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Assessment of persistent organic pollutants (POPs) in Ganga River at Varanasi city: Occurrence, characterization and remediation

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Abstract
The River Ganga, which sustains over 40% of India's population across its basin, is increasingly burdened by persistent organic pollutants (POPs) organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and a widening range of emerging organic contaminants (EOCs) including pharmaceuticals, agrochemicals and lifestyle compounds that resist degradation, bio-accumulate through the food chain and pose chronic ecological and human-health risks. This paper synthesizes current knowledge on the characterization and spatial distribution of POPs along the Ganga, with particular attention to the middle Gangetic stretch through Prayagraj, Varanasi and downstream reaches, drawing on recent validated analytical surveys and basin-scale monitoring studies. We review the principal point and non-point sources (untreated municipal sewage, tannery and textile effluent, agricultural run-off, and Gross Polluting Industries), the dominant compound classes reported in water and sediment, and the physicochemical and hydrological controls dilution by low-POP tributaries, sorption to suspended sediment, and seasonal flow variation that govern their downstream fate. We then critically evaluate current and prospective control measures, spanning conventional sewage treatment infrastructure under the Namami Gange programme, source-directed industrial effluent regulation, and emerging bio- and phyto-remediation technologies, and propose an integrated, tiered monitoring-and-mitigation framework combining suspect-screening analytical chemistry, catchment-scale source apportionment, and decentralised treatment technologies appropriate for the Ganga's data and infrastructure context. We conclude that meaningful reduction of the POP burden in the Ganga requires coupling analytical surveillance with source-control regulation and low-cost, scalable remediation suited to the basins dense and heterogeneous pollution loading.

Keywords: Persistent organic pollutants, River Ganga, organochlorine pesticides, polychlorinated biphenyls, emerging contaminants, Namami Gange, bioremediation, water quality

Introduction
Persistent organic pollutants (POPs) are a chemically diverse group of anthropogenic compounds characterized by environmental persistence, lipophilicity, long-range transport potential and bioaccumulation bio-magnification through trophic levels [1, 2]. Classical POPs regulated under the Stockholm Convention organochlorine pesticides (OCPs) such as DDT and hexachlorocyclohexane (HCH), and polychlorinated biphenyls (PCBs) continue to be detected in Indian riverine systems decades after restriction, owing to legacy contamination, continued informal use, and remobilization from contaminated sediment [2, 3]. More recently, broad-screening analytical surveys have documented an expanding suite of emerging organic contaminants (EOCs) pharmaceuticals, agrochemicals, industrial chemicals and lifestyle compounds such as artificial sweeteners co-occurring with classical POPs in the Ganga system, reflecting the river's dense population pressure and heterogeneous pollution loading [4, 5].
The Ganga basin supports over 40% of India's population and receives an estimated 2, 953 million liters per day of sewage along the main channel, alongside effluent from 1, 072 identified Gross Polluting Industries [6]. A validated longitudinal analytical review of 55 POPs across the urban stretches of Prayagraj and Varanasi confirmed the widespread presence of pesticides, pharmaceuticals and PAHs at concentrations warranting continued risk assessment [5], while a basin-scale suspect-screening study identified 51 distinct EOCs dominated by pharmaceuticals and agrochemicals, with lifestyle compounds contributing disproportionately to total concentration across the middle Gangetic Plain between Varanasi and Begusarai [4].
Despite this and other regional surveys, an integrated synthesis connecting POP characterization, spatial distribution drivers and control-measure evaluation specific to the Ganga remains limited, motivating the present review. Aim of this article is to (i) characterize the principal classes and sources of POPs reported in the River Ganga, (ii) synthesize spatial and seasonal distribution patterns and their physicochemical hydrological controls, and (iii) critically evaluate existing and prospective control measures, culminating in a proposed integrated monitoring-and-mitigation framework.

Characterization and Sources of POPs in the Ganga
1. Dominant compound classes
Reported POPs in the Ganga system fall into four broad classes: (i) organochlorine pesticides (HCH isomers, DDT and metabolites, heptachlor, endosulfan, aldrin, dieldrin),

historically dominant owing to decades of agricultural and public-health use [2, 3]; (ii) polychlorinated biphenyls, arising from historical industrial/electrical equipment use and continued leaching from contaminated sediment, with PCB concentrations in comparable Gangetic-basin rivers reported up to the low hundreds of ng L^{-1}[3, 7]; (iii) polycyclic aromatic hydrocarbons, associated with combustion, vehicular emissions and partially treated urban run-off; and (iv) a growing category of emerging organic contaminants pharmaceuticals (notably carbamazepine and antimicrobials), agrochemicals (atrazine, metribuzin, fipronil) and lifestyle compounds (artificial sweeteners) increasingly co-reported alongside classical POPs in broad-screening studies [4, 5].

2. Sources

Point sources include untreated or partially treated municipal sewage (the dominant contributor, estimated at roughly 80% of total river pollution load nationally [8]), tannery, textile and distillery effluent concentrated around industrial clusters such as Kanpur, and discharge from Gross Polluting Industries subject to nominal, unevenly enforced effluent standards [6, 8]. Non-point sources include agricultural run-off carrying OCP and agrochemical residues from the intensively cultivated Gangetic plain, atmospheric deposition, and remobilisation of legacy POPs from contaminated bed sediment during high-flow monsoon events [2, 3].

Table 1: Principal classes, representative compounds and sources of POPs reported in the River Ganga system

POP class	Representative compounds	Principal sources	Reference(s)
Organochlorine pesticides (OCPs)	HCH isomers, DDT/DDE/DDD, heptachlor, endosulfan	Agricultural run-off, legacy public-health use	[2, 3]
Polychlorinated biphenyls (PCBs)	PCB-18, PCB-52, PCB-44 and congeners	Industrial discharge, sediment remobilisation	[3, 7]
Polycyclic aromatic hydrocarbons (PAHs)	Naphthalene, pyrene, benzo[a]pyrene	Combustion, urban run-off, vehicular emission	[5]
Emerging organic contaminants (EOCs)	Carbamazepine, atrazine, fipronil, sweeteners	Sewage, pharmaceuticals, agrochemical use	[4, 5]

Spatial and Seasonal Distribution Patterns

Spatial surveys along the Ganga and comparable Gangetic-basin rivers consistently report a downstream decline in POP/EOC concentration between major urban centers, attributed chiefly to dilution by tributaries carrying substantially lower contaminant loads rather than to degradation or removal [4]. A basin-scale study spanning Varanasi (Uttar Pradesh) to Begusarai (Bihar) documented a significant reduction in EOC concentrations downstream of the three major tributary confluences in this reach, alongside compound-specific sorption and redox controls (e.g., for clopidol) and a substantial degree of longitudinal mixing [4]. EOC and hydro-chemical fluorescence parameters (tryptophan-, fulvic- and humic-like signals) were positively and significantly correlated, indicating that dissolved organic matter dynamics co-vary with, and may partly govern, the transport behaviour of several POPs/EOCs [4].

Seasonal dynamics are pronounced: comparative pre- and post-monsoon sampling in a Gangetic-basin tributary found PCB and OCP concentrations in both water and sediment to vary markedly between seasons, with generally higher sediment-bound concentrations reflecting long-term accumulation and monsoon-driven remobilisation of historically deposited residues [3]. Spatial distribution across the wider Ganga–Brahmaputra system further shows organochlorine pesticide levels ranked heptachlor > HCHs > DDTs > dieldrin > aldrin > endosulfan, with elevated HCH isomers at specific hotspots and fresh DDT inputs evidenced by parent-to-metabolite ratios, indicating both legacy contamination and ongoing, restricted-but-persistent use [7]. Collectively, these patterns indicate that POP/EOC distribution in the Ganga is governed by a combination of proximity to urban/industrial point sources, tributary dilution, sediment–water partitioning, and seasonal hydrology, rather than any single dominant control.

Ecological and Human Health Significance

POPs and co-occurring EOCs in the Ganga carry documented eco-toxicological concern through endocrine disruption, bioaccumulation in fish and other biota, and food-chain bio-magnification, with the river supporting both extensive fisheries and drinking-water abstraction for riparian populations [2, 5]. Risk-assessment components of recent analytical surveys have flagged select pharmaceuticals, pesticides and PAH congeners for continued monitoring on the basis of measured concentrations relative to eco-toxicological thresholds, underscoring that POP management in the Ganga cannot be treated as a legacy issue alone but must address a continually evolving contaminant mixture [5].

Control Measures: Current Status and Prospective Approaches

1. The Namami Gange programme

India's principal river-rejuvenation initiative, the Namami Gange Programme (launched 2014, implemented through the National Mission for Clean Ganga), pursues pollution abatement through sewage treatment infrastructure development across 118 urban centres, river-surface cleaning, industrial effluent monitoring, and biodiversity conservation, organised around the twin goals of *Nirmal Dhara* (unpolluted flow) and *Aviral Dhara* (continuous flow) [6, 9]. The programme has also piloted bioremediation techniques using plants and microorganisms at heavily polluted sites, particularly around Varanasi, alongside afforestation and riparian buffer development [10]. However, independent assessments note that installed sewage treatment capacity meets only an estimated 20–60% of generated sewage load across major Ganga-basin states, with rural sewage treatment coverage below 1% despite rural areas hosting the majority of the basin population, and with enforcement gaps allowing some Gross Polluting

Industries to continue or resume discharge despite formal restrictions [8, 11].

2. Source-directed and treatment-based measures

Effective POP control requires layered intervention: (i) source control through stricter, continuously monitored industrial effluent standards and real-time online effluent monitoring at Gross Polluting Industries [9]; (ii) expansion of decentralised, low-footprint sewage treatment (e.g., constructed wetlands, waste stabilisation ponds) suited to peri-urban and rural riparian settlements currently unserved by centralised STPs [8, 12]; (iii) in-situ and ex-situ bioremediation using POP-degrading bacterial and fungal consortia and phytoremediation with aquatic macrophytes for sediment-bound legacy residues [10]; and (iv) advanced tertiary treatment (activated carbon adsorption, advanced oxidation processes) targeted at EOC removal from municipal effluent prior to discharge, given that conventional secondary treatment alone is generally insufficient to remove pharmaceuticals and other polar EOCs [4, 12].

3. Proposed integrated monitoring-and-mitigation framework

Building on the reviewed evidence, we propose a tiered framework comprising: (a) suspect-screening, high-resolution mass-spectrometry-based monitoring at fixed longitudinal stations bracketing major urban and industrial inputs, replicated pre- and post-monsoon to capture seasonal variability; (b) source apportionment linking monitored concentrations to catchment land-use and discharge inventories to prioritise interventions; (c) staged expansion of decentralised treatment infrastructure in unserved peri-urban/rural stretches, informed by the observed dilution and tributary-mixing dynamics; and (d) pilot-scale deployment and field validation of bioremediation consortia at identified sediment hotspots, with pre- and post-intervention POP quantifications to establish efficacy under Ganga-specific hydrological conditions. Such integration of analytical surveillance with source-control regulation and scalable remediation is required to address both legacy and emerging components of the Ganga's POP burden.

Conclusion

Persistent organic pollutants in the River Ganga span legacy organochlorine pesticides and PCBs alongside a widening range of emerging organic contaminants, distributed along the river through a combination of urban/industrial point-source proximity, tributary dilution, sediment partitioning and seasonal hydrology. While the Namami Gange programme has delivered substantial sewage treatment and biodiversity investment, treatment capacity gaps particularly in rural and peri-urban stretches and enforcement limitations on industrial discharge constrain its effectiveness against the full POP contaminant mixture. Meaningful reduction in the Ganga's POP burden will require coupling sustained, suspect-screening analytical surveillance with source-directed industrial regulation, decentralized treatment expansion, and field-validated bio- and phyto-remediation technologies tailored to the basin's scale and hydrological complexity.

Author Contributions

All the authors contributed to the conception and design the study. Dinanath Tripathi and Akrit Vigya conceived the review focus and conducted the literature synthesis. Kashinath Tripathi and Vivek Singh prepared the first draft of the manuscript. Abhishek Singh supervised the conceptual framework and critically revised the manuscript. All authors reviewed and approved the final version of the manuscript for submission.

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