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Review

Rising tides of contamination from source to sink: The Yamuna's struggle with pollution (2014–2024)

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Abstract: The Yamuna River, a lifeline for millions in India, has been severely polluted over the decades. From 2014–2024, substantial research has been conducted to analyze the extent of its degradation, pollution sources, and mitigation efforts. This review synthesizes studies from this decade, focusing on chemical, biological, and physical parameters of pollution, industrial and municipal waste contributions, agricultural runoff, and policy interventions. Despite increased awareness and remedial measures, the river remains critically polluted, demanding urgent and sustainable solutions. Also, incomplete data has been collected over the years. The focus of researchers has been primarily on Delhi-NCR regions, mainly because industrial and agricultural activities are more prominent in these regions, neglecting the entire stretch of the River Yamuna which is very important to understand the overall health of the river and to analyze the areas that are contributing mostly to its polluted water.

Keywords: the Yamuna River; pollution; water quality; heavy metal; ecological impact

1. Introduction

The Yamuna River, revered as a lifeline for millions, has been grappling with severe pollution challenges that threaten its ecological integrity and the health of communities that depend on it. The river originates from the pristine Yamunotri Glacier in the Himalayas and travels approximately 1376 km. The river flows through several states, including Uttarakhand, Himachal Pradesh, Haryana, Delhi, and Uttar Pradesh, before merging with the Ganges at Allahabad. Along its journey, the Yamuna sustains millions of people, supports agriculture, and serves as a critical water source for urban centers such as Delhi, Agra, and Mathura (**Figures 1–3**). However, its waters are severely compromised, particularly downstream of Delhi, where untreated sewage, industrial effluents, and agricultural runoff overwhelm its self-purification capacity [1]. The National Green Tribunal (NGT) and the Central Pollution Control Board (CPCB) have identified the Yamuna as one of the most polluted rivers in India. Several flagship initiatives, including the Yamuna Action Plan (YAP) phases I, II, and III, were launched to restore the river's health. Despite these efforts, the river continues to struggle under the weight of anthropogenic stressors, leading to a myriad of ecological and public health concerns [2].

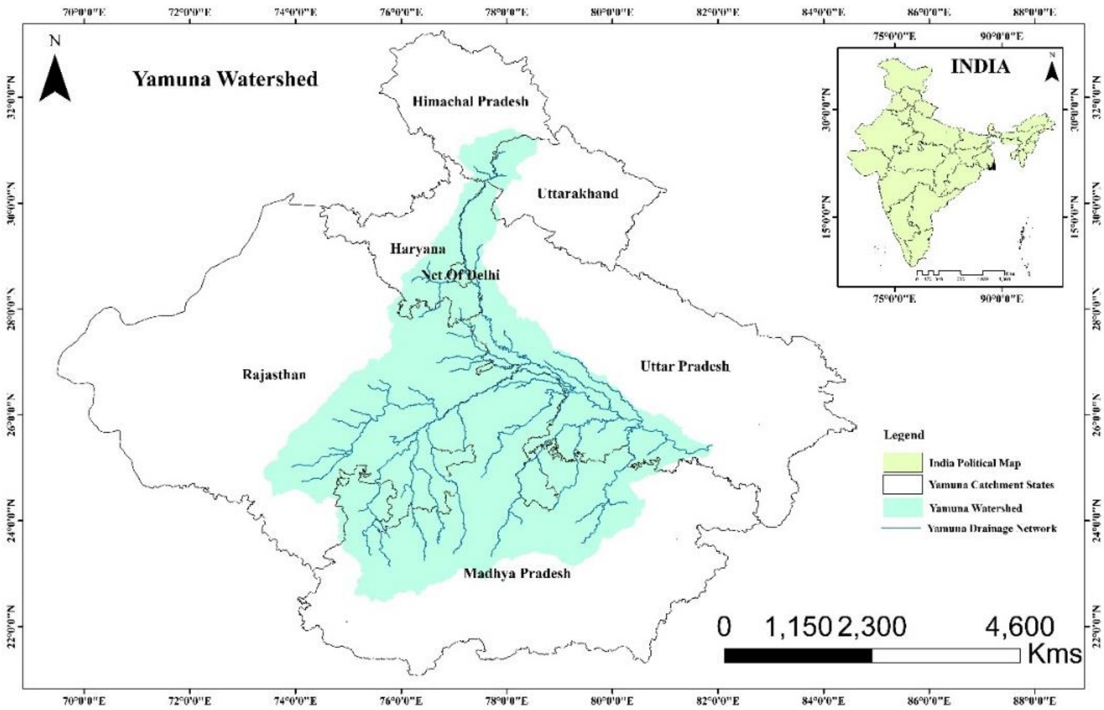

Figure 1. Watershed map of study area made using ARC-GIS.

However, rapid population growth, urbanization, and industrialization have resulted in the generation of lots and lots of waste which is ultimately dumped in water bodies leaving it deteriorated and unfit for consumption. In Delhi, there is a stretch of 22 km from Wazirabad to Okhla, which accounts for 75 percent of the river's pollution load. Twenty-two drains fall into the river in this stretch, says [3] which is often described as an "ecological dead zone", and epitomizes its critical health. The river's lean flow during winter reduces the natural dilution of pollutants, allowing them to concentrate. The river's lean flow during winter reduces the natural dilution of pollutants, allowing them to concentrate. There is the failure of several national programs run by the Centre for River Conservation and water quality monitoring, which have least contributed to its improvement of water quality, underscoring the inefficacy of existing strategies and the urgent need for sustainable solutions. The pollution of the Yamuna River is a result of multifaceted anthropogenic activities that have escalated significantly over the years. Industrial effluents and municipal waste are among the primary contributors with Delhi-NCR regions acting as hotspots due to high population density and industrial activity. Agricultural runoff laden with fertilizers and pesticides further exacerbates the river's pollution levels. These pollutants introduce heavy metals such as lead, cadmium, chromium, etc., into the river leading to long-term ecological and health consequences. Due to a lack of comprehensive monitoring, the ability to address pollution holistically has been limited.

The distribution of heavy metal varies across the river course. In its upper stretch, the Yamuna experiences relatively lower levels of contamination due to limited industrial activity. However, as the river flows through urban and industrial hubs, the concentration of heavy metals increases dramatically. For instance, studies have revealed that the heavy metal pollution index (HPI) in several regions consistently exceeds the safe threshold, with some sites classified as highly polluted. Key parameters such as pH, Biological Oxygen Demand (BOD), Dissolved Oxygen (DO), Conductivity, and Coliform levels reveal critical deviations from permissible standards. For instance, BOD levels in Delhi's stretch of the river frequently exceed the standards for outdoor bathing, while coliform levels indicate severe contamination from untreated sewage. The ecological consequences of Yamuna River pollution are profound. Heavy metal contamination disrupts aquatic food webs and reduces biodiversity by exerting toxic effects on aquatic organisms. Additionally, the accumulation of pollutants in sediments and biota can lead to long-term ecological damage. For example, the presence of heavy metals in fish and other aquatic organisms poses risks to predators, including humans, who rely on these resources for sustenance. The river's degraded state also affects its hydrological functions. Reduced flow due to upstream diversions and groundwater extraction has diminished the river's ability to self-purify [4,5] further compounding pollution levels. This disruption of natural processes threatens the river's ecological integrity and undermines its role as a critical water resource for millions of people.

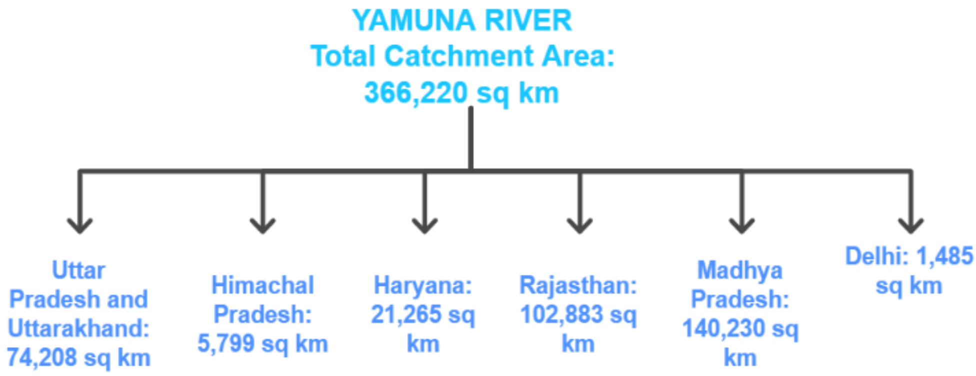

Figure 2. Total catchment area and their state-wise contribution to the River Yamuna.

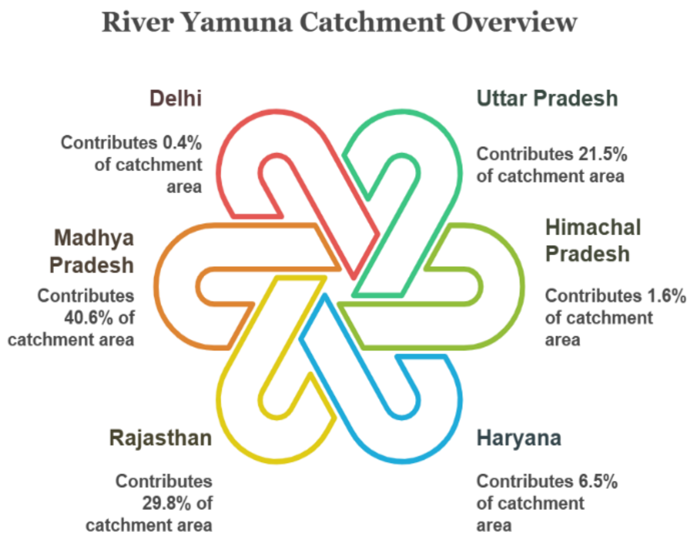

Figure 3. Total catchment area and their state-wise percentage contribution to the River Yamuna.

Source: CPCB DATA 2006.

Despite numerous studies on Yamuna River pollution, most research has focused on isolated aspects such as water quality monitoring, specific pollutant analysis, or the effectiveness of particular intervention strategies. This study offers a unique contribution by providing a comprehensive, decade-long analysis (2014–2024) of the river's contamination trends, integrating data from multiple sources to evaluate longitudinal changes in pollution levels, particularly heavy metal contamination. Unlike previous studies, which often examine pollution in static time frames, this study assesses the spatial and temporal variations, identifying patterns and emerging threats. Additionally, this study critically evaluates the effectiveness of past and ongoing remediation efforts, highlighting policy gaps and the inefficacy of existing water management strategies. By synthesizing data from various studies and reports, this work seeks to provide an updated and holistic understanding of the ongoing struggle against pollution in one of India's most vital rivers. The findings aim to inform future conservation policies and drive more effective, sustainable solutions for river restoration.

2. Methodology

Our study employed a multi-faceted approach to gather data using Semantic Scholar, Google Scholar, AI-based software like Napkin AI, and Whimsical to generate infographics, ArcGIS to generate maps, government reports, and news articles using keywords like "Yamuna River" and "Heavy Metal Toxicity" that showed 1900 articles related to these keywords. The key articles from the searched ones were used for presenting the topic in a clear, short, and concise manner presenting the understanding of heavy metal pollution status in Indian rivers.

In **Figure 4**, a steady increase in research efforts over time, with more publications in recent years (especially after 2018), suggests that concerns about pollution in the Yamuna River are growing which can be attributed to worsening pollution levels, government initiatives, or heightened public awareness. Increased studies align with environmental efforts such as the National Mission for Clean Ganga and improved water quality monitoring techniques, such as remote sensing, Geographical Information System (GIS) mapping, and advanced chemical analysis—**Figure 5**. Explain significant variation with lead, chromium, and cadmium being the most studied contaminants in the Yamuna River between 2014–2024. The Pie chart explains the toxic metal level that exceeds safe limits in several parts of the river. Trend analysis from (**Figure 6**) can be categorized into four main areas:

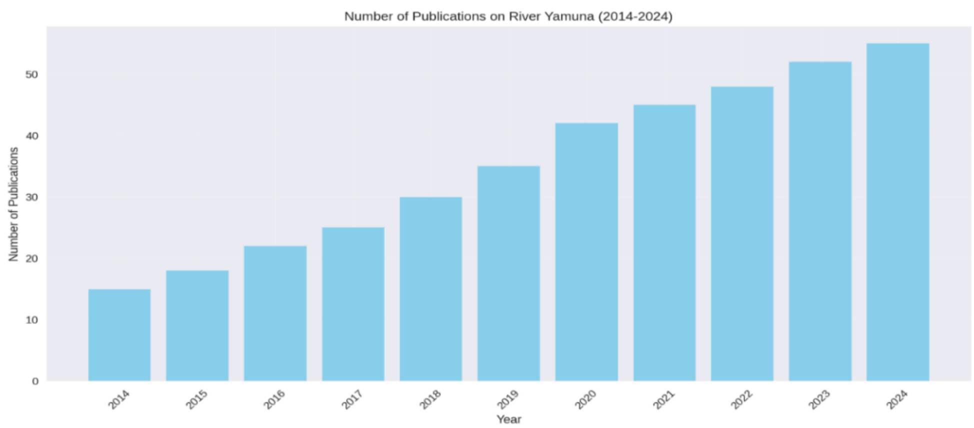

Figure 4. Number of publications related to Yamuna River and its pollution (from 2014–2024).

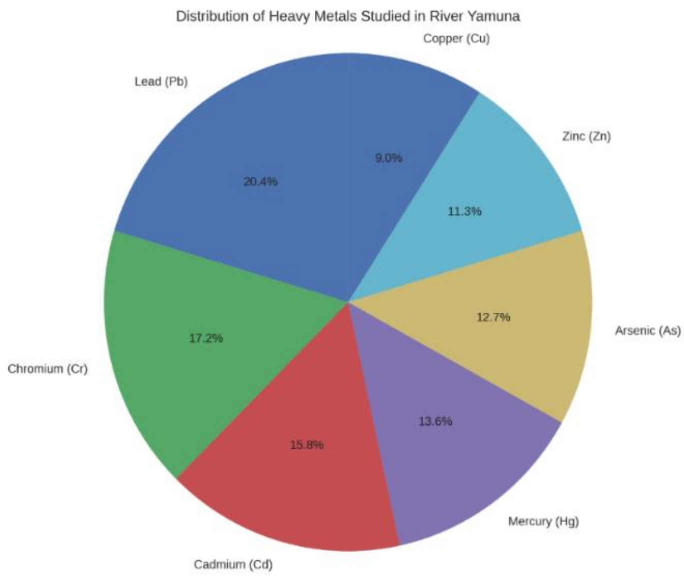

Figure 5. Distribution of heavy metal in Yamuna River.

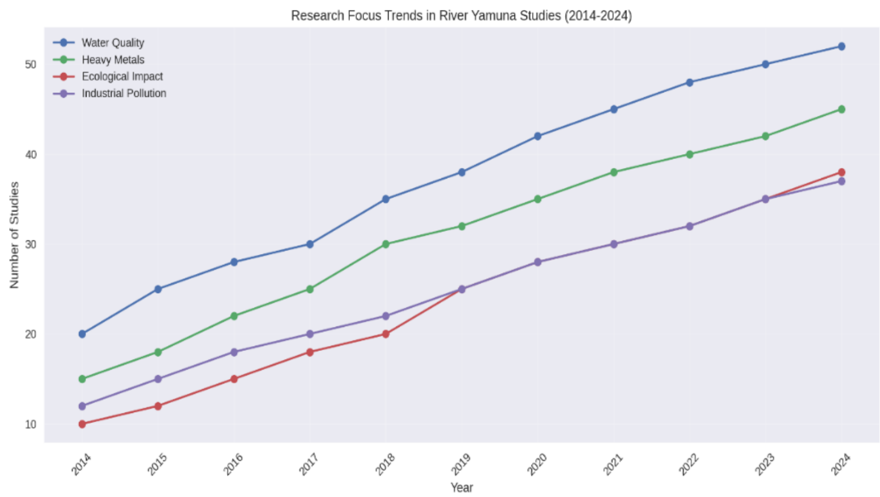

Figure 6. Research focus trends in Yamuna River (2014–2024).

a. Water Quality Monitoring (Blue Line).

Steady increase from (2014–2024) showing growing concern over the overall health and long-term degradation of Yamuna's water quality, prompting regular assessments.

b. Heavy Metal Pollution Studies (Green Line).

A sharp rise from 2015 onwards, peaking towards 2024 suggests persistent heavy metal contamination of toxic metals like lead, mercury, arsenic, cadmium, likely linked to industrial effluents, untreated sewage, and urban runoff.

c. Ecological Impact Studies (Purple Line).

Gradual increase but lower as compared to heavy metal research reflects growing awareness of bioaccumulation effects on aquatic biodiversity suggesting the need for remediation strategies like bioremediation and sediment dredging.

d. Industrial Pollution Studies (Red Line).

The consistent rise indicates increasing industrial discharge concerns, suggesting a focus on identifying polluting industries and regulatory measures in industrial zones near Delhi, Agra, and Mathura that likely contribute to high contamination levels.

3. Status of the River Yamuna

Rapid urbanization and population growth in fast-growing cities leading to industrialization pose a major threat of pollution for India's river ecosystem [6]. Several researchers have studied heavy metal contamination in various Indian rivers concerning industrial, municipal, and domestic pollution [7]. The Central Pollution Control Board (CPCB), Central Water Commission (CWC), Delhi Pollution Control Committee (DPCC), and State Pollution Control Board (SPCB) regularly monitor the Yamuna at 19 different locations. Major drain outfalls are monitored by the Central Water Commission (CWC, 2007). The ecological implications of heavy metal contamination in Yamuna River are profound; these metals can be toxic to aquatic organisms even at low concentrations [8]. Water contamination by heavy metals leads to reduced biodiversity and disruptions in the aquatic food web [9–14]. The health implications in Yamuna River are equally alarming for us as they are for the aquatic organisms. Long-term exposure to heavy metals can result in serious health problems, i.e., neurological disorders, kidney damage, and various forms of cancer. The Yamuna River demonstrates a varied gradient and flow dynamics as it traverses different geographical regions. In its upper stretch, spanning approx. 200 km, it collects water from numerous streams.

3.1. Water quality status and WQ index

The Yamuna River, a vital water source for millions in northern India, has faced significant pollution challenges over the past decade, primarily due to rapid urbanization, industrial discharge, and inadequate sewage treatment. Studies conducted between 2014 and 2024 reveal alarming contamination levels, with key physicochemical parameters consistently exceeding permissible limits. For instance, dissolved oxygen (DO) levels have frequently dropped to critical lows, often reaching zero mg/L in heavily polluted areas. This decline is closely linked to high Biological Oxygen Demand (BOD) values, which indicate substantial organic pollution. Research shows that BOD levels often exceed 30 mg/L, creating an unhealthy aquatic environment and contributing to the river's deteriorating health (**Figure 7**). Chemical Oxygen Demand (COD) values have also been alarmingly high, reflecting significant contamination from domestic and industrial effluents. Total Dissolved Solids (TDS) concentrations are elevated due to urban runoff and industrial discharges, often surpassing acceptable limits for drinking and irrigation purposes. Additionally, microbial contamination remains a serious concern, with total coliform counts frequently exceeding safe limits, rendering the water unsuitable for human consumption and agricultural use. The presence of pathogenic microorganisms poses considerable health risks to communities relying on the river for drinking water.

Spatial variability in water quality is evident along the Yamuna's course. Upstream areas generally exhibit better water quality than downstream locations where pollution from urban centers like Delhi is concentrated. Analysis of the Water

Quality Index (WQI) over the past decade reveals a troubling trend; many sampling points are categorized as "bad" or "very bad", particularly in heavily polluted areas downstream. Despite significant investments in sewage treatment infrastructure, there has been little improvement in water quality due to the continuous inflow of untreated sewage and industrial effluents [15,16]. In conclusion, the water quality status of the Yamuna River from 2014 to 2024 highlights ongoing environmental challenges exacerbated by urbanization and industrial activities. The consistently poor WQI scores underscore the urgent need for effective pollution control measures and sustainable management practices to restore this vital water resource. Continued monitoring and research are essential for developing strategies to improve water quality and ensure safe drinking water supplies for communities dependent on the Yamuna River [17].

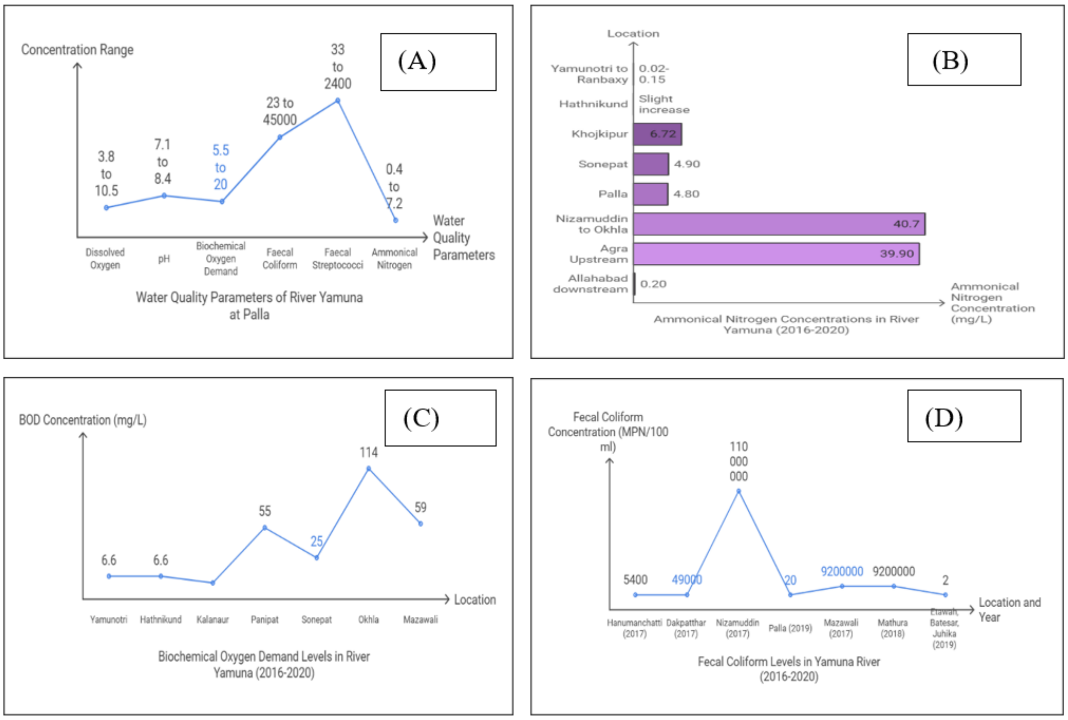

Figure 7. CPCB pollution study report on River Yamuna.

3.2. Heavy metal pollution status and HP index

The Yamuna River has been significantly impacted by heavy metal pollution over the past decade, primarily due to domestic and industrial discharges. Approximately 85% of the pollution in the river is attributed to these sources, leading to severe degradation of water quality. Industrial effluents remained the primary source of heavy metal pollution, with the Delhi-NCR stretch showing the highest contamination levels. [18] Documented the increase in mean heavy metal concentrations, attributing this rise to inadequate industrial waste treatment and rapid urbanization. Seasonal variations significantly influenced heavy metal distributions, with pre-monsoon periods showing peak concentrations. Studies by [19] revealed that dissolved metal concentrations were higher during summer months compared to winter, primarily due to reduced water flow and increased industrial discharge. Bioaccumulation studies in river sediments indicated chronic contamination, with enrichment factors for Cd and Pb ranging from 3.2 to 5.8, suggesting moderate to severe pollution levels.

The Heavy Metal Pollution Index (HPI) has been employed as a crucial tool to assess the extent of heavy metal contamination in the Yamuna River. The HPI is calculated based on the concentration of specific heavy metals and their respective permissible limits, providing a comprehensive overview of water quality. Recent analyses indicate that the HPI values for various sampling locations along the river consistently fall into categories indicating moderate to severe pollution. For instance, studies have shown that HPI scores often exceed 100, categorizing them as highly polluted sites [20,21].

The Heavy Metal Pollution Index (HPI) is a crucial indicator of water quality concerning heavy metals. In the Delhi stretch of the Yamuna, the HPI value was reported to be 1491.15, indicating critical levels of pollution [7]. This alarmingly high HPI value suggests that the river is severely contaminated with heavy metals, primarily due to anthropogenic activities.

Recent studies have shown that the HPI in groundwater near the Yamuna River has exceeded 200 at multiple locations, indicating severe contamination of the aquifers [22]. This highlights the diffusion of heavy metals from the river into the surrounding water bodies, exacerbating the pollution problem. Recent remediation efforts have shown mixed results. While certain stretches showed marginal improvement post-2020 following implemented treatment protocols, urban segments continued to exhibit concerning trends (**Figures 8–11**).

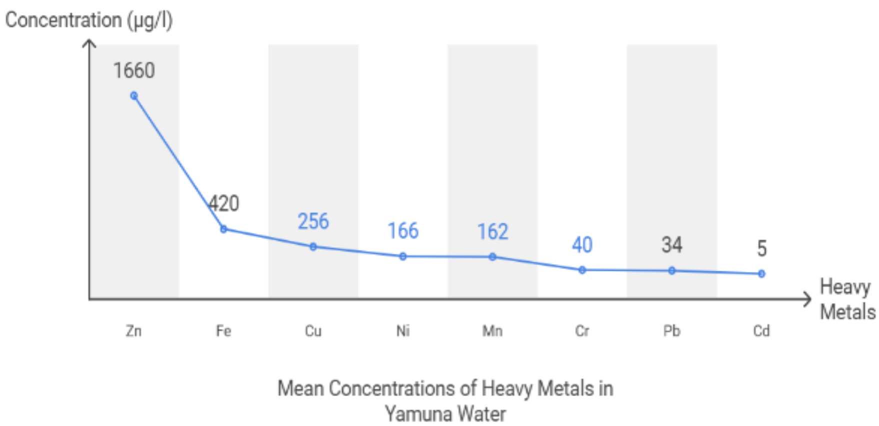

Figure 8. Heavy metal in Yamuna River in AGRA study (2017).

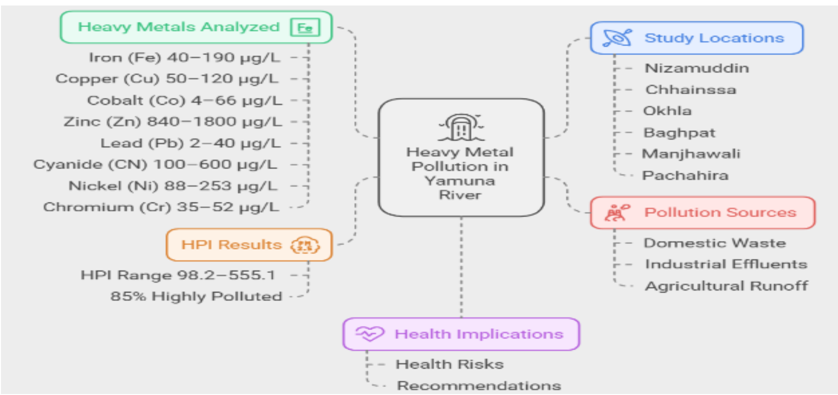

Figure 9. Heavy metal in Yamuna River study (2018).

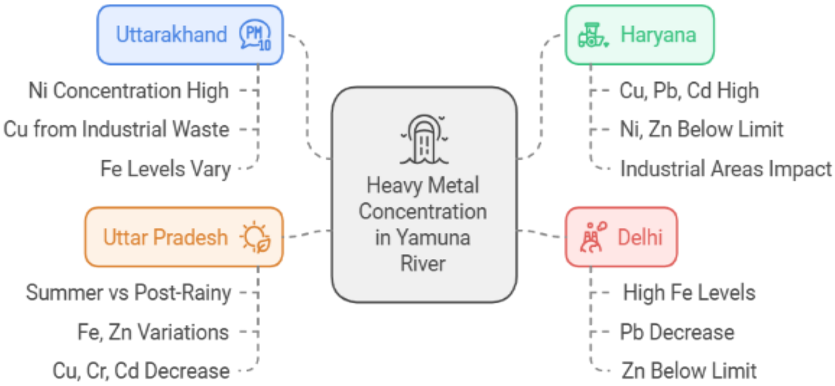

Figure 10. Mean concentration of heavy metal in Yamuna River (2019).

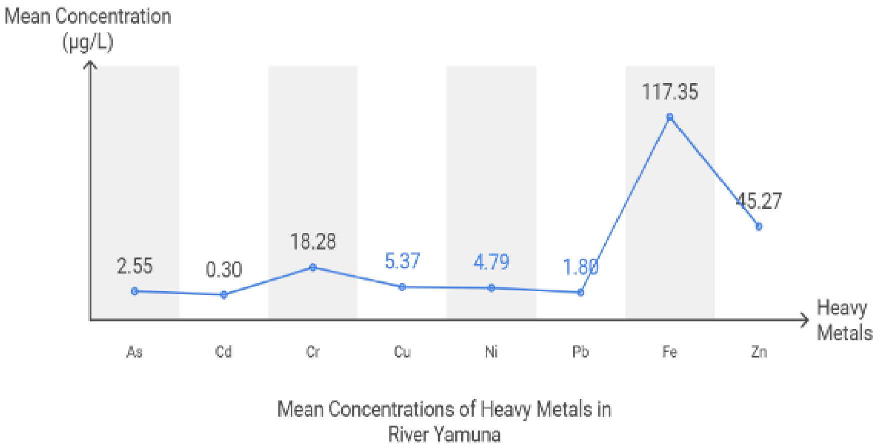

Figure 11. Mean concentration of heavy metal in Yamuna River study (2022).

3.3. Ecological impact

Ultimately, the Yamuna River is contributed to by significant tributaries to finally meet the Ganges at the Sangam (Prayagraj). [23] Reported in a journal the concentration of heavy metals in the water sample collected at different stations recently using Atomic Absorption Spectrometry (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). From 2007 to 2016, BOD levels consistently exceeded the standards for outdoor bathing, according to a study report conducted by CPCB. Total coliform (TC) and fecal coliform (FC) levels rose dramatically throughout (**Figure 7C**). In Agra, a study conducted by [24] shows Zinc (Zn) > Iron (Fe) > Copper (Cu) > Nickel (Ni) > Manganese (Mn) > Chromium (Cr) > Lead (Pb) > Cadmium (Cd) (**Figure 8**). In a study (**Figure 9**) conducted by [25], significant contamination issues and several metals exceeded one or the other permissible limits set by BIS (Bureau of Indian Standards), CPCB (Central Pollution Control Board), and WHO (World Health Organization). It was found that the Heavy Metal Pollution Index (HPI) range was between 98.2 and 555.1. 85% of the studied sites were classified as highly polluted based on the HPI. A comparison between heavy metal concentrations in the Yamuna River in Uttar Pradesh, Uttarakhand, Haryana, and Delhi has been shown in a study conducted by [26] (**Figure 10**).

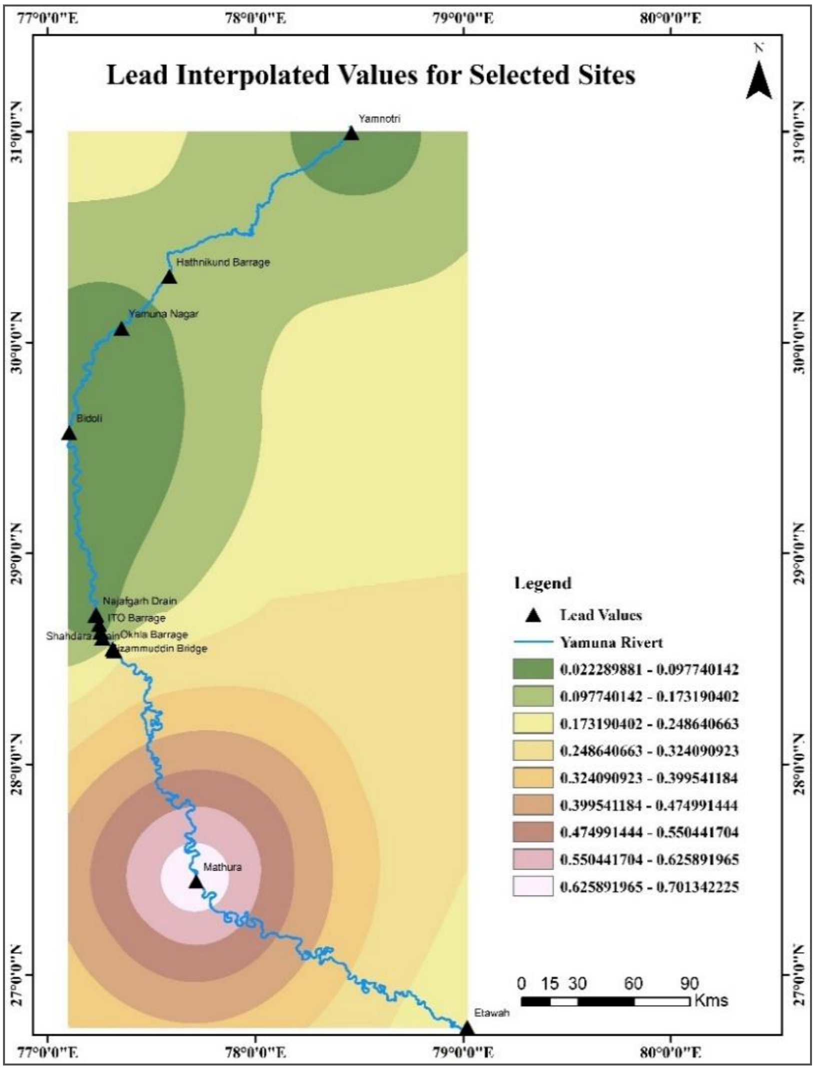

Figure 12. Interpolated value of lead from selected sites (made using CPCB data on Yamuna pollution with the help of ArcGIS).

In pollution reports by CPCB between 2016 and 2020, severe pollution levels in the Yamuna River, especially in urban and industrial stretches, have been indicated. These insights highlight the urgent need for improved wastewater treatment, stricter pollution controls, and consistent monitoring to restore and maintain the river's health. In a 2022 study conducted by [20], the mean concentration of heavy metals in 13 districts along the Yamuna River has been observed (**Figure 11**). High levels of heavy metals, such as iron and zinc, suggest significant industrial discharge and urban runoff. The presence of toxic metals like lead, cadmium, and chromium indicates pollution from industrial effluents. The data of the 2024 study highlights significant heavy metal pollution in the Yamuna River, particularly in urban and industrial regions such as ITO Barrage and Wazirabad. Addressing the pollution requires targeted efforts to reduce industrial discharge, improve wastewater treatment, and enforce stricter environmental regulations to protect both human health and the river's ecosystem [27]. As the data is incomplete, we can only analyze the maximum and minimum percentage values. Out of all the maximum percentages of Nickel & Zinc & Lead (**Figure 12**), they are in Mathura, Copper & Chromium, Iron in

Najafgarh drain, Cadmium in Arail ghat, and Mercury in ITO Barrage; pH is almost equivalent throughout in a range between 6–8. Maximum BOD at Okhla Barrage after meeting Shahdara Drain and Upper Stream of Mathura. Maximum conductivity at Mazawali, U.P. Maximum Chloride at ITO Barrage. Maximum Total & Faecal Coliform at Nizamuddin. Water quality data and heavy metal concentration as reported by different researchers along the river's course at different locations have been utilized to make an average percentage graph (**Figure 13**) to understand the quality of the Yamuna River through graphical representation.

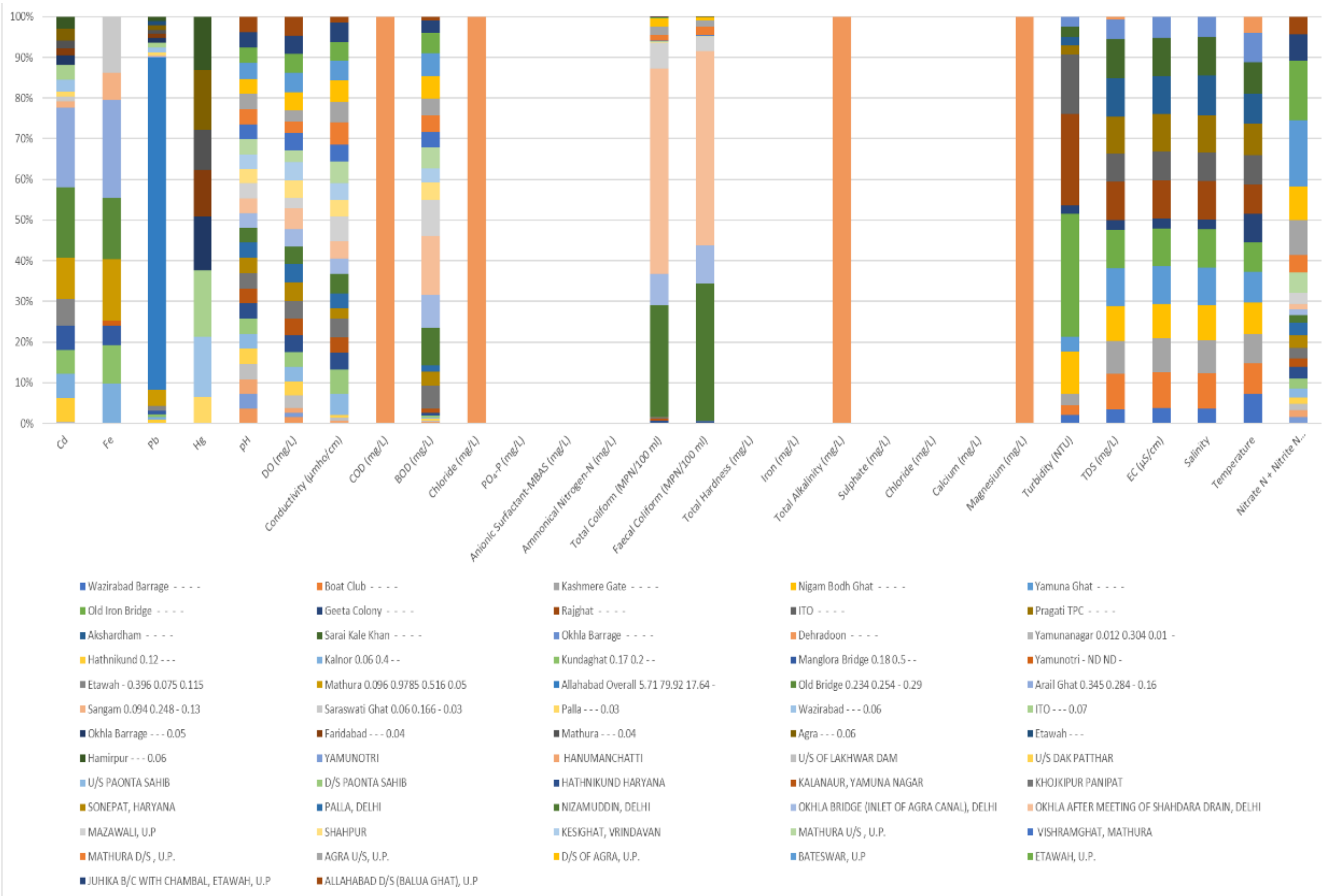

Figure 13. Graph representing the average amount of water quality parameters and heavy metals along the course of Yamuna River as studied.

3.4. Satellite-based water quality monitoring

High-resolution satellites like GeoEye-2 (**Figure 14**) [28], Sentinel, and Landsat provide real-time and multi-temporal data, enabling researchers to analyze water quality parameters such as turbidity, chlorophyll concentration, and chemical pollutants. The ability to use spectral band combinations and remote sensing models allows for targeted actions in an efficient, non-invasive, and scalable way, including AI-based image analysis and hyperspectral imaging.

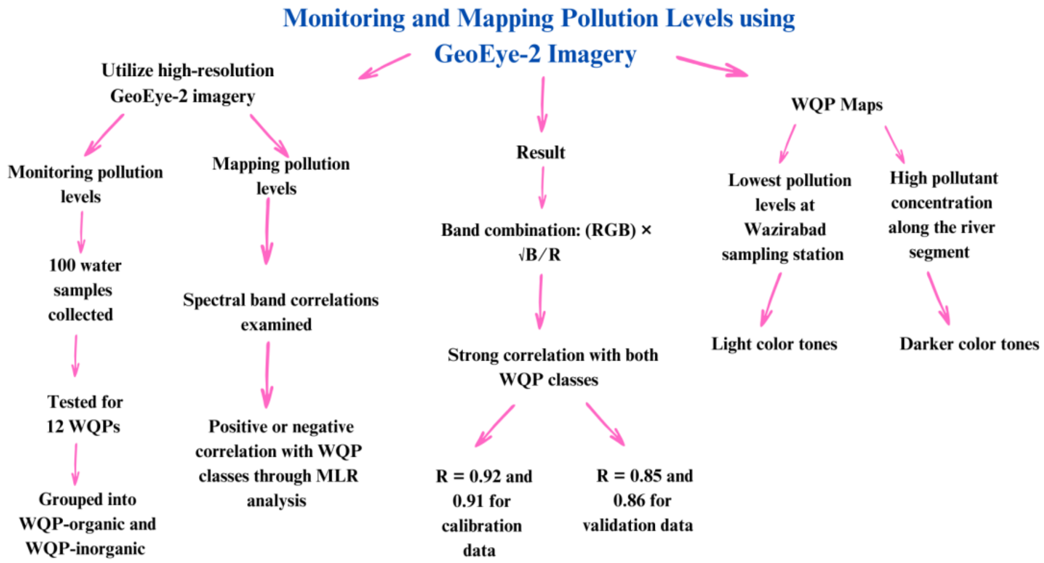

Figure 14. Flowchart of a research study done with the use of GEOEYE-2 imagery for studying pollution levels in River Yamuna.

4. Discussion and conclusion

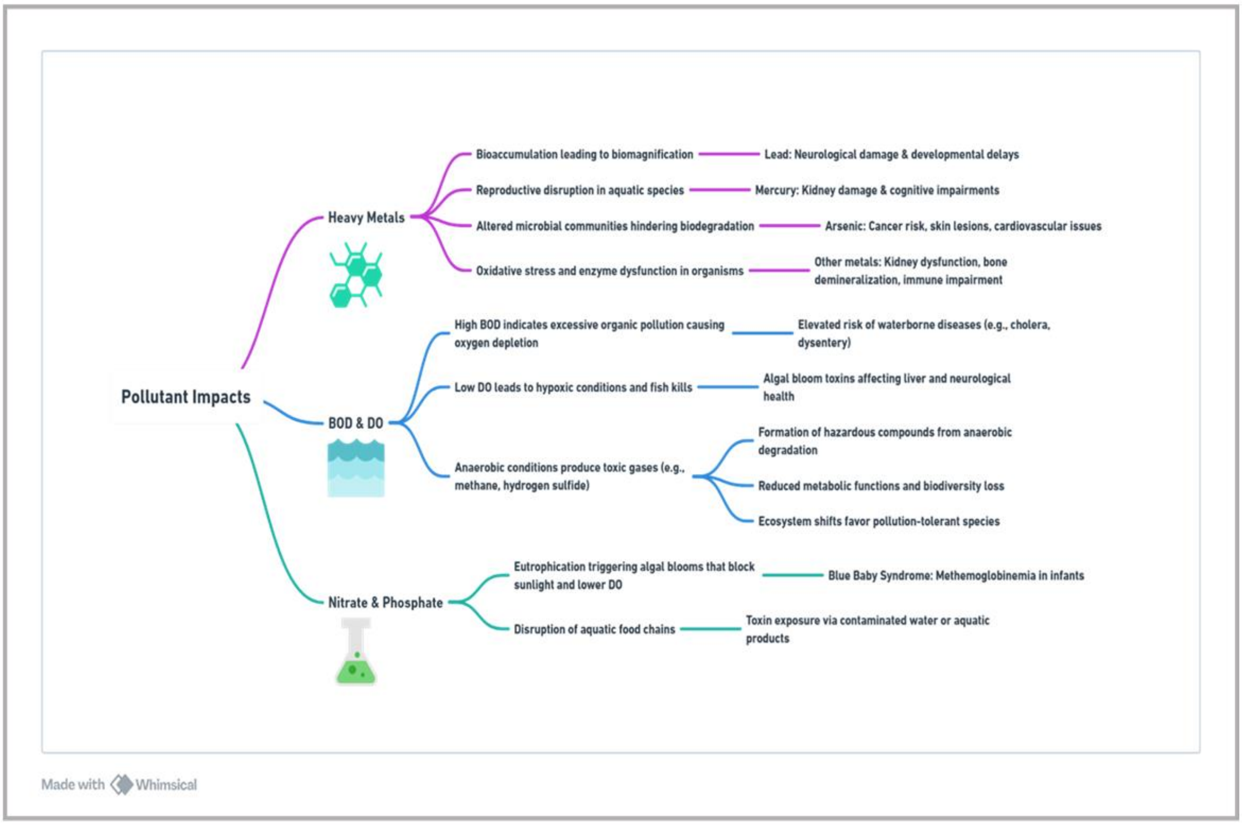

Figure 15. Impact of pollutants on the environment and human health.

The trends are not good and with the rapid development and generation of different forms of waste, we need to bring some immediate behavioral changes with a farsighted vision as soon as possible. Global partners are required in the field to work on innovative monitoring and restoration and suffer from high capital and operational costs which is a major issue in developing countries. In India, 3 out of every 4 monitoring stations have observed alarming levels of heavy toxic metals like Lead, Iron, Nickel, Cadmium, Arsenic, Chromium, Copper, etc. (**Figure 15**) [29]. Heavy metals can bioaccumulate and tend to biomagnify [30]. Its toxicity results in the production of free radicals, which damage DNA. These metals are not readily degradable and are related to developmental retardation, renal damage, a variety of cancers, and even death in extreme cases.

4.1. Site-Specific pollution management strategies

Through the thorough study of different research papers, it can be concluded that the Yamuna, as it passes through Delhi, is hardly 2% (22 km) of the river's total course but its polluted state is attributable to Delhi's failure to keep it in good shape. Recently, the draft [31] was prepared by the National Capital Region Planning Board (NCRPB). It has fixed 2026 as the new deadline to ensure zero discharge of untreated sewage and industrial sewage into the Yamuna. The Yamuna Action Plan, signed in 1992, was started with Japanese collaboration for improving the quality of the river basin and was extended from time to time with various flagship projects launched. The 3rd Yamuna Action Plan is underway, where the entire sewage load of Delhi is to be intercepted and treated. The city generates 720 million gallons per day of sewage of which 123 MGD remains untreated. Delhi Jal Board had informed NCT that it would increase its sewage plant treatment to 99%, but it remains at 86% according to news reports. The ministry of Jal Shakti observed that the 1994 water-sharing agreement between Uttarakhand, Himachal Pradesh, Uttar Pradesh, and Haryana is due for revision in 2025. This can help in diverting more water towards the Delhi Stretch of Yamuna to maintain a minimum water flow called ecological flow to reduce pollution load. Outdated technology in existing water treatment plants needs to be upgraded urgently to recycle treated sewage for non-domestic use. The site-wise disposition of heavy metal by producing a heavy metal pollution index can help identify and quantify trends in water quality [32,33] and can provide an accumulated assessment of overall water quality. According to a recent news report, several villagers in West Bengal are suffering from sores and ulcers due to arsenic poisoning from drinking water. According to the report, the number of arsenic-affected habitations has increased by 145% in the last 5 years (2015–2020) [34]. Palla U/S Delhi Water Quality Monitoring station indicated mercury levels of 8.903 µ/L, which are nine times the permissible limit of mercury set by the Bureau of Indian Standards (BIS) in the River Yamuna, according to the report of the Central Water Commission [35]. In a form that policymakers could utilize for regulation and control of pollution. "Until urgent steps are taken to clean and protect it, the Yamuna River will remain a contradiction: revered and poisoned, life-giving and yet dying at the hands of those it sustains" [36].

To restore the health of the Yamuna River, a paradigm shift in site-specific water resource management (**Figure 16**) is essential [37]. Modernizing existing plants with state-of-the-art technologies to enhance treatment efficiency and ensure compliance with environmental standards. Encouraging industries and agricultural sectors to adopt environmentally friendly practices, such as reducing chemical usage and implementing waste minimization strategies.

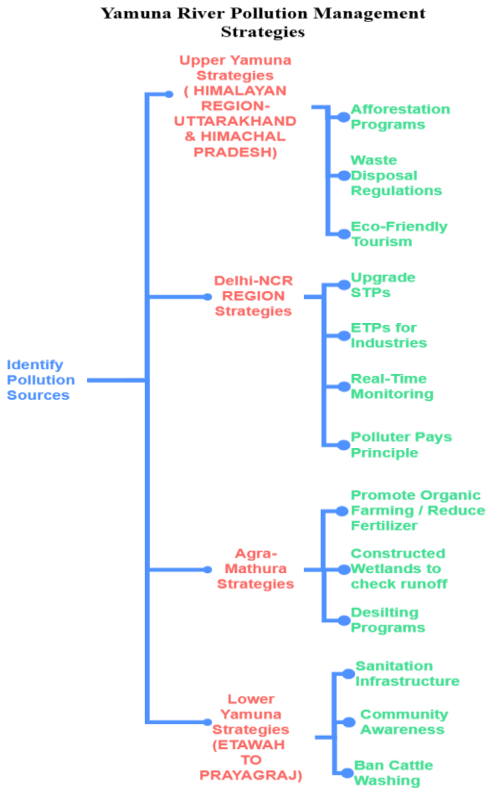

Figure 16. Location-specific pollution management strategies.

4.2. Water quality assessment using machine learning and techniques

Expanding knowledge among researchers by designing courses on water quality monitoring using AI and machine learning techniques to help them analyze data to give new perspectives in this direction (**Figure 17**) [38,39]. Including the entire stretch of the river and leveraging advanced technologies for real-time data collection and processing data. Conducting awareness campaigns to educate communities about the importance of preserving Yamuna and their role in pollution prevention.

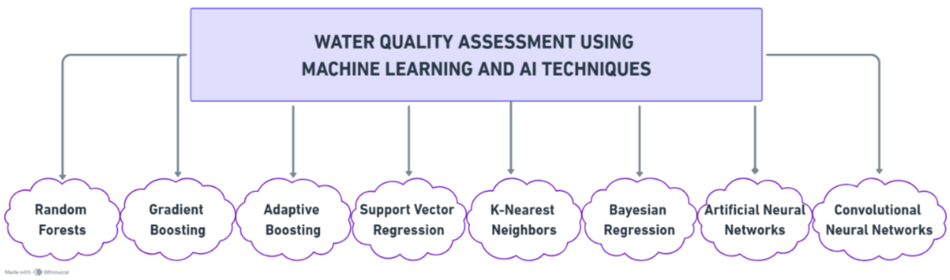

Figure 17. Water quality assessment techniques using machine learning and AI techniques.

Engaging global partners and fostering collaborations among governments, non-governmental organizations, and research institutions to develop innovative solutions for river restoration. Urgent action is needed to reverse the trends of degradation and to protect this invaluable natural resource for future generations. "Supporting water security by using treated wastewater for non-potable purposes like toilet flushing, car washing, construction, agriculture, and rejuvenating affected rivers and lakes is vital for the city's sustainable development," said Riccardo Zennaro, a Programme Management Officer for wastewater at United Nations Environment Programme (UNEP) [40]. "It can also improve access to clean tap water," he added. "Wastewater treatment supports the recycling and recovery of water and nutrients and is, therefore, critical for sustainable water and nutrient management while preventing pollution. However, it needs significant improvement to meet Indian government environmental standards".

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Conflict of interest: The authors declare no conflict of interest.

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