RESEARCH ARTICLE

Anthropogenic and Agricultural Impact on Hydrocarbon Contamination in the Ganga-Yamuna Confluence, Prayagraj, India

Ruchi Agnihotri[1,2], Sanjay Dwivedi[1,3*], Ravi Kumar Tiwari[1], Seema Mishra[4], Tuhina Verma[2] DOI: 10.18811/ijpen.v11i02.11

Abstract

The Ganga, one of the major rivers of northern India, originates in the Himalayas and flows through Uttarakhand, Uttar Pradesh, Bihar, and West Bengal, supporting diverse ecological and human activities. Spanning 2,525 km, the river receives significant urban discharge and agricultural runoff, impacting its water quality. This study assesses water quality and pesticide contamination in the middle stretch of the river, focusing on the *Sangam* area of Prayagraj. The analysis revealed variations in physicochemical properties, cation, and anion concentrations, polycyclic aromatic hydrocarbons (PAHs), chlorinated hydrocarbons (CHCs), trihalomethanes (THMs), bromate, polychlorinated biphenyls (PCBs), common pesticides, and trace and toxic elements among the Ganga, Yamuna, and *Sangam* waters. The concentrations of CHCs and THMs were relatively high in the Ganga, whereas PAHs and bromate levels were elevated in the *Sangam* waters. At *Sangam*, the level of PAH was exceeding the acceptable limit, with naphthalene concentrations approximately 14 times higher than in the Ganga and Yamuna. CHCs were higher in the Ganga, while dieldrin was in the Yamuna which exceeded the BIS limits for drinking water. The α-, β-, and δ-HCH isomers of HCH exceeded permissible levels, whereas γ-HCH remained within limits in Ganga. Most of the pesticides, including malathion, ethion, parathion-methyl, and endosulfan-II, were within acceptable thresholds, except atrazine, which was nearly twice the permissible level in the Yamuna. PCBs were undetectable, though traces of PCB-28, PCB-153, and PCB-209 were present. Trihalomethanes, such as chloroform, dibromochloromethane, and bromodichloromethane were also detected at all sites. These findings highlight significant variations in pollutant levels in the Ganga, Yamuna, and at their confluence at *Sangam*, underscoring the urgent need for more effective implementation of *Namami Gange* policies in the middle stretch of the Ganga to support its restoration and long-term sustainability.

Highlights

- PAH levels were highest in *Sangam* water exceeding BIS limits.
- CHC concentrations were relatively higher in Ganga than in Yamuna.
- Atrazine in Yamuna was two times higher than the permissible limit.
- Isomers of HCH are frequently detected in the Ganga River.

Keywords: PAHs; Water quality; Human health; Ganga.

International Journal of Plant and Environment (2025); **ISSN:** 2454-1117 (Print), 2455-202X (Online)

Introduction

The Ganga, the largest river in the Indian sub-continent, originates from the Gaumukh ice cave of the Gangotri Glacier at an altitude of 4,100 meters and flows for 2,525 km before amalgamation into the Bay of Bengal at Ganga Sagar (Basu, 1992; Singh & Singh, 2007). It serves as a vital lifeline for over 400 million people and holds immense cultural, religious, and ecological significance (Nautiyal, 2009a, 2009b; Rai, 2013). This holy river, supported by numerous tributaries, forms the vast Indo-Gangetic Plain (IGP), one of the world's most fertile and densely populated agricultural regions (Dwivedi *et al.*, 2018). Covering nearly 13% of India's geographical area, the IGP contributes approximately 50% of the country's total food grain production, sustaining 40% of its population (Pal *et al.*, 2009).

Agricultural intensification in the Ganga Basin has led to extensive pesticide use, with approximately 61,000 tonnes (t) applied in 2020 (FAO, 2022). In comparison, total pesticide consumption in Brazil, China, and Argentina stood at 377,000 t, 273,000 t, and 241,000 t, respectively. India is the fourth largest

[1]Plant Ecology and Climate Change Science Division, CSIR-National Botanical Research Institute, Rana Pratap Marg, Lucknow-226 001, India.

[2]Department of Microbiology, Dr. Ram Manohar Lohia Avadh University, Ayodhya, India-224001.

[3]Academy of Scientific and Innovative Research (AcSIR), Ghaziabad -201002, India.

[4]Department of Chemistry, University of Lucknow, Lucknow -226007, India.

***Corresponding author:** Sanjay Dwivedi, Plant Ecology and Climate Change Science Division, CSIR-National Botanical Research Institute, Rana Pratap Marg, Lucknow-226 001, India, Email: drs_dwivedi@yahoo.co.in

How to cite this article: Agnihotri, R., Dwivedi, S., Tiwari, R.K., Mishra, S., Verma, T. (2025). Anthropogenic and Agricultural Impact on Hydrocarbon Contamination in the Ganga-Yamuna Confluence, Prayagraj, India. International Journal of Plant and Environment. 11(2), 326-334.

Submitted: 04/04/2025 **Accepted:** 07/05/2025 **Published:** 30/06/2025

producer of agrochemicals, including pesticides, and ranks 12th globally in agrochemical exports. The country's pesticide production has nearly doubled over the past two decades, rising from 102,240 t in 1998 to 258,130 t between 2022 and 2023 (GoI, 2023), with the Ganga basin accounting for the highest consumption (Mohapatra *et al.,* 1995; Kumar *et al.,* 2013; Aktar *et al.,* 2009). Currently, India manufactures 104 pesticides out of 293 registered formulations (Nayak & Solanki, 2021). The excessive use of pesticides has significantly deteriorated the water quality of the Ganga, posing risks to aquatic life and human health. Contaminated irrigation water further affects crop productivity, leading to bioaccumulation of toxic residues in agricultural produce. Pesticides such as DDT and HCH, commonly sprayed on farmlands, are washed into the river through runoff, contaminating water used for drinking, bathing, and cooking (Alavanja & Bonner, 2012; FICCI, 2016). Despite official bans, many restricted pesticides including DDT, aldrin, and HCH continue to be used illegally due to their low cost and accessibility (Abhilash & Singh, 2009; Vijgen *et al.,* 2011). A study by Sah *et al.,* (2020) detected 13 banned and restricted organochlorine pesticides (OCPs) in the surface water of the river Ganga, highlighting the persistence of these contaminants in the river water ecosystem.

Studies have reported pesticide contamination in the Ganga exceeding WHO's permissible limits along different stretches of the river (Rehana *et al.,* 1995, 1996; Guzzella *et al.,* 2005; Mutiyar & Mittal, 2013). Highly contaminated sites, including Kanpur and Varanasi in Uttar Pradesh, exhibited localized pesticide accumulation (ITRC Annual Report, 1992; Semwal & Akolkar, 2006; Mutiyar & Mittal, 2013). The contamination levels, particularly of OCPs, have declined significantly in recent years, coinciding with the implementation of the National Ganga River Basin Authority (NGRBA) in 2009. However, the geographical trend in pesticide distribution has shifted, with Bihar now exhibiting the highest contamination levels, followed by Uttarakhand and Uttar Pradesh, suggesting long-range pollutant transport and persistence (Σ-HCH, Σ-aldrin, Σ-hepta in Bihar; Σ-DDT, Σ-endosulfan in Uttar Pradesh). Additionally, studies have detected pesticide residues in glaciers, highlighting their mobility through atmospheric and hydrological pathways. This emphasizes the persistent nature of pesticide contamination and its far-reaching environmental impact. In response to growing concerns, India has witnessed a paradigm shift from OCPs to contemporary-use pesticides (CUPs). The Ministry of Agriculture and Farmers Welfare (MoAFW) has been making concerted efforts to mitigate pesticide contamination, yet several CUPs, along with certain OCPs that remain in use, have been identified as potential endocrine-disrupting chemicals (EDCs) (Leemans *et al*., 2019; Sharma *et al*., 2019).

The confluence of the Ganga and Yamuna at *Sangam* in Prayagraj represents a critical ecological and hydrological junction, heavily influenced by both urban and agricultural runoff. While previous studies have extensively documented pesticide contamination in the Ganga (Dwivedi *et al.,* 2018; Behera *et al.,* 2021), limited research has focused on the levels of polycyclic aromatic hydrocarbons (PAHs), chlorinated hydrocarbons (CHCs), trihalomethanes (THMs), bromates, polychlorinated biphenyls (PCBs), and commonly used pesticides, as well as their relationship with the river's physicochemical properties. The Namami Gange program, launched by the Government of India (GoI 2014), aims to rejuvenate the Ganga by addressing pollution sources, including industrial and agricultural contaminants. However, the persistence of pesticides and other hazardous chemicals in the river system indicates the need for enhanced monitoring and stricter regulatory enforcement. This study analyzes the levels of PAHs, CHCs, THMs, bromates, PCBs, and commonly used pesticides, as well as their relationship with the river's physicochemical properties along with the concentrations of cations, anions, trace elements, and toxic elements in the Ganga, Yamuna, and *Sangam* waters to assess the current contamination status at this confluence. A comprehensive assessment of these contaminants is essential to evaluate the effectiveness of pollution control measures under the Namami Gange initiative and to develop targeted strategies for improving water quality in this ecologically significant stretch.

Material And Methods

Description of study area and sample collection

The *Sangam*, a confluence of the Ganga and Yamuna rivers, serves as the primary mass bathing site during the Ardha Kumbh, Kumbh and Maha-Kumbh, located in Prayagraj, Uttar Pradesh, India (25°28′ N, 81°54′ E). Three sampling sites were selected within a ~10 km radius of the *Sangam* to upstream of respective rivers. Water samples were collected ~8 km upstream of the confluence, near the Phaphamau bridge on the Kanpur side from Ganga River. Similarly, Yamuna river samples were also obtained ~8 km upstream of the confluence point. Samples collected directly from the confluence point, the focal area of activity during the mass bathing event, referred to as *Sangam* (Fig. 1).

Water samples from all three locations were collected at 6 AM. The samples were analyzed for PAHs, CHCs, THMs, bromates, PCBs, and commonly used pesticides, along with the physicochemical properties of the river water. Additionally, the concentrations of cations, anions, trace elements, and toxic elements were also assessed. To ensure accuracy and reliability,

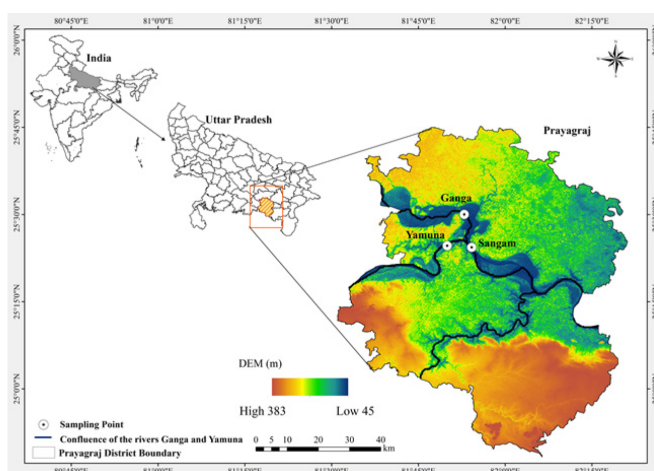

Fig. 1: Map showing three selected sampling sites Ganga, Yamuna and *Sangam* at Prayagraj. The white circle and black dot in the center indicate the sampling points

triplicate water samples were collected from each location using sterilized, acid-washed containers and plastic bottles. One set of samples was immediately acidified with 1 ml of 35% nitric acid to preserve trace and toxic elements for further analysis. Detailed methodologies for the analysis of various parameters are described in the respective subsections.

Analysis of polycyclic aromatic hydrocarbons and polychlorinated biphenyls

Five liters of water samples were collected in acid-washed containers, ensuring that the bottles were filled to avoid any air gaps, for the analysis of various PAHs and PCBs. The analysis included nine PAHs acenaphthalene, dibenzo(a,h) anthracene, benzo(b)fluoranthene, indeno(1,2,3-cd) pyrene, benzo(a) anthracene, anthracene, naphthalene, fluorene, and phenanthrene and CHCs DDD p,p′, dieldrin, aldrin, o,p′ DDE, p,p′ DDE, o,p′ DDT, p,p′ DDT, α-HCH, ß-HCH, lindane (γ-HCH), and δ-HCH. Additionally, twelve commonly used pesticides atrazine, malathion, ethion, endosulfan sulfate, deltamethrin, parathion-methyl, butachlor, endosulfan peak 1, endosulfan peak 2, alachlor, endosulfan-II, and phorate and six PCBs PCB 28 (2,4,4′-trichlorobiphenyl), PCB 52 (2,2′,4,5,5′-tetrachlorobiphenyl), PCB 101 (2,2′,4,5,5′-pentachlorobiphenyl), PCB 180 (2,2′,3,4,4′,5,5′-heptachlorobiphenyl), PCB 153, and PCB 209 were measured using GC-MS, (model: QP2010 Plus, Shimadzu) (Mondal *et al.,* 2018).

Analysis of trihalomethanes and bromate

One liter of water sample was collected in acid-washed container for the analysis of a total four THMs *i.e.* chloroform, bromoform, dibromochloromethane, and bromodichloromethane using GC-MS, while bromate was analyzed in these samples using Ion chromatography (model: Metrohm 761 compact) by using a standard protocol (APHA, 2017).

Evaluation of physicochemical parameters

Evaluation of physicochemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, alkalinity, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), chloride (Cl^{-}), and nitrate (NO_3^{-}), were analyzed in the collected river water samples to assess water quality following standard protocols (APHA, 2017). The pH, EC, TDS, and DO were measured on-site using a multi-parameter water analysis kit (Hanna, USA, HI98194). The remaining parameters, except turbidity, were analyzed in the laboratory after filtering the samples with Whatman filter paper (grade 41) to remove sand and other suspended particles. COD was measured using a COD reactor (Hanna, USA, HI839800), and turbidity was determined with a turbidimeter (Hanna, USA, HI98703). All other parameters were tested according to the APHA 23rd edition (APHA, 2017).

Quantification of trace and toxic elements

Eight trace elements Fe, Mn, Zn, Cu, Mo, Co, Se, and Ni, and four toxic elements Cr, Cd, Pb, and As were analyzed in the acidified river water samples using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS 7500ex, Agilent Technologies, USA). For analysis, 25 ml of water samples were digested with 3 ml of suprapur HNO_3 (65%). After digestion, the samples were filtered through a 0.22 µm syringe filter, and the volume was adjusted to 10 ml. The samples were then stored at 4°C until analysis (Dwivedi *et al.,* 2020).

Quality control and Quality assurance

To ensure the precision of multi-element analysis, we used calibration standards, including the multi-element calibration standard 2A (8500-6940, Agilent Technologies, USA), to calibrate the instrument. The analytical accuracy of the ICP-MS was maintained following the standards set by the National Accreditation Board for Testing and Calibration Laboratories (NABL), with certificate number TC-7972. Calibration and quality assurance for each analytical batch were verified through repeated analyses (n=5) of river water samples spiked with known quantities of elements. Recovery rates for Fe, Zn, Mn, Cu, Co, Se, Cr, Cd, Pb, and As from the water samples exceeded ~98%. The instrument's detection limit for each element was 1µgl^{-1}. Other physicochemical parameters, PAHs, PCBs, trihalomethanes, and bromate were analyzed following the calibration of the respective instruments using appropriate standards.

Results And Discussion

Several categories of pesticides, including organochlorines, organophosphates, carbamates, and pyrethroids, are widely used in Indian agriculture. However, the uncontrolled application of these pesticides has led to significant pollution in India's major rivers. Studies have documented pesticide contamination in major rivers such as the Ganga, Yamuna, Cauvery, and Gomti, primarily due to runoff from agricultural fields, posing serious environmental, ecological, and health risks (Dwivedi *et al.,* 2018, Shah and Praveen, 2021, Behera *et al.,* 2024). Present study evaluates and discusses the current status of various pesticides, including PAHs, CHCs, PCBs, common pesticides, THMs, bromates and their isomers. Additionally, trace and toxic elements along with major ions, and physicochemical properties of water in the Ganga, Yamuna, and *Sangam*, were analyzed and compared with BIS standards in the subheadings as under:

Levels of PAHs, CHCs and PCBs

Polycyclic aromatic hydrocarbons (PAHs) and CHCs are now classified as priority pollutants. Their non-biodegradable and lipophilic nature has led to severe ecological and human health risks (Kafilzadeh *et al.,* 2011, Wolska *et al.,* 2012, Duttagupta *et al.,* 2020). In the present study, the concentrations of PAHs were higher in the *Sangam* water, whereas CHCs were relatively high in the Ganga. A total of eight PAHs such as ace-naphthalene, fluorene, naphthalene, anthracene, benzo(a) anthracene, indeno (1,2,3-cd) pyrene, benzo (b) fluoranthene, dibenzo (a,h) anthracene were analyzed, and found significantly different levels in Ganga, Yamuna and *Sangam* water (Fig. 2). Five types of PAHs (ace-naphthalene, fluorene, naphthalene, benzo(a) anthracene and benzo (b) fluoranthene were more in *Sangam* water and have crossed their BIS limits (0.1µgl^{-1}), whereas level of indeno (1,2,3-cd) pyrene, and dibenzo (a, h) anthracene were several fold higher in Yamuna then their limit of BIS (BIS-2012), while the level of anthracene was higher in Ganga. In a recent study, Sonwani and Bharti, (2023) analyzed PAH levels in the middle stretch of the Ganga River. Among the sixteen PAHs studied, only eight were detected at higher concentrations, particularly at the Kanpur site (Jajmau), an urban and industrial waste hotspot, compared to two other locations Dala Khera (Fatehpur) and Kara Kachar (Kaushambi). In the current study, PAH concentrations in the *Sangam* water were several times higher than previously reported at Kanpur, Fatehpur, and Kaushambi (Sonwani & Bharti, 2023), except for Acenaphthalene (0.13µgl^{-1} in *Sangam* water), which was lower than its concentration found previously at Jajmau, Kanpur (3.83µgl^{-1}).

A total of eleven CHCs, DDD (p,p′), dieldrin, aldrin, o,p′ DDE, p,p′ DDE, o,p′ DDT, p,p′ DDT, α-HCH, ß-HCH, lindane (γ-HCH), and δ-HCH were detected across the selected sites. The concentration of CHCs was higher in the Ganga compared to the Yamuna and *Sangam* (Fig. 3). Among the detected HCH isomers, α-HCH, ß-HCH, and δ-HCH exceeded the BIS limit in the Ganga, whereas γ-HCH remained within the permissible limit of 2µgl^{-1}. In the Yamuna, dieldrin, ß-HCH, and δ-HCH surpassed their respective BIS limits. However, CHC levels in the *Sangam* water showed no significant variation, except for α-HCH and ß-HCH. The elevated concentrations of these HCH isomers can be attributed to the erosion of weathered agricultural soils containing HCH residues, as well as the microbial, chemical, and photodegradation of parent HCH compounds (Kumar *et al.,* 1995; Malik *et al.,* 2009; Rajan *et al.,* 2023). The widespread presence of α-HCH in the Ganga, Yamuna, and *Sangam* waters suggests its potential for long-range transport via agricultural runoff (Malik *et al.,* 2009; Willett *et al.,* 1998). Additionally, the persistently high γ-HCH concentrations may be associated with the continued use of lindane, which typically comprises more than 90% γ-HCH (Sah *et al.,* 2020; Rajan *et al.,* 2023). Among the six PCBs analyzed, only PCB-28, PCB-153, and PCB-209 were detected, with their concentrations varying across the three locations, (Table 1). The levels of PCBs were within the permissible limit of 0.05µgl^{-1}, PCB153 was present only in *Sangam* water while PCB-52, PCB-101, and PCB-180 were found below the detection limit (BDL) at all the three sites. The presence of these PCBs may be attributed to the high deposition of pesticide residues in the waters of the Ganga and Yamuna, which subsequently flow downstream to the *Sangam*. Since the catchment areas of the Ganga and Yamuna rivers are predominantly agricultural, the accumulation of pesticide residues in these waters is relatively higher (Chakraborty *et al.,* 2014).

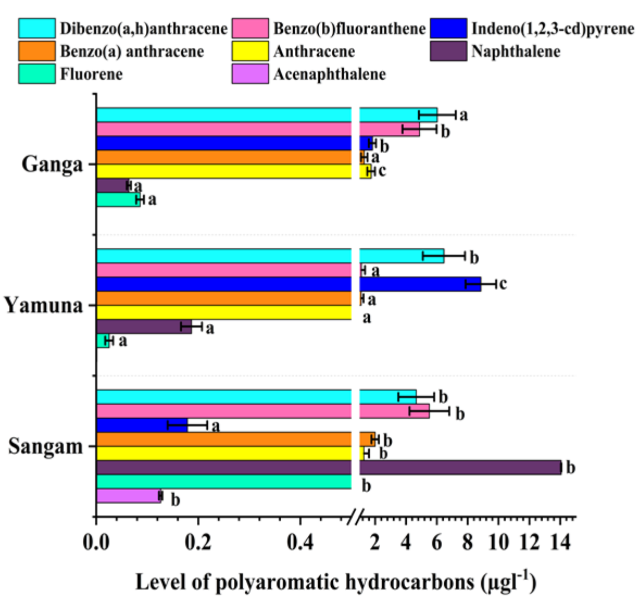

Fig. 2: Changes in levels of polyaromatic hydrocarbons in the Ganga and Yamuna river, and at their confluence point at *Sangam*

Levels of common pesticides, trihalomethanes, and bromate

Nine commonly detected pesticides were present at these sites, though their concentrations varied significantly among the Ganga, Yamuna, and *Sangam* waters (Fig. 4). While the concentrations of malathion, ethion, endosulfan-II, endosulfan sulfate, phorate, alachlor and deltamethrin remained within permissible limits across all sites, atrazine was found to be 1.8 times higher in the Yamuna but remained within safe limits in the Ganga and at the *Sangam*. In contrast, methyl parathion exceeded its permissible limit at all three locations. Methyl parathion is a broad-spectrum insecticide that is banned in the European Union, China, Japan and several other countries (Garcia *et al.,* 2003). While its use continues in many regions, the elevated concentrations observed at all sites raise serious concerns for both ecological and human health. Similarly, atrazine, a synthetic herbicide widely used to control grassy and broadleaf weeds in crops, has become a major pollutant of soil and water ecosystems (Singh *et al.,* 2018). Its high concentration in the Yamuna may be linked to excessive agricultural use in the river's catchment area, where farmers likely rely on it more heavily than those in the Ganga basin.

The levels of THMs, chloroform, dibromochloromethane, and bromodichloromethane varied significantly across all sites, while bromoform was absent (Fig. 5A). The concentration of THMs was ~3 times higher in Ganga water than Yamuna and its level further lowered in *Sangam* water. However, their concentrations remained within permissible limits in Ganga,

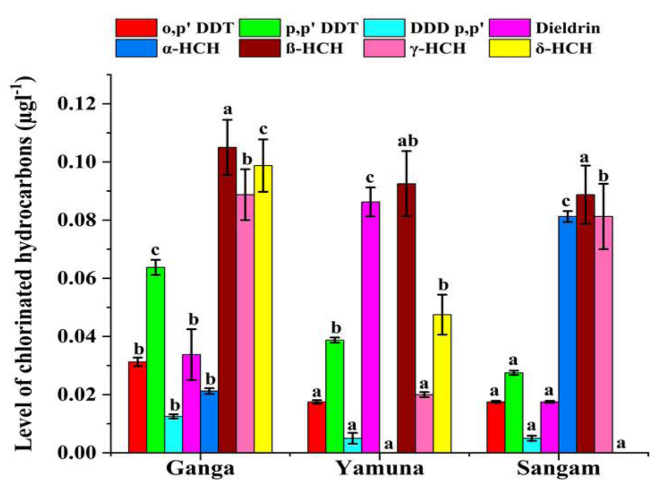

Fig. 3: Alteration in levels of chlorinated hydrocarbons in the Ganga and Yamuna and at their confluence point at *Sangam*

Table 1: Level of polychlorinated biphenyls present in Ganga, Yamuna and *Sangam* water

Name of PCBs	*Ganga*	*Yamuna*	*Sangam*	*MCL* according to U.S.EPA*
PCB 28 (2,4,4′-trichlorobiphenyl)	0.0412±0.00875	0.01125±0.00137	0.045±0.00312	
PCB 52 (2,2′,4,5,5′-tetrachlorobiphenyl)	0.0±0	0.0±0	0.0±0	
PCB 101 (2,2′,4,5,5′-pentachlorobiphenyl)	0.0±0	0.0±0	0.0±0	
PCB 180 (2,2′,3,4,4′,5,5′-heptachlorobiphenyl)	0.0±0	0.0±0	0.0±0	5µgl^{-1}
PCB 153	0.0±0	0.0±0	0.005±0.00062	
PCB 209	0.0037±0.00087	0.0075±0.001125	0.00375±0.00012	

***MCL** = Maximum contaminant level; values in µgl^{-1}.

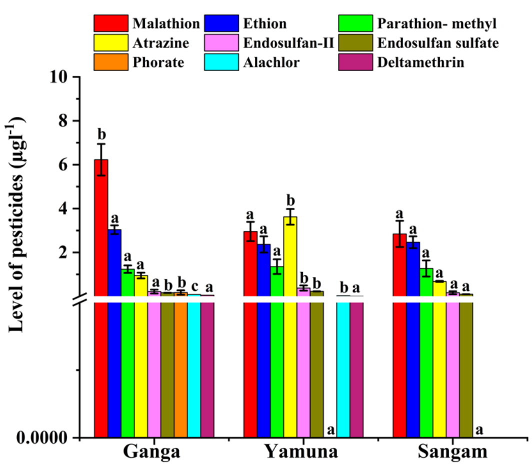

Fig. 4: Changes in levels of common pesticides in the Ganga and Yamuna rivers, and at their confluence point at *Sangam*

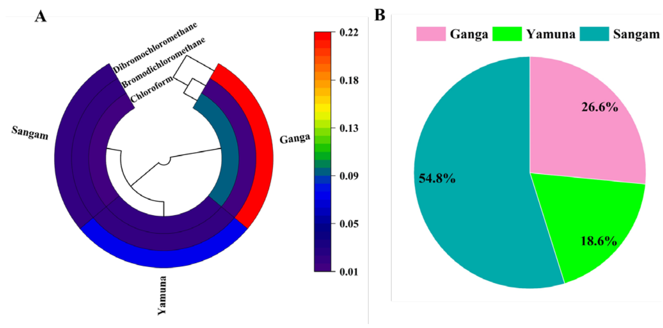

Fig. 5: Changes in levels of trihalomethane **(A)** and bromate **(B)** in the Ganga, Yamuna and *Sangam* water

Yamuna and *Sangam*. Chlorination is the most widely used method for water disinfection globally, including in India, due to its low cost, ease of use, broad-spectrum effectiveness against microorganisms and ability to maintain residual protection. Despite its advantages, chlorination has a significant drawback: the formation of disinfection by-products (DBPs), a concern that has been recognized since the 1970s (Rook, 1974; Bellar *et al.*, 1974; Symons, 1976). These by-products form when chlorine reacts with natural organic compounds present in water, leading to the production of potentially harmful substances, including THMs, which have been reported to be potent carcinogens (IPCS, 2000; IARC, 2004). Among various DBPs, THMs are of particular concern due to their high concentrations in drinking water and their frequent use as indicators of overall DBP formation (Kumari, 2014). The presence of these compounds in river water may be attributed to urban wastewater discharge, where chlorinated household water eventually enters river water. Additionally, chlorination efforts at the *Sangam* aimed at maintaining hygienic conditions could further contribute to THM formation in this stretch of Ganga and Yamuna. However, the bromate concentration in *Sangam* water was approximately three times higher than in the Ganga and Yamuna, yet it remained within the maximum contaminant level (MCL) of 10µgl^{-1} (Fig. 5B). Bromate is not typically present in natural waters but can form during the ozonation process in post-treatment disinfection if bromide is present in raw or makeup water (WHO, 2005; Aljundi, 2011).

Water quality of Ganga, Yamuna and *Sangam* water

The average pH values across all the selected sites ranged from 8.25 to 8.76, indicating that the water quality was predominantly alkaline. The observed change in the pH value was not statistically significant. However, due to the high alkalinity of the sampled water, it was not suitable for drinking (Kanaujiya and Tiwari, 2024). The Yamuna River exhibited a higher level of alkalinity compared to the Ganga and *Sangam* waters, as reflected by an alkalinity concentration of approximately 77mgl^{-1} (Fig. 6). The Ganga recorded the highest average DO levels, followed by the Yamuna and *Sangam*. The average conductivity in the Yamuna was 800µscm^{-1}, significantly surpassing that of the Ganga and *Sangam*. The BOD was elevated in *Sangam*, whereas COD was higher in the Yamuna. Turbidity levels were notably higher in *Sangam*, measuring 1.5 times that of the Ganga and 8 times that of the Yamuna. Total dissolved solids concentrations were measured at 177mgl^{-1} in the Ganga, 400mgl^{-1} in the Yamuna, and 181mgl^{-1} in *Sangam* (Fig. 6). TDS concentration usually increases at the mass bathing sites which may be due to addition of organic matter and dissolved nutrients (Purohit *et al.*, 2020; Varma *et al.*, 2022). The average concentration of cations was higher in the Yamuna water compared to the Ganga and *Sangam*. Monovalent cation i.e. Na^+ was three times higher in the Yamuna than in the Ganga and 11 times in comparison to *Sangam*. In contrast, K^+ levels were three times higher in the

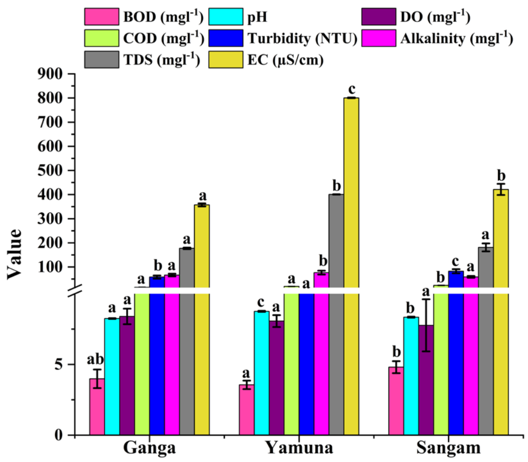

Fig. 6: Changes in physico-chemical properties of Ganga, Yamuna, and *Sangam* water

Table 2: Changes in the level of trace and toxic elements in Ganga, Yamuna and *Sangam* water

	Ganga	*Yamuna*	*Sangam*
A. Trace elements in μgl^{-1}			
Fe	756.96^{b}±84.28	382.71^{a} ±46.63	607.44^{ab}±75.29
Zn	19.64^{a}±2.53	15.06^{a}±2.61	16.38^{a}±2.11
Mn	126.69^{b}±14.85	28.75^{b}±3.51	66.62^{a}±7.41
Cu	3.80^{a}±0.87	9.20^{b}±1.53	5.76^{a}±0.74
Co	3.15^{a} ± 0.82	0.72^{a}±0.095	2.28^{b}±0.90
Mo	3.39^{a} ± 0.94	0.13^{a}±0.01	1.85^{a}±0.09
Se	0.63^{a} ± 0.07	0.72^{a}±0.09	0.21^{a}±0.03
Ni	0.81^{a} ± 0.09	0.07^{a}±0.01	1.64^{a}±0.09
B. Toxic elements in μgl^{-1}			
Pb	11.71^{a}±2.52	7.96^{a}±0.92	8.66^{a}±0.98
As	7.22^{b}±0.82	7.24^{b}±0.97	6.76^{a}±0.84
Cr	3.75^{a}±0.04	0.69^{a}±0.09	9.64^{b}±0.98
Cd	0.23^{a}±0.01	0.29^{a}±0.01	0.16^{a}±0.01

Sangam than in the Ganga and four times higher than in the Yamuna (Fig. 7A). Divalent cations, including Ca^{2+} and Mg^{2+}, exhibited similar concentrations in the Ganga and *Sangam*, while differing in the Yamuna. The concentration of Ca^{2+} was approximately 1.5 times higher in the Yamuna compared to Ganga and *Sangam*. While, Mg^{2+} levels were nearly identical in the Ganga and *Sangam* (~30mgl^{-1}), whereas in the Yamuna, the concentration was notably lower at 11.94mgl^{-1} (Fig. 7A).

The concentration of anions was found to be higher in the Yamuna compared to the Ganga and *Sangam* (Fig. 7B). Phosphate ions were more abundant in the Ganga, with levels approximately 28% higher than in the Yamuna and 16% higher than in the *Sangam*. In contrast, SO_4^{2-} and Cl^- concentrations were significantly elevated in the Yamuna, measuring 55% and 53% higher than in the Ganga, and around 55% and 25% higher than in the *Sangam*, respectively. While, NO_3^- level was highest in the Ganga, exceeding by 32% from Yamuna and 55% from *Sangam*. Spatial variations were observed in the distribution of heavy metals in the river waters of the Ganga, Yamuna, and *Sangam*. The concentrations of trace elements, including Mo, Co, Se, Zn, Mn, and Fe, were higher in the Ganga, while Cu level was elevated in the Yamuna and Ni was highest in the *Sangam* (Table 2). The level of Fe was found ~2 times higher in Ganga and *Sangam* in comparison to Yamuna water. While the level of Mn was higher in Ganga in comparison to Yamuna (4 times) and *Sangam* (~2 times). The level of toxic elements was not significantly changed in all the selected sites, but As and Pb were more abundant in the Ganga, Cd was higher in the Yamuna, and Cr was most prevalent in the *Sangam* (Table 2). The Pearson correlation analysis revealed a strong negative correlation between the mean of common pesticide and pH, while a strong positive correlation was observed with DO and alkalinity (Fig. 8).

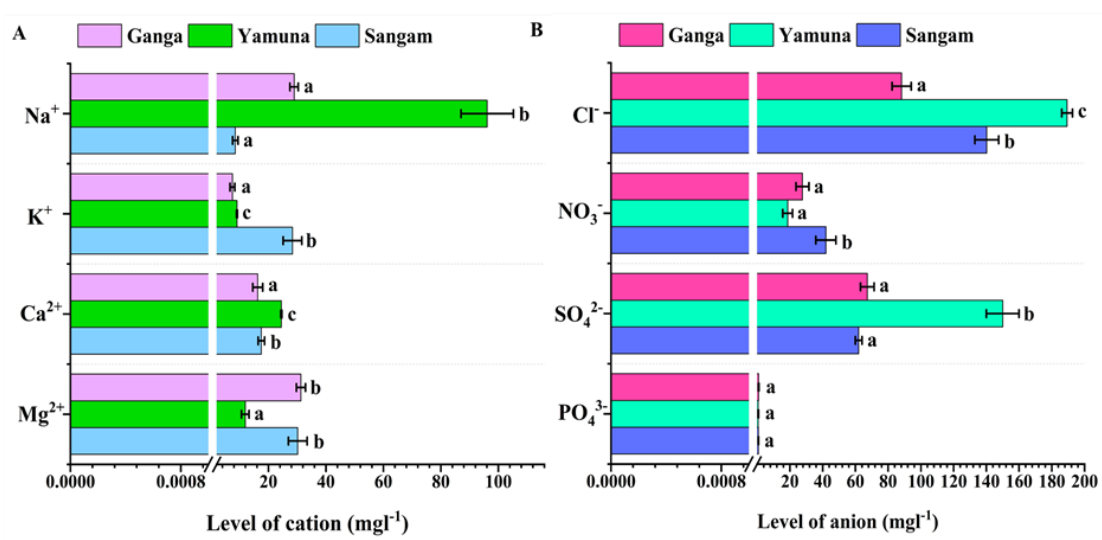

Fig. 7: Changes in level of cations **(A)** and anions **(B)** in Ganga, Yamuna, and *Sangam* water.

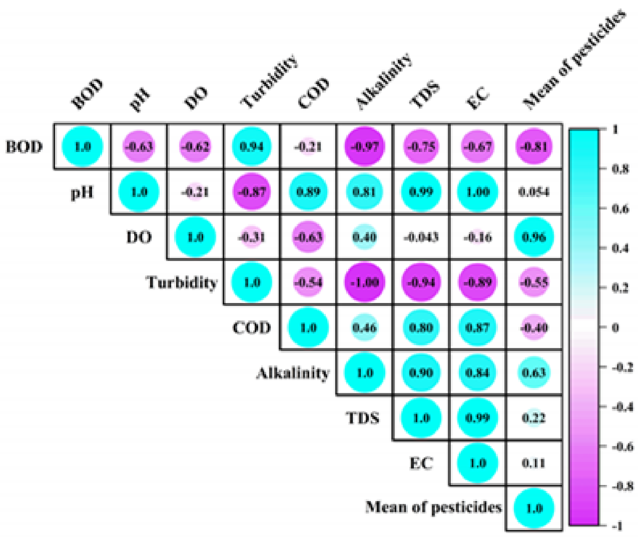

Fig. 8: Correlation between physicochemical properties and mean of pesticides present in Ganga, Yamuna, and *Sangam*

Conclusion

Present study highlights significant contamination of PAHs, CHCs, PCBs, common pesticides, THMs and bromates across the Ganga, Yamuna and *Sangam* waters. The findings indicate that PAH levels were highest in *Sangam* water, while CHC levels were predominantly elevated in the Ganga. Several PAHs and CHCs exceeded permissible limits, posing significant risks to aquatic ecosystems and public health. The widespread distribution of these contaminants suggest contributions from agricultural runoff, urban wastewater, and industrial discharges, which align with key concerns addressed under the Namami Gange Programme. The detection of pesticides such as methyl parathion and atrazine raises further concerns. Their elevated concentrations, particularly in the Yamuna, suggest excessive agricultural chemical use, highlighting the need for sustainable farming practices, a key focus of Namami Gange's Agricultural Interventions aimed at reducing agrochemical runoff. Additionally, the presence of PCBs in all three sampling points, particularly PCB-153 in *Sangam* water, suggests legacy industrial pollution, reinforcing the necessity of strict industrial effluent management, one of the pillars of the Namami Gange Pollution Abatement Strategy. The study also underscores the formation of DBPs such as THMs and bromate due to chlorination. While THM concentrations remained within limits, bromate levels in *Sangam* water were three times higher than in the Ganga and Yamuna, suggesting potential impacts from urban wastewater discharges and water treatment practices. This aligns with Namami Gange's Urban Sanitation and Sewage Treatment Initiatives, which focus on upgrading sewage treatment plants (STPs) and implementing advanced water treatment technologies to prevent harmful DBP formation. Overall, the presence of persistent organic pollutants (POPs), pesticides, and DBPs across these river systems underscores ecological and public health risks, reinforcing the need for stringent monitoring, improved wastewater treatment and sustainable agricultural practices. These findings strongly support the objectives of the Namami Gange Programme, emphasizing the importance of industrial pollution control, eco-friendly farming practices, urban wastewater management and enhanced water treatment solutions to safeguard the health of the Ganga River basin.

Author's Contributions

RA: Interpretation of the data and first draft preparation of the MS, analysis of physicochemical parameters, cations, anions, trace & toxic elements, pesticides, trihalomethane and bromate preparation of graphs. **SD:** Conception and important intellectual content, collection of water samples, interpretation of the data and first draft preparation of the MS and critical revision. **RKT**: Prepare the graphs. **SM**: collection of water samples, critical revision of the MS. **TV:** Scientific inputs, logistic support.

Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose.

Acknowledgments

The authors are thankful to the Director, CSIR-National Botanical Research Institute, Lucknow, for providing the infrastructure and laboratory facilities. SM gratefully acknowledges the financial support from the Uttar Pradesh Council of Science and Technology (UP-CST) through Project No. CST/ENV./D-739 (Project ID: 3630) for research on emerging contaminants in Ganga water.

Ethical approval

The manuscript number CSIR-NBRI_MS/2025/04/16 was allocated by the Institutional Ethics Committee after subjecting the MS through ethical and plagiarism check.

References

Abhilash, P. C. & Singh, N. (2009). Pesticide use and application: an Indian scenario. *Journal of hazardous materials*, 165(1-3), 1-12. https://doi.org/10.1016/j.jhazmat.2008.10.061

Aktar, M. W., Paramasivam, M., Sengupta, D., Purkait, S., Ganguly, M., Banerjee, S. (2009). Impact assessment of pesticide residue in fish of Ganga river around Kolkata in West Bengal. *Environmental Monitoring and Assessment*, 157, 97-104. doi: 10.1007/s10661-008-0518-9.

Alavanja, M. C., & Bonner, M. R. (2012). Occupational pesticide exposures and cancer risk: a review. *Journal of Toxicology and Environmental Health*, Part B, 15(4), 238-263. doi: 10.1080/10937404.2012.632358.

Aljundi, I. H., (2011). Bromate formation during ozonation of drinking water: A response surface methodology study. *Desalination*, 277(1-3), 24-28. https://doi.org/10.1016/j.desal.2011.03.090

APHA (American Public Health Association), (2017). Standard methods for examination of water and wastewater. In American Public Health Association (APHA), 23rd edition.

Basu, A. K. (1992). Ecological and resource study of the Ganga Delta. (in India*)*. Netaji Institute for Asian Studies.

Behera, B. C., Patel, A. K., Udgata, S. K. & Behera, B. (2024). A review on pesticide contamination in Indian water bodies. *International Journal of Chemical Studies*, 12(2), 37-46. https://www.chemijournal.com/archives/2024/vol12issue2/PartA/12-2-17-482.pdf

Behera, B. K., Sahu, P., Rout, A. K., Parida, P. K., Sarkar, D. J., Kaushik, N. K., … & Mohapatra, T. (2021). Exploring microbiome from sediments of River Ganga using a metagenomic approach. *Aquatic Ecosystem Health & Management*, 24(4), 12-22. Doi: 10.14321/aehm.024.04.04

Bellar, T. A., Lichtenberg, J. J., & Kroner, R.C. (1974). The occurrence of organohalides in chlorinated drinking waters. *Journal-American Water Works Association*, 66(12), 703-706. https://doi.org/10.1002/j.1551-8833.1974.tb02129.x

Chakraborty, P., Sakthivel, S., Kumar, B., Kumar, S., Mishra, M., Verma, V.K. & Gaur, R. (2014). Spatial distribution of persistent organic pollutants in the surface water of river Brahmaputra and river Ganga in India. *Reviews on Environmental Health*, 29(1-2), 45-48. doi: 10.1515/reveh-2014-0014.

Duttagupta, S., Mukherjee, A., Bhattacharya, A., & Bhattacharya, J. (2020). Wide exposure of persistent organic pollutants (PoPs) in natural waters and sediments of the densely populated Western Bengal basin, India. *Science of the Total Environment*, 717, 137187. https://doi.org/10.1016/j.scitotenv.2020.137187

Dwivedi, S., Chauhan, P. S., Mishra, S., Kumar, A., Singh, P. K., Kamthan, M., … & Mallick, S. (2020). Self-cleansing properties of Ganga during mass ritualistic bathing on Maha-Kumbh. *Environmental Monitoring and Assessment*, 192, 1-15. doi: 10.1007/s10661-020-8152-2.

Dwivedi, S., Mishra, S., & Tripathi, R.D. (2018). Ganga water pollution: a potential health threat to inhabitants of Ganga basin. *Environment international*, 117, 327-338. doi: 10.1016/j.envint.2018.05.015.

FAO, 2022. Food and Agriculture Organization of the United Nations. Available at: https://www.fao.org/3/cc0918en/cc0918en.pdf. (Accessed 24 February 2023).

FICCI (Federation of Indian Chambers of Commerce & Industry), (2016). Next generation Indian agriculture: Role of crop protection solutions. Report on Indian agrochemical Industry, Federations of Indian Chambers of Commerce and Industry, New Delhi. 1-56. https://ficci.in/study- page.asp?spid=20744&sectorid=7.

Garcia, S., Abu-Qare, A., Meeker-O'Connell, W., Borton, A., & Abou-Donia, M. (2003). Methyl parathion: A review of health effects. *Journal of Toxicology and Environmental Health Part B: Critical Reviews*, 6(2), 185-210. doi: 10.1080/10937400306471.

GoI (Government of India), (2023). Ministry of Agriculture & Farmers Welfare Department of Agriculture, Cooperation & Farmers Welfare Directorate of Plant Protection, Quarantine & Storage, Available at: (https://ppqs.gov.in/statistical-database) (Accessed on: 28th February 2023).

GoI, Gange, N., (2014). Namami Gange Programme, National Mission for Clean Ganga.

Guzzella, L., Roscioli, C., Vigano, L., Saha, M., Sarkar, S.K., & Bhattacharya, A., (2005). Evaluation of the concentration of HCH, DDT, HCB, PCB and PAH in the sediments along the lower stretch of Hugli estuary, West Bengal, northeast India. *Environment International*, 31(4), 523-534. https://doi.org/10.1016/j.envint.2004.10.014

IARC (International Agency for Research on Cancer), (2004). Monographs on the evaluation of carcinogenic risks to humans. Some drinking water disinfectants and contaminants, including arsenic. 84. doi:10.1016/S1470-2045(05)70380-6

IPCS (International Programme on Chemical Safety), (2000). Disinfectants and disinfectant by-products. *Environmental Health Criteria*. 216. https://iris.who.int/bitstream/handle/10665/42274/WHO_EHC_216.pdf;jsessionid=265FC785123C00256607A7D25CDAD8AD?sequence=1

ITRC (Industrial Toxicological Research Centre, Lucknow), (1992). 6th Annual Progress Report (July 1991–June 1992), Measurements on Ganga water quality – Heavy metal and Pesticides, http://www.itrc.org.

Kafilzadeh, F., Shiva, A. H., & Malekpour, R. (2011). Determination of polycyclic aromatic hydrocarbons (PAHs) in water and sediments of the Kor River, Iran. *Middle-East journal of scientific research*, 10(1), 1-7.

Kanaujiya, A. K., & Tiwari, V. (2024). Water quality analysis of river Ganga and Yamuna using water quality index (WQI) during Kumbh Mela 2019, Prayagraj, India. *Environment, Development and Sustainability*, 26(2), 5451-5472. doi: 10.1007/s10668-023-02907-9

Kumar, B., Verma, V. K., Naskar, A. K., Chakraborty, P., Kumar, S., Mukherjee, D. (2013). Human health risk from hexachlorocyclohexane and dichlorodiphenyltrichloroethane pesticides, through consumption of vegetables: estimation of daily intake and hazard quotients. *J. Xenobio*. 3, 29–35.

Kumar, S., Singh, K. P., & Gopal, K. (1995). Organochlorine residues in rural drinking water sources of Northern and North Eastern India. *Journal of Environmental Science & Health Part A*, 30(6), 1211-1222.

Kumari Minashree, S.G., (2014). Factors influencing the formation of trihalomethanes in drinking water supplies. Strategic technologies of complex environmental issues-a sustainable approach, 225. https://krishisanskriti.org/vol_image/10Sep201512095436.pdf

Leemans, M., Couderq, S., Demeneix, B., & Fini, J. B. (2019). Pesticides with potential thyroid hormone-disrupting effects: a review of recent data. *Frontiers in Endocrinology*, 10, 743. https://doi.org/10.3389/fendo.2019.00743

Malik, A., Ojha, P., & Singh, K. P. (2009). Levels and distribution of persistent organochlorine pesticide residues in water and sediments of Gomti river (India)—a tributary of the Ganges River. *Environmental Monitoring and Assessment*, 148, 421-435. https://doi.org/10.1007/s10661-008-0172-2

Mohapatra, S. P., Gajbhiye, V. T., Agnihotri, N. P., & Raina, M. (1995). Insecticide pollution of India rivers. *Environmentalist* 15, 41–44. https://doi.org/10.1007/BF01888888

Mondal, R., Mukherjee, A., Biswas, S., & Kole, R.K. (2018). GC-MS/MS determination and ecological risk assessment of pesticides in aquatic system: a case study in Hooghly River basin in West Bengal, India. *Chemosphere*, 206, 217-230. doi: 10.1016/j.chemosphere.2018.04.168.

Mutiyar, P.K., & Mittal, A.K. (2013). Status of organochlorine pesticides in Ganga river basin: anthropogenic or glacial? *Drinking Water Engineering and Science*, 6(2), 69-80. https://doi.org/10.5194/dwes-6-69-2013

Nautiyal, C. S. (2009a). Scientific validation of incorruptible self-purificatory characteristic of Ganga water. *Asian Agri-History* 13, 53–56. https://www.asianagrihistory.org/pdf/research/Scientific-Validation.pdf

Nautiyal, C. S. (2009b). Self-purification Ganga water facilitates death of pathogenic Escherichia coli O157:H7. *Curr. Microbiol.* 58, 25–29. doi: 10.1007/s00284-008-9260-3.

Nayak, P., & Solanki, H. (2021). Pesticides and Indian agriculture—a review. *Int J Res Granthaalayah* 9, 250–263. doi: 10.29121/granthaalayah.v9.i5.2021.3930

Pal, D. K., Bhattacharyya, T., Srivastava, P., Chandran, P., & Ray, S.K. (2009). Soils of the Indo-Gangetic Plains: their historical perspective and management. *Curr. Sci.* 96, 1193–1202.

Purohit, M., Diwan, V., Parashar, V., Tamhankar, A. J., Lundborg, C. S. (2020). Mass bathing events in river Kshipra, Central India-influence on the water quality and the antibiotic susceptibility pattern of commensal *E. coli*. Plos one, 15(3), 0229664. https://doi.org/10.1371/journal.pone.0229664

Rai, B. (2013). Pollution and conservation of Ganga River in modern India. *Intl. J. Sci. Res. Pub.* 3(4), 1–4.

Rajan, S., Parween, M., & Raju, N. J. (2023). Pesticides in the hydrogeo-environment: a review of contaminant prevalence, source and mobilisation in India. *Environmental geochemistry and health*, 45(8), 5481-5513. doi: 10.1007/s10653-023-01608-6.

Rehana, Z., Malik, A. and Ahmad, M., (1996). Genotoxicity of the Ganges water at Narora (UP), India. *Mutation Research/Genetic Toxicology*, 367(4), pp.187-193.

Rehana, Z., Malik, A., & Ahmad, M. (1995). Mutagenic activity of the Ganges water with special reference to the pesticide pollution in the river between Kachla to Kannauj (UP), India. *Mutation Research/Genetic Toxicology*, 343(2-3),137-144. doi: 10.1016/0165-1218(95)90079-9.

Rook, J. J., (1974). Formation of haloform during chlorination of natural water. *Water treatment and examination*, 21, 259.

Sah, R., Baroth, A., & Hussain, S.A. (2020). First account of spatio-temporal analysis, historical trends, source apportionment and ecological risk assessment of banned organochlorine pesticides along the Ganga River. *Environmental Pollution*, 263, 114229. https://doi.org/10.1016/j.envpol.2020.114229

Semwal, N., & Akolkar, P. (2006). Water quality assessment of sacred Himalayan rivers of Uttaranchal. *Current Science*, 486-496.

Shah, Z.U. & Parveen, S. (2021). Pesticides pollution and risk assessment of river Ganga: A review. Heliyon, 7(8).

Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Sidhu, G. P. S., Handa, N., & Dar, O.I. (2019). Worldwide pesticide usage and its impacts on ecosystem. *SN Applied Sciences*, 1, 1-16. doi: 10.1007/s42452-019-1485-1

Singh, M., & Singh, A. K. (2007). Bibliography of environmental studies in natural characteristics and anthropogenic influences on the Ganga River. *Environmental Monitoring and Assessment* 129, 421–432. doi: 10.1007/s10661-006-9374-7.

Singh, S., Kumar, V., Chauhan, A., Datta, S., Wani, A.B., … & Singh, J. (2018). Toxicity, degradation and analysis of the herbicide atrazine. *Environmental Chemistry Letters*, 16, 211-237. doi: 10.1007/s10311-017-0665-8

Sonwani, P., & Bharti, S. (2023). Analyses of polycyclic aromatic hydrocarbons (PAHs) in the Ganga River water in Uttar Pradesh, India. *Nature Environment and Pollution Technology*, 22(2), 869-877. https://doi.org/10.46488/NEPT.2023.v22i02.029

Symons, J. M., (1976). Interim treatment guide for the control of chloroform and other trihalomethanes. Environmental Protection Agency, Office of Research and Development, Municipal Environmental Research Laboratory, Water Supply Research Division.

Varma, K., Tripathi, P., Upadhyaya, S., Srivastava, A., Ravi, N. K., …& Jha, P. K., (2022). Assessment of mass bathing event (Kumbh-2019) impact on the river water quality by using multivariate analysis and water quality index (WQI) techniques at Sangam (Prayagraj), India. *Groundwater for Sustainable Development*, 17, 100750. https://doi.org/10.1016/j.gsd.2022.100750

Vijgen, J., Abhilash, P. C., Li, Y. F., Lal, R., Forter, M., Torres, J., & Weber, R. (2011). Hexachlorocyclohexane (HCH) as new Stockholm Convention POPs—a global perspective on the management of Lindane and its waste isomers. *Environmental Science and Pollution Research*, 18, 152-162. doi: 10.1007/s11356-010-0417-9.

WHO (2005). Bromate in drinking-water: background document for development of WHO guidelines for drinking-water quality. World Health Organization, Geneva, Switzerland (WHO/SDE/WSH/05.08/78; www.who.int/water_sanitation_health/dwq/chemicals/bromate260505.pdf).

Willett, K. L., Ulrich, E. M., & Hites, R. A. (1998). Differential toxicity and environmental fates of hexachlorocyclohexane isomers. *Environmental Science & Technology*, 32(15), 2197-2207. https://doi.org/10.1021/es9708530.

Wolska, L., Mechlinska, A., Rogowska, J., & Namiesnik, J. (2012). Sources and fate of PAHs and PCBs in the marine environment. *Critical Reviews in Environmental Science and Technology*, 42(11), 1172-1189. doi: 10.1080/10643389.2011.556546