Deteriorating State of the Yamuna River: A review to Explore Multiple Restoration Measures for Revitalization

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**Abstract**

*Due to increased industrialization and urbanisation, the Yamuna River, one of the biggest tributaries of the Ganges River in India, has been severely polluted and contaminated with heavy metals. Both human health and the aquatic ecosystem are gravely impacted by heavy metals. The purpose of this research is to investigate and assess the different remediation methods used to lessen heavy metal contamination in the Yamuna River. The evaluation focuses on the merits, drawbacks, and potential of different approaches, offering insights into the difficulties and challenges for sustainable river restoration.*

**Keywords:** Yamuna river, phytoremediation, bioremediation, Wetland, Heavy metals

# Introduction

Yamuna is the largest tributary of the Ganges and plays a crucial role in the religious, cultural, and economic landscape of northern India. It is one of the significant rivers of India. The Yamunotri Glacier is the origin in the lower Himalayas and flows through the states of Uttarakhand, Himachal Pradesh, Haryana, Delhi, and Uttar Pradesh before conferencing River Ganges in Allahabad.

The Yamuna River is mentioned in ancient scriptures and it is said to be the sister of Lord Yama, the god of death. That’s why is considered very sacred in Hindu culture with very rich history. Several pilgrimage sites are located along the banks of the Yamuna River which hold great religious importance. Thousands of devotees visit these banks to do cultural rituals and find spiritual solace. More than 70% of drinking water supply of Delhi is abstracted from river Yamuna (CPCB, 1996., Upadhyay et al., 2010).

Unfortunately, over the years, the river is almost dyeing. It is facing heavy pollution and the quality of water is deteriorating due to human activities. Delhi, the capital of India is the major contributor of pollution in the Yamuna River, followed by Agra and Mathura (Misra, 2010). Domestic sources contribute approximately 85% of the pollution in river (CWC, 2009). Other sources which contribute to the pollution of Yamuna are: untreated sewage, Industrial effluents, sewage, and solid waste which contributed to the river's pollution, affecting both its water quality and the surrounding ecosystem, the dumping of garbage and dead bodies, immersion of idols and pollution due to in-stream uses of water (CPCB, 2006). Sewage treatment plants (STPs) have been constructed at various urban areas in order to maintain the water quality of the river. The treated, untreated or partially treated sewage form STPs is discharged into the river (CSE India, 2007). STPs are unable to operate continuously due to Power failures, mechanical problems or maintenance issues. This is another major threat to water quality, as the collected sewage is discharged into the river at a few locations without any treatment (CPCB, 2006).

As per the data collected by CPCB (2000) there were approximately 359 industrial units out of which 22 industrial units in Haryana, 42 units in Delhi and 17 units in Uttar Pradesh which directly discharge the effluent thus polluting the river. These industries include paper, sugar, chemical, leather, distillery, pharmaceuticals, power etc.

Efforts are underway by the government and other authorities to clean, restore and remediate the contamination of the river, but those plans are not delivering enough for its sustainable management. These include wastewater treatment plants, riverfront development projects, and public awareness campaigns to promote responsible waste disposal and conservation practices.

Despite its poor condition, the Yamuna River persist to be the lifeline for millions of people of India. It is a major source of drinking water and provides water for irrigation for number of cities and towns along its bank. Other than this the river supports a varied range of flora and fauna, providing a vital habitat for various aquatic species.

**Water Quality Trend of Yamuna River**

Due to great religious, cultural, social, and economic significance for a large number of Indians. However, similar to many other riverine systems in the nation, Yamuna is also negatively impacted by the setbacks of urbanisation, industrialization, and the country's rapid agricultural development (Maheshwari et al., 2011). According to C.K. Jain's (2004) research, all industrial effluent finds up in the Yamuna River basin as a result of the industrialization of the towns along its path. He added that the Yamuna River's tributaries contributed to its pollution load as well. Water is used for a variety of purposes, producing a large amount of effluent that degrades the Yamuna River's water quality. There are numerous point and non-point sources that contaminate the Yamuna River.

The Central Pollution Control Board (CPCB) is the apex statutory organization responsible for monitoring and controlling environmental pollution in India. It operates several monitoring sites in Delhi to assess the pollution levels in the Yamuna River. Four sites monitored by CPCB may be used in Delhi to assess the pollution levels in the Yamuna River. The deteriorating water quality was observed in 2008 from Wazirabad barrage till Chambhal River confluence at Panchnada with very high BOD and Coliform content, at Nizzamuddin bridge and Agra Canal the DO was almost absent (CPCB 2008). The numbers of observed TC values < 500 MPN/100 ml were between 44-63% during 1995-2008. The water quality monitoring data collected between 1995 to 2009 indicate that the organic and bacterial contamination continued to be critical, primarily due to increasing discharge of untreated sewage (CPCB2009). The number of observed BOD values < 3 mg/l, 3-6 mg/l and > 6 mg/l were between 57-69%, 17-18% and 13-19% respectively during year 1995 to 2011( CPCB 2011).In 2012 no DO was observed from Wazirabad to Ohkhla , after Waziarabad BOD always found violating the prescribed standards from 4-113 mg/l and variation in annual mean is 26-56 mg/l ( CBCP 2012).In 2014 to 2018, the Do from Wazirabad to okhla barrage 0.7-6.2 mg/l, which is obviously violating the prescribed limit. BOD was in range 4-64 mg/l with annual average of 29 mg/l which indicate reduction in value compared to previous year (CPCB 2014). In 2020 the DO level was almost Nil at ITO and Nizamuddin bridge and was observed as 8 mg/l and 5.6 mg/l at wazirabad and Okhla barrage respectively, whereas BOD was 4.9 mg/l,12 mg/l,15 mg/l,11 mg/l at these locations, the high value of MPN (CPCB 2020-21).

According to a report by NGT (2020) it's critical to clean up UP drains' pollution as the cities of Sahibabad and Loni produce 575 MLD of sewage, for which there are seven STPs with a combined capacity of 427 MLD. However, only 2 of these STPs are treating 80 MLD according to the required requirements. Consequently, the Sahibabad and Indirapuri drains are being used to carry a lot of sewage. Additionally, the Noida drain, which flows from Delhi via Noida before joining the Yamuna, dumps 354 MLD of sewage into the river.

Table no. 1 Information on flow and pollution load of Sahihabad Drain, Indrapuri drain and Noida drain.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| S.no | Name of Drain | Discharge | BOD(mg/l) | COD(mg/l) | TSS( mg/l) |
| 1 | Shahihabd | 40 MLD | 744 | 1615 | 1189 |
| 2 | Indrapuri | 31MLD | 743 | 1463 | 647 |
| 3 | Noida | 354MLD | 46 | 163 | 83 |

The overall mean concentration of heavy metals was observed in the following order Fe 4 Zn 4 Cu 4 Ni 4 Cr 4 Pb 4 Cd. It can be concluded that our study area as a whole is critically polluted in terms of mean Fe concentration (6.175 mg/L) due to pollutant load from various anthropogenic activities and need treatment before further use (Yadav et. Al 2019).

## **Biological Contamination of Yamuna River**

Delhi stretch for Yamuna river contributes to the total pollution load of the river. Yamuna flows from Palla to Okhla at a stretch of 22 kms in Delhi receiving discharge from 18 major drains. Water quality of river Yamuna is being monitored by the Central Pollution Control Board (CPCB) under National Water Quality Monitoring Programme (NWMP) in association with State Pollution Control Boards (SPCBs)/ Pollution Control 21 Committees (PCCs) of Uttarakhand, Himachal Pradesh, Haryana, Delhi and Uttar Pradesh at 33 locations. Based on the concentration of BOD analysis of water quality data of river. Yamuna during the year 2019- 2021 observed the highest concentration of BOD in river Yamuna in Delhi during all the three years (i.e., from 2019-2021) followed by downstream Uttar Pradesh locations. Maximum concentration observed is 114 mg/L during 2022. Major depletion in oxygen levels indicates heavy pollution by organic matter, the main sources of which are domestic sewage, agricultural run offs and food processing industries (Pande and Sharma, 1998).

In addition, twenty-eight major drain outfalls into Yamuna are also being monitored by the (CWC, 2007). The organic pollution level increase significantly at Delhi and the Biochemical Oxygen Demand (BOD) level do not confirm to the stipulated standard form. The stretch of the river also shows variations in Dissolved Oxygen (DO) level from Nil to well above the saturation level. Hence depicts the presence of organic pollution load and prevalence of eutrophic conditions. Contamination pertaining to bacteria’s is significantly high in the entire Yamuna River stretch (Malik et al 2014)

The BOD load, earlier noted was 117 tonnes per day (TPD) in 1980 increased to 276 TPD in 2005. The anaerobic condition in the river is observed which is evident from the froth of rising sludge, gas bubbles and floating solids on the surface (CPCB, 2006). Sixteen of the 26 sewage treatment plants (STPs) in Delhi are currently not meeting the quality parameters set by the Central Pollution Control Board, findings of a report prepared by the Delhi Pollution Control Committee which analysed samples collected in June 2022 (Hindustan times, Aug 10, 2022)As per the report of National Inventory of Sewage Treatment Plants March 2021 ,Estimated sewage generation for the union territory of NCT Delhi is 3,330 MLD and total treatment capacity is 2,896 MLD (38 STPs). It shows that there is gap in treatment capacity of 434 MLD. Out of 2,896 MLD installed capacity developed, operationalized capacity is 2715 MLD (35 STPs) (93.75 %) and actual utilized capacity is 2412 MLD and further capacity of complied STPs is only Approximately 40% of India’s sewage treatment capacity belongs to Delhi, yet a massive gap remains between sewage generation and treatment (Anon, 2006).

**Heavy metal contamination in the Yamuna River**

The Yamuna River's heavy metal contamination is a serious environmental concern. Heavy metals are present in the river due to industrial and human activities such mining, manufacturing, sewage discharge, and agricultural runoff.

Lead, mercury, cadmium, chromium, and arsenic are examples of heavy metals that are harmful to both aquatic life and people. These metals can build up in the river's sediments and biota, posing a number of ecological and health hazards. There are a number of techniques now in use to rid the environment of these types of toxins, but the majority of them are expensive and fall short of their potential. Chemical treatments produce huge volumes of sludge and raise prices (Rakhshaee et. al 2009); thermal technologies are expensive and technically challenging, and all of these techniques have the potential to destroy soils' valuable components (Hinchmen et. al 1995).

Various studies are being conducted for analysing the concentration of heavy metal in the river Yamuna. In a study for determination of heavy metals in fish species (Sen et al., 2011), characterization of heavy metals in fish elucidated that the concentrations of Ca, K, Mg, Na and P were too high as compared with other metal and were not in the maximum permissible level set by World Health Organization (WHO). The findings indicate the substantial contamination of heavy metals such as arsenic, cadmium, chromium, copper, lead, and zinc especially in the sediment samples of Yamuna River (Singh et al. 2014).

Eutrophication is mostly brought on by a decrease in oxygen levels, which have been brought on by industrial discharge, organic material releases into water, domestic waste, etc. Another study by TERI (Yamuna, the poisoned river, 2012) revealed some areas of the river to have water with moderate quantities of harmful metals. The samples were collected at several Delhi and Haryana locales near Yamuna. The study also placed a focus on how heavy metals affect both the population that depends on river water and the plants that grow along river banks (Sehgal et al., 2016). The order of the average heavy metal content in the Yamuna River water varied from Fe>Cr>Mn> Zn>Pb>Cu> Ni>Hg>As>Cd at various sites. The average soil heavy metal content varied by Fe>Mn>Zn>Cr> Pb> Ni>Hg>Cu>As>Cd at several places. Free ammonia concentrations of 1.4–6.6 mg/l were determined to be unsafe for fisheries and animal reproduction at Okhla Barrage. Numerous flocks of flamingos have been spotted in the lake created by the Okhla Barrage, where marginthat resemble depressions. It is very necessary to improve the water quality in order to preserve the habitat of rare and endangered species. (Mamta et al., 2013) Flamingos near Okhla Barrage. Due to their durability and the fact that the majority of them have hazardous effects on species, heavy metal contamination of the aquatic environment has recently become a global issue. Metals are among the most dangerous environmental contaminants because of their potential for toxic effects and capacity for bioaccumulation in aquatic ecosystems (Goldstein, 1990; Gledhill et al., 1997). Due to their toxicity and ability to accumulate in marine creatures, heavy metals are regarded as the most significant kind of aquatic environment pollution (Malik, 2014; Gurnham, 1975). The amount of heavy metals identified in the fish samples was higher than the range of WHO's maximum permitted levels, according to research on the concentration of heavy metals in river water. The heavy metals in the Yamuna are likely caused by the different industrial outlets that discharge into the river, which has serious negative effects on people, fish, and plants (Sen et al., 2011). The recommended range of heavy metals considered safe for human health has been established by numerous national and international organisations (CPCB, WHO) (Singh et al., 2014). The sampling site (Nizamuddin) has the highest level of heavy metals, followed by (Chhainssa), (Okhla), (Baghpat), (Manjhawali), and (Pachahira). The average content of heavy metals was high, often exceeding the permitted limits set by the Bureau of Indian Standards (BIS) and World Health Organisation (WHO) for drinking surface water. About 85% of the river water was rated as very contaminated by HPI (which ranges from 98.2 to 555.1), making it unsafe to consume (Mohd Asim et al., 2021). The study found that lower flow conditions and less dilution could be responsible for the increased levels of most metals in the river Yamuna during non-monsoon seasons. Overall, both anthropogenic and natural sources were responsible for the heavy metals in the Yamuna River water (Jaiswal et al.,2022). Nickel is listed as a metal that could lead to cancer by the International Agency for Research on Cancer (IARC) (Sall et al.,2022), While necessary for many chemical or biological processes in the body, metals like zinc, copper, and iron are toxic over a certain concentration (Odobas et al., 2019).

There are various health risks associated with the contamination of heavy metals which involves Acute and Chronic Toxicity including kidney damage, neurological disorders, respiratory problems, and increased risk of certain cancers. Some heavy metals, such as lead and mercury, can also impact reproductive health and fertility in both males and females. Several heavy metals, including lead, mercury, and cadmium, can cause neurotoxicity. They can impair cognitive function, cause learning disabilities in children, and contribute to the development of neurodegenerative diseases in adults, such as Parkinson's and Alzheimer's.

**Strategies and Policies to Reduce Pollution**

1.Enforce and improve current environmental laws and guidelines that deal with water contamination. This includes establishing strong regulations for the treatment of sewage and industrial effluents and enforcing severe fines for non-compliance (Sharma, et al.2020).

2.As per Delhi Jal board the water treatment capacity has seen an increase of 13% over the past decade to 943 Million Gallons per day in 2022 from 906 MGD in 2014 (Economic survey 2022.2023). DJB should make plans making the system more efficient by using the plants to their optimum capacity, build new plants, develop or import new treatment technology. Along with that, smaller units can be set up along the 18 drains to reduce the discharge near the spot only specially the Najafgarh Drain, which passes from North-west to North Delhi.

3. Sewage treatment plants (STPs) should be built and maintained in the towns and cities along the Yamuna River to improve sewage management. Ensure that these STPs are operating properly and encourage the use of decentralised sewage treatment systems in smaller communities (Jin, Guang, et al., 2019)( Tiwari, S., et al.2020)

4. Implement proper measures to protect and restore the riverbank and floodplain areas. This includes afforestation, preventing encroachments, and implementing erosion control measures. Restoring the natural habitat along the river helps in improving the quality of water and prevents pollution (Wang, H., et al.2019)

5.To decrease the usage of artificial fertilizers and pesticides, encourage eco-friendly and sustainable farming practices. To reduce agricultural runoff into rivers, encourage farmers to adopt organic farming practices and promote effective irrigation practices (Mohan, et al. 2020).

6. Establish a robust monitoring system to regularly assess water quality parameters, ecological health, and pollutant levels of the river. This data can help identify pollution sources, evaluate the effectiveness of pollution control measures.

7. Launching River rejuvenation and conservation programs, such as the Namami Gange program, aimed at restoring the ecological health of rivers through various interventions, including afforestation, riverfront development, and biodiversity conservation (Mookerjee, Sounak, et al.2018).

7.Along with that, additional precautions are created to prevent river pollution on auspicious festivals like Ganesh Visarjan, Chatth Puja, Diwali, etc. as now only biodegradable effigies can be dumped in the river (Tiwari, S., et al.2020).

**Remediation Techniques**

***Physical methods***

The affected river by pollution, and implementing physical remediation techniques is crucial to help clean and restore its health. Some physical remediation techniques commonly used for river cleaning are:

Table2. Efficiency, advantages, and disadvantages of different physical/engineering-based treatment methods of river water.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Physical Treatment Techniques** | **Process Description** | **Advantages** | **Disadvantages** | **Reference** |
| Dredging river sediment | Removal of polluted sediment by dredging machine | Improve sediment and river water environment | Potential increase of pollution | Bai et.al.,2020,  Kondratyev et. Al., 2003 |
| Riverbank filtration | Flow through riverbed and groundwater aquifer to the pumping wells | Remove organic and inorganic contaminants through natural filtration process | Slow | Hu et. Al., 2016,  Tyagi et. Al.,2013 |
| Artificial aeration | Air flow increases the microbial diversity and degrades organic compounds in water | Effectively improve water quality, simple and easy to apply, sustainable and widely applicable | Cost intensive during operation and maintenance phase | Bai et.al.,2020,  Zhang et. A., 2016 |
| Wetland Construction | Artificial wetland along the river bank or in specific location | They act as natural filters | Slow process | Wang et.al.,2020,  Vymazal et. Al., 2010 |
| Constructed floating Islands | Uses floating plate forms made of vegetation or other material that imitate natural islands | Absorbs excess nutrient and contaminants from the water . | Slow | Gosh et. Al., 2018, Wolkersdorfer et.al., 2012 |

Phytoremediation: Heavy metal uptake by plant through phytoremediation technologies is using these mechanisms of phytoextraction, phytostabilisation, rhizofiltration, and phytovolatilization.

Phytoextraction: In this method, soil pollutants are absorbed and accumulated by plants. Hyperaccumulators, or plants with high metal uptake capacities, are frequently used in phytoextraction (A. Erakhrumen et al., 2007.) (L. Erdei et al.,2005), (V. M. Ibeanusi et al., 2004). Once the toxins have been accumulated in the plants, they can be harvested and disposed of correctly. Plants act as both accumulators and excluders. Despite concentrating pollutants in their aerial tissues, accumulators are how According to Sinha et al. (R. K. Sinha et al.,2004), Plants act as both "accumulators" and "excluders". Despite concentrating pollutants in their aerial tissues, accumulators persist. In their tissues, the pollutants are biodegraded or transformed into inert forms. The excluders limit the uptake of contaminants into their biomass.

Phytodegradation: The ability of plants to degrade and breakdown contaminants through various enzymatic or metabolic processes. Phytodegradation technique is commonly used for organic pollutants, such as hydrocarbons, pesticides, and explosives (N. Merkl et al., 2005).

Phytostabilization: Plants are used to reduce the bioavailability and mobility of contaminants in the soil. Such plants immobilize contaminants in their roots or through the formation of barriers that prevent their movement. This process is for organics and metals contaminants in soils, sediments, and sludge (USEPA 2000), (M. N. V. Prasad et al. 2003).

Phytovolatilization: The method involves, uptake of pollutants by plants and then released into the atmosphere. Plants are capable of absorbing volatile pollutants like volatile organic compounds (VOCs) and transpiring them out through their leaves. Phytovolatilization occurs as growing trees and other plants take up water along with the contaminants. Some of these contaminants can pass through the plants to the leaves and volatilize into the atmosphere at comparatively low concentrations (L. Erdei et al.,2005), (V. M. Ibeanusi et al., 2004).

Phytostimulation: It involves the use of plants to stimulate the activity of microorganisms in the rhizosphere, the soil zone surrounding the roots. These microorganisms can then degrade or transform contaminants more effectively. Phytostimulation can be achieved through the secretion of root exudates that promote microbial growth (A. Erakhrumen et al., 2007), (L. Erdei et al.,2005), (V. M. Ibeanusi et al., 2004)

Rhizofiltration: It uses plant roots to filter impurities from soil or water. For this method grasses with extensive root systems are frequently used like vetiver grass, lemon grass etc. Contaminants are either trapped or changed as water moves through the root zone of the plant, making the water cleaner. This process is for metals, excess nutrients, and radionuclide contaminants in groundwater, surface water, and wastewater medium [USEPA 2000, T. Bhattacharya et al., 2009, (V. M. Ibeanusi et al., 2004).

With their root systems, plants have a crucial secondary role in physically stabilising the soil, preventing erosion, defending the soil surface, and lessening the impact of rain. In the rhizosphere, nutrients released by plant roots support a diverse microbial life. Complex interactions between soil type, plant species, and the location of the root zone influence the bacterial community composition in the rhizosphere. In comparison to soil without roots, microbial populations are often higher in the rhizosphere. This results from a symbiotic link between plants and soil microbes. Some bioremediation procedures can be improved by this symbiotic interaction. A surface for the sorption or precipitation of metal pollutants may also be provided by plant roots (A. Sas-Nowosielska et al., 2008).

These techniques can be used individually or in combination, depending on the specific contaminants, site conditions, and desired outcomes of the phytoremediation project. It's important to note that the success of phytoremediation relies on careful selection of appropriate plant species and thorough site assessment and monitoring

***Chemical methods***

1.Coagulation-flocculation -Coagulation/Flocculation: To aggregate and destabilise suspended pollutants and particles in water, chemical coagulants such aluminium sulphate (alum) or ferric chloride are used. Larger flocs are produced by this technique, which are simple to separate from water using filtering or sedimentation (Mohapatra et al.,2020) (Gavrilescu, M. 2009)

2.Precipitation - By adding chemicals to the contaminated water, precipitation creates insoluble precipitates that contain the intended contaminants. Depending on the individual pollutants present, common precipitation agents include lime (calcium hydroxide), sodium hydroxide, and other metal salts (Jadhav et al., (2019).

3. Ion exchange- Ion exchange involves using a solid material (ion exchange resin) to exchange ions between the water and the resin surface. This process is effective for removing dissolved heavy metals and other ions (Hamid, F. S., et al. 2019)

4.AOP- AOPs use hydroxyl radicals (OH), which are extremely reactive, to break down organic contaminants. Examples of AOPs include Fenton's reagent, which includes the interaction between hydrogen peroxide and ferrous ions to produce OH, and photocatalysis, in which a catalyst (such as titanium dioxide) is activated by UV light (Lu, X., et al. 2019).

Chemical produce a huge number of byproducts or introducing compounds that could have their own negative effects on the environment. Thus, proper handling and disposal of any leftover residues or byproducts is crucial.

***Biological methods***

Bioremediation and Microbial remediation

Bioremediation techniques can be applied directly in the river or in constructed wetlands specifically designed for the purpose (Stottmeiste et al.,2003). In-situ bioremediation involves introducing the microorganisms into the contaminated river, allowing them to thrive and degrade pollutants on-site. This method is advantageous as it minimizes disruption to the ecosystem and reduces the need for extensive infrastructure. Ex-situ bioremediation is a different strategy that entails extracting contaminated river water and treating it in a controlled setting. Although this strategy may call for more infrastructure and resources, it allows for greater monitoring and control of the cleanup process.To target and destroy contaminants in the river water, specialised strains of microorganisms are used in microbial treatments. These microorganisms, also referred to as biodegraders, have the natural ability to transform organic and inorganic contaminants into less hazardous materials through biochemical processes (Megharaj et al.,2011) (Pichtel, J. Ed. 2012).

In conclusion, microbial treatments and bioremediation are potential approaches to dealing with polluted rivers. These methods restore the health and functionality of river-polluted ecosystems by utilising microorganisms' capacity to break down contaminants in an environmentally friendly and cost-effective manner (Eweis et al., 2000). The effectiveness of these techniques, meanwhile, is dependent on a number of variables, including the kind and concentration of pollutants, the availability of suitable microorganisms, and the environmental parameters of the river Mallick at al.,2021). Continued research and implementation of these techniques can contribute significantly to the sustainable management of our water resources

Constructed wetlands and Sequential system: Constructed wetlands are engineered ecosystems designed to imitate the natural processes of wetlands and effectively treat polluted water. They consist of a series of shallow basins or channels filled with specially selected plants, soil, and substrate materials. The polluted river water is directed into these wetland systems, where it undergoes a sequential treatment process (Vymazal, J. 2013). Sequential treatment, on the other hand multi-step techniques used to clean up contaminated rivers. These systems are made up of a number of treatment units that are organised in a particular order to ensure effective contaminant removal. Each treatment unit targets particular pollutants or treatment procedures as it receives the dirty river water in a sequential manner (Cooper et al., 1990).

In the case of polluted river remediation, a sequential treatment system may involve various stages such as pre-treatment, physical treatment, chemical treatment, and biological treatment (Hammer et al., 2000). Pre-treatment involves the removal of large debris and sediment from the river water. Physical treatment techniques such as sedimentation or filtration can be employed to further remove suspended solids.

**Research gaps and areas for further investigation**

There is an urgent need for long-term studies to assess the ecological, social, and economic impacts of Yamuna River pollution. It can help in understanding better mitigation strategies. Research on emerging contaminants, such as pharmaceuticals, microplastics and personal care products, in the Yamuna River is limited. Further studies are required to assess the presence, potential risk and fate, of these emerging pollutants. Comprehensive ecotoxicological studies are needed to evaluate the impact of pollutants on aquatic organisms and the overall ecosystem health of the Yamuna River. There is a need to investigate the cumulative effects of multiple pollutants and their interactions on the Yamuna River ecosystem. Most studies focus on individual pollutants or specific pollution sources. Climate Change Impacts: Limited research has been conducted on the interaction between pollution and climate change in the Yamuna River. Understanding the combined effects of pollution and climate change can provide insights into the future challenges and inform adaptive management strategies. Effectiveness of Mitigation Measures: Lack of information on various mitigation measures, further research is required to assess the effectiveness of these measures in reducing pollution and improving water quality in the Yamuna River. Hence, Comparative studies can be helpful in identifying the most efficient and sustainable mitigation techniques.

**Conclusion and Perspectives**

To conclude, the pollution of the Yamuna River is a grave concern that requires immediate attention and effective remediation measures. Among the best available remediation techniques, a multi-faceted approach is essential and the integration of advanced technologies, such as remote sensing and GIS, can enhance monitoring capabilities. Additionally, strict enforcement of environmental regulations, implementation of pollution control measures, and collaborative efforts among government agencies, environmental organizations, researchers, and local communities along with public awareness and active participation, is crucial for the restoration and long-term preservation of the Yamuna River's ecological health and socio-economic significance.

The Yamuna River is highly polluted with high levels of organic and inorganic pollutants, primarily due to the discharge of untreated sewage and industrial effluents. The major pollutants in the river include heavy metals, organic matter, pesticides, fertilizers, and pathogens (CPCB2022). The dissolved oxygen (DO) levels in the river are critically low, leading to the death of aquatic life. Delhi, is a major contributor to the pollution of the Yamuna River. Industrial activities along the river banks, such as chemical manufacturing, tanneries, and textile mills, release a significant number of toxic effluents. Agricultural runoff, containing pesticides and fertilizers, also contributes to water pollution. Eco friendly and cost-effective technique, Phytoremediation makes use of plants to remove contaminants from the contaminated water (Yadav et al.,2019). Plants such as water hyacinth and water lettuce can absorb pollutants and improve water quality (Wani et al., 2021). The effectiveness of constructed wetlands in treating wastewater before it enters the Yamuna River was studies and proves very effective (Gupta et al., 2021). These wetlands use natural processes involving plants and microorganisms to remove pollutants (Tripathi et al.,2019). The identification of specific bacteria and fungi capable of breaking down contaminants have been investigated for the degradation of organic pollutants (Singh et al., 2022). Bioremediation, a microbial based technique as a mitigation measure to remove contamination. River Bank Filtration (RBF) is another technique which involves the extraction of water from riverbanks where natural filtration processes occur. It has been explored as a technique to treat Yamuna River water and provide cleaner drinking water (Gupta et al., 2021). These are some of the remediation techniques which are cost effective and ecofriendly.

In the future, A comprehensive and multi-faceted approach is required for the remediation and control of pollution load in the Yamuna River. The standard given by (CPCB) for discharge of treated effluent into water body in terms of BOD and COD are 30 mg/l and 250 mg/l respectively. After spending Rs. 1187.54 – 1443.84 cr (CSE, 2005) in YAP the BOD load from the NCT has increased from 117 tons/day in 1982, 211 tons/day in 1998 (CPCB, 1999-2000), 231.2 tons/day in 2003 (CPCB, 2003) to 260 tons/day in 2004 (CPCB, 2004). Implementing and enforcing strict environmental regulations and standards is very important, like setting limits on municipal and industrial effluent, agricultural runoff, and other pollution sources. The industries located near riverbanks should adopt cutting-edge pollution management techniques and procedures. Regulatory agencies should have adequate resources to monitor compliance and impose penalties for violation of the rules. Upgradation of wastewater treatment plants is essential to reduce the discharge of untreated or inadequately treated sewage into the Yamuna River. Existing infrastructure should be upgraded and construct of the new treatment facilities can help remove pollutants and improve water quality. Controlled use of harmful fertilizers and pesticides, can help in reducing the pollution load from agricultural runoff. Farmers awareness programs should be promoted. Engaging the public and raising awareness about the importance of a clean Yamuna River is of great importance. Therefore, it's crucial to educate the public about river pollution, how it happens, and the consequences that follow. Effective management of solid waste is essential to prevent its accumulation in the river and the drains approaching river. Implementing waste segregation, recycling programs, and establishing proper disposal facilities can help reduce the waste load on the river ecosystem. Investing in advanced monitoring technologies and establishing a comprehensive data collection network can provide accurate information for decision-making and timely intervention.

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