

Water Quality and Phytotoxicity Assessment of Yamuna River Water using *Brassica campestris* L. (Mustard Seeds)

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Abstract

The Yamuna River water-induced phytotoxicity was investigated in mustard seeds (*Brassica campestris* L.). Phytotoxicity assays were conducted on water samples from the Yamuna River in Delhi to assess the water quality at the Wazirabad barrage (upstream), ITO barrage (midstream), and Okhla barrage (downstream) sites. Two samples were collected from the Wazirabad barrage, another from the ITO barrage, and a third from the Okhla barrage. When compared to plants grown under normal conditions, seedlings exposed to 50% sample concentration showed significant increases in root and shoot length and biomass by 5% and 25%, respectively. After 5 days of treatment, there was a reduction in germination. Mustard seedlings that were exposed to water samples with concentrations ranging from 5 to 50% v/v showed a significant decrease in germination index compared to the control plants (0%), indicating water-induced phytotoxicity. Rapid industrialization and development have led to river water pollution, posing a serious concern. This form of pollution is often irreversible. In Delhi-NCR, industrial and domestic waste have become a major threat to the Yamuna River, which is a crucial water source. The Central Pollution Control Board (CPCB) has labelled the river as "unfit for drinking" and "unsafe for bathing" due to high pollutant levels. Recent studies have indicated a deterioration in the water quality of the Yamuna River, which has been found to have harmful effects on various plant models.

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Keywords

Yamuna River, Water Pollution, Phytotoxicity, *Brassica Campestris*, Heavy Metals.

Introduction

Over the last six decades, Delhi has experienced unprecedented environmental degradation and biodiversity loss. Delhi has undergone complete changes in its demography and land-use patterns. Various developmental activities occurred at a faster rate along the Yamuna plains of Delhi. The actions and activities of human beings have greatly altered Delhi's landscape and nature (Singh et al., 2020). Due to the deterioration of various habitats, a number of plant species recorded in the flora of Delhi might have already disappeared or are on the verge of extinction. Yamuna is crucial to the flora of Delhi (Saxena et al., 2021). A tributary of the Ganges, the Yamuna River originates at an elevation of approximately 6387m, as it flows from the Yamunotri glacier near the Banderpoonch peaks in the Mussourie range of the lower Himalayas (Nishat and Singh, 2018). Part of the catchment of the Yamuna River lies in the states of Uttarakhand, Uttar Pradesh, Himachal Pradesh, Haryana, Rajasthan, Madhya Pradesh, and the entire state of Delhi. From the Saharanpur district of Uttar Pradesh to the confluence with the Ganga at Allahabad, the river Yamuna traverses a distance of about 1370 km in the plains. A total of 70.9% of the catchment area is covered by Tons, Betwa, Chambal, Ken, and Sindh, whereas 29.1% is covered by direct drainage from the main river and smaller tributaries. The Yamuna catchment basin accounts for 40.2% of the Ganga Basin and 10.7% of the country, Central Water Commission, 2007 (Nishat and Singh, 2018). As the Yamuna enters Delhi in Palla village and leaves the Okhla barrage, traveling a distance of 48 km within Delhi and a 22km stretch downstream from Wazirabad to the Okhla barrage, it travels a total distance of 48 km within Delhi (Water Quality Status of Yamuna River, Ahmad et al., 2018). There are immense anthropogenic pressures on the 22-kilometer stretch of riparian habitat connecting Wazirabad to Okhla, causing this ecosystem to be one of the most threatened in the world. Yamuna River stretches may be classified into five distinct stretches: the Himalayan stretch, upper stretch, Delhi stretch, mixed stretch, and diluted stretch (Mariya et al. 2019). Even though the river Yamuna is a major source of water for Delhi, indiscriminate and unplanned development has essentially transformed it into a seasonal drain at many locations (Ahmad et al., 2018). The rapid population growth, unplanned urbanisation, industrialisation and rampant encroachments have led to severe pollution of the river Yamuna (Kumar et al., 2020). Due to the discharge of untreated domestic sewage and industrial effluents through major and minor

drains, the river Yamuna has become highly polluted. Today, the Yamuna River is one of the most polluted rivers in India due to rapid urbanization and industrialization. Approximately 58% of treated or partially treated waste is dumped into rivers (Ahmad et al., 2018). These Yamuna floodplains are under immense pressure for other development activities. The Floodplain of this holy river from Wazirabad to the Okhla region has mainly been converted to agricultural use, resulting in a reduction in subsoil moisture content. Pesticides are frequently used to grow vegetables and, pose a great health risk (Table 1). Birds, fishes, and plant species found in the Yamuna wetlands have decreased their natural habitats (Sharma et al., 2024). Ahmad et al., (2018) concluded that domestic pollution was a major source of pollution in the Yamuna River. About 85% of the pollution in the river is caused by the domestic sources and unsuitable use of land resources has serious negative effects on flora of the Yamuna plains. Plant materials are cheap, with respect to treatment, and plant materials together contribute to the improvement of human welfare. *Brassica campestris* belongs to family Brassicaceae and the genus Brassica is a crop of immense economic importance and is among the oldest cultivated crop known from the early human civilization and has been used as oilseed crop and condiments. Brassica spp. have been reported to be active hyperaccumulators (Zand erg et al., 2022b). Several studies have confirmed the toxic and phytotoxic effects of polluted water on living organisms. Most of this work has been carried out in Canada and Europe, but insufficient data is available from Asia, including India (Shah et al., 2023). It is thus necessary to assess the phytotoxic effects of effluents discharged by the Yamuna River. The sensitivity of plants to different compounds can be used in toxicity tests to identify toxicants. Plant bioassays are well-established systems used for screening and monitoring of environmental pollutants. Phytotoxicity is the impact of various compounds or pollutants on seed germination and subsequent growth (Kumar and Choudhury, 2024). In the present work, toxic and phytotoxic effect of river Yamuna surface water was investigated on mustard seeds (*Brassica campestris* L.). Brassica plants are an important test species used to evaluate the phytotoxicity of environmental pollutants like heavy metals, effluents, and herbicides. Plant materials are affordable, and their use contributes to the improvement of human welfare and a sustainable environment. *Brassica campestris* belongs to the family Brassicaceae and the genus Brassica is a crop of immense economic importance and is among the oldest cultivated crop known from the early human civilization and has been used as an oilseed crop and condiments. It is thus necessary to assess the phytotoxic effects of effluents discharged by the Yamuna River (Al-Huqail et al., 2024). The sensitivity of plants to different compounds can be used in toxicity

tests to identify toxicants. Plant bioassays are well-established systems used for screening and monitoring of environmental pollutants. Phytotoxicity is the impact of various compounds or pollutants on seed germination and subsequent growth (Kumar and Choudhury, 2024). Various studies on phytotoxicity have been conducted worldwide and are presented in Table 2. In the present work, the toxic and phytotoxic effect of river Yamuna surface water was investigated on mustard seeds (*Brassica campestris* L.) (Table 2). Brassica plant species was used for chemical screening and in situ monitoring of the phytotoxicity of heavy metals, effluents, and herbicides in present study.

Table 1 Effects of Heavy metals/Trace Elements on plants and humans.

Metals	Pathological Health Risks on Human	Effects on Plants	References
Arsenic (As)	Distributed peripheral circulation, mental disturbance, liver cirrhosis, hyper kurtosis, lung cancer, ulcer in gastrointestinal tract, kidney damage.	Severe inhibition of plant growth and biomass accumulation, losses in fertility, yielding and fruit production.	(Abedin et al., 2002; Sharma & Agrawal, 2005; Martin & Griswold, 2009)
Aluminum (Al)	Damage to CNS, Dementia, loss of memory, listlessness, severe trembling.	Growth inhibition in plants, blocks the process in cell division of root elongation, results in root damage.	(Mariano & Keltjens, 2005)
Cadmium (Cd)	Diarrhea, bone deformation, growth retardation, kidney damage, hypertension, anemia, injury of central nervous system and liver problems.	Decrease in seed germination, lipid content, and plant growth.	(Martin & Griswold, 2009; Liu et al., 2014)

Copper (Cu)	Hypertension, uremia, coma, sporadic fever.	Chlorosis and necrosis, discoloration of leaf and inhibition of root growth.	(Sharma and Azad, 2020)
Chromium (Cr)	Cancer, diseases in CNS, nephritis, gastrointestinal ulceration.	Decreases enzyme activity and plant growth.	(Martin & Griswold, 2009; Srivastava et al., 2024)
Iron (Fe)	Nausea, Vomiting, Hemochromatosis	Damage lipids, proteins, and DNA.	(Jaishankar et al., 2014; Gupta and Gupta, 2023)
Lead (Pb)	Anemia, Vomiting, loss of appetite, convulsion, damage of brain, liver and kidney.	Reduces chlorophyll production, increases superoxide dismutase, also reduce growth of plant.	(Sharma & Agrawal, 2005; Martin & Griswold, 2009)
Mercury (Hg)	Abdominal pain, headache, diarrhea, hemolytic, chest pain.	Decrease in photosynthesis, water uptake and antioxidant enzymes.	(Boening, 2000; Martin & Griswold, 2009)
Nickel (Ni)	Acute poisoning, brain haemorrhage, chromosomal aberrations, asthma, spontaneous abortions.	Reduction in seed germination and affect enzymes.	(Sharma & Agrawal, 2005; Mahurpawar, 2015)
Zinc (Zn)	Vomiting and cramps.	Reduces Nickel toxicity and seed germination, increase plant growth.	(Sharma & Agrawal, 2005)

Table 2 Various studies on Phytotoxicity.

Study/ Site	Species	Parameters monitored	Their effects on plants	References
Kanpur, tannery effluent	<i>Vigna radiata</i>	Physiochemical parameters, heavy metals, phytotoxicity assay	Inhibition of seed reduction and growth,	Kumari V et al., 2015
Italy	Wheat (<i>Triticum aestivum</i>)	Phytotoxicity: Seed Germination	Adverse effect on growth of seedlings	C. Vannini et al., 2014
Industrial Wastewater, Aligarh and Mathura	Onion bulbs (<i>Allium cepa</i>)	Phytotoxicity: Chromosomal aberration	Root growth inhibition	N.A. Fazili and M. Ahmad, 2014
Brazil	Brassica plants	Phytoremediation: Heavy metals	Helps in decontamination, hyper accumulation	G.A. Bortoloti and D. Baron, 2022
Rio Grande Reservoir, Brazil	Garden cress (<i>Lepidium sativum</i>), Mustard (<i>Sinapis alba</i>) and Cucumber (<i>Cucumis sativus</i>)	Water Quality, Plant Bioassays and seed germination	<i>L. sativum</i> was more sensitive to toxicity	Peduto et al., 2020
Tannery effluent, Palar	<i>Allium cepa</i>	Physiochemical Parameters, Phytotoxic effects	Inhibition of root growth	S. Roy et al., 2015

river basin, Tamil Nadu				
Kanpur, Paper mill effluent	Allium cepa	Physiochemical parameters, heavy metals, phytotoxicity assay	Inhibition of seed reduction and growth	Haq I., 2018
Present study/Yamuna River water	Brassica campestris	Physiochemical parameters, heavy metals, ionic composition, phytotoxicity assay	Reduction in plant growth especially root inhibition.	Kumari and Singh, 2025

Materials and Methods

Study Area and Sampling Sites

Delhi, the national capital of India located on the bank of River Yamuna. River Yamuna in Delhi is notorious for water pollution situated between 28°42'42.443" N and 77°13'52.482" E to 28°37'43.879" N and 77°15'11.415" E (Fig. 1).

Water and soil samples were successfully collected from four georeferenced sites along the Yamuna River in Delhi to assess water quality and toxicant load. The sampling locations included two sites at Wazirabad, one at the ITO Barrage, and one at the Okhla Barrage. These sites were strategically selected based on their relevance to the potential pollutant influx and urban influence. The geographic coordinates and distributions of all the sampling points are shown in Fig. 1. These locations provide spatial coverage across key segments of the river flowing through Delhi, enabling a comparative evaluation of water quality parameters and pollutant concentrations across varying levels of anthropogenic activity. At geocoordinate map of the sampling locations and sampling points is shown in Fig. 1.

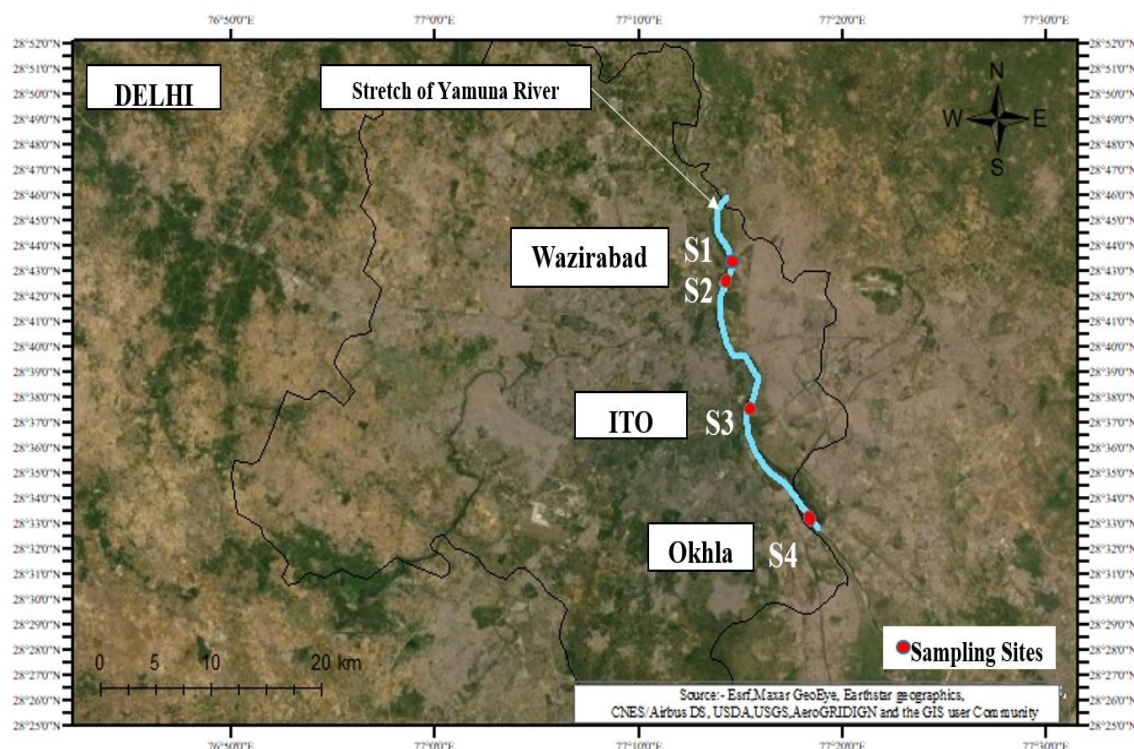


Fig1. Map represents geographical location and sampling points of our study area in Delhi.

Sample Collection and Analysis

Water samples were collected from the Yamuna River in plastic containers of 5 litres. All samples were transported to the laboratory in an ice-box and stored at 4 °C until analysis. The geographical coordinates were recorded using GPS tracking system (Trimble, Juno SA). Water quality parameters, such as pH, conductivity, TDS, and salinity, were measured at the time of sampling using a water sampling kit (PCSTestr 35 multiparameter kit). The sampling approach was adopted to understand the variation and load of pollutants in the river body. The physiochemical and heavy analysis of water was done as per APHA guidelines.

The water samples were analyzed for various physiochemical parameters (Table 3) using a standard protocol (APHA, 2012). After filtration, the pH of the samples was measured using a digital pH meter. It is a high-resolution pH meter calibrated using buffers with pH values of 4 and 7. Conductivity was measured using a conductivity meter. This method estimates the amount of soluble salts in water or wastewater by measuring the electrical conductivity (EC) of a sample. The Biochemical Oxygen Demand of the samples was determined by measuring the dissolved oxygen content in the samples before and after incubation for five days at 20 °C. The difference between the dissolved oxygen content in the samples (before and after

incubation) was given the BOD value. The COD was determined by the dichromate method (Closed Reflux-Dichromate Method) after the digestion of samples in a COD digester. The solids in the wastewater samples were quantified by gravimetric analysis after oven-drying. Solids refer to matter suspended or dissolved in the water. Nitrogen is the total concentration of organic nitrogen and ammonia. Heavy metal analysis was performed using an atomic absorption spectrometer (AAS) (iCE 3000 Series). AAS detects minute concentrations of a metallic elements present in a sample of the solution. This technique is based on the fact that ground-state metals absorb light at specific wavelengths. Metal Ions in a solution are converted to the atomic state by means of a flame. Light of the appropriate wavelength is supplied and the amount of light absorbed can be measured against a standard curve.

Phytotoxicity Test

Mustard seeds were purchased from a local certified shop, surface-sterilized with 0.1% (w/v) HgCl_2 , and washed three times with distilled water to remove all mercury traces. The seed germination test was conducted on filter paper in Petri dishes (20×120 mm) with two layers of filter paper (125 mm in diameter, Whatman No. 1) followed by a layer of cotton on the bottom. Four test solutions (0, 5, 25, and 50% v/v) of the effluent were prepared using dechlorinated tap water. Each dish contained 10 mL of test solution or drinking water (control). Ten seeds were kept on filter paper in each petri dish soaked with the respective test solution. The plates were incubated at $28 \pm 1^\circ\text{C}$ in the dark and the number of seeds germinated was observed after 48 h. The experiment was conducted for four samples collected from different locations. After five days, five randomly selected seedlings were taken from each Petri dish to measure root and shoot lengths. For biomass estimation, 10 seedlings from each petri dish were wrapped with aluminium foil and weighed the fresh weight first and then they were dried in oven at 70°C for 48 h and weighed the dry weight. Biomass was calculated by subtracting the dry weight from fresh biomass and was expressed in grams.

Result and Discussion

The physiochemical parameters of water samples from four different sites were analyzed during the summer and winter seasons (Table 3), and graphical representation of variation in physiochemical and ion concentrations in river water are shown in Fig. 2 and Fig. 3

Table 3 Physiochemical parameters in the Yamuna River Water.

S.No.	Parameters	Sampling								Drinking water permissible limit (BIS: 10500)	Inland surface water limit (CPCB)
		Summer				Winter					
		S1	S2	S3	S4	S1	S2	S3	S4		
1	pH	8.51±0.3	8.02±0.5	7.97±0.4	8.20±0.8	8.72±0.04	8.53±0.01	7.69±0.01	7.24±0.03	6.5-8.5	6.5-8.5
2	TDS (ppm)	908.6±10.2	735.6±2.1	ND	ND	810.6±12.5	904±3	ND	962±56.3	500	500
3	Conductivity (µs/cm)	1319.3±17	1028.3±9.6	2002.3±5.9	1392.6±3	1198.6±4.6	1250±4.4	1654.6±6.5	1388±26.9	--	--
4	Salinity (ppm)	643±8.9	518.3±6.7	103.6±2.5	695±6.1	579±1	608.6±28.4	806±7.8	690.6±2.1	--	--
5	DO (mg/l)	1.96±0.7	4.33±1.96	2.4±1.99	10.3±5.3	7.73±0.3	1.23±0.2	1.46±0.3	4.33±0.3	--	6.0
6	BOD ₅ (mg/l)	4.3±0.2	1.96±0.4	4.2±0.2	4.36±0.6	7.4±0.2	3.9±0.1	1.46±0.3	4.33±0.3	--	2.0
7	COD (mg/l)	260±87.2	320±80	180±87.1	236.6±5.8	146.6±61.1	160±80	200±174.3	193.3±41.6	--	--

8	Total Hardness as CaCO ₃ (mg/l)	231.6±6.6 5	278.6±7.6	456±5.3	284±4	294±5.3	344±46.8	372.6±20	310±10	300-600	--
9	Magnesium as Mg (mg/l)	105.7±3.9 5	161.06±1.1	291±1	158.6±4.3	131.1±1.2	209.2±8.4	189.8±0.8	144.2±4	30-100	--
10	Calcium as Ca (mg/l)	124.2±2.2	124.2±2.2	150.5±15.5	128.0±2.1	159.2±1.1	154.4±1.3	196.8±0.7	170.0±2.1	75-200	--
11	Chloride (mg/l)	88.9±0.98	96.3±5.5	118.9±0.9	128.6±1.5	77.9±2.6	149.6±0.6	159.6±0.6	99.3±1.1	250	--
12	Sodium (ppm)	171.1±1.3	181±1	231±1	151.1±1	163.3±0.6	208.5±16.8	272.6±14	235±13.4	200	--
13	Potassium (ppm)	24.0±0.1	17.6±0.6	32.6±0.6	22.7±0.6	21.5±0.5	22.4±0.4	26.7±2.7	25.7±0.7	--	--
14	Nitrate (mg/l)	5.0±1	5.6±0.6	9.0±1	5.2±0.3	7.8±0.3	9.5±0.5	24.0±1	12.6±2.1	45	--
15	Sulphate (mg/l)	2.4±0.2	2.9±0.1	5.03±0.2	1.7±0.2	3.9±0.1	5.0±0.2	9.7±0.3	3.7±0.2	200	--
16	F ⁻ (mg/l)	2.2±1.6	0.3±0.04	0.4±0.2	0.5±0.03	0.3±0.03	0.3±0.03	0.4±0.1	0.3		

All values are presented in mean±SD

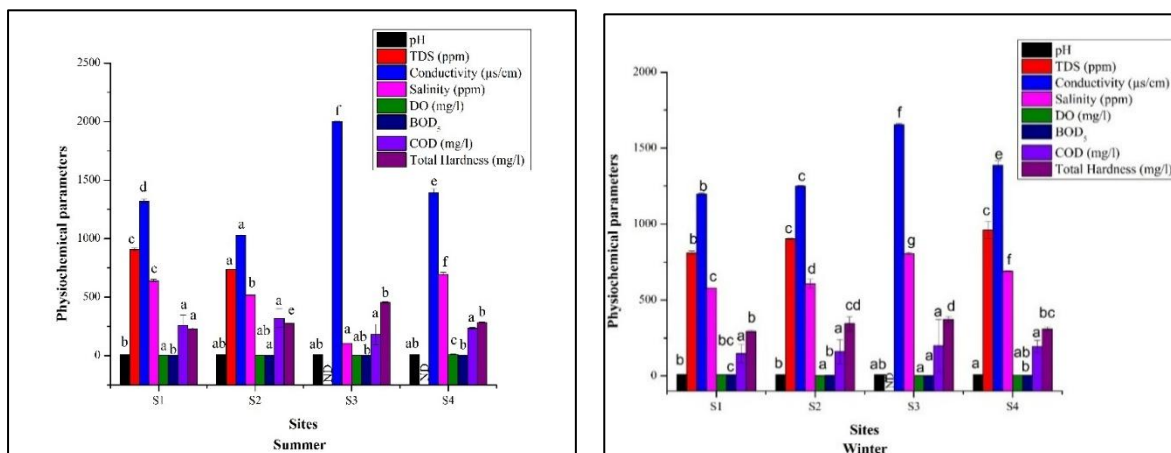


Fig 2. Physicochemical parameters in summer and winter in river water.

The physicochemical parameters of water samples collected from four sites along the Yamuna River revealed notable seasonal variations across both summer and winter. The pH of the water samples across all sites remained within the alkaline range during both seasons. Values varied slightly, from a minimum of 7.24 ± 0.03 at site 2 in winter to a maximum of 8.72 ± 0.04 at site 1 in winter, indicating relatively stable yet slightly more alkaline conditions during the colder months. Total Dissolved Solids (TDS) were not detected (ND) in the samples from sites 3 and 4 during summer. However, they were measurable in winter, with the highest concentration recorded at site 4 (962 ± 56.3 ppm). This seasonal difference points an increased ionic load during the winter season, potentially due to reduced dilution from decreased flow (Taka et al., 2017). Electrical conductivity (EC) was found to be highest at site 3 in the summer (2002.3 ± 5.6 µS/cm), indicating a significant presence of dissolved ions at this site. In line with this, salinity also showed elevated values at site 3 during winter (806 ± 7.8), while the lowest values was observed during summer at the same site (103.6 ± 2.5), suggesting seasonal accumulation of salts. Dissolved oxygen (DO) levels varied considerably across sites and seasons. The highest DO concentration was recorded at site 4 in summer (10.33 ± 5.3 mg/L), likely due to increased aeration or photosynthetic activity, while the lowest was noted at site 2 during winter (1.23 ± 0.2 mg/L), which could be attributed to organic pollution and reduced water flow. The Biochemical Oxygen Demand (BOD₅) was notably higher in winter at site 1 (7.4 ± 0.2 mg/L), indicating an increased organic load that could lead to oxygen depletion. Meanwhile, Chemical Oxygen Demand (COD) values peaked at site 2 in summer (320 ± 80 mg/L) and generally declined during the winter, reflecting possible seasonal variations in pollutant input and degradation rates. Total hardness also exhibited seasonal fluctuation. The highest levels were recorded at site 3 during summer (456 ± 5.3 mg/L), with slightly lower but still elevated values in winter

(372.6±20.03 mg/L). Similarly, magnesium (Mg) concentrations were highest at site 3 in summer (291±1 mg/L) and showed a reduction in winter.

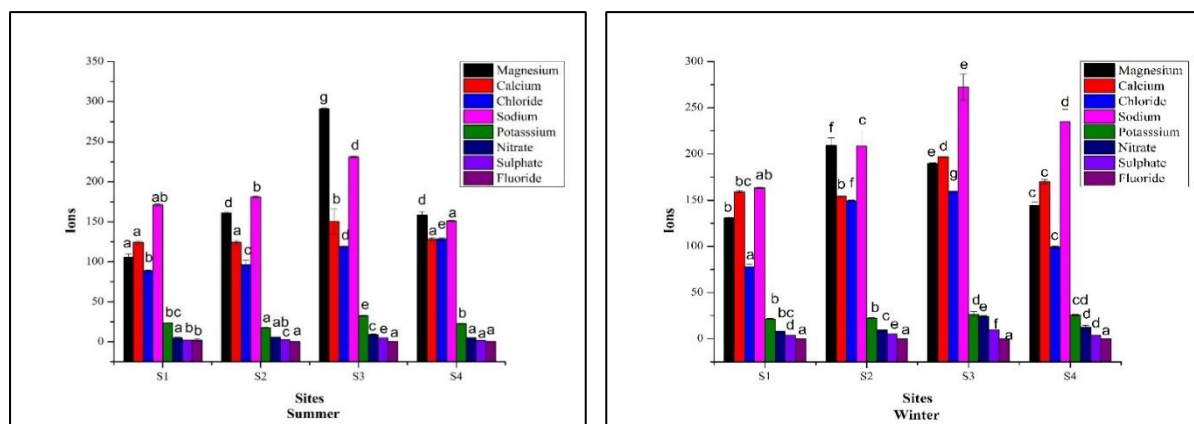


Fig 3. Variation in ion concentration in summer and winter in river water

Calcium (Ca) concentrations ranged between 124.2±2.19 and 196.8±0.7 mg/L, with the highest levels again observed at site 3 in winter. Chloride (Cl⁻) levels were also elevated at site 3 during winter (159.6±0.6 mg/L), suggesting significant mineral input or effluent discharge at this location. Among cations, sodium (Na⁺) concentrations were higher in winter, with a maximum of 272.6±14 mg/L at site 3, while potassium (K⁺) peaked during summer at the same site (32.6±0.6 mg/L). These variations may result from differential inputs of domestic or industrial waste (Zhou et al., 2023). Regarding nutrient content, nitrate (NO₃⁻) levels showed a sharp increase at Site 3 in winter (24±1 mg/L), which may be linked to runoff from nearby agricultural activities. Similarly, sulfate (SO₄²⁻) concentrations were highest at the same site and season (9.7±0.25 mg/L), reinforcing the likelihood of anthropogenic influence. Fluoride (F⁻) levels across all sites remained below the permissible limit, although a relatively higher concentration was observed at site 1 in summer (2.2±1.6 mg/L), suggesting a potential local source of contamination (Cao et al., 2016).

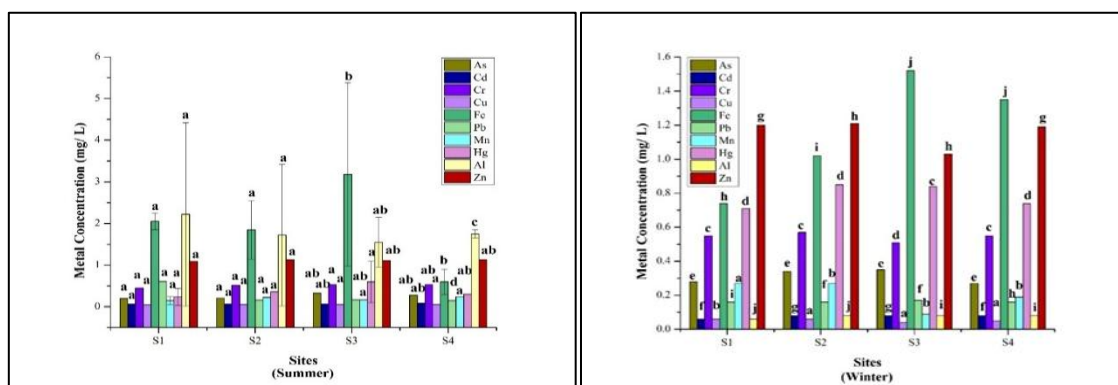


Fig 4. Seasonal variation in heavy metal concentration at different study sites.

Table 4 Site wise seasonal variation in heavy metal concentration.

S.No.	Heavy Metal	Samples (concentration, mg/L)								Drinking water permissible limit (BIS: 10500)	Inland surface water limit (CPCB)
		Summer				Winter					
		S1	S2	S3	S4	S1	S2	S3	S4		
1	As	0.20±0.1	0.20±0.01	0.33±0.01	0.28	0.28±0.01	0.34±0.1	0.35±0.01	0.27±0.2	0.05	0.2
2	Cd	0.07±0.02	0.07	0.07±0.02	0.08	0.06±0.02	0.08±0.1	0.08±0.02	0.08	0.003	2
3	Cr	0.45±0.3	0.52±0.1	0.53±0.1	0.53±0.01	0.55±0.1	0.57±0.4	0.51±0.2	0.55	0.05	2
4	Cu	0.05	0.06	0.06	0.04	0.06±0.01	0.06	0.04	0.05	1.5	3
5	Fe	2.05±0.2	1.85±0.7	3.18±2.2	0.60±0.3	0.74±0.1	1.02±0.2	1.52±0.3	1.35±0.4	0.3	3
6	Pb	0.61±0.3	0.16±0.01	0.17±0.01	0.15	0.16	0.16	0.17±0.02	0.16	0.01	0.1
7	Mn	0.15±0.2	0.23±0.01	0.17±0.02	0.24±0.01	0.27	0.27±0.2	0.09	0.19±0.02	0.3	2
8	Hg	0.24±0.2	0.36	0.60±0.5	0.30	0.7±0.01	0.85±0.3	0.84±0.2	0.74±0.1	0.001	0.01
9	Al	2.22±2.2	1.72±1.7	1.55±0.6	1.75±0.1	0.06	0.08±0.1	0.08	0.08	-	-
10	Zn	1.09	1.13±0.2	1.11±0.1	1.13±0.2	1.20	1.21±0.3	1.03±0.3	1.19±0.3	15	5

All values are presented in mean±SD

The concentrations of the selected heavy metals in water samples collected from four sites (S1 to S4) along the Yamuna River during the summer and winter seasons are summarized in Table 4. These concentrations were evaluated against the permissible limits outlined by the Bureau of Indian Standards (BIS 10500:2012) for drinking water and the Central Pollution Control Board (CPCB) standards for inland surface water. Arsenic (As) concentrations were found to exceed the BIS permissible limit of 0.05 mg/L at all sites during both seasons, ranging from 0.20 ± 0.1 to 0.35 ± 0.01 mg/L. The highest arsenic levels were recorded at S2 and S3 during winter, suggesting a potential seasonal influence or accumulation due to the reduced dilution capacity in colder months. Similarly, Cadmium (Cd) levels were significantly elevated in all samples, consistently exceeding the BIS threshold of 0.003 mg/L. Concentrations reached up to 0.08 ± 0.02 mg/L, indicating a substantial contamination load possibly originating from industrial discharges, especially electroplating or battery-related activities (Gomez-Delgado et al., 2023). Chromium (Cr) concentrations varied between 0.45 ± 0.3 to 0.57 ± 0.4 mg/L, greatly surpassing the BIS drinking water limit of 0.05 mg/L at all sites. The consistently high chromium content points toward anthropogenic sources such as tannery or metal-processing industries in the vicinity. In contrast, Copper (Cu) concentrations remained within safe limits, ranging between 0.04 to 0.06 ± 0.01 mg/L, and did not pose any significant risk according to BIS (1.5 mg/L) and CPCB (3 mg/L) standards. This suggests a relatively lower presence of copper-based pollutants in the sampled regions. Iron (Fe) was detected at elevated levels across all sites and both seasons, far exceeding the BIS permissible limit of 0.3 mg/L. The maximum concentration was observed during summer at S3 (3.18 ± 2.2 mg/L), possibly due to enhanced sediment dissolution or anthropogenic contributions. Lead (Pb) levels were exceptionally high, with the maximum concentration at S1 during summer (0.61 ± 0.3 mg/L), over 60 times the BIS limit of 0.01 mg/L. Elevated levels at other sites also point to widespread lead contamination, likely from vehicular runoff, battery disposal, or outdated plumbing systems. Manganese (Mn) concentrations were comparatively low and remained within BIS limits (0.3 mg/L) across all sites during both seasons. This indicates that manganese contamination is not a major concern in the sampled stretches of the river (Singh et al., 2016).

In contrast, Mercury (Hg) presented extremely concerning levels, particularly during winter at S2 and S3, where values reached 0.85 ± 0.3 and 0.84 ± 0.2 mg/L respectively. These concentrations exceeded the BIS guideline of 0.001 mg/L by several hundred-fold, suggesting severe mercury pollution likely stemming from industrial effluents, medical waste, or illegal dumping. Aluminium (Al) levels showed distinct seasonal variation, with notably high

concentrations observed during summer at S1 (2.22 ± 2.2 mg/L). However, the winter values were substantially lower across all sites, suggesting dilution during increased flow or lower input during the colder season. Zinc (Zn) concentrations remained within acceptable limits according to both the BIS (15 mg/L) and CPCB (5 mg/L) guidelines. Slight seasonal variations were observed; however, but no significant elevation was noted that could pose environmental or health risks.

Phytotoxicity Test

The phytotoxicity assessment of water samples collected from four sites (S1-S4) of the Yamuna River in Delhi was evaluated based on seed germination, root and shoot length, and biomass accumulation at different treatment concentrations (0%, 5%, 25%, and 50%) during summer and winter (Table 5).

Germination Percentage

At the 0% concentration (control), all sites showed 100% germination across both seasons. However, as the concentration of contaminated water increased, a decline in germination was observed. In summer, germination dropped notably at S4 ($66 \pm 15\%$) and S2 ($80 \pm 10\%$) at 25% concentration, while in winter, S4 again showed the lowest germination ($66 \pm 15\%$) at 50% concentration (Abedini, 2025).

Root and Shoot Length

Root and shoot lengths demonstrated concentration-dependent variations. During summer, S3 showed the highest root length (9.8 ± 1.3 cm) at 25%, while S2 exhibited a reduction to 5.9 ± 0.4 cm at the same concentration in winter. Shoot length was also suppressed at higher concentrations, particularly at S4 during winter, where the shoot length reduced to 4.5 ± 0.7 cm at 50% concentration (Tarimo, 2013).

Biomass

The biomass accumulation was significantly lower at higher concentrations. Across all sites and seasons, a consistent trend of reduced biomass was evident, especially at 50% concentration. The most drastic reduction was noted at S2 and S4 in winter (0.2 ± 0.01 to 0.3 ± 0.04 g), compared to the control (1.2 ± 0.0 g) Teodoro et al., (2020).

Table 5. Effect of different concentrations of Yamuna River water on seed germination, root length, shoot length, and biomass (five-day test).

Study Sites	Concentration (%)	Sampling period							
		Summer				Winter			
		Germination (%)	Root Length* (cm)	Shoot Length* (cm)	Biomass* (g)	Germination (%)	Root Length* (cm)	Shoot Length* (cm)	Biomass* (g)
S1	0	100±0	7.4±1.7	3.5±1.8	0.3±0.09	100±0	5.9±1.1	1.9±0.6	1.2±0.2
	5	8.6±0.5	8.1±2.7	3.0±1.1	0.4±0.07	8.3±1.5	9.1±1.0	2.0±0.4	0.2±0.1
	25	8.0±0	6.7±1.6	3.7±2.1	0.3±0.02	8.0±0.5	7.4±1.3	3.3±0.5	0.3±0.02
	50	9.0±1.0	6.4±1.6	5.9±0.6	0.3±0.07	9.1±1.0	5.8±1.1	2.8±1.8	0.3±0.08
S2	0	100±0	7.4±1.7	3.5±1.8	0.3±0.09	100±0	5.9±1.1	1.9±0.6	1.2±0.2
	5	8.3±0.5	9.2±1.6	3.2±0.6	0.2±0.06	9.0±1.0	8.2±1.3	2.4±0.1	0.2±0.05
	25	8.0±1.0	8.5±1.3	5.3±1.0	0.2±0.03	8.6±0.5	6.6±1.3	2.8±1.0	0.3±0.04
	50	9.0±1.0	12.4±2.1	5.9±0.1	0.4±0.05	8.0±1.0	7.6±0.3	3.7±0.6	0.3±0.01
S3	0	100±0	7.4±1.7	3.5±1.8	0.3±0.09	100±0	5.9±1.1	1.9±0.6	1.2±0.2
	5	8.3±0.5	11.5±2.8	4.1±0.6	0.3±0.05	7.3±2.1	7.1±0.7	2.1±0.2	0.2±0.04
	25	9.0±1.0	10.3±2.0	7.5±4.8	0.4±0.02	8.6±0.5	5.2±2.7	1.9±0.6	0.3±0.01
	50	8.6±1.5	8.9±3.5	3.6±1.6	0.3±0.10	7.0±2.0	3.7±0.6	2.0±0.8	0.3±0.09
S4	0	100	7.4±1.7	3.5±1.8	0.3±0.09	100±0	5.9±1.1	1.9±0.6	1.2±0.2

5	8.0±0	10.5±0.2	3.6±0.7	0.4±0.08	8.3±1.5	6.7±3.0	2.4±0.2	0.2±0.07
25	8.0±1.0	10.0±1.7	3.7±1.2	0.3±0.11	7.6±0.5	6.9±1.5	2.4±0.2	0.2±0.04
50	6.6±1.5	10.0±0.9	5.6±1.1	0.3±0.04	5.6±1.5	5.9±1.3	2.6±0.5	0.2±0.04

* Values are presented in mean±SD

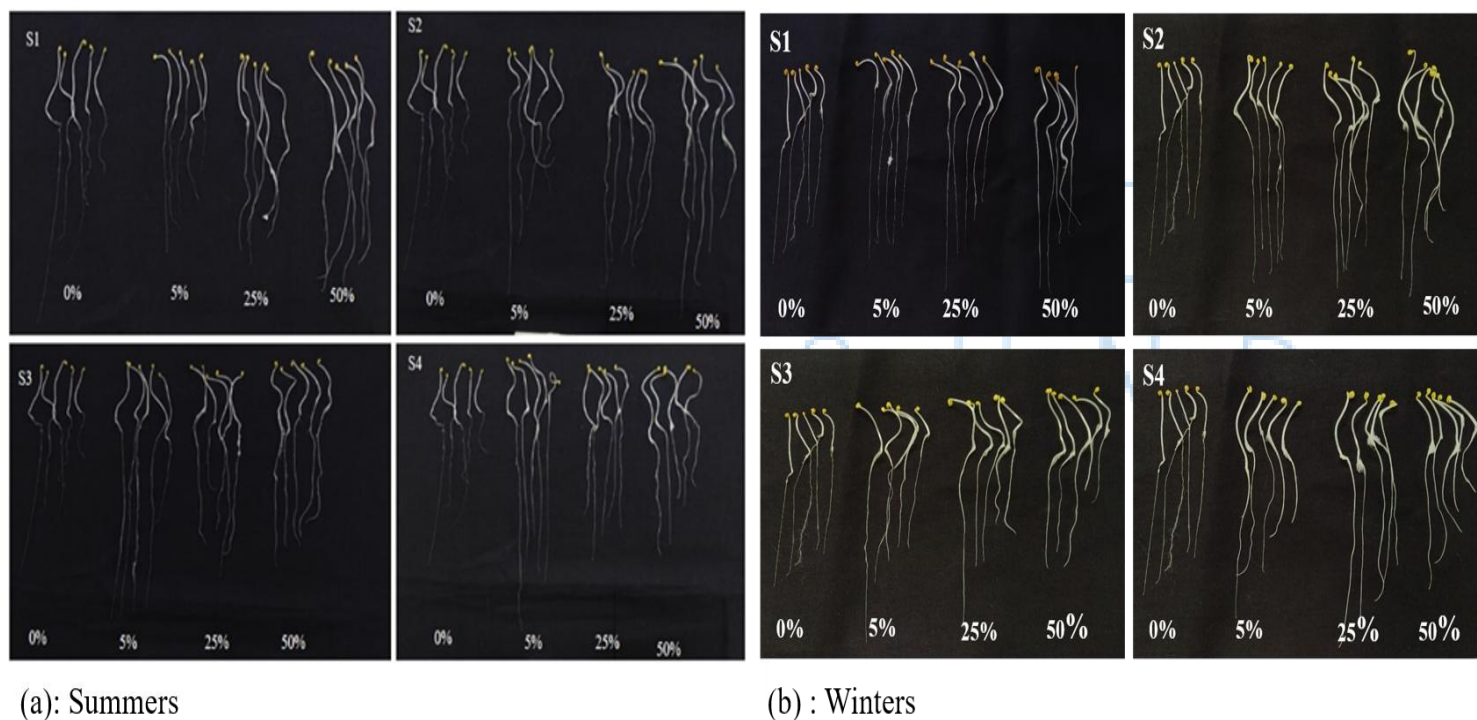


Fig 5. (a) and (b) Phytotoxic effects of different concentrations of Yamuna River water on early seedling growth of mustard seeds.

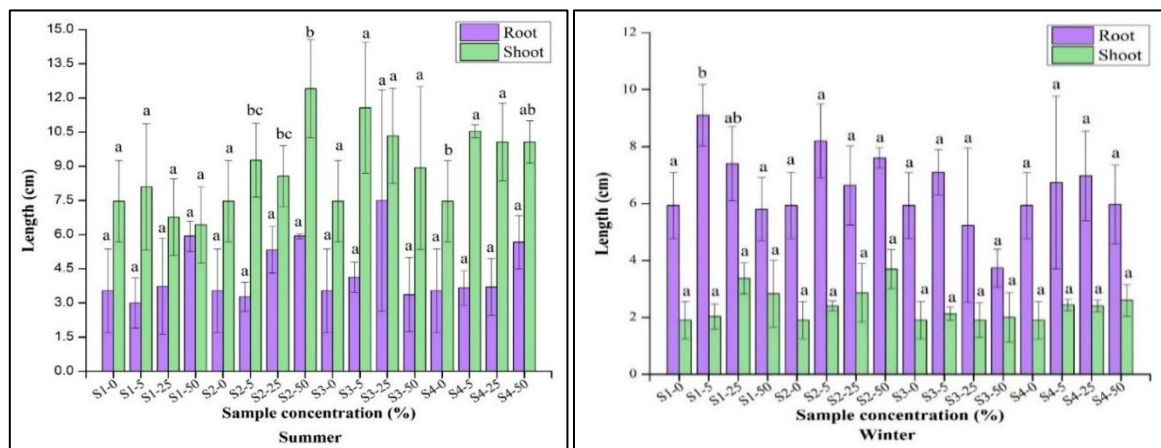


Fig 6. Representation of different concentrations of Yamuna River water on seed germination, root length, and shoot length.

The water quality assessment revealed spatial and temporal variations influenced by site-specific activities and seasonal dynamics. The alkaline pH across all sites indicates the absence of acidic contamination, with marginally higher values in winter, possibly due to reduced rainfall dilution. TDS and EC trends suggest a higher ionic load at site 3, particularly during summer, which could be attributed to industrial or domestic discharge (Chidiac et al., 2025). The elevated EC and salinity values at this site correspond to higher concentrations of sodium, chloride, and other dissolved ions, indicating anthropogenic influence. DO levels were highly variable, with site 4 in summer showing excellent oxygenation, likely due to enhanced aeration or flowing conditions, whereas low DO levels at site 2 in winter may reflect organic pollution or reduced turbulence. This pattern was also reflected in the BOD₅ and COD values, which peaked in the colder months, suggesting increased organic and chemical oxygen demand under lower temperatures and limited microbial degradation. Hardness, calcium, and magnesium contents showed clear seasonal variation, with site 3 exhibiting the highest hardness levels in both seasons, likely due to lithological composition or effluent influx (Dey et al., 2021). Elevated nitrate and sulphate concentrations at site 3 in winter suggest agricultural runoff or sewage contamination. This is a matter of concern as high nitrate levels can lead to eutrophication and pose health risks, especially for infants. Fluoride (F⁻) concentrations remained within acceptable limits per WHO guidelines (1.5 mg/L), although site 1 in summer exceeded this threshold slightly, warranting further monitoring. Overall, site 3 emerged as the most impacted site, likely due to urban or industrial effluents, while site 4 generally exhibited better water quality. Seasonal fluctuations further underline the importance of continuous monitoring and implementation of site-specific mitigation strategies to maintain aquatic

ecosystem health and water usability. The results indicate significant contamination of the Yamuna River with multiple heavy metals, particularly As, Cd, Cr, Pb, Fe, and Hg, exceeding both national drinking water (BIS) and surface water (CPCB) standards. Arsenic, a well-known carcinogen, was detected in concentrations 4 to 7 times higher than the BIS limit, with elevated levels during winter possibly due to lower dilution from reduced river flow. Similarly, Cadmium exceeded safe limits consistently, highlighting probable industrial or sewage effluent discharge into the river system. Chromium, typically linked to tanning and electroplating industries, showed persistently high values throughout, raising concerns over direct industrial discharge. In contrast, Copper and Zinc remained within safe thresholds, suggesting less influence of these metals from anthropogenic sources. Iron concentrations were particularly high in summer, possibly due to increased sediment transport and reduced precipitation-related dilution. Seasonal disparity in Aluminum levels suggests that it originates from leaching and sediment mobilization during the dry season (Sharma et al., 2024).

Of utmost concern were the extremely high Mercury levels, far exceeding permissible limits. These levels pose serious ecological and health risks, including bioaccumulation in aquatic organisms and mercury poisoning in humans. Similarly, Lead contamination especially at site 1 was significantly above safe limits, likely from vehicular runoff or battery disposal sites upstream. The elevated metal concentrations, particularly in the urban and industrial zones (S2 and S3), strongly indicate untreated waste discharge and inadequate regulation enforcement. Seasonal variations suggest that summer intensifies pollutant concentrations due to lower flow, while winter dilution reduces some but not all metal levels. Overall, the heavy metal pollution load in the Yamuna River exceeds safe thresholds, necessitating urgent monitoring, industrial effluent regulation, and remediation strategies to prevent long-term environmental degradation and health hazards (Maurya et al., 2019).

The observed phytotoxicity patterns suggest that water from the Yamuna River, particularly at higher concentrations, exerts inhibitory effects on seed germination and early seedling growth. The reduction in germination percentage and growth parameters at 25% and 50% concentrations is indicative of the presence of toxic substances, most likely heavy metals and organic pollutants, as corroborated by earlier water quality analyses. Among all sites, S4 consistently exhibited the most negative impact, especially during the winter season. This could be attributed to the increased contaminant load during the dry season, when the river flow diminishes and the pollutant concentration rises due to limited dilution. In contrast, S3 demonstrated comparatively better root and shoot elongation, suggesting a relatively lower

phytotoxic burden at this site. The declining trends in root and shoot lengths and biomass under increasing concentrations support the idea that these endpoints are reliable bio-indicators of aquatic toxicity. Roots were generally more sensitive than shoots, as root elongation was markedly inhibited even at moderate concentrations highlighting their direct contact with toxicants in the medium. Seasonal variation also played a role in toxicity expression. While summer samples showed moderate growth inhibition, winter samples reflected sharper toxicity, likely due to seasonal changes in pollutant composition, bioavailability, or synergistic interactions between contaminants. These findings highlight the potential risks posed by polluted river water to plant development and suggest that phytotoxicity assays can serve as an early warning tool for ecological risk assessments. The results underscore the urgent need for treatment of industrial and domestic effluents before discharge into the Yamuna River to protect both aquatic ecosystems and agricultural viability (Kaur and Mehra, 2012).

Conclusion

This study will aid in the removal of toxic pollutants from water, and their quality enhancement by incorporating a sustainable approach seems to be a holistic solution harnessing the combined potential of the human mind and natural system for agricultural sustainability, enabling the prosperity of ecology, economy and society. Therefore, from this study, it can be concluded that river samples are toxic, and that the treatment process is not efficient in removing these toxic pollutants. Hence, there is an urgent need for promising biological treatment technology to be implemented at treatment plants to protect the environment safely.

Post-COVID-19 lockdowns led to a temporary improvement in the Yamuna Rivers water quality due to reduced industrial and human activity. In response, the Delhi government launched major initiatives, such as the Six-Point Action Plan and Yamuna Cleaning Cell, supported by the Ministry of Jal Shakti's Namami Gange Programme and CPCB's real-time water quality monitoring with significant budget allocations and upgraded sewage treatment infrastructure. Despite initial progress, sustained inter-agency coordination and infrastructure upgrades remain crucial for long-term restoration.

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Competing Interests

The authors declare that there is no conflict of interest.

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