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A REVIEW ON HEAVY METAL POLLUTION IN RIVER BASINS DRIVEN BY AGRICULTURAL PRACTICES

N.P. Chandni, K.S. Devesh, and Sushmitha Baskar*

*Discipline of Environmental Studies, School of Interdisciplinary and Trans-disciplinary Studies
Indira Gandhi National Open University, New Delhi 110068.
Orcid ID: 0009-0003-9521-625X; 0009-0004-2642-4773

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Abstract
River ecosystems are precious lifelines of any nation that drives economic activities and is crucial for human survival. But rivers are threatened with environmental pollution and a load of toxic substances. One of the main human-made causes of environmental pollution in river basins is farming, which includes using fertilisers and pesticides, livestock, fisheries and aquaculture. The presence of these contaminants impacts the riverine system in a devastating way. To meet the food needs of the growing population, enhanced crop yield is achieved through the extensive use of chemical-based fertilisers and pesticides. These leads to runoff from the agricultural sites to the river basins. In addition to the river water contamination, the sediments of the river retain these contaminants and accumulation of these further worsen the quality of the river systems. In India alone more than 350 river stretches contain heavy metals such as arsenic, chromium, zinc, cadmium. These advance the negative impacts in the environment including threatening the life forms and humans with different health impacts. The contaminating pollutants, their source and transport should be governed as to know whether their concentrations are within or above the standard limits. Different river systems that serve as major resources supporting livelihoods and connecting places should be considered, as their pollution can lead to deleterious effect at various levels. This calls for immediate action, stricter policies, and community involvement. This review paper details the heavy metal pollution in river basins caused mainly due to agricultural activities.

Keywords
Agriculture, river water quality, pollution.

INTRODUCTION

Rivers play a crucial role in economic productivity and ecosystem services supporting human development (Vörösmarty et al., 2010). But the water quality in these rivers is declining due to natural and anthropogenic factors. One of the important anthropogenic factors that leads to water pollution is the agricultural activities involving application of fertilizers and pesticides, animal husbandry activities, irrigation practices and deforestation (Anh et al., 2023). Surface water degradation is one of the most pressing challenges faced in the present world. This restricts the use of water for human consumption. Reports have discussed that agriculture is a non-point source pollution damages surface water quality as it travels across land, through natural occurrences like precipitation and irrigation water, and eventually reaches rivers and lakes (Ongley et al., 2010). Heavy precipitation can transport nutrients and poisonous pesticides from the land to water altering its salinity and optimum conditions for aquatic species survival and eventually leading to its mortality (Matthews & Marsh-Matthews, 2003). The increased demand for the food production has led to the extensive use of inorganic fertilizers to increase the crop yield. This has resulted in the enhanced nutrient availability in the fields, subsequently leading to eutrophication in many aquatic ecosystems globally (Darradi et al., 2012). The high toxicity and considerable amounts in the environment, make heavy metals one of the most hazardous substances. Both natural and anthropogenic sources paves way for the heavy metals into the environment (Wang et al., 2014). Heavy metals are classified into one in

CONTACT *Corresponding author: *sushmithab@ignou.ac.in; Orcid ID: 0000-0003-3839-5557*
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which metals are of no use biologically, and another where some are essential metals but they become toxic at higher concentrations (Chen, 2012). The application of extracted mineral resources in industries and agriculture has enhanced the concentration of heavy metals in biogeochemical cycles (Ali et al., 2019).

Agricultural activities, produces high concentration of heavy metals that are washed away to aquatic ecosystems. The main sources of heavy metals in agriculture comes from the rigorous use of pesticides and fertilizers. Heavy metals like Pb and Cd are found in the surface water that is aligned with the agricultural activities in their basins. These metals are bioaccumulative in nature that leads to various physical damages and also neuro-disorders (Candra et al., 2024).

The aim of this review is to identify the role of agriculture in river heavy metal pollution, the impacts and effective management strategies to bring them under baseline limits.

1. Heavy metals in rivers

The rivers are polluted with various pollutants including the heavy metals. The present scenario of heavy metal contamination is concerning. Riverine sediments act as the reservoirs that receive all the heavy metal inputs from natural and anthropogenic sources and subsequently impart ecological risk and human health risk including children and adults (Zeb et al., 2024). Common sources of heavy metal inputs in the rivers include industrial inputs, domestic sewage in rural areas and agricultural activities (Liu et al., 2021; Skorbiłowicz et al., 2024). Recent studies in Southern India have observed increased levels of heavy metals in surface waters, sediments and riverbank soils above the permissible limits that leads to ecological, biological and human health risks (Subramanian & Baskar, 2022). Abirami et al., 2023; Chandni et al., 2026). Urban river sediments are highly associated with the heavy metals than the rural river sediments suggesting escalating anthropogenic activities resulting in the active forms of metals (Zhang et al., 2017). With the surge in the concentration of the heavy metal inputs in the rivers including the riverine sediments urgent implementation of the management strategies and regulations is crucial to prevent growing pollution in surface water, to protect the ecosystems and reduce the health impacts that is caused due to this (Proshad et al., 2025).

(a) Heavy metal contamination: The definition of heavy metals is explained in various ways. The review by Ali et al. (2019) summarises these different explanations for heavy metals that is expressed with specific gravity (greater than 5), another one that is associated with the potential of contamination and toxicity, and additionally it is also expressed with atomic number (greater than 20) and density(greater than 5 $g\cdot cm^{-3}$). The sources of heavy metal pollution in river water have sources varying from mining, industrial, manufacturing, along with fertiliser and pesticide use and also the geogenic source of rock weathering. These sources vary with respect to different continents based on the primary activities that are carried out in the riverine environments. The presence of multi-metal pollution is more prominent than the single metal pollution with increasing number of varying heavy metal-based activities. The waste discharge is another important source of heavy metals where there is an enhancement in the concentration of the heavy metals (Zhou et al., 2020). The presence of heavy metals in fertilisers, sewage sludge and liquid manure are some of the major sources of contamination in soil. The co-selection of antibiotic resistance that is driven by heavy metals, are influenced by agriculture and aquaculture. These when reaching the environment undergo accumulation that can negatively impact the environment. Heavy metals that act as the antimicrobial agents, have the potential in creating a pressure that drive the spread of the antibiotic and heavy metal resistance in the natural environment (Seiler & Berendonk, 2012).

Globally, the heavy metal pollution is a major concern. The spike in activities of populations contribute towards this pollution. In most river basins in India, metals such as Cr, Mn, Co, Ni, As and Cd have their concentration above the regulatory limits. This excessive presence of heavy metals has led to polluted water bodies unfit to meet the needs of the human populations. These are assessed to have potential carcinogenic risk in humans both adults and children. The ingestion route is more risky when compared to the dermal route pathway for the heavy metals entering the human body (Kumar et al., 2019). Considering the effect of heavy metals in urban soils, research done by Adewumi and Ogundele, (2023) summarised that many of the metals had concentrations above the average crustal value. Pollution indices were apparently impacted by Pb, Hg and Cd. Similar to the pollution with water bodies, heavy metal impacts in soil also posed ecological risk and carcinogenic risks. Some studies of the heavy metal contamination in different environments in India are shown in Table 1.

Table 1: Heavy metal contamination studies in India.

Environment	Metal of High Concern	Risk Factors	Reference
Indian soils	Cd, As	Ecological Risk	Kumar et al., 2019
Urban soils	As, Cr	Health risk (Carcinogenic and non-carcinogenic risk)	Adimalla, 2020
Groundwater	Fe, Mn, Zn, B, As, Ni, Pb	Health risk (Carcinogenic and non-carcinogenic risk)	Sharma et al., 2022
Road dust	Cr, Ni, Cu, Zn, Pb	Non-carcinogenic risk to children and carcinogenic risk to adults and children	Gorka et al., 2022
River (surface water)	Ni, Cr, Cd, Pb	Carcinogenic risk	Setia et al., 2020
River sediment	Cr, Mn, Cu, Pb	High risk to aquatic life, Cr has Carcinogenic risk in children.	Gupta et al., 2025

(a) ***Long-term effects:*** The deleterious effect of heavy metals lies in its persistent nature in the environment, the bioaccumulation and their toxicity to life forms. The soil environment is prone to heavy metal pollution. Microbes, an integral part of the soil environment are terribly affected by heavy metal pollution that disrupts the different functions including the physiological, biochemical, metabolic and biogeochemical processes that are occurring in the environment. Water resources including the surface water and groundwater are polluted with the spike in heavy metal concentrations from variable sources and reaches the sea and sink to the bottom of the sea harming the benthic organisms in these habitats (Ehis-Eriakha & Akemu, 2022). Being originated from various sources, heavy metals cause a great concern in the health of the consumers of the food chain. The heavy metals get transferred through the food chain and undergo bioaccumulation. Furthermore, with the accumulation of heavy metals in organisms in a food chain, the highest trophic level species are at higher risk due to the biomagnification of the heavy metals. These can therefore impact humans who are the higher order consumers (Ali et al., 2019). The transfer of heavy metals into the higher trophic levels may result in increase or decrease of its concentration. This is due to various mechanisms including the speciation of the metals, physiological response by the organism, and detoxification of the heavy metals. The chemical form of the metal species is has a distinct effect on its retention in the body (Ali & Khan, 2018). Anything that connects with the heavy metals are affected by them. The review by Singh and Kalamdhad (2011) observed the effects of heavy metal contamination in soil, plant, aquatic life and human beings. The authors observed an increase in the metal concentration which led to the disruption of soil microbiota and its activity. They also observed that the plant physiological metabolism is affected by heavy metals. When the heavy metals are washed down to the aquatic systems, they effect fishes and other aquatic organisms, due to the activation of reactive oxygen species (ROS) that damages these life forms.

The foods that human consume are also not free of heavy metal contamination. The work of Uddin et al. (2021) reviews the heavy metal accumulation in rice and aquatic plants that are used by humans as food. When these foods are grown in heavy metal contaminated aquatic environments, the transfer of these metals into plants impacts the food chain causing serious health consequences. Not only the health impacts in the human, the physicochemical functions, growth and the crop yield are affected by the contamination of these heavy metals. Briffa et al. (2020), explained that human exposure to the heavy metals and their impacts in our system are through different pathways. The known impacts of the heavy metals include neurotoxicity, carcinogenesis, cell damage and loss of cellular function. These consequences are due to the damage that the heavy metals inflict on neurons, DNA, cell membranes and protein. The toxic potential of the heavy metals is such that they are able to damage the fundamental units of a living organism.

(b) ***Techniques used to analyse heavy metals in river waters:*** The contamination and the effects of these persisting heavy metals necessitate for their measurement in the natural environments. Different methods are used for assessing the concentration of heavy metals. The heavy metal detection using optical techniques was reviewed in a study by El-Saeed et al. (2024). Techniques such as inductively coupled plasma mass spectrometry (ICP-MS), inductively coupled plasma optical emission spectroscopy (ICP OES), atomic absorption spectroscopy (AAS), laser ablation inductively coupled plasma mass spectrometry (LA-

ICP-MS), laser ablation inductively coupled plasma optical emission spectroscopy (LA-ICP-OES), laser-induced breakdown spectroscopy (LIBS), energy dispersive X-ray spectroscopy (EDS), and X-ray fluorescence spectroscopy (XRFS) are some of the common approaches through which the metal detection is carried out. Each analysis technique has its own distinct features in which, the sample, its prerequisites and the situational aspects determine the appropriate methods that needs to be utilised (El-Saeed et al., 2024). Apart from the optical approaches, chromatographic practices are employed. The chromatographic techniques such as the gas chromatography, liquid chromatography and high-performance liquid chromatography techniques provides high sensitivity and selectivity for the detection of these pollutants (Patnaik, 2017).

Different environment samples require variable techniques for the determination of the pollutants. Common practices in chromatography includes Gas Chromatography-Mass Spectrometry (GC-MS) for air samples, Gas Chromatography (GC) for organic contaminants and heavy metals, whereas High Performance Liquid Chromatography (HPLC) is used for water and soil samples. Advancements in the use of materials for chromatography and integrative technique such as GC-MS and LC-MS are useful for the analysis of pollutants with high, selectivity, sensitivity and better identification. The application of portable chromatographic techniques are useful in frequent regular monitoring of the pollutants even in remote areas (Kiani et al., 2024). Further mass spectrometry along with chromatographic analytical techniques has enhanced the sensitivity and even the selectivity in identifying mixtures of pollutants (Alshannaq et al., 2018).

A riverine surface water quality assessment for the trace metals carried out by Hussain et al. (2020) in river Mahanadi used the atomic absorption spectrometer (AAS) for quantifying the metal content whereas a recent study on trace metal concentration on surface water in Periyar river used inductively coupled plasma – optical emission spectroscopy (ICP- OES) for their assessments (Chandni et al., 2026). Studies have assessed the heavy metal concentration of river surface water that have utilised the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) technique (Dulama et al., 2017; Subramanian & Baskar (2022).

A study was done for the determination of heavy metals and pesticides in soil, water and plant along the Asa-River Tributary. It observed the gas chromatography – mass spectrometry (GC-MS) analytical technique when employed produced in determination of the pesticides with excellent linearity, selectivity and recovery. In addition to that the heavy metals were determined through atomic absorption spectroscopy (AAS). The regular monitoring of pesticide and heavy metals are required to ensure food safety and understand the current environmental contamination level and thereby prevent from further degradation and help in reversing the situation by taking proper regulatory measures. These analytical techniques thereby help in producing appropriate results (Olokoba, 2025).

1. Agricultural practices and river water quality

(a) *Agricultural structures and Cropping patterns:*

River its water and its whole ecosystem are crucial role in agriculture and farming system both in river bank farming and general farming as these are the main carrier of sediments and plays a fundamental role in formation of most fertile land soil like alluvial soil for example in northern part of our country river Ganga. This region is highly populated because intensive and easy agriculture can be done because of favourable soil and hydrological conditions. But the modern practice of faming for better yield and more economical return desire is pushing for the combination of natural as well as artificial system of irrigation structures to maintain the productivity (Shah et al., 2018).

(b) *Agricultural Structures in Indian River Basin Regions:*

Irrigation Infrastructure and Ground Water Use

In the Indian river basin, irrigation systems are mainly categorized into surface irrigation (canals, barrages) and ground water irrigation (tube wells, dug wells). And the practice of ground water usage has been increasing since Green Revolution due to its reliability and accessibility (Dhawan, 1995). Studies indicate that the irrigation through ground water is nearly 60 - 65% of the total irrigated area in India specially in Indo-Gangetic plain (Shah et al., 2018).

Surface water controlling structures:

- ❖ Dams and barrages regulate river flow and store water.
- ❖ Canal networks distribute water across agricultural lands.
- ❖ Embankments (levees) protect farmlands from floods.

Example, Farakka Barrage plays a crucial role in regulating the water flow in eastern India. Such infrastructures enable controlled irrigation and flood management, improving cropping stability (Amarasinghe et al., 2007).

Drainage and Flood management: River basins in India are highly prone to seasonal flooding and waterlogging. Effective drainage systems are necessary to remove excess water prevent soil salinity and degradation. Poor drainage has been identified as a major constraint in sustaining productivity in irrigated river basins (Singh et al., 2012).

Emerging Irrigation Technologies: Modern irrigation practices such as drip and sprinkler systems are being introduced to improve water-use efficiency. These methods are significant in regions experiencing groundwater stress (Kumar et al., 2013).

(c) *Cropping Patterns in Indian River basin areas*

Intensive and multiple cropping patterns are adopted. River basin cropping in India exhibit high cropping intensity, often exceeding 150 - 200%, due to assured irrigation and fertile soil conditions (Dhawan, 2095). In kharif season, crops like Rice, Maize etc. are grown and in rabi season, Wheat, Mustard etc. are grown and in zaid season, Pulses and vegetables like cucurbits are grown. Rice wheat system is particularly dominant in the Indo-Gangetic plains being a staple food crop (Ladha et al., 2003).

Crop diversification: This has been stated in recent studies to reduce water stress and sustainability in terms of soil health and productivity. Over dependence on water-intensive crops like rice and sugarcane has led to more depletion of ground water in several river basins (Kumar et al., 2013). Diversification towards less water-intensive crops like pulses, oilseeds, enhances water use efficiency, soil fertility and more farmers stability in terms of income.

Groundwater- Driven Cropping Patterns: The utilisation of tube wells and other artificial groundwater extraction methods greatly enhances the irrigation water availability, hence influencing cropping decisions. Regions with high ground water availability tends to favour rice and sugarcane (high water demand), wheat in winter seasons. Though, excessive ground water use has led to unstable cropping patterns, particularly in north-western India (Shah et al., 2018) like growing rice in a new trend in Panjab province.

Interrelationship between agricultural Structures and Cropping Patterns: The irrigation infrastructure in river basins and river bank farming systems significantly influences cropping intensity, while groundwater availability influences crop selection, and flood control systems enable stable agricultural production. Studies clearly, shows that improved irrigation system leads to not only higher productivity but also increase the pressure on water resources, necessitating balanced management strategies (Amarasinghe et al., 2007).

(d) Challenges in Indian River basin agriculture:

Despite of advantages there are many challenges such as over extraction of ground water due to expansion of artificial methods, waterlogging and salinity issues in canal - irrigated areas, flood damage and soil erosion, climate variability effecting the river flow and cropping cycles (Kumar et al., 2013). Many other challenges include the contamination through water drainage into the river from these agricultural lands where there is application of various chemical pesticides and fertilizers sprayed to protect the crop and increase its yield.

(e) Nutrients, Fertilizers and contamination: In the agricultural sector fertilizers and plant nutrients are crucial for plant growth and productivity. Both chemical and organic fertilizers exist and their application is widely followed all over the world. Generally, for plants to flourish, fertilisers like NPK (nitrogen, phosphorus, and potassium) must be applied. However, they also contribute to groundwater acidification and contamination. Over time, chemical fertilisers deteriorate the well-being of the soil. Several reviews have focussed on the effects of chemical fertilizers. Agricultural intensification along coastal areas have polluted the soil and water with nitrates, nitrogen and phosphates. Bartley et al. (2003) reported an increase in phytoplankton activity in surface waters due to nitrates inducing algal blooms and eutrophication. Howarth (2008) studied that coastal eutrophication in some places is very high due to very high nitrogen flows into the waters. Glibert et al. (2006) contended that this coastal eutrophication is due to the extensive usage of urea containing fertilizers which are more soluble in waters. Zadeh (2018) reported that many waterbodies in North America and Europe were contaminated with high levels of nitrogen and nitrates due to the intensification of agricultural activities prior to 1970. Liu et al. (2010) observed that 50% nitrogen fertilizers are found in about half of the yearly global N flows into croplands. They calculated that leaching and soil erosion occurs and nitrogen is easily transformed into nitrate in aerobic soils, and a majority of the nitrate that is not absorbed dissolves in irrigation water before finally seeping through the soil and into surface waters or subsurface aquifers (Liu et al., 2010). Meisinger et al. (2006) reported that approximately 30 percent of nitrogen (N) used in agricultural lands is lost but bio-physio-chemical mechanisms drive the fate of N in the subsurface. Zhang et al. (2018) conducted isotopic measurements revealing a direct correlation between nitrate concentration in rivers and the extensive application of mineral fertilisers. Reports have also discussed that nitrates accumulate in the deeper zones of the soil such as the vadose-zone due to excessive applications which is prone to leaching and causing river and groundwater pollution (Ju and Zhang, 2017). Further researchers explain that plants are unable to absorb this deep nitrate -N which is present in these zones (Zhou et al., 2016). Eutrophication due to over enrichment of rivers, lakes and water systems causes mortality and lethality among fishes and defaces the landscape. Glibert et al. (2006) stated that shellfish poisoning was caused by toxic algal blooms which was induced by increased urea application from 1970 – 2000. Therefore excessive application of fertilizers can cause irreversible damage to soil and river ecosystems. But there are alternatives to chemicals. In a recent review by Shukla and Baskar (2026), the role of organic farming practices in sustainable agriculture was and the many benefits of biofertilizers were reported. Biofertilizers are environmentally sustainable, comprising live microorganisms such as bacteria, fungi, or algae which augment soil fertility and improve plant nutrient absorption. They enhance agricultural yields by 10–25%, promote soil health, and function as sustainable substitutes for artificial fertilisers. Examples comprise Rhizobium, Azotobacter, Phosphorus-Solubilizing/Mobilizing microorganisms; Potassium-Solubilizing microbial species such as *Frateuria aurantia* and Plant Growth-Promoting Rhizobacteria (PGPR). Such natural inputs to the soil are safer alternatives to synthetic and chemical fertilizers. Therefore integrated pest management, along with improved legislations, and user education, advocating for a systematic transition to approaches that reduce environmental damage are needed to protect human health.

(f) ***Pesticides and contamination:*** Pesticides are one of the significant chemicals that impart toxicity to the rivers from agriculture. Commonly used in agricultural sectors, pesticides are chemical used for pest control (Cooper & Dobson, 2007). They are disseminated via air transport, soil leaching and run off from fields. Ecosystems are interconnected in nature and pesticides can easily traverse different ecosystems causing harm and toxicity. Zhang et al. (2022) identified twenty-seven distinct pesticides, among others, in maritime environments, demonstrating their capacity to permeate various ecosystems. Sah et al. (2020) examined five regions of the Ganga River and detected pesticide residues from banned chemicals, including DDT and endosulfan, as per Indian Government regulations. Their research indicated that agricultural practices and industrial establishments influenced this, with elevated levels of γ-HCH observed during the post-monsoon period (Sah et al. 2020). A brief report on classification of pesticides and their effects is presented in table 2 (Garud et al., 2024).

Table 2: Classification of pesticides and their effects.

Pesticide Classes (Chemical Composition)	**Pesticide Classes (Target)**	**Effect of Pesticides**
Organochlorines	Fungicides	Pollution of soil and water
Carbamates	Herbicides	Negative effects on non-target organisms
Organophosphates	Nematicides	Health problems in humans
Pyrethroids	Insecticides	Pollution of other vegetations
Neonicotinoids	Rodenticides	Neurotoxicity, genotoxicity and carcinogenicity

The pesticide formulations contain heavy metals. Majority of the pesticides that are used globally are glyphosate-based herbicides. Heavy metals such as arsenic, cobalt, chromium, nickel and lead are found in pesticide formulations. The formulants in the pesticides including heavy metals are largely responsible for endocrine disruption toxicity. Reports suggest that the concentration limit of the heavy metals included in the formulations are substantially higher than the permissible limits (Defarge et al., 2018). The presence of heavy metals in these pesticides causes severe negative toxic effect in soil, plants and the food we obtain from the plants. Several copper-based fungicides are also used. But excessive use of this essential metal can also result in toxicity in the plant and agricultural soil (Chandrudu et al., 2025). The mode of action of pesticides are not species-specific. They are known to cause life threatening diseases including cancer. The people working in sectors that are related to the pesticides are known to be exposed to various different concentration of pesticides (Alengebawy et al., 2021).

3. *Impacts of agriculture on water quality*

Agricultural inputs into rivers deteriorates the water quality which in turn leads to various impacts. The primary impact of agriculture on water quality is the higher concentration of nutrients in it, particularly nitrates and phosphates. Groundwater is more affected with the nutrient surcharge due to agriculture than running water (Lawniczak-Malińska et al., 2023). Increased fertilizer application can lead into the degradation of water quality. The amount and intensity of fertilizer application have effect on river water quality pollution. With precipitation, there will be transboundary water quality pollution in lower watershed from the upper watershed (Xu et al., 2022). The presence of agricultural runoff into rivers poses ecological threat to the river system (Awhefeada et al., 2025). The excessive runoff of the nutrients into the aquatic system, leads to enormous algal growth, a phenomenon known as eutrophication. It has negative effects on the aquatic species, due to the absence of light penetrating to the water at greater depths and also depletion of dissolved oxygen, affecting aquatic plants. Eutrophication leads to poor water quality leading to human health issues when this water is consumed (Madjar et al., 2024).

The use of pesticides in agriculture is common. These harmful compounds, through irrigation or precipitation from the agricultural site, contaminate aquatic sources. They can inflict physiological harm on aquatic creatures. They may even have deadly effects on aquatic creatures that occupy various trophic levels. The runoff of herbicides is adversely affecting even non-target creatures. (Shefali et al., 2021). The heavy metal pollution from the agricultural sources also impact aquatic ecosystems. The non-biodegradable and persistent characteristics of heavy metals result in their accumulation in living organisms, including fish. In addition to bioaccumulation, the biotransformation of heavy metals occurs, posing a risk to human health. Heavy metals has carcinogenic properties. Oxidative stress in fish species is triggered by exposure to various pollutants, while pesticides and heavy metals might compromise their immune systems (Ghafarifarsani et al., 2024).

4. Future perspectives and Management of river basin pollution

Due to the rising concentration of contaminants in natural resources from various anthropogenic sources, steps must be implemented to reduce concentrations below regulatory requirements to mitigate their impact on connected environmental entities.

(a) ***Removal of heavy metals from water bodies:*** The issue of heavy metal pollution, and its removal have been largely studied by employing different strategies aimed for decreasing the concentration. Bioremediation is observed as one of the cost effective, cleaner and environment friendly approaches for the reduction of heavy metals and it is one of the most effective management tools used for managing the polluted sites (Kulshreshtha et al., 2014). Different microbial mechanisms that are involved for the heavy metal reduction includes biosorption, bioaccumulation, bioleaching, biotransformation and within these some advanced approaches are rhizoremediation and genetically engineered organisms (Zhou et al., 2023).

Phytoremediation utilising hyper accumulator plants to detoxify the heavy metals in the environment is another promising tool. The different mechanisms with which phytoremediation implemented are through phytoextraction, phytodegradation, phytovolatilization, rhizofiltration, phytostabilisation. Along with these approaches assisted phytoremediation involving the use of microbes, arbuscular mycorrhizal fungi, earthworm, phytohormones, nanoparticles are some of the advancements in this field (Nedjimi, 2021).

The use of plants and microbes for removing the metals often serve as a choice for the bioremediation of heavy metals. Phytoremediation approach by the use of plants have been used for the removal processes. Different strategies using microbe, fungi and microalgal mediated bioremediation are commonly used. In addition to that the advancement in nanotechnology also serve as a tool for reducing the concentration of the heavy metals. An integrated approach of microbiome mediated nano bioremediation towards the toxic metals have been studied (Karnwal et al., 2024). Utilising activated carbon, biochar and zeolites some of the common adsorbents have been employed for its effectiveness in heavy metal ion removal (Iyer et al., 2024). The removal of heavy metals from water with the use of adsorbents were reviewed by Zaimee et al. (2021). The authors reported the different types of adsorbents that are used for the heavy metal removal. These include carbon-based nanomaterial adsorbents, cost-effective adsorbents, composite and nanocomposite adsorbents, and several other adsorbents. The study examines many classes of adsorbents, including polymeric, natural mineral, industrial by-product, and nanomaterial adsorbents (Zaimee et al. 2021). In the context of designing removal tactics, low-cost approaches are more appropriate. The use of adsorbents that are naturally occurring or from wastes can be used for these removal processes. The agricultural wastes including, waste from rice production, residual from peanuts, fruit and vegetable wastes have shown different degrees of adsorbing capacities. Along with that, naturally occurring soil and mineral deposit have shown different affinities towards heavy metals making it useful for its reduction. Aquatic as well as terrestrial biomass have been used as a low-cost bioremediation source for heavy metals. Other available waste including the tea waste, coal ash, shells from aquatic species are also utilised for remediation of heavy metals though adsorption (Joseph et al., 2019).

(b) Eco innovations in agriculture:

They include advanced technologies with nature based practices to protect water quality flood risk and soil health. Recent practices includes precision water management through AI, IoT, VRI to deliver the resources where it is needed at right time right place and right dose through real time monitoring dashboard. Nature based eco-innovations like floating bed agriculture called as aquaponics are useful in which crops are grown in buoyant platforms made from bamboo or water hyacinth in order to rise and fall with the water level providing flood resilience and naturally filter river pollutants. Annother innovation is the use of Constructed Wetland and riparian buffers which checks and filter the runoff before it reaches the river. Bio-Input and Circularity convert bio organic waste into affordable fertilizers with accuracy with AI-enabled WasteBots.

(c) Crop and Fertilizer management:

Usually near or adjacent to river waters short duration crops are grown - short duration cash crops with quick returns like cucurbits, and other short duration vegetables. While in the regions beyond this, rice, legume, wheat and oilseed system is adopted (ICAR, 2020). Flood plains are generally fertile and require less application of supplements and combining NPK with FYM which significantly increases the nutrient use efficiency and crop productivity (Saini et.al, 2019). INM approach is widely adopted with chemical fertilizers, organic and biofertilizers, which improves the soil organic carbon, nutrient efficiency and sustainable crop productibility (Baskar et.al, 2014). Key practices include spilt dose of nitrogen, heavy integration of organic and biofertilizers is recommended specially in flood prone areas.

5. Policy tools for management of pollution

Even with the improved technologies and researches for effective methodologies for the removal of heavy metals alone cannot survive to build a contaminated environment. The deposition of heavy metals and their concentration relative to anthropogenic sources can be effectively managed through appropriate policy instruments. Studies often reflect on the water potability requirement with considerations on the several contaminant levels provided by the regulatory units. These reputable agencies include WHO (World Health Organisation), EUC (European Commission) and USEPA (United States Environmental Protection Agency). Water pollutant levels are often above these regulatory limits for pollutants including heavy metals. These levels should be regularly monitored as these polluted waters directly affect the human populations (Basheer et al., 2020).

Agricultural non-point source pollution has nutrient runoff, pesticide leaching and inadequate livestock management as the primary factors of pollution. Some of the mitigation strategies for the non-point source pollution includes cover cropping, conservation tillage, management of the fertilizer usage and irrigation conservation. The adoption of precision agriculture in which the application of fertilisers and the inputs are accurate and efficient that leverages information and communication technology. Therefore, precision agriculture balances with productivity and environmental conservation (Hussain et al., 2025). The non-point source pollution is more difficult to manage due to its diffuse nature. For economic assessment of the policies to reduce the pollution due to agriculture, the economic value of the change in water quality is an important criteria. From the farmers end they can scale down the pollution towards water. Different structural and management strategies are performed for the attenuation of the pollutants into water and these practices include irrigation water management, integrated pest management, nutrient management planning, animal waste management, conservation agriculture and also the industrial waste, sewage and stormwater pretreatment (Wato & Amare, 2020). Agricultural pollutants can be controlled during different stages of practices. Incorporating insource control technology may enhance agricultural methods like as conservation tillage, rotational tillage, fertilisation management, and water-efficient irrigation. In-process control solutions utilise ecological ditch systems and microbial treatment technologies. The common end treatment technologies leveraged are constructed wetlands, buffer strips and land infiltration systems (Xia et al., 2020).

The non-point source of agricultural pollutions should be managed properly to reduce its impact on the environmental resources. The implementation of best management practices, in which local government agencies, NGOs, universities and media act as the providers of the information are needed. But it is observed that the lack of trust the farmers have in governments affects the adoption of these practices where as a peer-to-peer communication enhances some of the implementation. Building trust, creating channels for effective communication to the farmers and also understanding the farmers economic realities paves way for better management practices (Dingkuhn et al., 2024). To effectively address diffuse pollution, a cohesive governance framework should be promoted. In this the policy makers as well as the interest group work together by building trust and cooperation that leads to stricter enforcement of regulations. Concerning diffuse agricultural contamination, governance has influenced policy decisions through cooperation, consistency, and salience (De Vito et al., 2020). Governance is implemented through different modes to reduce heavy metal pollution which is discussed in a review by Chen and Ding (2023). The four different governance modes are state-centric governance, market governance, network governance and voluntary governance. The integration of government for stricter regulations along with business cooperations, organisations and industries and also the stakeholders together form a wide network to adopt these practices through effective regulations to reduce the heavy metal pollution in various ecosystems.

Conclusion

This review provides an overview of the impacts of agricultural activities and heavy metal contamination in river basins and water quality. Several organic substances, persistent organic pollutants and heavy metals have been observed in riverine systems. The persistent and non-biodegradable nature of heavy metals in the environment results in bioaccumulation and biomagnification that threatens the higher trophic level organisms including humans. This contamination leads to various eco-biological risks and human health risks like carcinogenic and non-carcinogenic risks that poses danger to life. Farming using chemical based derivatives causes irreversible effects in ecosystems and certain heavy metals are bioconcentrated in living organisms. When it comes to maintaining river basin water quality, knowing the significant factors that impact the overall river water quality is vital. Shifting towards greener alternatives is a sustainable solution. Adopting efficient practices such as irrigation water management, animal waste management, management planning of using nutrients and fertilisers etc. can bring down the factors that triggers contamination. Governance on the current situation of the river pollution and continuous monitoring of the sites with implementation of remedial strategies should be employed to protect further degradation. The permissible limit of the contaminants by the statutory bodies should be strictly considered to maintain the water quality of rivers from any pollution sources including agriculture. Building trust and good relationship with the farmers, encouraging them towards more sustainable practices through different policies, understanding their concerns and also encouraging institutions, organisations to play important role in educating the farmers on eco-friendly practices and building a bridge between farmers and the governing institutions is crucial. Therefore, best management practices and good governance is essential for achieving minimal metal concentrations loads in river waters.

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