB) is broadly allocated and ably defined (Mondal et al., 2021). *Sinorhizobium* *meliloti* has a novel detoxification route in which As(III) is extruded via an aquaglyceroporin (AqpS)-encoded aquaglyceroporin. Surprisingly, AqpS replaces arsB inside the ars operon (Yang et al., 2005). An overview of As resistant mechanisms and plant growth promotion activities are given in Figure 5.

Novel Technological advances in the As bioremediation field

The application of nanoparticles, non-living biomass and genetically modified plants for abolition of metal pollution from various origins attributed to having fast and big bioremediation capacity (Gaur et al., 2014).

Nanoparticle utilization

Use of nanotechnology is being widely utilized for the progress of creative, methodical and environment friendly nanomaterial structures in various domains of bioremediation. The physiochemical characteristics of the nanoscale molecules vary notably from their bigger counterparts. Due to high surface to volume ratio of nanomaterials it gives them big amount of adsorption potentiality. They also have a low cost and increased bioavailability, making them ideal candidates for bioremediation.

Because of this, nanoparticles have been discovered to be employed as an adsorbent; in compared to macroparticles, this opens up a wider range of possibilities. Arsenic has previously been removed using nanoparticle-based adsorbents generated from metals and metal oxides such as TiO_2, Fe_2O_3, and NiO nanoparticles, as well as cupric oxide nanoparticles. This method has been employed for nano iron (hydr) oxide impregnated granulated activated carbon in this context (Hristovski et al., 2009). It is preferable to use ecologically friendly materials in the production of metal nanoparticles. In this respect, attempts have been made to produce silver nanoparticles using fungal extracellular enzymes, such as the silver nanoparticles synthesised by using *Aspergillus foetidus* (Roy et al., 2013).

Non-living biomass

Heavy metals can be absorbed by nonliving marine algae from dilute water solutions. Such sorbents have yielded promising results; many studies on the sorption ability of marine organisms may be found in the literature (Jalali et al., 2002). Cationic metals, like as copper, have been shown to be beneficial to macrophytes. Arsenic, lead, cadmium, zinc, and chromium are just a few examples of such phenomenon (Mudhoo et al., 2012). Cystoseira and Dictyopterisare the two brown algal candidates which have a high As adsorption capacity. Dictyopteris performed admirably, with As-specific absorption values comparable to the highest ever recorded (Pennesi et al., 2012).

Transgenic crops

Transgenic *Arabidopsis thaliana* plants that expressed the *C. reinhardtii* As (III)-S-adenosylmethyltransferase (arsM) gene was also reported (Kabiraj et al., 2022). These plants were able to convert the majority of inorganic As into DMA(V) and volatile As species in their shoots. By heterologously indicating PvACR3 in the athac1 background and beating down the HAC1 gene, *Arabidopsis thaliana* was transformed into an As accumulator. AtHAC1 is an As reductase (Wang et al. 2018). As efflux was decreased in the medium when the As reductase was mutated (Zhang et al. 2018). The utterance of the vacuolar As transporter ACR3 in the roots did not promote As(III) efflux into the medium or vacuolar sequestration in these transgenic plants, but it did aid As loading into the vasculature and encouraged translocation to the shoots. PvPht1;3 is expressed in stele cells in transgenic A. thaliana and soybean, and it is thought to have contributed to P/As translocation. As move and build-up in shoots are increased by PvPht1;3 expression, which may enhance As phytoextraction in As-contaminated soils (Bertin et al., 2021).

Conclusion and future scope

The United Nations' Sustainable Development Goals (SDGs) place a major emphasis on decreasing pollution. For example, SDG 3.9 seeks to “substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination" by 2030. Achieving sustainable global development requires urgent action to limit As pollution exposure through effective management of both historic pollution legacies and contemporary releases of pollutant. To maximise the opportunity to manage or mitigate As pollution effectively, bioremediation technique is effective and promising in terms of its sustainability and eco friendliness. Use of PGPMs (bacteria, fungi and algae) for remediation of As contaminated soils has been explored by researchers worldwide but it still warrants refinement. More research is desired to screen the prospective microorganisms for remediation of As polluted soils as well as to address the issues of co-contamination of other heavy metals at a time and also to identify the potential combination of the PGPMs. Research should be carried out on the feasibility and applicability of these potential bioremediation techniques in field conditions. This will enable the researchers to identify and address the issues faced by the stakeholders (farmers) in application of a technology at the real time field condition.

References:

Adams WJ, DeForest DK, Tear LM, Payne K, Brix KV (2015) Long-term monitoring of arsenic, copper, selenium, and other elements in Great Salt Lake (Utah, USA) surface water, brine shrimp, and brine flies. Environmental monitoring and assessment. 187(3):1-3.

Armendariz AL, Talano MA, Oller AL, Medina MI, Agostini E. (2015) Effect of arsenic on tolerance mechanisms of two plant growth-promoting bacteria used as biological inoculants. Journal of Environmental Sciences. 33: 203-10.

Awasthi S, Chauhan R, Srivastava S, Tripathi RD (2017) The journey of arsenic from soil to grain in rice. Frontiers in Plant Science, 8, 1007.

Ben Fekih I, Zhang C, Li YP, Zhao Y, Alwathnani HA, Saquib Q, Rensing C, Cervantes C. (2018) Distribution of arsenic resistance genes in prokaryotes. Frontiers in microbiology. 9:2473.

Bertin PN, Crognale S, Plewniak F, Battaglia-Brunet F, Rossetti S, Mench M. (2021)Water and soil contaminated by arsenic: the use of microorganisms and plants in bioremediation. Environmental Science and Pollution Research. 2:1-28.

Bhattacharyya K, Sengupta S, Pari A, Halder S, Bhattacharya P, Pandian BJ, Chinchmalatpure AR (2021) Characterization and risk assessment of arsenic contamination in soil–plant (vegetable) system and its mitigation through water harvesting and organic amendment. Environmental Geochemistry and Health. 43(8):2819-34.

Bhattacharyya K, Sengupta, S. (2020). Arsenic management options in soil-plant-food chain. Proceedings-cum-Abstract book National Webinar On Arsenic, p.17. India.

Burgin AJ, Yang WH, Hamilton SK, Silver WL (2011). Beyond carbon and nitrogen: how the microbial energy economy couples elemental cycles in diverse ecosystems. Frontiers in Ecology and the Environment, 9(1), 44-52.

Challenger F (1945) Biological methylation. Chemical Reviews 36:315–361

Chandra R, Banik A. (2021) Detoxification and bioconversion of arsenic and chromium. In Nanobiotechnology (pp 253-270) Elsevier. United States.

Cullen WR, Bentley R (2005) The toxicity of trimethylarsine: an urban myth. Journal of Environmental Monitoring. 7:11–15

Cullen WR, Reimer KJ (1989) Arsenic speciation in the environment. Chemical reviews. 89(4):713-64.

Das TK (2019) Arsenic menace in West Bengal (India) and its mitigation through toolbox intervention: an experience to share. InGround Water Development-Issues and Sustainable Solutions (pp. 305-314). Springer, Singapore.

Datta BK, Bhar MK, Patra PH, Majumdar D, Dey RR, Sarkar S, Mandal TK, Chakraborty AK (2012) Effect of environmental exposure of arsenic on cattle and poultry in Nadia district, West Bengal, India. Toxicology international. 19(1):59.

de Souza TD, Borges AC, Braga AF, Veloso RW, de Matos AT (2019) Phytoremediation of arsenic-contaminated water by Lemna Valdiviana: An optimization study. Chemosphere. 234:402-8.

Elekwachi CO, Andresen J, Hodgman TC. (2014) Global use of bioremediation technologies for decontamination of ecosystems Journal of Bioremediation & Biodegredation. 5(4):1.

Elless MP, Poynton CY, Willms CA, Doyle MP, Lopez AC, Sokkary DA, Ferguson BW, Blaylock MJ. (2005) Pilot-scale demonstration of phytofiltration for treatment of arsenic in New Mexico drinking water. Water Research. 39(16):3863-72.

Fernández M, Morel B, Ramos JL, Krell T. (2016) Paralogous regulators ArsR1 and ArsR2 of Pseudomonas putida KT2440 as a basis for arsenic biosensor development. Applied and environmental microbiology. 82(14):4133-44.

Garbinski LD, Rosen BP, Chen J. (2019). Pathways of arsenic uptake and efflux. Environment international, 126, 585-597.

Gaur N, Flora G, Yadav M, Tiwari A. (2014) A review with recent advancements on bioremediation-based abolition of heavy metals. Environmental Science: Processes & Impacts. 16(2):180-93.

Gonzalez Henao S, Ghneim-Herrera T. (2021) Heavy metals in soils and the remediation potential of bacteria associated with the plant microbiome. Frontiers in Environmental Science. 15.

Gupta DK, Srivastava S, Huang HG, Romero-Puertas MC, Sandalio LM. Arsenic tolerance and detoxification mechanisms in plants (2011) InDetoxification of heavy metals (pp. 169-179). Springer, Berlin, Heidelberg.

Gupta K, Srivastava A, Kumar A. (2020). Arsenic: threat to water as well as soil. In *Contaminants and clean technologies* (pp. 165-187). CRC Press. Boca Raton.

Kabiraj A, Biswas R, Halder U, Bandopadhyay R. (2022) Bacterial Arsenic Metabolism and Its Role in Arsenic Bioremediation. Current Microbiology. 79(5): 1-5.

Kato K, Davis KL (1996) Current use of bioremediation for TCE cleanup: results of a survey. Remediation Journal 6(4):1-4.

Kowitwiwat A, Sampanpanish P. (2020) Phytostabilization of arsenic and manganese in mine tailings using Pennisetum purpureum cv. Mott supplemented with cow manure and acacia wood-derived biochar. Heliyon. 1;6(7):e04552.

Kumar S, Joshi SK, Pant N, Singh S, Chakravorty B, Saini RK, Kumar V, Singh A, Ghosh NC, Mukherjee A, Rai P. (2021) Hydrogeochemical evolution and groundwater recharge processes in arsenic enriched area in central Gangetic plain, India. Applied Geochemistry.131:105044.

Laha A, Bhattacharyya S, Sengupta S, Bhattacharyya K, GuhaRoy S (2021) Investigation of arsenic-resistant, arsenite-oxidizing bacteria for plant growth promoting traits isolated from arsenic contaminated soils. Archives of Microbiology. 203(7):4677-92.

Leiva ED, dP Rámila C, Vargas IT, Escauriaza CR, Bonilla CA, Pizarro GE, Regan JM, Pasten PA (2014) Natural attenuation process via microbial oxidation of arsenic in a high Andean watershed. Science of the Total Environment. 466:490-502.

Lim KT, Shukor MY, Wasoh H (2014) Physical, chemical, and biological methods for the removal of arsenic compounds. BioMed research international. 2014.

Mahimairaja S, Bolan NS, Adriano DC, Robinson B (2005) Arsenic contamination and its risk management in complex environmental settings. Advances in Agronomy. 86:1-82.

Mandal J, Sengupta S, Sarkar S, Mukherjee A, Wood MD, Hutchinson SM, Mondal D (2021) Meta-analysis enables prediction of the maximum permissible arsenic concentration in Asian paddy soil. Frontiers in Environmental Science. 547.

Mandal J, Golui D, Datta SP. (2019a). Assessing equilibria of organo-arsenic complexes and predicting uptake of arsenic by wheat grain from organic matter amended soils. *Chemosphere*, 234, 419–26.

Mandal J, Golui D, Raj A, Ganguly P. (2019b). Risk Assessment of Arsenic in Wheat and Maize Grown in Organic Matter Amended Soils of Indo-Gangetic Plain of Bihar, India. *Soil Sediment Contamination*: *An International Journal*, 28(8), 757-772.

Menon M, Sarkar B, Hufton J, Reynolds C, Reina SV, Young S. (2020) Do arsenic levels in rice pose a health risk to the UK population?. Ecotoxicology and Environmental Safety. 197:110601.

Mondal S, Pramanik K, Ghosh SK, Pal P, Mondal T, Soren T, Maiti TK. (2021)Unraveling the role of plant growth-promoting rhizobacteria in the alleviation of arsenic phytotoxicity: A review Microbiological Research. 250:126809.

Mudhoo A, Garg VK, Wang S. (2012) Removal of heavy metals by biosorption. Environmental Chemistry Letters. 10(2):109-17.

Mukherjee A, Gupta S, Coomar P, Fryar AE, Guillot S, Verma S, Bhattacharya P, Bundschuh J, Charlet L. (2019) Plate tectonics influence on geogenic arsenic cycling: From primary sources to global groundwater enrichment. Science of the total environment. 15; 683:793-807.

Oremland RS, Saltikov CW, Wolfe-Simon F, Stolz JF. (2009) Arsenic in the evolution of earth and extraterrestrial ecosystems. Geomicrobiology Journal. 26(7):522-36.

Ospino MC, Kojima H, Fukui M. (2019) Arsenite oxidation by a newly isolated betaproteobacterium possessing arx genes and diversity of the arx gene cluster in bacterial genomes. Frontiers in microbiology. 29;10:1210**.**

Páez-Espino, D., Tamames, J., de Lorenzo, V., & Cánovas, D. (2009). Microbial responses to environmental arsenic. Biometals, *22*(1), 117-130.

Pennesi C, Vegliò F, Totti C, Romagnoli T, Beolchini F. Nonliving biomass of marine macrophytes as arsenic (V) biosorbents (2012) Journal of Applied Phycology. (6): 1495-502.

Roy P, Mondal NK, Bhattacharya S, Das B, Das K. (2013). Removal of arsenic (III) and arsenic (V) on chemically modified low-cost adsorbent: batch and column operations. Applied Water Science. 3(1):293-309.

Sanyal SK. (2017) A textbook of soil chemistry. Daya Publishing House, A division of Astral International Pvt. Limited. India.

Satyapal GK, Rani S, Kumar M, Kumar N. (2016) Potential role of arsenic resistant bacteria in bioremediation: current status and future prospects. J Microb Biochem Technol. 8(3): 256-8.

Saxena P, Misra N. (2010) Remediation of heavy metal contaminated tropical land. In Soil heavy metals 431-477. Springer, Berlin, Heidelberg.

Sengupta S, Bhattacharyya K, Mandal J, Bhattacharya P, Halder S, Pari A (2021) Deficit irrigation and organic amendments can reduce dietary arsenic risk from rice:

Introducing machine learning-based prediction models from field data. Agriculture, Ecosystems & Environment. 319:107516.

Sengupta S, Bhattacharyya K, Mandal J, Chattopadhyay AP. (2022). Complexation, retention and release pattern of arsenic from humic/fulvic acid extracted from zinc and iron enriched vermicompost. Journal of Environmental Management. 318:115531.

Sengupta S., Dey S. (2019). Universal multi-nutrient extractants in soil analysis-Scope & Prospects. Agriculture and Food, 1(11), 406-410.

Shackira AM, Puthur JT. (2019) Phytostabilization of heavy metals: understanding of principles and practices. In: Plant-metal interactions pp. 263-282. Springer, Cham.

Shaji E, Santosh M, Sarath KV, Prakash P, Deepchand V, Divya BV (2021) Arsenic contamination of groundwater: A global synopsis with focus on the Indian Peninsula. Geoscience frontiers. 12(3):101079.

Sharma I (2020) Bioremediation techniques for polluted environment: concept, advantages, limitations, and prospects. InTrace Metals in the Environment-New Approaches and Recent Advances IntechOpen. Austria

Sharma RK, Archana G (2016) Cadmium minimization in food crops by cadmium resistant plant growth promoting rhizobacteria. Applied soil ecology. 107:66-78.

Singh P, Borthakur A, Singh R, Bhadouria R, Singh VK, Devi P. (2021). A critical review on the research trends and emerging technologies for arsenic decontamination from water. Groundwater for Sustainable Development, 14, 100607.

Srivastava S, Suprasanna P, D’souza SF. (2012) Mechanisms of arsenic tolerance and detoxification in plants and their application in transgenic technology: a critical appraisal. International journal of phytoremediation. 14(5): 506-17.

Stolz JE, Basu P, Santini JM, Oremland RS (2006) Arsenic and selenium in microbial metabolism. Annual Review of Microbiology. 60:107–130

Susarla S, Medina VF, McCutcheon SC. (2002) Phytoremediation: an ecological solution to organic chemical contamination. Ecological engineering. 18(5):647-58.

Tsai SL, Singh S, Chen W (2009) Arsenic metabolism by microbes in nature and the impact on arsenic remediation. Current Opinion in Biotechnology 20:659–667

Ultra Jr VU, Nakayama A, Tanaka S, Kang Y, Sakurai K, Iwasaki K. (2009) Potential for the alleviation of arsenic toxicity in paddy rice using amorphous iron-(hydr) oxide amendments. Soil Science and Plant Nutrition. 55(1):160-9.

Upadhyay MK, Yadav P, Shukla A, Srivastava S (2018) Utilizing the potential of microorganisms for managing arsenic contamination: a feasible and sustainable approach. Frontiers in Environmental Science. 6:24.

USEPA (2007) Treatment Technologies for Site Cleanup: Annual Status Report.

Vejan P, Abdullah R, Khadiran T, Ismail S, Nasrulhaq Boyce A (2016) Role of plant growth promoting rhizobacteria in agricultural sustainability—a review. Molecules. 21(5):573.

Vezza ME, Olmos Nicotra MF, Agostini E, Talano MA. (2020) Biochemical and molecular characterization of arsenic response from Azospirillum brasilense Cd, a bacterial strain used as plant inoculant. Environmental Science and Pollution Research. 27(2): 2287-300.

Wang D, Zhu S, Lu Y, Zeng R, Hu Z, Li X, Jie Y (2021) Phytoextraction of lead and arsenic from agricultural soils by different intercropping density of Boehmeria nivea (L.) and Pteris vittata (L.). Agronomy Journal. 13(2):923-31.

Wang X, Ma LQ. (2015) Recent advances in phytoremediation of arsenic-contaminated soils. In-Situ Remediation of Arsenic-Contaminated Sites. Taylor & Francis Group :69-86.

Waychunas GA, Kim CS, Banfield JF (2005) Nanoparticulate iron oxide minerals in soils and sediments: unique properties and contaminant scavenging mechanisms. Journal of nanoparticle research. 7(4):409-33.

Wei Z, Van Le Q, Peng W, Yang Y, Yang H, Gu H, Lam SS, Sonne C. (2021) A review on phytoremediation of contaminants in air, water and soil. Journal of hazardous materials. 403:123658.

WHO (2011) Arsenic in Drinking-water. Background Document for Preparation of WHO Guidelines for Drinking-water Quality. World Health Organization, Geneva.

Yadav KK, Gupta N, Kumar A, Reece LM, Singh N, Rezania S, Khan SA (2018) Mechanistic understanding and holistic approach of phytoremediation: a review on application and future prospects. Ecological engineering. 120:274-98.

Yang HC, Fu HL, Lin YF, Rosen BP (2012) Pathways of arsenic uptake and efflux. InCurrent topics in membranes (Vol. 69, pp. 325-358). Academic Press.

Zhang W, Zhang G, Liu C, Li J, Zheng T, Ma J, Wang L, Jiang J, Zhai X. (2018) Enhanced removal of arsenite and arsenate by a multifunctional Fe-Ti-Mn composite oxide: Photooxidation, oxidation and adsorption. Water research. 147: 264-75.

Zhao FJ, McGrath SP, Meharg AA. (2010) Arsenic as a food chain contaminant: mechanisms of plant uptake and metabolism and mitigation strategies. Annual review of plant biology. 61:535-59.

Table 1:-List of the microorganisms which help in bioremediation

Name of the microorganisms	**As tolerance capacity**	**Mode of action**	**References**
Bacteria			
Bacillus flexus	12%	Bioaccumulation	Upadhyay et al., 2018
Bacillus sp. SF-1	56% within 70 h	Mobilization by reduction	Wan et al.,2020
Bacillus vietnamensis	Tolerate 20mM of As(III)	Reduced bioavailability	Upadhyay et al., 2018
Bacillus aryabhattai AS6	20 mM 100 mM	Bioaccumulation	Mondal et al.,2021
Bacillus tequilensis	18 mM	Arsenite oxidation	Mondal et al.,2021
Bacillus licheniformis	30 mM	Biofilm formation	Mondal et al.,2021
Burkholderia cepacia	55% of arsenate	Biotransformation	Laha et al.,2021
Burkholderia metallica	73% of arsenate	Biotransformation	Laha et al.,2021
Brevibacillus sp KUMAs1	55% within 96 h	Oxidation	Wan et al.,2020
Rhodopseudomonas palustris	Remove 2.2%–4.5% of As	Bio volatilization	Wan et al.,2020
Geobacter metallireducens GS-15	-	Mobilization	Wan et al.,2020
Acinetobacter junii	Volatize 14% of As within 72 h	Biovolatilization	Wan et al.,2020
Acinetobacter lwoffii (RJB-2)	125mM As(V), 50mM As(III)	Biofilm formation	Mondal et al.,2021
Sporosarcina ginsengisoli CR5	99% within 10 d	-	Upadhyay et al., 2018
Kocuria flava	Can tolerate 35mM of As(III)	Reduced bioavailability	Mondal et al.,2021
Methylobacterium oryzae	580µM As(V)	-	Mondal et al.,2021
Ralstonia eutropha	Reduced As content (22–50%) of edible portion of crop	Mobilization	Mondal et al.,2021
Rhizobium tropici	Reduced As content (22–50%) of edible portion of crops	Mobilization	Mondal et al.,2021
Exiguobacterium aurantiacum	Reduced As content (22–50%) of edible portion of crops	Mobilization	Mondal et al.,2021
Brevundimonas diminuta	150 ppm As(V), 20 ppm As(III)	-	Mondal et al.,2021
Brevundimonas diminuta NBRI012	150 mM	Bioaccumulation	Mondal et al.,2021
Exiguobacterium sp. As-9	180 mM	-	Mondal et al.,2021
Klebsiella pneumoniae	50 mM	As(III) oxidation	Mondal et al.,2021
Klebsiella oxytoca	50 mM	As(III) oxidation/Arsenite	Mondal et al.,2021

		oxidase gene	
Luteimonas aestuarii	50 mM	As(III) oxidation/Arsenite oxidase gene	Mondal et al.,2021
Escherichia fergusonii	50 mM	As(III) oxidation/Arsenite oxidase gene	Mondal et al.,2021
Psychrobacter faecalis	50 mM	As(III) oxidation/Arsenite oxidase gene	Mondal et al.,2021
Bacillus safensis	50 mM	As(III) oxidation/Arsenite oxidase gene	Mondal et al., 2021
Escherichia fergusonii	50 mM	As(III) oxidation/Arsenite oxidase gene	Mondal et al., 2021
Rhizosphere Fungi			
Trichoderma sp.	650 ppm As(III)	-	Upadhyay et al., 2018
Piriformospora indica	100µM As	Bioadsorption	Upadhyay et al., 2018
Arbuscular mycorrhizal fungi			
Rhizoglomus intraradices	100 ppm As(V)	Maintaining favorable P: As	Upadhyay et al., 2018
Rhizophagus intraradices	Decreased plant As accumulation from 7.8mg As kg^{-1} to 6.0mg As kg^{-1}	Up regulation of phosphate transporter-*RiPT*, putative As efflux pump-*RiArsA*	Upadhyay et al., 2018
Rhizophagus intraradices	60 ppm As(V)	Biomethylation	Upadhyay et al., 2018
Glomus geosporum	50% reduction of arsenic	Through enhancing P/As ratios	Upadhyay et al., 2018
Glomus versiforme	50% reduction of arsenic	Through enhancing P/As ratios	Upadhyay et al., 2018
Glomus mosseae	50% reduction of arsenic	Through enhancing P/As ratios	Upadhyay et al., 2018
Glomus etunicatum	100 ppm As(V)	Maintaining favorable P: As	Upadhyay et al., 2018
Algae			
Chlorella vulgaris and Nannochloropsis sp.	-	Reduced oxidative stress, As toxicity 1000µM As(III)	Upadhyay et al., 2016
Anabaena sp	60µM As(V) and As(III). As transporter	Mobilization	Upadhyay et al., 2018
Pseudomonas putida and *Chlorella vulgaris* consortium	50µM As(V)	Biofilm formation	Upadhyay et al., 2018

LIST OF FIGURES:

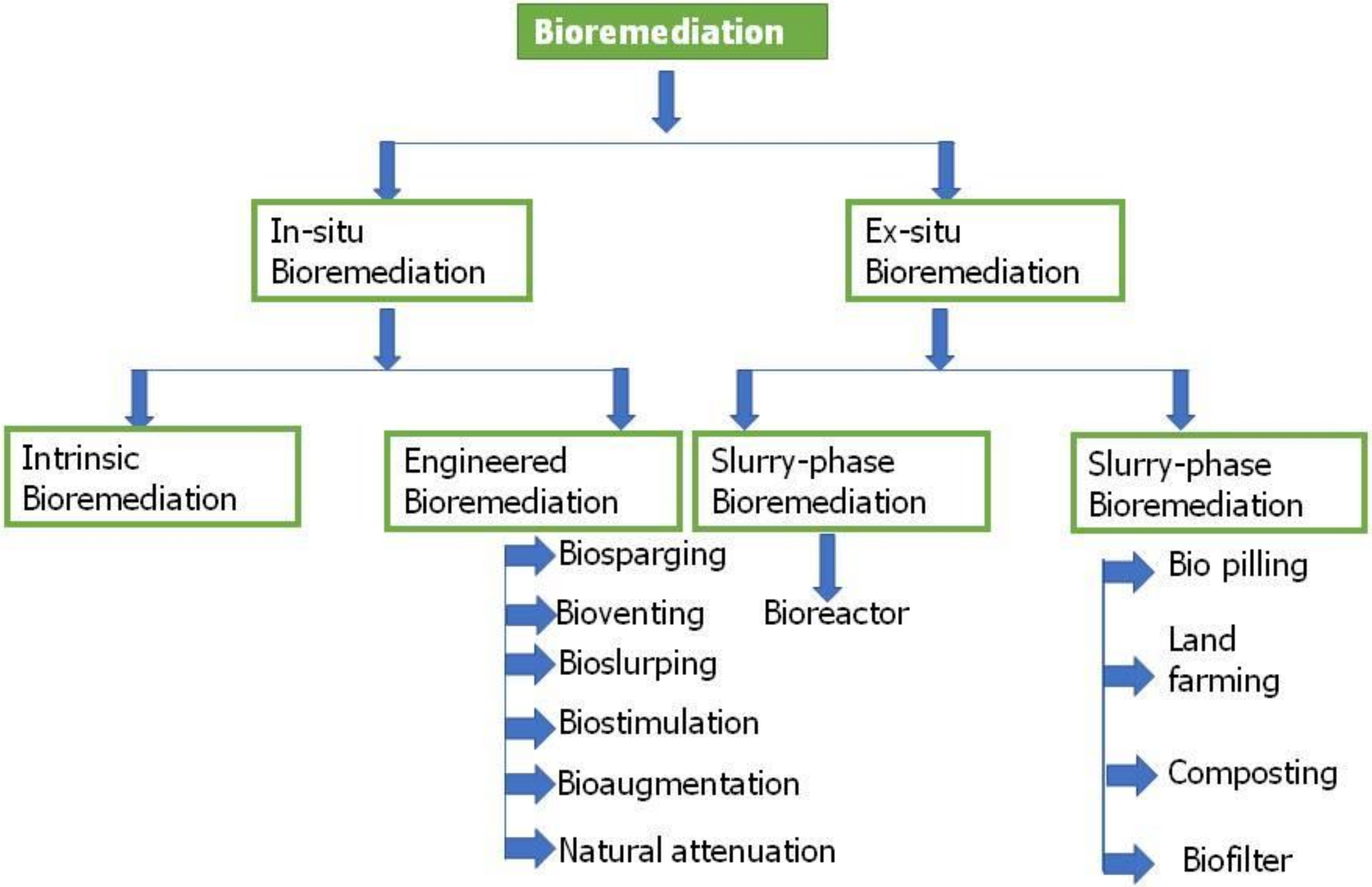
Figure 1. Bioremediation approaches for environmental clean-up (Sharma, 2020).

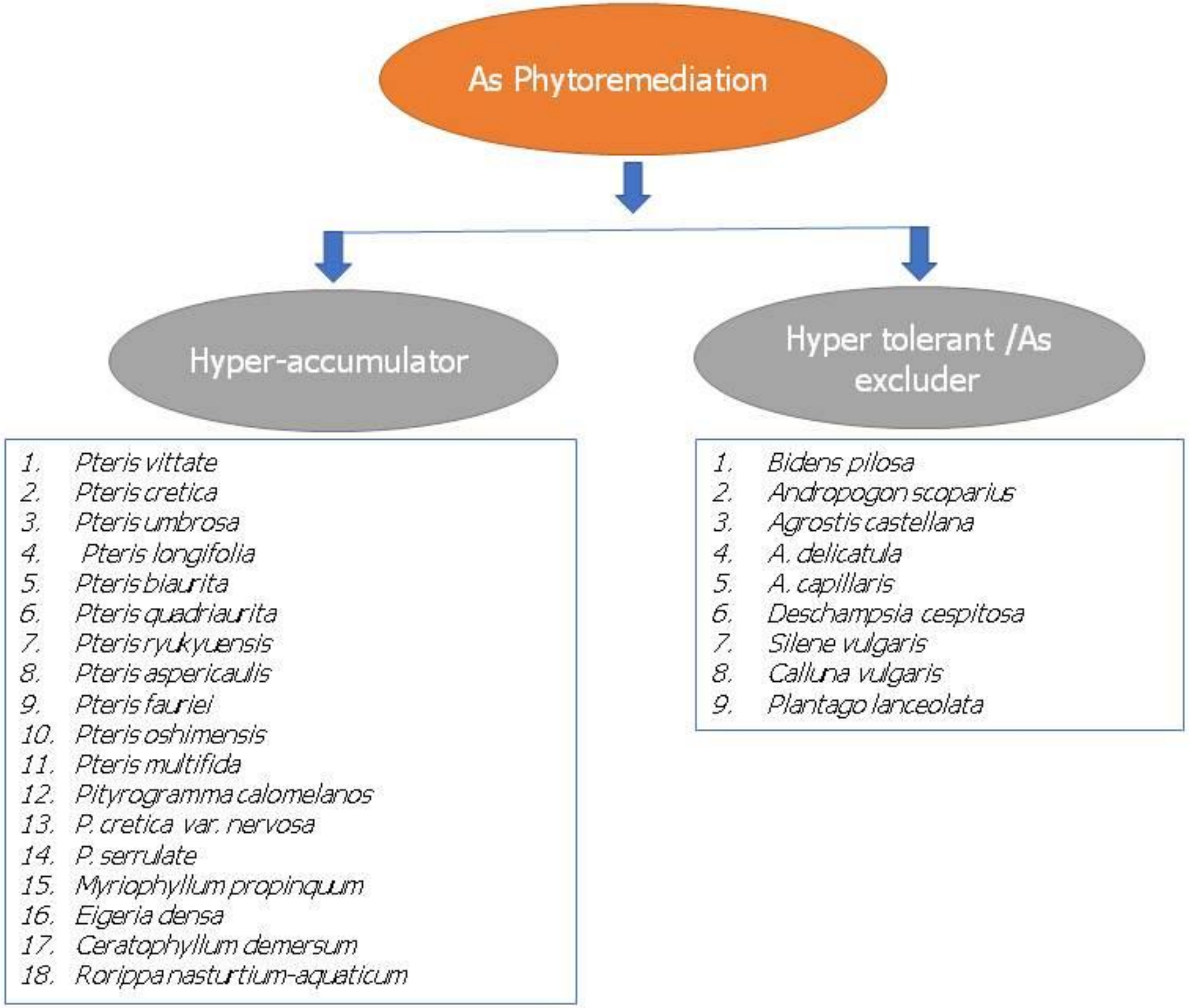
Figure 2. Plant used in arsenic phytoremediation

Figure 3. Chemical reaction of arsenic (As) transformation/removal from soils (Shrivastava et al., 2015)

Figure 4. Bacterial arsenic metabolism mechanism. As enters in cell through glycerol or phosphate transporters. Arsenate is transformed to arsenite which may then be extruded from the cell by ArsAB. Further As is methylated by ArsM. During methylation, the formation of volatile intermediates monomethyl arsenite (MMAs (III)), dimethyl arsenite (DMAs (III)), and trimethyl arsine (TMAs) is found. Arsenite's presence regulates the ars operon's expression and has an impact on a number of functions, including DNA repair, oxidative stress response, motility, and EPS synthesis. Arsenite oxidation or arsenate reduction can be employed to get energy from arsenic that isn't inside the cytoplasm.

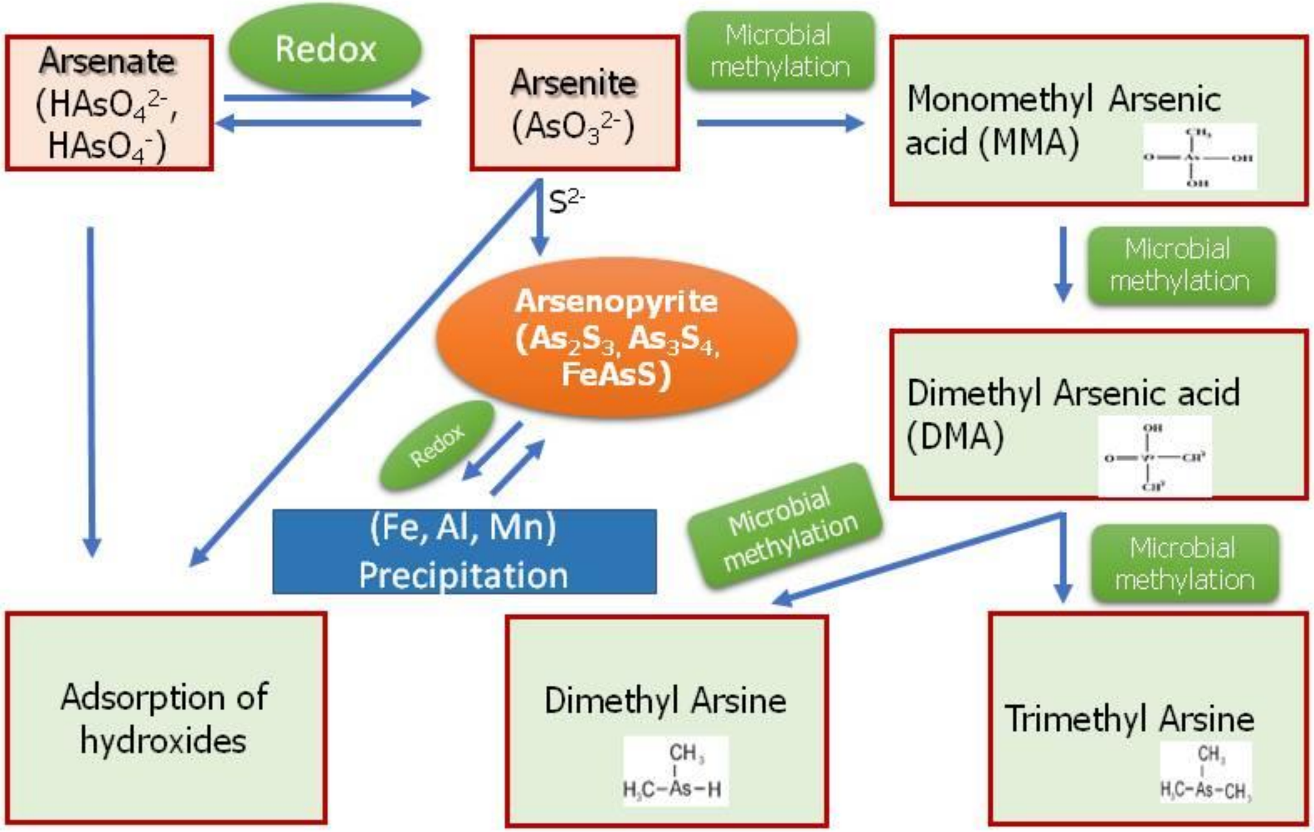
Figure 5. Mechanisms of bioremediation and plant growth promotion by microbes

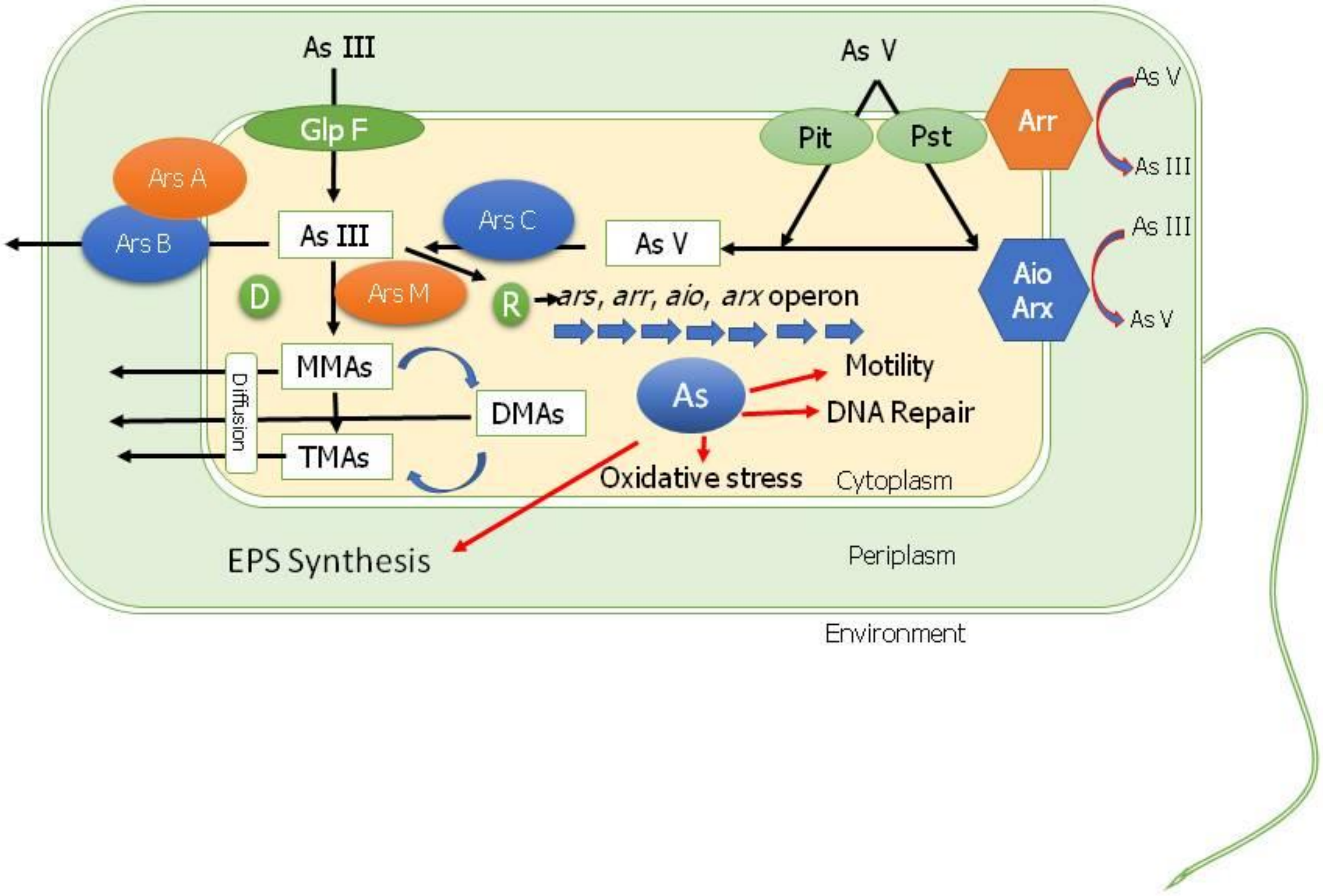

Bioremediation
In-situ Bioremediation
Ex-situ Bioremediation
Intrinsic Bioremediation
Engineered Bioremediation
Slurry-phase Bioremediation
Slurry-phase Bioremediation
Biosparging
Bioventing
Bioslurping
Biostimulation
Bioaugmentation
Natural attenuation
Bioreactor
Bio pilling
Land farming
Composting
Biofilter

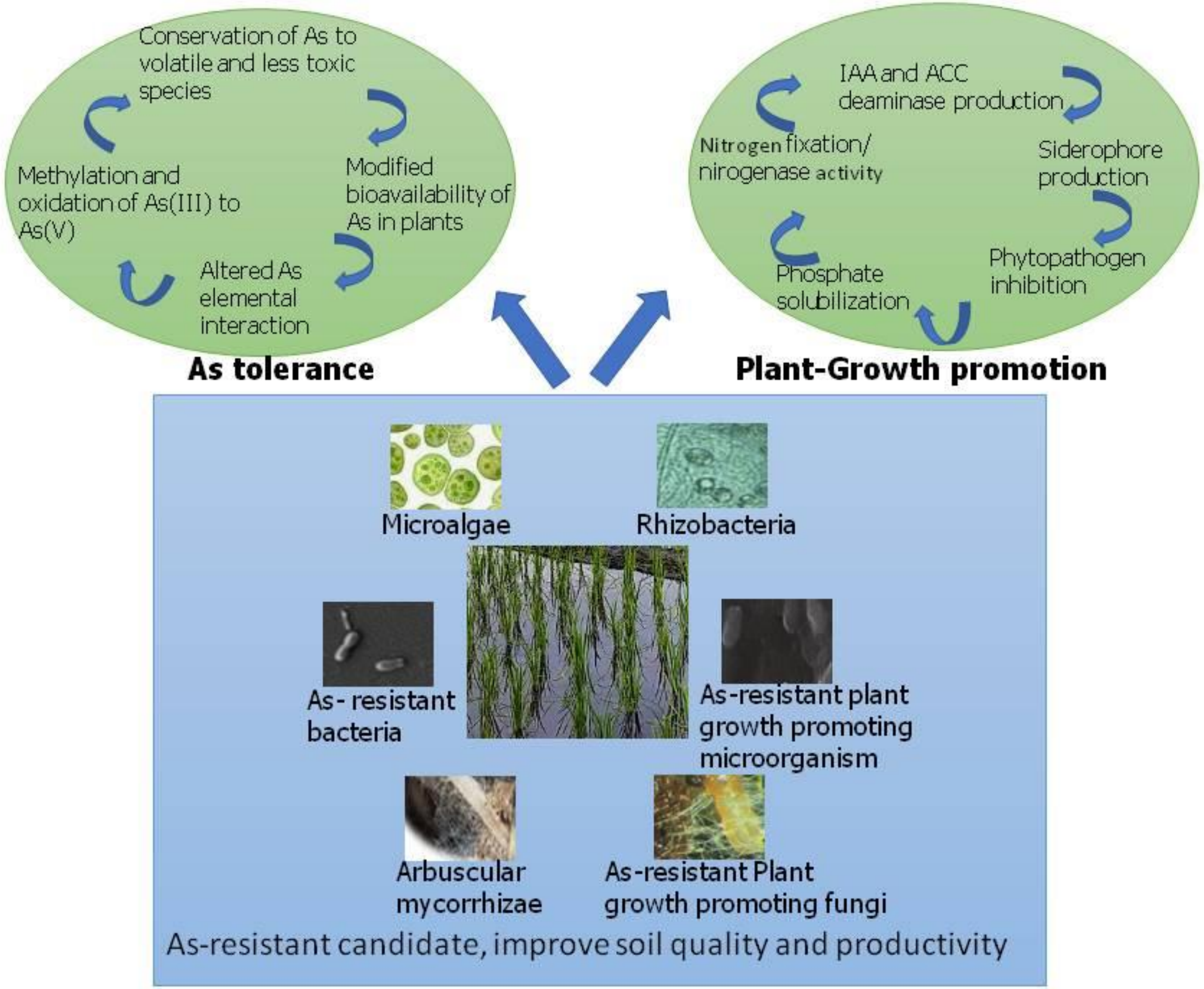


1. *Pteris vittate*
2. *Pteris cretica*
3. *Pteris umbrosa*
4. *Pteris longifolia*
5. *Pteris biaurita*
6. *Pteris quadriaurita*
7. *Pteris ryukyuensis*
8. *Pteris aspericaulis*
9. *Pteris fauriei*
10. *Pteris oshimensis*
11. *Pteris multifida*
12. *Pityrogramma calomelanos*
13. *P. cretica var. nervosa*
14. *P. serrulate*
15. *Myriophyllum propinquum*
16. *Eigeria densa*
17. *Ceratophyllum demersum*
18. *Rorippa nasturtium-aquaticum*

1. *Bidens pilosa*
2. *Andropogon scoparius*
3. *Agrostis castellana*
4. *A. delicatula*
5. *A. capillaris*
6. *Deschampsia cespitosa*
7. *Silene vulgaris*
8. *Calluna vulgaris*
9. *Plantago lanceolata*


Arsenate ($HAsO_4^{2-}$, $HAsO_4^-$)
Redox
Arsenite (AsO_3^{2-})
Microbial methylation
Monomethyl Arsenic acid (MMA)
S^{2-}
Arsenopyrite (As_2S_3, As_3S_4, FeAsS)
Microbial methylation
Dimethyl Arsenic acid (DMA)
Redox
(Fe, Al, Mn) Precipitation
Microbial methylation
Microbial methylation
Adsorption of hydroxides
Dimethyl Arsine
Trimethyl Arsine


As III
Glp F
Ars A
Ars B
As III
Ars C
As V
Ars M
D
R
ars, arr, aio, arx operon
MMAs
DMAs
TMAs
Diffusion
As V
Pit
Pst
Arr
As V
As III
Aio
Arx
As III
As V
As
Motility
DNA Repair
Oxidative stress
Cytoplasm
EPS Synthesis
Periplasm
Environment


Conservation of As to volatile and less toxic species
Modified bioavailability of As in plants
Altered As elemental interaction
Methylation and oxidation of As(III) to As(V)
As tolerance
IAA and ACC deaminase production
Siderophore production
Phytopathogen inhibition
Phosphate solubilization
Nitrogen fixation/ nirogenase activity
Plant-Growth promotion
Microalgae
Rhizobacteria
As- resistant bacteria
As-resistant plant growth promoting microorganism
Arbuscular mycorrhizae
As-resistant Plant growth promoting fungi
As-resistant candidate, improve soil quality and productivity