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Review Article

Environmental Challenges and Restoration Opportunities of the Hindon River: A Review of Pollution Control, Bioremediation, and Sustainable Management Practices

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Abstract

The Hindon River, flowing through Ghaziabad, India, faces severe pollution mainly due to untreated municipal sewage, industrial effluents, and solid waste dumping. This pollution results in increased levels of organic pollutants, heavy metals such as Cd, Pb, and Ni, and pathogenic contamination, making the river water unfit for domestic, agricultural, and other uses. Conventional physico-chemical remediation methods, such as chemical precipitation or dredging, are often expensive, generate secondary pollutants, and do not offer a sustainable, long-term solution. In this context, sustainable and eco-friendly remediation approaches are urgently needed to restore the river's ecological health. Bioremediation, which harnesses the metabolic activities of microorganisms and plants to degrade or remove contaminants, emerges as a promising method due to its cost-effectiveness, environmental compatibility, and potential for complete degradation of pollutants. This review comprehensively discusses the pollution status of the Hindon River, bioremediation techniques applicable to its restoration, government initiatives, challenges faced, and integrated strategies for sustainable river cleanup.

1. Introduction

Rapid urbanization and industrial growth in India have placed immense pressure on freshwater ecosystems, particularly small and medium rivers flowing through urban and sub-urban areas. Many such rivers have transitioned from natural aquatic environments to wastewater-dominated channels, losing ecological integrity and posing significant public-health risks. The Hindon River serves as a prime example of this issue.

The Hindon River originates in the Shivalik foothills of the Saharanpur district. The basin area falls in the districts of Saharanpur, Muzaffarnagar, Shamli, Meerut, Bagpat, Ghaziabad, and Gautambudh Nagar in Western Uttar Pradesh and flows approximately 400 km before joining the Yamuna near Greater Noida. The River Kali (West) and River Krishni are the main tributaries of River Hindon. It is a major source of water to the highly populated and predominantly rural population of western Uttar Pradesh, India.

Due to the rising pollution day by day, Hindon River is now gasping for breath. Among its downstream segments, the Ghaziabad stretch has been consistently identified as critically polluted due to the confluence of municipal drains, industrial discharges, agricultural run-off and limited dilution capacity during non-monsoon months. It is severely polluted with high levels of organic pollutants, heavy metals (such as Cd, Pb, Ni), and pathogenic contamination. Currently, the river is on the edge of dying since the poisonous level in the river water has reached dangerously high levels. The Central Pollution Control Board rated the river "unfit" for bathing in a 2015 study [1].

There is a need for continuous monitoring of Hindon River water to protect the health of aquatic ecosystems and human well-being. Further, treatment of Hindon river water is also a challenging task due to the large variety of inorganic, organic chemicals and microorganisms [2]. Traditional river restoration efforts in the Hindon basin have focused on centralized sewage treatment plants (STPs) and regulatory enforcement. However, multiple evidence indicate that end-of-pipe solutions alone are insufficient for such type of heavily polluted rivers with wide range of pollutants. Consequently, attention has shifted toward bioremediation and nature-based solutions, which use biological processes to degrade, transform, or immobilize contaminants in situ.

This review aims to provide a comprehensive synthesis of research on bioremediation of the Hindon River, with a specific focus on the Ghaziabad stretch. The objectives are to:

1. Summarize the river's pollution status and contaminant profile.
2. Review bioremediation techniques relevant to its restoration.
3. Evaluate key challenges in implementation.
4. Review Government and Regulatory Initiatives.
5. Identify future directions and integration frameworks

2. Materials and Methods (Review Methodology)

This review was conducted to assess the pollution status of the Hindon River and to evaluate the potential of bioremediation approaches for its restoration. A systematic literature survey was conducted using databases including Scopus, Web of Science, Google Scholar, SpringerLink, Elsevier and ScienceDirect and DOAJ. Keywords used included *"Hindon River," "Ghaziabad," "bioremediation," "heavy metals," "constructed wetlands," "microbial remediation," and "urban river pollution."*

Peer-reviewed journal articles, conference proceedings, doctoral theses, and government reports published between 2000 and 2025 were considered. The retrieved publications were screened based on their relevance to the objectives of the review. Studies were included if they focused on pollution status of the Hindon River, sources of contamination, environmental impacts, and remediation strategies. Studies lacking sufficient scientific evidence, presenting duplicate information and unrelated environmental remediation were excluded.

The selected literature was screened and categorized into themes including pollution sources, water quality status, microbial remediation, phytoremediation, wetland-based treatment systems, challenges, and future restoration opportunities. The findings from these studies were critically analyzed to identify current knowledge gaps, limitations of existing remediation approaches, and future research directions for sustainable restoration of the Hindon River.

3. Overview of Pollution Status in the Hindon River (Ghaziabad)

The Hindon River is heavily polluted due to untreated industrial effluents and sewage, agricultural runoff, dysfunctional sewage treatment plants (STPs), and lack of effluent treatment plants (ETPs), making its water unsafe for human consumption and harmful to aquatic life. All the water pollution indicating parameters are found higher than the prescribed limit by the National Pollution Control Agency, i.e. CPCB [3].

3.1. Organic and Nutrient Pollution

Multiple studies consistently report extreme organic pollution in the Ghaziabad stretch of the Hindon River. Very high BOD, COD, TDS, hardness, nutrients, and turbidity at Ghaziabad sites indicate severely degraded water, making it unfit for domestic use. A study conducted at Mohan Nagar barrage, Ghaziabad (2015–2017) compared pre-monsoon vs. post-monsoon water samples for different parameters. Post-monsoon values are slightly lower due to rainwater mixing, but contamination remains severe year-round.

3.2. Microbiological Contamination

Researchers report extremely high total and faucal coliform counts from large volumes of untreated domestic sewage, especially at Mohan Nagar and nearby drains.

3.3. Heavy-Metal Contamination in Water and Sediments

Heavy metal contamination of the environment has got world-wide consideration due to their non-biodegradable nature, long-biological half-lives for elimination from the body. Their accumulation in the food chain will have a substantial effect on human health in the long term [4]. Hindon River suffers severe heavy metal contamination. All metals like Cd, Pb, Cr, Ni, Zn, Fe, and Mn exceeded permissible limits at every site. Ghaziabad–Delhi stretch is most polluted due to industrial activity in this region. Electroplating, steel, pharmaceuticals, textile, paper & pulp industries are major contributors.

A Summary of reported water quality parameters in the Ghaziabad stretch of the Hindon River and comparison with Indian standards is given in Table 1.

4. Remediation of Polluted River Water

The remediation of contaminated river water is a challenging issue in many developing countries due to the high level of pollution. Different methods that can be applied for remediation of polluted river water are categorised into physical, chemical, and biological, but a single method is not sometimes effective for the purification of heavily contaminated river water. Therefore, hybrid techniques, which combine two or more single methods, are more widely recommended for their effective treatment.

Physical treatment processes include mechanical aeration processes, water transfer or diversion and dilution [5], mechanical algae removal, building hydraulic structures [6], dredging river sediment, etc. Application of these physical processes can effectively improve river

Table 1: Water quality parameters in the Ghaziabad stretch of the Hindon River and comparison with Indian standards

Parameter	BIS Standard	Reported range	Pollution implication
pH	6.5–8.5	7.0 – 7.5	Within limits
Turbidity (NTU)	≤ 5	7 – 18	Exceeds the permissible limits indicating contamination
TDS (mg/L)	≤ 500	540 – 780	Very high, salinity stress
DO (mg/L)	≥ 5	2.1 – 4.0	Below standard, indicates poor quality
BOD (mg/L)	≤ 3	6 – 12	Very high, extreme organic pollution
COD (mg/L)	≤ 10	22 – 42	Very high indicating high oxidizable load
Cd (mg/L)	≤ 0.003	0.005 – 0.012	Exceeds everywhere
Cr (mg/L)	≤ 0.05	0.07 – 0.18	Exceeds everywhere
Pb (mg/L)	≤ 0.01	0.02 – 0.06	Exceeds everywhere
Mn (mg/L)	≤ 0.1	0.19 – 0.42	Exceeds everywhere
Fe (mg/L)	≤ 0.3	0.6 – 1.2	Exceeds everywhere
Zn (mg/L)	≤ 5	1.9 – 2.8	Within limits
Total Coliforms (MPN/100 ml)	7.4×10^4	5.8×10^4	Far above safe limits
Fecal Coliforms (MPN/100 ml)	4.5×10^4	3.6×10^4	Indicates sewage contamination

water and sediment quality, resulting in river restoration. But some of these methods may cause adverse effects, such as the destruction of natural ecosystems and an economic burden due to their high capital and maintenance cost.

Chemical treatment of polluted water includes flocculation, precipitation, oxidation, and algal removal by chemicals, which can remove suspended solids (SS) and algae. Chemical processes provide quick and emergency remediation of polluted river water, but they are temporary and may produce secondary pollutants, which can cause other risks.

Biological methods include plant purification technology, combinatorial biotechnology, bioremediation technology, biofilm technology [7], and artificial wetland technology. These methods are eco-friendly, cost- effective and sustainable solutions for river restoration. However, these processes need an extended time, ranging from several months to years for microbial growth and, sometimes, different environmental factors such as temperature and rainfall affect their performance. Some of these technologies are costly and labour intensive in their implementation [8]. Therefore, more research is needed to overcome the cost related issues and technical difficulties in near future to save the rivers globally.

5. Bioremediation

Bioremediation technology, invented by George M. Robinson, is defined as the process of degrading pollutants into less toxic forms biologically under particular conditions using microorganisms. This technique utilizes naturally present bacteria, fungi, as well as plants to terminate or degrade substances that are a threat to human health as well as the environment. The microbes used in the process are mostly native to the polluted site or sometimes collected from somewhere else to be introduced into the polluted site (bioaugmentation). These techniques provide sustainable, cost-effective, and ecofriendly options to traditional remediation procedures by utilizing natural processes to clean soil and water contaminants. Moreover, these processes have potential for complete degradation of pollutants.

The process of bioremediation can be applied to soil and water media through in- and ex-situ techniques. ex-situ techniques involve the removal and treatment of contaminated materials in a controlled lab environment. in-situ techniques address pollutants directly in their original surrounding using native species or by introducing engineered microbes or by adding oxygen/nutrients into the soil or water to stimulate the activity of indigenous degrading microbes (biostimulation).

A summary of comparison of different methods for remediation of river is given in Table 2 [9].

6. Bioremediation Techniques for the Hindon River

6.1. Microbial Bioremediation

Microbial bioremediation exploits the metabolic capabilities of bacteria, fungi, and algae to degrade organic pollutants or remove metals from soil and water. Laboratory-scale studies using Hindon-derived isolates such as Bacillus subtilis and Pseudomonas aeruginosa have demonstrated significant biosorption and bioaccumulation of Cd, Ni, and Pb. Experimental studies demonstrate that Bacillus subtilis HIB2 achieves removal efficiencies of 71.7% for Lead, 68.6% for Nickel, and 53.9% for Cadmium, while Pseudomonas aeruginosa HIB11 shows 70.7%, 66.4%, and 57.6% removal respectively after 14 days. These findings support the feasibility of site-specific bioaugmentation, where indigenous strains are reintroduced to enhance remediation efficiency. Multiple studies have reported the bacterial strains in the Hindon River which have the potential to be used as sensitive biomarkers for the development of bioremediation strategies and their monitoring 35.

6.2. Phytoremediation

Phytoremediation is a bioremediation technique performed in situ using plant species to minimize the toxic effects of pollutants in water, soil, and air. Species such as *Echinochloa stagnina, Phragmites australis, Eichhornia crassipes*, and *Ludwigia stolonifera*, have been widely reported to remove nutrients and metals from contaminated waters [10]. A study report shows that Brassica *juncea* can accumulate Hg, Cd, Pb, Ni, Zn from Hindon water, indicating potential for phytoextraction at contaminated sites [11].

Table 2: Comparison of River Remediation Methods

Aspect	Bioremediation	Physical Methods (e.g., dredging, aeration)	Chemical Methods (e.g., oxidation, precipitation)
Cost	Low to moderate; microbes and nutrients are inexpensive, long-term maintenance minimal	High upfront cost (equipment, labor, energy); recurring expenses for operation	High cost of chemicals; repeated dosing required; disposal of by-products adds expense
Scalability	Scalable for small-to-medium rivers/drains; limited by environmental conditions but adaptable	Scalable only with significant infrastructure; difficult for large polluted rivers	Scalable in controlled plants, but impractical for large open rivers
Effectiveness	Strong for organic waste, sewage, and heavy metals (with specialized microbes); slower but sustainable	Effective for suspended solids and sludge removal; limited for dissolved pollutants	Rapid pollutant reduction; effective for specific contaminants (e.g., industrial effluents), but may leave secondary pollutants
Sustainability	Eco-friendly, self-sustaining once microbial communities establish	Not sustainable; requires continuous mechanical input	Not sustainable; chemical residues may harm ecosystems
Community Involvement	High potential (local NGOs, residents can help with planting, monitoring)	Low; requires technical expertise and machinery	Low; requires trained operators and chemical handling

6.3. Constructed Wetlands and floating treatment beds

Constructed wetlands represent an effective, low-cost, and ecologically sustainable hybrid treatment technology where microbial activity, plant-mediated nutrient uptake, and physical filtration converge to improve wastewater quality. Pilot wetlands at Ghaziabad drain outfalls embody this approach and have shown considerable reductions of BOD, suspended solids, and nutrients prior to river discharge. Similar systems have proven effective in urban river restoration globally [12]. Floating Treatment Bed systems (FTBs) also provide an effective approach to remove pollutants from the rivers. These systems consist of aquatic plants anchored on mats, which support the growth of microbial communities. The FTBs have helped in the rejuvenation of polluted water from the Mini River in Gujarat, India.

6.4. Integrated and advanced approaches

Researchers emphasize that bioremediation must be integrated with sewage interception and functional STPs to achieve significant water quality improvement. Bioremediation acts most effectively as a polishing and load-reduction strategy, rather than a replacement for conventional treatment. A combined engineering approach using aeration, microorganisms, biological aerated filtration, artificial biofilms, and ecological floating beds effectively remediates heavily polluted rivers, which increase dissolved oxygen, water clarity, and removes odour [9]. AI-driven bioremediation has the potential to revolutionize river pollution control. It advocates for urgent action to address the challenges involved, so that the sustainable and effective river pollution control strategies can be developed [13].

7. Government and Regulatory Initiatives

The Hindon is widely described as heavily polluted by untreated sewage, industrial effluent, and organic waste. It has been treated as a priority restoration river since 2015. A restoration roadmap for the Hindon river emphasizes catchment protection, afforestation, wetland revival, and better waste management rather than relying on a single treatment technology (2030 Water Resources Group, 2019). This matter because bioremediation works best when pollutant loads are reduced at the source and supported by ecological and sustainable restoration.

A government report published in 2025 says that Ghaziabad Nagar Nigam has established a tertiary sewage treatment plant (TSTP) at Indirapuram with a 68 km pipeline, which delivers 40 MLD of treated water to approximately 1400 industrial units of Ghaziabad. This project focuses on advanced membrane filtration technologies like microfiltration, ultrafiltration, nanofiltration, and reverse osmosis for high quality water treatment. Ghaziabad authorities have started bioremediation of Hindon using microbes, fungi, algae, and phytoremediation using plants to reduce pollution in the river's drains before wastewater reaches the main channel. Targeted Locations are City Forest, Karhera, Nandgram, Hindon Vihar, Arthla, Kaila Bhatta, Pratap Vihar, Rahul Vihar, and Dasna. There are significant improvements in water quality parameters such as BOD (Biochemical Oxygen Demand) and COD (Chemical Oxygen Demand) in influent samples. Among the nine drains in Ghaziabad Municipal Corporation that remain uncovered, a proposal has been developed to cover seven of them, Nandgram, Hindon Vihar, Pratap Vihar, Rahul Vihar, Kaila Bhatta, City Forest, and Dasna, using the IND technique under the AMRUT 2.0 scheme. There is also a plan to build in-situ (on-site) wetlands on the drains that flow into the river, where large boulders, cut stone ridges, and microbes dwelling in the roots of wetland plants will work together as natural filters, purifying the water before it reaches the Hindon [14]. Hindon is included under Namami Gange / NMCG programs as a polluted tributary of the Ganga–Yamuna system. Planned measures include expanding sewage treatment capacity, strengthening STPs and tertiary treatment.

The latest reporting suggests the project is moving from planning into execution, but with multiple drains still untreated or only partly addressed. A May 2025 report said a project for seven untapped drains was being revised and shifted toward Namami Gange funding, while an AMRUT 2.0 project for two drains was already underway with a June 2026 completion target and about 45% work done. This indicates a staggered rollout rather than a single finished bioremediation program.

8. Discussion

Analysis of the reviewed literature reveals a clear progression in research related to the Hindon River. Initial studies primarily focused on identifying pollution sources and evaluating physicochemical water quality parameters. Subsequently, research expanded to investigate heavy metal contamination, ecological degradation, and associated risk to human health. More recent studies have increasingly emphasized sustainable remediation technologies, including microbial remediation, phytoremediation, and wetland-based treatment systems. This trend reflects a shift from pollution characterization toward the development of practical restoration and management strategies.

The reviewed literature indicates that bioremediation techniques, including microbial augmentation/stimulation, phytoremediation with hyperaccumulator plants/aquatic macrophytes, constructed wetlands, floating treatment beds and algal-based systems, hold promise for addressing the complex pollution load of the Hindon River. Microbial approaches are particularly effective in degrading organic pollutants, while plant-based methods are proficient in removing heavy metals through phytoextraction/rhizofiltration.

The most prominent bioremediation strategy identified for the Hindon River is microbial treatment in drains, where bacteria, fungi, yeasts, and algae can degrade organic contaminants and mitigate the pollutant load entering the river. Another promising strategy involves constructed or in-situ wetlands, where boulders, plant roots, and microbes collectively function as a living filtration system for drain water. These strategies are frequently combined with engineering techniques to improve the results.

Evidence from the Hindon River aligns with findings from other Indian rivers such as the Yamuna, Ganga, and Kalyani Rivers, where bioremediation has shown promising results in reducing organic pollution and improving DO locally [15, 16].

However, challenges remain:

- Performance of bioremediation techniques depends upon the type and concentration of pollutants; certain methods demonstrate reduced efficacy under high pollutant loads or when dealing with recalcitrant compounds.
- Environmental factors such as temperature and rainfall also affect efficacy.
- Phytoremediation offers a more sustainable and visually acceptable approach but generally requires longer treatment periods.
- Regular harvesting and maintenance are essential to prevent the re-release of pollutants.
- Large-scale implementation requires careful design considering local hydrology/ecology.
- Some studies highlight risks such as accumulation of antibiotic-resistant pathogens or incomplete removal of certain contaminants.
- There exists a significant disparity between the volume of sewage systems installed and the volume actually treated, with numerous drains continuing to discharge untreated sewage.
- Integration with engineering solutions, such as aeration, can enhance outcomes but also increases complexity and costs.
- Although AI-driven optimization presents future potential, it has not yet been widely adopted in India.

The reviewed literature highlights several important gaps in current research on the Hindon River and its restoration. A major research gap identified in the literature is lack of studies which evaluate the long-term effectiveness of bioremediation strategies under real field conditions. Most of the studies for hindon river have been conducted at laboratory or pilot scales, making it difficult to assess the sustainability and scalability of these approaches under real environmental conditions. In addition, existing research often examines microbial remediation, phytoremediation, and constructed wetlands as separate approaches, with limited consideration given to integrated remediation frameworks that may provide enhanced treatment efficiency. Furthermore, long-term monitoring programs and comparative assessment of different remediation technologies are scarce, making it difficult to identify the most sustainable and cost-effective restoration strategies for the Hindon River. Addressing these research gaps will be essential for developing scientifically strong and practically applicable solutions for river restoration and management.

9. Conclusion

Research shows the Hindon at Ghaziabad is severely polluted by untreated sewage, industrial effluents, heavy metals and pathogens, posing clear health risks. Government programs have begun addressing this issue through expanded treatment, regulation and in-situ bioremediation and phytoremediation plans, but implementation gaps remain large. Evidence from Hindon and from other rivers supports that using native metal-accumulating plants, resistant microbial communities, ecological floating beds, constructed wetlands and combined aeration–biological systems, together with strict source control and enforcement help in restoration of rivers. But successful large-scale implementation will require integrated approaches adopted to local conditions.

Article Information

Disclaimer (Artificial Intelligence): The author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.), and text-to-image generators have been used during writing or editing of manuscripts.

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