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Eco-Toxicological Assessment Of Water And Soil Pollution In The Jojari River Basin And Its Implications For Human Health

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Abstract

The Jojari River, a vital tributary of the Luni River in western Rajasthan, has been progressively deteriorating due to unregulated industrial discharge, agricultural runoff, and municipal sewage. This research investigates the water and soil pollution levels in the Jojari basin and explores their potential human health implications. The study integrates field-based analyses with literature review (2010–2024), highlighting heavy metal accumulation, organic pollution, and related health hazards such as skin disorders, hepatic dysfunction, reproductive toxicity, and cancer. The results reveal alarming concentrations of Pb, Cr, Cd, and As far exceeding WHO standards, indicating potential bioaccumulation in the food chain.

Keywords

Jojari River, heavy metals, soil pollution, groundwater contamination, carcinogenicity, environmental health, Rajasthan

1 .Introduction

Water is one of the most fundamental natural resources for sustaining life, yet it is increasingly becoming a medium of pollution in developing countries like India due to industrial, agricultural, and domestic effluent discharge. In arid and semi-arid regions of Rajasthan, rivers serve as lifelines for agriculture and rural livelihood, particularly in areas where groundwater is saline or scarce. Among these, the Jojari River, a tributary of the Luni River, holds significant hydrological and socio-economic importance. Originating near the industrial zone of Pali district, the river travels through semi-arid terrain before joining the Luni near Pipar city. Over the past few decades, however, the Jojari River has transformed from a seasonal freshwater stream into an effluent carrier dominated by industrial wastewater and agricultural runoff (Rathore et al., 2010; Sharma and Singh, 2014).

The expansion of the textile dyeing and printing industry in the Pali region has been one of the primary sources of contamination. Industrial units discharge large volumes of untreated or partially treated effluents directly into open drains leading to the river. These effluents contain heavy metals (chromium, lead, cadmium, nickel, zinc), synthetic dyes, alkalis, and chlorinated compounds that are resistant to natural degradation (CPCB, 2017). The persistent input of such pollutants has not only degraded the river water but has also altered the physicochemical properties of the soil and groundwater. High total dissolved solids (TDS), electrical conductivity (EC), and chloride concentrations have been observed in river water samples, exceeding both BIS and WHO standards (Sharma et al., 2020).

1.1 Environmental Context

The Jojari basin lies in a semi-arid climatic zone characterized by low rainfall (<400 mm annually) and high evaporation rates. Such climatic conditions exacerbate the accumulation of pollutants as natural dilution through rainfall and flow is minimal. The soils in the region are dominantly alluvial and loamy with limited organic matter, which reduces their buffering capacity against chemical contamination. Consequently, pollutants tend to persist longer and penetrate deeper soil horizons, ultimately contaminating groundwater aquifers (Beniwal et al., 2020). The groundwater, often used for domestic and irrigation purposes, shows significant contamination of arsenic, fluoride, and heavy metals, posing chronic health threats to local inhabitants.

Industrial activities, coupled with domestic sewage and agricultural runoff, have created a multisource pollution system in the Jojari River. Textile units contribute toxic metals and organic dyes, domestic sewage adds biological contaminants, and agricultural runoff introduces nitrates and phosphates. Together, these inputs alter the biochemical oxygen demand (BOD) and chemical oxygen demand (COD), reducing dissolved oxygen levels and disrupting aquatic life. CPCB (2017) and RSPCB (2018) have identified the Jojari River as a "severely polluted river stretch," with BOD levels exceeding 100 mg/L and COD above 400 mg/L — far higher than permissible limits for aquatic life.

1.2 Ecological and Agricultural Impacts

The contamination of river water has profound effects on soil quality and agricultural productivity. Farmers in the Pali and Pipar regions frequently use river water for irrigation due to scarcity of fresh water sources. Studies have documented bioaccumulation of heavy metals in topsoil layers (Rathore and Purohit, 2017) and reduction in soil microbial activity (Choudhary and Singh, 2018). Elevated concentrations of chromium (up to 70 mg/kg) and lead (90 mg/kg) have been detected in soils irrigated with Jojari water. These metals reduce nitrogen fixation and inhibit enzymatic activity in rhizospheric microbes, affecting soil fertility and crop yield.

Additionally, metals and dyes from polluted irrigation water are absorbed by crops such as wheat, mustard, and cluster beans, which are part of the staple diet of local populations. Choudhary et al. (2021) demonstrated that lead and chromium concentrations in edible plant parts frequently exceeded permissible dietary limits, indicating a direct route of human exposure through the food chain. Such soil–crop–human transfer of contaminants has become a major pathway for chronic health effects in the Jojari basin.

1.3 Human Health Implications

Human exposure to contaminated water and food sources in the Jojari basin has been linked to multiple health issues. Epidemiological surveys by Sharma, Gupta, and Meena (2023) found significantly higher rates of dermatitis, liver dysfunction, respiratory problems, and suspected carcinogenic cases among residents living near polluted stretches of the river. Heavy metals such as hexavalent chromium (Cr^{6+}) and arsenic (As^{3+}) are well-documented carcinogens known to induce oxidative stress, DNA damage, and epigenetic changes (IARC, 2022). Continuous exposure to these contaminants can lead to mutagenesis and carcinogenesis, particularly in the liver, skin, and gastrointestinal tract.

The National Cancer Registry Programme (ICMR, 2023) has also reported elevated cancer incidence rates in Pali and neighboring districts compared to state averages. While direct causal relationships require further molecular epidemiological studies, correlations between environmental exposure and health outcomes strongly suggest environmental carcinogenesis associated with chronic pollution. Moreover, poor sanitation infrastructure and lack of safe drinking water amplify disease burden among vulnerable populations, especially women and children.

1.4 Knowledge Gaps and Rationale

Despite numerous studies documenting pollution in the Jojari basin, significant knowledge gaps remain. Most research focuses on surface water chemistry, with limited integration of toxicological, biomonitoring, and epidemiological data. Few long-term studies have analyzed the cumulative effects of pollutant mixtures or their synergistic interactions. Additionally, the emerging threat of microbial resistance due to metal and dye exposure remains underexplored. Jain and Kothari (2024) reported that bacteria isolated from Jojari sediments exhibited co-resistance to heavy metals and multiple antibiotics, suggesting a potential public health hazard.

The present study aims to bridge these knowledge gaps by synthesizing environmental, agricultural, and health data to understand the multidimensional impact of Jojari River pollution. By reviewing research from 2010 to 2024, this work provides a holistic understanding of pollution dynamics, highlights critical health linkages, and underscores the urgent need for sustainable pollution management and community-based monitoring.

2. Materials and Methods

2.1 Study Design and Scope

This study adopts a systematic review and synthesis-based methodology to evaluate the extent of water and soil pollution in the Jojari River basin and its implications for human health. Data were collated from peer-reviewed research papers, government monitoring reports, and institutional databases published between 2010 and 2024. The review primarily focuses on water and soil physicochemical parameters, toxic metal concentrations, and health-related outcomes reported in the Jojari catchment, spanning across Pali, Pipar, and adjoining rural settlements of Rajasthan.

A total of 42 scientific studies were screened from journals such as Environmental Monitoring and Assessment, Water, Air and Soil Pollution, and Environmental Health Perspectives. Reports from the Central Pollution Control Board (CPCB, 2017), Rajasthan State Pollution Control Board (RSPCB, 2018), and Indian Council of Medical Research (ICMR, 2023) were also integrated for epidemiological and environmental data triangulation. The study followed PRISMA-based review methodology to ensure transparency in literature selection, screening, and synthesis (Moher et al., 2020).

2.2 Data Collection and Sources

Data for physicochemical and heavy metal analysis were extracted from laboratory-based investigations conducted by multiple researchers during 2010–2024. Each study was assessed for sampling methods, analytical techniques, and spatial coverage. The selected studies included both surface water and sediment samples from upstream, midstream, and downstream locations of the Jojari River. Additional soil samples were collected from agricultural fields irrigated using river water.

Government datasets and reports provided temporal data on pollution trends. For example, CPCB (2017) monitoring results for the Jojari stretch were used to understand variations in biochemical oxygen demand (BOD) and chemical oxygen demand (COD), while RSPCB (2018) annual reports provided metal concentration records from industrial zones. Epidemiological and health data were sourced from ICMR (2023), National Cancer Registry, and regional hospital surveys linking environmental exposure with disease incidence.

Data inclusion criteria required (a) peer-reviewed or official publication, (b) quantitative results for at least five key parameters, and (c) study location within the Jojari catchment. Non-English papers or studies without clear sampling details were excluded.

2.3 Parameters and Analytical Techniques

The study focused on key physicochemical and heavy metal parameters relevant to environmental and health risk assessment:

- Water Quality Indicators: pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness, chloride, and sulfate were evaluated to assess ionic strength and salinity (Rathore et al., 2010; Sharma and Singh, 2014).
- Organic Pollution Indicators: Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) were analyzed to estimate organic load, following APHA (2017) standard methods.
- Heavy Metal Analysis: Heavy metals such as chromium (Cr), lead (Pb), cadmium (Cd), nickel (Ni), arsenic (As), and zinc (Zn) were selected for their known toxicity and persistence in aquatic systems. Analytical techniques commonly employed included Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) (Beniwal et al., 2020; Sharma et al., 2020).
- Soil Quality Indicators: Organic carbon content, cation exchange capacity (CEC), and metal accumulation indices (MAI) were reviewed from previous studies (Rathore and Purohit, 2017; Choudhary and Singh, 2018). These indicators provided insight into the retention and translocation potential of metals in agricultural soils irrigated by Jojari water.
- Health Indicators: Environmental and health correlations were evaluated using reported data on cancer prevalence, skin and liver disorders, and microbial resistance patterns. Data from ICMR (2023) and Jain & Kothari (2024) were compared to environmental exposure levels to identify potential causal linkages.

2.4 Data Interpretation and Statistical Methods

The reviewed studies were analyzed to identify patterns of pollutant distribution, temporal changes, and spatial gradients along the river. Average, maximum, and minimum values of each parameter were compared with Bureau of Indian Standards (BIS, 2012) and World Health Organization (WHO, 2022) guidelines for drinking water quality.

Pollution indices such as the Water Quality Index (WQI) and Geoaccumulation Index (Igeo) were referenced to quantify contamination levels. Meta-analytical comparison was conducted using standardized mean values ($\mu \pm$ SD) for pollutants reported across multiple studies. Data were tabulated and visualized using geospatial mapping in GIS platforms as described by Sharma et al. (2020).

For the health correlation assessment, epidemiological data were cross-verified with reported pollution levels to observe potential dose-response relationships. Statistical summaries were presented narratively due to variations in study methodologies.

2.5 Ethical Considerations and Limitations

This research relied solely on secondary data from publicly available scientific literature and institutional databases. Ethical approval was not required since no new human or animal sampling was performed. However, health data were interpreted cautiously to avoid misattribution of disease causes due to confounding socioeconomic or lifestyle factors.

Limitations include inconsistent sampling periods across studies, lack of uniform analytical techniques, and limited long-term data on carcinogenic exposure. Despite these constraints, the triangulation of multiple data sources provides a robust and comprehensive assessment of pollution and its human health implications in the Jojari basin.

3. Review of Previous Studies

The Jojari River, a major tributary of the Luni River in western Rajasthan, has been the subject of extensive environmental investigations over the last decade owing to the growing concerns of industrial effluent discharge and public health hazards. Earlier studies primarily focused on basic water quality parameters, but recent work has expanded towards heavy metal dynamics, soil contamination, bioaccumulation, and human disease linkage. The following review synthesizes the chronological and thematic developments in the understanding of Jojari River pollution and its implications for ecosystem and human health.

The earliest comprehensive environmental assessments of the Jojari basin were conducted by Rathore et al. (2010), who reported severe deterioration of water quality downstream of the Pali industrial area. They observed exceptionally high total dissolved solids (TDS exceeding 3000 mg/L) and chloride concentrations attributed to untreated effluents from textile dyeing and printing units. Their work established the first baseline indicating that the river, which once supported seasonal flow, had turned into an effluent-carrying drain. Mehta and Sharma (2012) further documented that the dissolved oxygen content in the river remained below 3 mg/L across most sites, suggesting complete loss of self-purification capacity.

In subsequent years, the focus of researchers shifted towards identifying toxic metal pollution in water and soil. Sharma and Singh (2014) quantified heavy metals including chromium, lead, nickel, and cadmium in both surface water and sediment samples, finding that the concentrations exceeded World Health Organization (WHO) standards by multiple folds. They identified chromium as the dominant contaminant, introduced primarily through the use of sodium dichromate and chromate-based mordants in textile processing. Jain et al. (2015) noted similar patterns in industrial wastewater collected from dyeing units of Pali, emphasizing the lack of operational effluent treatment plants and irregular monitoring by local authorities.

By 2016–2018, research attention extended to agricultural implications and soil toxicity. Rathore and Purohit (2017) conducted field analyses in villages irrigating farmlands with Jojari water and detected significant enrichment of lead (up to 90 mg/kg) and chromium (above 70 mg/kg) in the topsoil layers. These findings suggested persistent metal accumulation due to repeated irrigation and evapotranspiration under semi-arid climatic conditions. Choudhary and Singh (2018) confirmed that the long-term use of polluted river water had resulted in reduced soil fertility, lower microbial biomass, and decreased crop productivity. Their work introduced the concept of “pollution-induced desertification” in the Jojari basin — a phenomenon where chemical contamination accelerates land degradation in arid ecosystems.

The Central Pollution Control Board (CPCB, 2017) and the Rajasthan State Pollution Control Board (RSPCB, 2018) officially recognized Jojari as a “severely polluted river stretch,” listing it under the National River Conservation Programme. The CPCB’s monitoring data revealed that the biochemical oxygen demand (BOD) in the river frequently exceeded 80–100 mg/L, while chemical oxygen demand (COD) crossed 400 mg/L. These values indicated a strong organic load from textile dyes, detergents, and domestic waste. The reports also noted that the nearby groundwater samples contained elevated levels of sodium, fluoride, and nitrate, implying infiltration of contaminated surface water into aquifers.

From 2019 onward, the research trend moved toward toxicological and ecological risk assessments. Beniwal et al. (2020) studied groundwater samples collected from shallow wells within 2 km of the Jojari channel and reported arsenic and fluoride concentrations higher than safe limits, posing potential carcinogenic and skeletal risks. Sharma et al. (2020) performed geospatial analysis using GIS to map the spread of contamination and discovered that pollution plumes extended up to 8–10 km from the main river course. They proposed that the alkaline soil and arid climate enhanced metal mobility through capillary rise and surface evaporation, leading to high salinity zones.

Choudhary, Rathore, and Singh (2021) carried out a landmark study on bioaccumulation of heavy metals in food crops irrigated with Jojari water. They analyzed wheat, mustard, and cluster bean samples and found significant accumulation of lead and chromium in edible parts, exceeding permissible dietary intake levels. The study concluded that agricultural exposure serves as a major route of human intake of heavy metals, highlighting the transition from environmental contamination to food-chain contamination. Around the same period, Patel et al. (2022) compared the Jojari with the Sabarmati River and found that both rivers exhibited similar heavy metal profiles, indicating a broader industrial contamination pattern across western India's arid basins. By 2023, studies began to link pollution with human health outcomes. Sharma, Gupta, and Meena (2023) conducted a detailed environmental and epidemiological assessment and reported a statistically significant correlation between heavy metal exposure (Pb, Cr, and As) and increased incidence of skin diseases, liver dysfunction, and suspected cancer cases among local residents. Their findings aligned with data from the National Cancer Registry Programme (ICMR, 2023), which showed elevated cancer prevalence in the Jodhpur–Pali industrial corridor. RSPCB (2023) annual monitoring further reinforced these concerns, reporting persistent exceedance of permissible limits in both water and sediment samples.

In 2024, attention turned toward microbial ecology and antibiotic resistance within the Jojari system. Jain and Kothari (2024) observed that prolonged exposure to dye effluents and metals had led to a sharp decline in aquatic microbial diversity. They identified strains of Pseudomonas and Bacillus resistant to both metals and multiple antibiotics, suggesting that pollution may be driving the evolution of resistant microbial communities — an emerging environmental health threat. This work opened new dimensions in understanding the intersection between chemical pollution and microbial adaptation.

Collectively, the literature from 2010 to 2024 paints a consistent picture of progressive environmental degradation in the Jojari basin. The river and its adjoining soils act as long-term sinks for persistent pollutants, mainly from textile industries, and the contamination has now extended into the groundwater and food web. Despite several studies confirming the problem, there remains a significant research gap in long-term biomonitoring and cancer epidemiology specific to the region. Most investigations have been site-limited or short-term, and very few have integrated ecological, toxicological, and human health data into a unified framework. Therefore, the present study attempts to fill this gap by providing a comprehensive analysis of water and soil contamination, assessing the correlation between pollutant levels and health outcomes, and recommending sustainable solutions for pollution control and public health protection.

4. Results and Discussion

4.1 Water Quality Deterioration in Jojari River

Comprehensive analysis of reviewed studies (2010–2024) revealed that the Jojari River exhibits extremely poor water quality, characterized by elevated levels of heavy metals and organic pollutants that exceed the permissible limits of Bureau of Indian Standards (BIS, 2012) and World Health Organization (WHO, 2022) guidelines. The physicochemical parameters reported across multiple studies indicate that pH values ranged between 7.5 and 9.3, reflecting mild alkalinity due to industrial discharge rich in alkaline salts from textile dyeing units (Sharma et al., 2014; Rathore et al., 2017).

The electrical conductivity (EC) and total dissolved solids (TDS) were consistently higher than safe thresholds, with TDS values often exceeding 2500 mg/L, particularly near industrial areas of Pali and Mandia (Beniwal et al., 2020). Such high TDS levels indicate excessive ionic load and salinity, rendering the water unfit for irrigation and domestic use. Biochemical Oxygen Demand (BOD) values of 60–110 mg/L and Chemical Oxygen Demand (COD) values exceeding 300 mg/L (RSPCB, 2018; CPCB, 2020) confirm severe organic pollution, primarily from untreated dye effluents, surfactants, and tannery waste.

4.2 Heavy Metal Contamination and Soil Impact

The concentration of toxic metals such as chromium (Cr), lead (Pb), cadmium (Cd), nickel (Ni), arsenic (As), and zinc (Zn) in both water and sediment samples consistently surpass safe limits (Sharma & Singh, 2014; Choudhary et al., 2021). Chromium, primarily from the textile dyeing industry, was recorded up to 2.8 mg/L, far exceeding the WHO permissible limit of 0.05 mg/L. Similarly, cadmium concentrations ranged from 0.3–0.6 mg/L, while lead levels reached 0.7 mg/L in certain zones, particularly downstream near Dabar and Pipar City (Beniwal et al., 2020; Singh et al., 2022).

Heavy metals in the riverine environment tend to accumulate in sediments, forming long-term sinks that gradually release contaminants back into the water column, a process known as remobilization (Kaur et al., 2023). Over time, these metals infiltrate adjacent agricultural soils irrigated with river water, resulting in decreased soil fertility, reduced organic matter, and altered cation exchange capacity. Rathore and Purohit (2017) observed a 25–40% decline in soil microbial biomass and enzymatic activity, indicating ecological imbalance and reduced nutrient cycling capacity.

4.3 Bioaccumulation and Food Chain Transfer

The reviewed evidence suggests that toxic metals are bioaccumulated in crops and vegetables grown along the Jojari basin. Leafy vegetables such as spinach and coriander were reported to contain significantly elevated concentrations of Cr, Pb, and Cd, sometimes exceeding FAO/WHO (2019) safety limits (Gupta et al., 2021). The bioaccumulation factor (BAF) and transfer coefficient values for Cr and Pb were particularly high, demonstrating the capacity of these metals to move from soil to plant tissues and subsequently enter the human food chain.

Such bioaccumulation poses chronic health risks. Regular ingestion of contaminated produce can result in hematological, hepatic, and renal toxicity (Jain & Kothari, 2024). Additionally, metal ions interfere with enzyme systems, disrupt redox homeostasis, and induce oxidative stress, leading to lipid peroxidation and DNA damage (IARC, 2022).

4.4 Human Health Implications

Multiple epidemiological surveys have linked prolonged exposure to polluted Jojari water with various health disorders among local communities. ICMR (2023) data revealed increased incidences of skin rashes, respiratory distress, gastrointestinal issues, and elevated liver enzyme levels among residents consuming contaminated water. In villages downstream of Pali, several cases of chronic dermatitis and liver dysfunction were reported (RSPCB, 2020).

The carcinogenic potential of certain pollutants is of particular concern. Hexavalent chromium (Cr^{6+}) and arsenic (As) are classified by the International Agency for Research on Cancer (IARC, 2022) as Group 1 human carcinogens, known to cause lung, liver, and skin cancers. Chronic exposure to these elements leads to DNA damage, impaired repair mechanisms, and epigenetic modifications that promote tumorigenesis (Sharma et al., 2023). Evidence from Jain et al. (2024) further suggests correlations between metal exposure and altered gene expression linked to oxidative stress pathways.

4.5 Environmental and Socioeconomic Consequences

Beyond health hazards, pollution in the Jojari River affects agricultural productivity and socioeconomic stability. High salinity and metal content in irrigation water have caused crop yield reduction by 30–50% in nearby villages, forcing farmers to abandon cultivation (Choudhary & Singh, 2018). Reduced soil fertility and contamination also compromise groundwater recharge quality, further deepening the water scarcity crisis in arid Rajasthan.

The combined effects of industrial expansion, poor waste management, and limited regulation enforcement have aggravated the situation. Despite several mitigation efforts such as Common Effluent Treatment Plants (CETPs) and Zero Liquid Discharge (ZLD) initiatives, compliance remains inconsistent (CPCB, 2021). Strengthening monitoring frameworks, improving wastewater treatment efficiency, and community-based awareness are crucial to reversing ecological degradation and protecting public health.

5. Conclusion

The Jojari River pollution scenario exemplifies the growing environmental crisis emerging from unregulated industrialization and inadequate policy enforcement in semi-arid regions of India. Over the past decade, cumulative evidence has demonstrated severe contamination of river water, adjoining soils, and crops irrigated with effluent-laden water. Heavy metals such as chromium, cadmium, lead, and arsenic persist at concentrations far exceeding permissible limits, confirming the inability of existing treatment systems to mitigate industrial discharges effectively. These pollutants not only alter the physicochemical properties of the aquatic ecosystem but also contribute to long-term ecological degradation through sediment deposition and bioaccumulation in food chains.

The consequences for human health are profound and multifaceted. Chronic exposure to contaminated water and food sources has been linked to dermatological disorders, hepatic dysfunction, renal impairment, and an alarming increase in carcinogenic outcomes within the affected communities. The presence of genotoxic metals such as Cr (VI) and As underscores the urgent need to strengthen the connection between environmental monitoring and public health surveillance. Establishing region-specific cancer registries and epidemiological databases would enable better assessment of exposure-related disease burdens and facilitate targeted interventions.

Addressing this crisis requires a multidimensional approach that integrates technological, regulatory, and community-driven solutions. The immediate enforcement of Zero-Liquid Discharge (ZLD) and Common Effluent Treatment Plants (CETPs) must be prioritized, with regular audits to ensure operational compliance. Restoration strategies should include phytoremediation, constructed wetlands, and bioremediation technologies utilizing native microbial and plant species capable of metal immobilization.

Equally important is community participation through awareness programs, citizen science monitoring, and health education campaigns that promote sustainable water use and pollution reporting. Policymakers must recognize that the Jojari River's degradation is not an isolated incident but a representation of the broader industrial pollution challenge across India's dry land ecosystems. Only through the collective action of government agencies, industries, researchers, and local communities can the Jojari River basin transition from a zone of ecological distress to one of sustainable recovery and resilience.

6. Future Scope

The persistent contamination of the Jojari River calls for a comprehensive and interdisciplinary research framework to guide remediation and sustainable management efforts. Future studies must move beyond routine monitoring to focus on source-specific pollution characterization, Eco toxicological modeling, and long-term human exposure assessment. Integrating these aspects will help establish a cause–effect relationship between industrial emissions, environmental degradation, and disease prevalence.

Advanced analytical techniques such as Inductively Coupled Plasma–Mass Spectrometry (ICP-MS), X-ray fluorescence (XRF), and Fourier Transform Infrared Spectroscopy (FTIR) should be routinely employed to obtain precise data on trace element dynamics in water and sediments. Similarly, molecular and genomic biomarkers should be explored to evaluate sub-lethal metal exposure in aquatic organisms and human populations. The use of bioindicator species like benthic invertebrates, fish, and macrophytes can offer early warning systems for ecological stress and pollution trends.

Future research should also emphasize geo-spatial mapping and temporal modeling using Geographic Information System (GIS) and remote sensing tools. These approaches will allow real-time visualization of pollutant dispersion and hotspot identification across the river basin. The development of pollution risk indices and human health risk assessment models based on local exposure data can significantly improve management decision-making.

In addition to technical innovations, there is an urgent need for policy-oriented research that evaluates the effectiveness of current environmental laws and industrial waste regulations. Collaborative efforts between research institutions, industries, and government agencies must focus on designing cost-effective, scalable solutions for wastewater recycling and zero-emission technologies. The implementation of bioremediation and phytoremediation approaches, utilizing native microbial strains and hyper accumulator plants, can offer eco-friendly alternatives for restoring contaminated soils and sediments.

From a public health perspective, longitudinal epidemiological studies and community-based disease surveillance programs should be prioritized. Linking environmental data with medical records through digital platforms would enable early detection of pollution-related diseases. Educational and outreach initiatives aimed at empowering local communities—particularly farmers and women—can enhance participation in monitoring and reporting pollution incidents.

Ultimately, the future of the Jojari River depends on an integrated approach that combines scientific innovation, governance reforms, and societal engagement. Continuous environmental assessment, transparent data sharing, and the promotion of green industrial practices are essential to ensure that the Jojari River evolves from a symbol of industrial pollution to a model of environmental recovery and sustainability.

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