STATUS OF HEAVY METAL POLLUTION IN GANGES WITH PHYTOREMEDIATION AS A SOLUTION

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Abstract

Ganges, the largest and the most sacred river of India is under a heavy crisis of enduring problem of pollution due to heavy metals and microplastics giving rise to momentous risks to the surrounding environment and the residing population in terms of health. Though numerous proposals have been initiated towards cleaning of the river, however, no significant impacts are being successful yet due to heavy expenses and socio-political reasons. Therefore, defining the fundamental issues for Ganges pollution and eradication of the same using cost-effective yet sustainable management system is utmost necessary at present. With this notion, this review summarizes the underlying anthropogenic causes posing threats to Ganges and elaborates on the plausible green technology mechanisms that may be applied to overcome the pollution in near future.

Keywords: Ganges, pollution, anthropogenic, sustainable, cost-effective management

Introduction

The main route of exposure to heavy metals (HMs) in humans is via the consumption of contaminated food stuffs. These metals include both vital (Cobalt: Co, Cupper: Cu, Iron: Fe, Manganese: Mn, Molybdenum: Mo, Selenium: Se and Zinc: Zn) and non-vital elements or trace elements, TE (Arsenic: As, Cadmium: Cd, Chromium: Cr, Mercury: Hg, Nickel: Ni and Lead: Pb) where the former are toxic at high concentrations and the latter are harmful even at low dosages, causing respiratory distress, benign and malignant tumors, nervous system, kidney and liver damage (Ghosh et al., 2020; Chakraborty et al., 2022). The variations and the complexities in the source of HMs pollution in the environment make the process of identification of specific sites of pollution very challenging. However, application of Monte-Carlo simulations and Principal Component analysis aid to measure the risk of spread of pollution (Kuerban et al., 2020). Enormous literature exists focusing on the pollution of marine ecosystems (Wendt-Potthoff et al., 2020). However, fresh water HMs pollution also need to be focused as the fresh water regions form an important site for development of social lives.

The river Ganges, stretching for 2510 Kms is the largest river of India that originates from Gangotri glacier in Himalayas and flows into the Sundarban delta, covering an area of 1 million km 2, support the livelihood of half of the Indian population residing within Indo-Gangetic plains. Therefore, the importance of the Ganges as well as the high anthropogenic influences upon it is quite well understood. Surveys have concluded that the main causes for pollution include anthropometric activities, domestic land uses, sewages, atmospheric sedimentation in catchments, animal wastes and industrial wastes (Mondal et al., 2020). The latter industrial wastes include the HMs and microplastic debris and account for 12% of the total pollution of the river. Though this proportion seems to be very low, but is of an enormous concern because of it's ecotoxicity and non-biodegradable nature (Chakraborty et al., 2021). The three important factors that influence the deposition of TE include the short spans of highly variable climatic conditions, sea currents and salinity. The variable climatic conditions and the sea currents result in the mixing and sorption of the elements within the sediments (Trifuoggi et al., 2022).

The present review focuses on the discussion about the present challenges faced due to HMs accumulation in Ganges, with emphasis on the possible natural and anthropometric sources of contamination and concludes with a note on the mechanisms of phytoremediation of HMs – a green technology-based mechanism for sustainable environment.

Present status of HMs pollution in Ganges

The study of dynamics of pollution in Ganges is relatively challenging due to its vastness which poorly defines the multiplicity in the source-inputs of environmental pollution and anthropometric influences arising from the high upstream areas. Also, the heterogeneity in the inherent systems and limitations in accumulation and processing of data pose hindrance to the understanding of the complex dynamicity of the system (Richards et al., 2022). However, the factors that relatively impose pollution in Ganges include anthropometric pressure, high demand for water and agriculture. Huge bodies of literature in the past fifteen years (2010-2024) have reported on surface pollution describing a few basic parameters including temperature, pH, dissolved oxygen, nitrates, biochemical oxygen demand, electrical conductivity and coliform microorganisms (CPCB, 2019). Organic contaminants, HMs and declining water quality with respect to nutrients and microorganisms have been studied intensively from Ganges (Bowes et al., 2020). A long four-year study from 2014-2017 showed a two-sixteen-fold increase of As, Pb, Ni, Cd, As, Uranium (U) in the brackish and fluvial waters of Hooghly estuary with Ni being at peak during post-monsoon seasons with severe risks to ecology (risk index= 300-600 and contamination index > 6) (Trifuoggi et al., 2022).

The Indo-Ganga basin from Devprayag (Uttarakhand) to Noorpur (West Bengal) showed variable patterns of distribution of metals calcium, sodium, magnesium and nitrate, chlorides and sulphates, particularly in lower parts of the delta, indicating high urban inputs, sewage effluents together with the interactions with rocks and groundwater (Richards et al., 2022). Similar patterns of distribution of HMS like Cd, Pb, Mn, Cr in Ganges water were observed from Varanasi, making the pollution load index as high as 6.698 (normal <1; Rashed, 2010). The tissues of the fishes collected and tested from these sites showed high hazard index (HI) due to accumulation of HMs above permissible limits (Mishra et al., 2022). Spatio-temporal analyses of sediments from Varanasi Ganga sites have shown that most of the metals are lithogenic except for Cd and Pb which have originated from anthropogenic functions, particularly agricultural activities (Debnath et al., 2024). The pollution may also originate from further upstream like Yarlung Tsangbo River of southern Tibet, where the river water has high concentrations of As mainly originating from Upper Crustal zones and have been transported to lower Ganga-Brahmaputra basin during Holocene due to wet climatic conditions (Kuerban et al., 2020). A high bioaccumulation of Zn has been found from water, sediments and catfish muscles of Ganges in Allahabad which is at par with the fact that the river receives high industrial effluents at these sites (Gupta et al., 2009). Concentrations of HMs and metalloids from fish and vegetables of high Ganges floodplains of Bangladesh have been recorded with limits higher than maximum allowable concentration, indicating contamination from atmospheric emission, agricultural activities, irrigation processes and other contaminated items (Chakraborty et al., 2021; Hossain et al., 2022). An accumulation of Zn in alluvial soils from these plains (10.12 mg/kg) and roots of the maize plants (>1.0) have been recorded (Islam et al., 2024). In addition to Zn, statistical analyses have revealed that the long-term exposure to other transition metals, Cu and Fe also contributed to increased ecological risks for aquatic species in Ganges basin (Wang et al., 2022). A difference in pollution index for HMs has been observed between the lower and upper Ganga-Brahmaputra-Meghna delta reveling that the upper basins have inputs from natural sources only while anthropometric activities additionally give inputs to the lower delta sediments (Haque et al., 2023). The Sajnekhali regions from Sundarban mangrove ecosystem zones also showed the natural-driven and anthropometric contributions towards the accumulation of TE that are finally affecting the benthos population (Mondal et al., 2018). The evaluation of health parameters in population from all these sites is also indicative to a considerable risk for carcinoma.

The high concentrations of HMs, along with the antibiotics, also contribute to the elevated levels of metal resistance genes (MRGs) to Fe, Co, Cu and antibiotic resistance genes (ARGs) in the sediments and water along the highly anthropometrically active Ganga basins. Resistance genes against the antibiotics elfamycine, fosmidomycin, beta-lactame and tetracycline from Arcobacter, Acidibacter, Burkholderia, Terrimicrobium, Pseudomonads and Stenotrophomonas species have been identified from Varanasi and along 1500 km long stretch of Haridwar to Bhagalpur regions, India. Unique bacteriopahges and coliform bacteria have also been isolated from Ganga basin regions indicating the contamination of human fecal matters (Ali et al., 2021; Reddy and Dubey, 2019).

These data are highly concerning as the microorganisms would lead to entry of ARGs into the food chain, affecting the ecological cycles. Recent studies have shown the dumping of hazardous and domestic wastes into the riverine systems, which might be a potential risk factor for the emerging trends in the resistome and fecal coliform microbes in the Ganges water (Naqvi and Kumar, 2020). The tributary rivers Yamuna, Danro, rivulets at Narora and alluvial plain from eastern Ganges harbor distinct distribution of HMs, above the permissible limits, and the contaminants vary depending on the sources of pollution, including discharges of wastewater, domestic uses, sand mining and industries (Rajan et al., 2024; Majumder et al., 2025; Bandey et al., 2019). The HMs: Cd and Pb have been found to exceed permissible limits in these soils, emphasizing on the mixing of industrial effluents with the sediments and soils from Ganges. Seasonal variations of HMs have also been observed with the rise of pollutants in the Ganges water during monsoon season with the flushes from catchment areas with spilled oil contaminants and boat washing (Haque et al., 2020). The Cd replaces the essential elements from the metalloproteins and also binds to sulphur residues of different proteins and enzymes and make them functionally inactive in living species (Ueno et al., 2011). The concentrations of Fe and Hg are found to be five times higher than national water quality standards of India, making it’s status more polluted than even it’s counterpart from Bangladesh (Wang et al., 2022). The dynamicity of flood plains including the alkaline pH, soil texture, and reductive dissolution of HMs hydroxides influence the HMs deposits in the Ganga basins (Rajmohan et al., 2014).

The architecture of aquifers, chemistry of groundwater, organic matter contents and redox reactions are also responsible in determination of the variability of redox-sensitive solutes like As, Fe and Mn along the two banks of Bhagirathi-Hooghly distributaries of Ganges, resulting in high proportion of As on eastern and Mn on western banks respectively (Chakraborty et al., 2022).

Plausible Remedies

The cost-effective bioremediation offers a promising solution based on modern green technology for HMs removal from soil and sediments. Researches on phytoextraction of HMs have developed better approaches for mitigation of the HMs pollution problem globally. Noccaea caerulescens (J. & C. Presl, 'Ganges') is an important hyper-accumulator plant species that have been identified from Ganges soil. The field-based experiments with Noccaea caerulescens confirmed the prospective of the plants to be used in moderately-contaminated sediments for Zn and Cd remediation (Ingwersen et al., 2006; Jacobs et al., 2017). High organic matter content and and low bulk soil density stimulates the growth of Noccaea caerulescens and positively influences the uptake of metals from the soil (Jacobs et al., 2019). The accumulation of Ni and Fe by Noccaea caerulescens was found to be higher than Noccaea japonica under high Ni conditions (Enomoto et al., 2021). The tolerance to Ni in Noccaea japonica is also due to the low root to shoot translocation of Ni due to high expression of IREG2 gene expression in roots which sequester the metal and inhibits the transport to aboveground tissues (Nishida et al., 2020). The Ganges ecotype of Thlaspi caerulescens were able to dissolute these two metals, decreasing the metal concentrations in the soil (Benzarti et al., 2008; Koopmans et al., 2008).

Thlaspi caerulescens also accumulate Cd, Zn and Cu by binding them with oxygen and sulphur ligands (metallothioneins) as well as non-proteogenic amino acids respectively, after which they are being internalized into the vacuoles and are loosely bound to organic acids (Mijovilovich et al., 2009). The tolerance to Ni in The adsorption of HMs was also found to be effective using composites of clay, peanut husks and saw-dust (Mungondori et al., 2017). Earlier studies have identified from the Ganges-specific hyperaccumulating plants, that plant-age and developmental stage-specific transporter proteins are involved in hyperaccumulation of metals and help in acclimatization of the plants during metal toxicity (Küpper and Kochian, 2010). Also, the mechanism of formation of vacuoles and internalization of the metals within the vacuoles is the preferred detoxifying technique used by the plants rather than chelating the metals with ligands (Küpper and Kochian, 2010). As compared to non-accumulator species, the epigenetic regulation through CpG DNA methylation, expression of transcripts associated with metal homeostasis genes, glucosinolate biosynthesis genes and metallothionein3 (MT3) in Noccaea caerulescens (Ganges) and high ATPase activity, thiol accumulation and Cysteine expression in Thlaspi caerulescens (Ganges) are responsible for their capacity of accumulation and tolerance of HMs under HMs pollution (Lin et al., 2014; Galati et al., 2023; Hernández-Allica et al., 2006). Metatranscriptome studies have also revealed the expression of wide range of potential candidate genes associated with iron and calcium ion binding metal ion, cation and anion transmembrane transporter activity and antioxidant activity in Noccaea caerulescens (Halimaa et al., 2014).

The increased tolerance towards Cd in these plants is also associated with enhanced metabolism of odd-carbon fatty acids (Pavlík et al., 2017).

Therefore, the findings show substantial capacity for using hyperaccumulator ecotypes to gain a sufficient amount of phytoextraction of HMs in highly metal-polluted soils and sediments like Ganges. The findings will also aid to the in production of genetically modified plants for sustainable phytoremediation.

Conclusion

The advances in knowledge on plant biology to phytoremediate the HMs contamination in soil and water has widened our vision in environmental engineering in the recent times. The environmental restoration is possible through use of transformed plants capable of degrading HMs. The colossal of plantation of trees and grasses on the polluted soils would provide efficient, log-lasting and cost-effective solutions towards limitation of HMs pollution. The HMs in the polluted sites thus can be leveled down to adequate levels for agricultural activities The socio-economic challenges can be addressed through rehabilitation of contaminated lands simultaneously supporting the local residents economically by selling the extracted metals and bio-products obtained from the remediation processing.

Conflicts of interest

The authors declare there is no conflicts of interest.

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