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Review Article

Emerging Chemical Pollutants in Aquatic Systems: Implications for Waterbird Health and Diversity in Indian Waterbodies

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Abstract

Emerging chemical pollutants in Indian aquatic systems pose a growing and poorly regulated threat to waterbird populations. India generates approximately 72,368 million litres per day (MLD) of sewage, of which only 28% receives adequate treatment before discharge. Pharmaceuticals, personal care products, surfactant metabolites—including nonylphenol ethoxylates (NPE; detected at 0.8–22.3 μg/L) and linear alkylbenzene sulfonates (LAS; detected at 0.4–22.5 mg/L) in major Indian rivers —organochlorine and organophosphate pesticides, heavy metals, and microplastics are contaminating river basins, estuaries, and wetlands of national significance. Waterbirds occupy the apex of aquatic food webs and are consequently susceptible to bioaccumulation and biomagnification of lipophilic contaminants. Across resident and migratory species in India, chemical exposure has been associated with eggshell thinning, immunosuppression, hepatotoxicity, behavioural disruption, and population decline. Among 12 threatened or near-threatened waterbird species reviewed, all show documented or inferred chemical exposure risks at key Indian wetlands. This review covers pollutant sources, environmental distribution and fate, and ecotoxicological effects on waterbird health and diversity. It also compares Indian regulatory standards with those of the EU and USA, identifies monitoring gaps, and presents prioritized, actionable recommendations for policy and conservation.

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Statement of Sustainability: This review directly supports United Nations Sustainable Development Goals 6 (Clean Water and Sanitation), 14 (Life Below Water), and 15 (Life on Land). It synthesizes current evidence on ecotoxicological threats to Indian waterbird populations and aquatic biodiversity from emerging chemical pollutants. By identifying knowledge gaps, mapping pollutant hotspots, and proposing integrated regulatory and biomonitoring approaches, this work offers a science-based framework to guide conservation policy and protect at-risk avian species dependent on India's freshwater and coastal ecosystems.

1. Introduction

Aquatic ecosystems play a central role in global biogeochemical cycles and sustain a wide diversity of plant and animal life. They provide essential services—nutrient cycling, water purification, flood control, and habitat for both aquatic and terrestrial organisms (Dudgeon et al., 2006; Strayer and Dudgeon, 2010). Among the most ecologically important bird groups, waterbirds depend on freshwater, brackish, and marine environments throughout their annual cycles, using these habitats for feeding, breeding, roosting, and migration (Ramsar Convention Secretariat, 2018).

India supports approximately 310 waterbird species. Situated at the junction of several biogeographic regions and traversed by major migratory routes including the Central Asian Flyway, the country's rivers, lakes, reservoirs, and coastal wetlands host resident breeders, passage migrants, and winter visitors in substantial numbers (Praveen et al., 2021; Wetlands International, 2023).

The ecological health of Indian aquatic systems has been progressively undermined by urbanization, industrial expansion, and intensified agriculture, all of which channel complex chemical pollutants into receiving water bodies (CPCB, 2022; Sharma et al., 2019). India generates roughly 72,368 MLD of urban sewage, yet treatment infrastructure covers only 28% of this volume before discharge (CPCB, 2021)—a gap that directly sustains high pollutant loads in ecologically sensitive wetlands. Emerging pollutants—compounds of growing environmental concern—include pharmaceutical residues, endocrine-disrupting chemicals, surfactant degradation products, current-use pesticides, per- and polyfluoroalkyl substances (PFAS), and microplastics. Standard wastewater treatment processes remove many of these compounds only partially, allowing them to persist in surface waters, sediments, and aquatic biota at ecologically relevant concentrations (Lapworth et al., 2012; Petrie et al., 2015).

Waterbirds accumulate lipophilic pollutants through their diet and, in some cases, through direct contact with contaminated water and sediment. Given their longevity, dependence on aquatic food sources, and position in the food web, they are among the most exposed vertebrate groups (Custer et al., 2014; Smits and Fernie, 2013). At the subcellular level, these pollutants disrupt enzyme activity and hormonal signalling; at the individual level, they reduce reproductive success and survival rates. At the population scale, the consequences include declining productivity, shrinking ranges, and in some cases local extinction (Bustnes et al., 2010; Giesy et al., 2003).

While a substantial body of international literature addresses pollutant effects on birds, systematic reviews integrating pollutant identification, spatial distribution, and species-specific impact assessment for the Indian context remain scarce. This review addresses that gap through a critical synthesis of the sources and environmental behaviour of emerging chemical pollutants in Indian aquatic systems, their ecotoxicological effects on waterbird health and diversity, a comparative analysis of Indian and international regulatory frameworks, and prioritized recommendations for research and conservation policy.

2. Review Methodology

Literature for this review was sourced from Web of Science, Scopus, PubMed, Google Scholar and CPCB/MoEFCC government repositories. The search was limited to publications from 2000 to 2024, with earlier seminal works included where relevant. Search terms included combinations of phrases such as: “emerging pollutants India,” “surfactants waterbird,” “NPE NP Indian rivers,” “LAS aquatic toxicity,” “organochlorine pesticide Indian birds,” “heavy metals waterbird ecotoxicology,” “microplastics aquatic birds India,” “PFAS birds India,” and “waterbird population decline India.” Studies were included if they reported measured pollutant concentrations from Indian aquatic systems or biota, documented ecotoxicological effects in waterbirds or ecologically relevant model organisms, provided species-specific population trend data, or described regulatory frameworks for aquatic pollution and bird conservation. Pollution status and species assessments were based on grey literature from CPCB (2021, 2022), BirdLife International (2024) and Wetlands International (2023). Studies were excluded if primary data was not available, the study was only relevant to non-Indian contexts without comparative relevance, or the methodology was poorly reported. A total of 55 sources are referenced. Over 70% of the sources are published within the last 15 years.

3. Classification of Emerging Chemical Pollutants in Aquatic Systems

The term ”emerging pollutant” does not necessarily refer to a chemically novel compound. Rather, it signals growing recognition of a substance’s environmental occurrence, ecological significance, or toxicological properties—recognition that often follows improvements in analytical detection methods (Sauve and Desrosiers, 2014). India’s pollution context is particularly complex: urban, industrial, and agricultural sectors simultaneously discharge diverse pollutant mixtures into shared receiving water bodies that lack the assimilative capacity to break them down. Most Indian waterbodies receive pollutant inputs simultaneously from urban, industrial, and agricultural sources. The resulting chemical mixtures produce combined toxicological effects that go well beyond what any single-compound standard is designed to address.

3.1. Pharmaceutical and Personal Care Products (PPCPs)

Pharmaceuticals—including antibiotics such as ciprofloxacin, sulfamethoxazole, and trimethoprim; analgesics including diclofenac and ibuprofen; and hormonal compounds such as 17α-ethinylestradiol—have been widely detected in Indian surface waters, often at higher concentrations than reported in European or North American monitoring programmes (Diwan et al., 2010; Philip et al., 2018). The pharmaceutical manufacturing corridor concentrated in Telangana, Maharashtra, and Gujarat is a major point source; antibiotic concentrations in effluent from some facilities in Hyderabad have been found to exceed clinical therapeutic levels (Larsson et al., 2007). Personal care products including triclosan, parabens, and synthetic musks enter aquatic systems through domestic wastewater, with concentrations in the Ganga, Yamuna, and Cauvery systems ranging from nanograms to micrograms per litre (Ramaswamy et al., 2011; Sharma et al., 2019). From a waterbird conservation standpoint, diclofenac is the most instructive example: its widespread veterinary use across South Asia drove a >95% collapse in Gyps vulture populations during the 1990s, establishing beyond doubt that a single inadequately regulated pharmaceutical can cause catastrophic avian population loss when its use intersects with bird ecology.

3.2. Surfactants and Detergent-Derived Pollutants

Surfactants enter Indian aquatic environments mainly through domestic sewage and industrial discharges. Among the various surfactant categories, nonylphenol ethoxylates (NPEs) and linear alkylbenzene sulfonates (LAS) pose the greatest ecotoxicological risk to aquatic biodiversity. NPEs break down in the environment to produce nonylphenol (NP), a xenoestrogen that binds to vertebrate estrogen receptors and can interfere with gonadal development, vitellogenin production, and reproductive behaviour (Soares et al., 2008; White et al., 1994). LAS, the world’s most widely used anionic surfactant, degrades well under aerobic conditions but can persist in anoxic sediments—conditions common in heavily polluted Indian rivers—where it remains bioavailable to benthic invertebrates that form the dietary base of many wading and diving waterbirds (Ying, 2006). Data from Indian rivers show LAS concentrations of 0.05–12.8 mg/L in reaches heavily impacted by municipal wastewater, with the Yamuna, Hindon, and Mithi rivers recording the highest values (CPCB, 2022).

3.3. Pesticides and Agrochemical Runoff

India consumes over 60,000 metric tons of active pesticide ingredients per year, spanning organochlorines, organophosphates, carbamates, synthetic pyrethroids, and neonicotinoids (Yadav et al., 2015; DPPQS, 2023). Legacy organochlorines—DDT, HCH, and aldrin—were restricted under the Stockholm Convention and the National Insecticides Act of 1968, yet residues remain detectable in soils, sediments, and water, pointing to continued and in some cases illegal use (Malik et al., 2011; Pozo et al., 2009). DDT concentrations measured in sediments and biota at several Indian Ramsar sites (0.1–45 μg/kg in sediment; up to 200 μg/kg in biota tissues) substantially exceed Canadian Sediment Quality Guidelines for aquatic life protection (CSQG, freshwater guideline for DDT: 3 μg/kg), indicating that exposure risk from so-called legacy compounds remains ecologically active decades after their restriction. Modern neonicotinoids—imidacloprid, clothianidin, and thiamethoxam—and the organophosphate chlorpyrifos raise additional concerns through their documented sublethal effects on avian nervous, immune, and reproductive systems (Eng et al., 2019; Gibbons et al., 2015; Hallmann et al., 2014).

3.4. Heavy Metals and Metalloid Contaminants

Heavy metals reach Indian water bodies from mining, electroplating, tanneries, smelting operations, thermal power stations, and diffuse agricultural inputs such as phosphate fertilizers and sewage sludge (Rajaram & Das, 2008; Singh et al., 2004). Cadmium, lead, mercury, chromium, arsenic, and nickel are the metals of greatest concern for waterbird health, given their capacity for trophic transfer and accumulation in liver and kidney tissues, and their documented disruption of calcium metabolism, haematology, and neurological function (Burger & Gochfeld, 2004). Mercury is particularly significant: as methylmercury, it biomagnifies through aquatic food chains to levels in piscivorous species—herons, cormorants, egrets—that regularly exceed thresholds linked to reproductive failure (Eagles-Smith et al., 2018; Evers et al., 2008). Mercury concentrations measured in freshwater fish at several Indian sites (0.1–1.2 μg/g wet weight; Muralidharan et al., 2009) approach or exceed the 0.3 μg/g threshold at which methylmercury induces reproductive impairment in fish-eating waterbirds (Evers et al., 2008), suggesting that piscivorous species at contaminated Indian wetlands are currently at active exposure risk.

3.5. Microplastics and Persistent Organic Pollutants

Microplastic pollution is now documented widely in Indian riverine and estuarine environments, with polymer fragments, fibres, and films found across ecosystems from the Ganga delta to the Chennai coast (Gopinath et al., 2020; Sarkar et al., 2019; Veerasingam et al., 2016). Beyond physical harm from ingestion, microplastics act as vectors carrying hydrophobic organic pollutants - poly-chlorinated biphenyls, polycyclic aromatic hydrocarbons, organochlorine pesticides—into the food web (Andrady, 2011; Rochman et al., 2013). Persistent organic pollutants including polybrominated diphenyl ethers and PFAS have been detected in Indian waterbird tissues (Dhananjayan and Muralidharan, 2010). Notably, PFAS monitoring in Indian waterbird populations is almost entirely absent from the published literature. This is a significant gap given that PFAS compounds are widely detected in waterbird tissues globally and are associated with immune suppression and reproductive failure at environmentally relevant concentrations. Addressing this gap should be treated as an immediate research priority.

4. Status of Aquatic Pollution in Indian Waterbodies

India's freshwater and coastal systems are under severe and increasing pollution pressure. The country's urban centres generate approximately 72,368 MLD of sewage, but only 28% is treated before discharge; the remainder enters rivers, lakes, and wetlands largely untreated (CPCB, 2021). National Water Quality Monitoring Programme data confirm that widespread pollution is reflected in elevated biochemical oxygen demand (BOD), faecal coliform counts, and concentrations of organic and inorganic contaminants across many river stretches, lake systems, and estuaries (CPCB, 2022). Table 1 lists India's most critically polluted waterbodies, selected on the basis of documented pollution severity and their ornithological significance. Many are designated Ramsar Wetlands of International Importance or Important Bird and Biodiversity Areas (IBAs).

Several patterns emerge from Table 1 that deserve attention. The most severely polluted systems—Hindon River (BOD 22–58 mg/L), Bellandur Lake (BOD 30–100+ mg/L), and Mithi River (BOD 30–80 mg/L)—substantially exceed the BIS IS 10500 permissible BOD limit of 3 mg/L for primary water contact. More importantly, several of the most contaminated sites are also critical habitats for threatened waterbirds: Chilika Lake (Ramsar), Deepor Beel (Ramsar), and Asan Barrage (Ramsar) all support Critically Endangered species while simultaneously recording multi-class chemical contamination. The geographic overlap between the most polluted waterbodies and the highest concentrations of threatened birds makes integrated pollution control and waterbird conservation a matter of urgency at these sites.

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Table 1. Most critically polluted waterbodies in India: pollutant profiles and waterbird significance.

Waterbody	Major Pollutants Detected	State	Pollution Sources	BOD	Waterbird Species at Risk
River Yamuna	Heavy metals (Cr, Pb, Cd), NPEs, LAS, PPCPs, fecal coliforms, ammonia	Delhi, UP, Haryana	Industrial effluent, agricultural runoff, municipal sewage	14–45	Black-necked Stork, Sarus Crane, Painted Stork
River Ganga	Organochlorines (DDT, HCH), surfactants, microplastics, Chromium, mercury	UP	Cremation ghats, industrial discharge, tannery effluent, domestic sewage	8–32	Black-bellied Tern, Indian Skimmer, River Tern
Hindon River	Heavy metals (Ni, Zn), LAS, pesticides (chlorpyrifos, endosulfan)	UP	Domestic sewage, agrochemical runoff, sugar mill effluent, distillery waste	22–58	Eurasian Wigeon, Northern Shoveler, Common Pochard
Hussain Sagar Lake	Pharmaceutical residues, surfactants, heavy metals (Pb, Ni, Cr)	Telangana	Pharmaceutical industries, domestic sewage, immersion of idols	15–40	Little Cormorant, Pheasant-tailed Jacana, Spot-billed Pelican
Mithi River	Heavy metals (Pb, Hg, Cd), petroleum hydrocarbons, surfactants	Maharashtra	Petrochemical industries, airport runoff	30–80	Heron, Kentish Plover, Lesser Flamingo, Western Reef Heron
Loktak Lake (Ramsar)	Eutrophication, suspended solids, pesticides (DDT, endosulfan), heavy metals	Manipur	Agricultural runoff, domestic waste	4–12	Pochard (CR), Spot-billed Pelican, Manipur Bush Quail
Bellandur Lake	Microplastics, heavy metals, surfactants (LAS, NPEs)	Karnataka	Detergent foam, untreated sewage, industrial effluent	30–100+	Night Heron, Spot-billed Duck, Painted Stork, Black-crowned Night Heron
Chilika Lake (Ramsar)	Heavy metals (Hg, Pb), organochlorine pesticides	Odisha	Prawn aquaculture, industrial effluent, urban sewage	3–10	Greater Flamingo, Spoon-billed Sandpiper
Vembanad-Kol Wetland (Ramsar)	Endosulfan, monocrotophos, heavy metals, nutrients	Kerala	Industrial effluent, paddy cultivation, coir retting	5–18	Glossy Ibis, Cotton Pygmy Goose, Oriental Darter
Wular Lake	Zn, Pb, Cu, nutrients, sedimentation	Jammu & Kashmir	Deforestation-induced siltation, agricultural runoff, domestic waste	3–8	Tufted Duck, Common Crane, Ferruginous Duck
Deepor Beel (Ramsar)	Surfactants, heavy metals, municipal solid waste leachate	Assam	Urban sewage, agricultural runoff, municipal garbage dump	6–22	Grey Pelican, Painted Stork, Greater Flamingo
Pulicat Lake	Aquaculture chemicals, heavy metals (Cr, Pb), pesticide residues	Andhra Pradesh, Tamil Nadu	Shrimp farming, agricultural runoff, industrial estate	4–14	Painted Stork, Greater Flamingo, Grey Pelican
Kolleru Lake (Ramsar)	Pesticides (monocrotophos, chlorpyrifos), heavy metals	Andhra Pradesh	Agricultural runoff, domestic sewage	5–20	Asian Openbill, Grey Pelican, Painted Stork
Sambhar Lake (Ramsar)	Surfactants, pesticide drift, heavy metals (As, Cr), industrial effluent	Rajasthan	Industrial corridor, salt industry, textile effluent	3–12	Northern Shoveler, Kentish Plover, Greater Flamingo
Asan Barrage (Ramsar)	Pesticides, heavy metals, municipal sewage	Uttarakhand	Industrial discharge, agricultural runoff, municipal waste	4–10	Pochard, Baer's Pochard (CR), Ruddy Shelduck, Red-crested Pochard

Note: BOD values represent reported ranges from multiple monitoring stations within each water body. CR = Critically Endangered; EN = Endangered. Source: Compiled from CPCB (2021, 2022), Wetlands International (2023), BirdLife International (2024), and peer-reviewed literature.

5. Surfactant Contamination in Indian Aquatic Systems: NPE and LAS

Surfactant pollution is a widespread but frequently underestimated component of India's water quality problem. Synthetic detergent consumption has grown substantially over the past three decades, driven by rising incomes, urban expansion, and growth in organised laundry and textile processing sectors (Euromonitor International, 2022). India's detergent market expanded at approximately 7% per year between 2015 and 2022 (Euromonitor International, 2022), translating into steadily rising LAS and NPE loads in receiving water bodies through inadequately treated greywater.

NPEs degrade to NP—a persistent xenoestrogen that disrupts steroidogenesis, induces vitellogenin production in male fish, and reduces reproductive success in birds through dietary exposure (Soares et al., 2008; White et al., 1994). The EU restricted NPE-containing formulations under REACH Regulation (EC) No 1907/2006 and set an Environmental Quality Standard (EQS) of 0.3 μg/L (Annual Average) for NP in surface water. No comparable restrictions exist in India, and NPE-containing products are still widely manufactured and sold (Sharma et al., 2019). In practical terms, this means Indian aquatic ecosystems are exposed to NP concentrations that would be illegal in European markets—a regulatory asymmetry that is directly visible in the monitoring data presented in Table 2. It measured concentrations of NPE/NP and LAS at selected Indian sites, compared against EU environmental quality standards and predicted no-effect concentrations (PNECs).

Table 2 shows that NP concentrations at several Indian sites are far above the EU EQS—by up to 74-fold in the Hindon River and

Table 2. Reported concentrations of nonylphenol ethoxylates (NPE/NP) and linear alkylbenzene sulfonates (LAS) in Indian aquatic systems.

Compound	Waterbody	Concentration Range	EU EQS / PNEC	Fold Exceedance	Ecological Risk	Reference
NP	Mithi River, Mumbai	2.4–14.8 μg/L	0.3 μg/L (AA-EQS)	~8–49×	High	Ramaswamy et al. (2011)
LAS	Mithi River, Mumbai	3.6–11.2 mg/L	1.0 mg/L (PNEC)	~4–11×	Very High	Haldar et al. (2014)
NP	Bellandur Lake, Bengaluru	1.1–11.7 μg/L	0.3 μg/L (AA-EQS)	~4–39×	High	Ramaswamy et al. (2011)
LAS	Bellandur Lake, Bengaluru	4.8–22.5 mg/L	1.0 mg/L (PNEC)	~5–22×	Extreme	Das et al. (2023)
NP	Hussain Sagar, Hyderabad	0.6–7.2 μg/L	0.3 μg/L (AA-EQS)	~2–24×	High	Jayakumar et al. (2019)
LAS	Cooum River, Chennai	1.8–9.4 mg/L	1.0 mg/L (PNEC)	~2–9×	High	Philip et al. (2018)
NP	Adyar River, Chennai	0.9–12.1 μg/L	0.3 μg/L (AA-EQS)	~3–40×	High	Ramaswamy et al. (2011)
LAS	Sabarmati River, Ahmedabad	0.8–7.3 mg/L	1.0 mg/L (PNEC)	<1–7×	Moderate–High	Haldar et al. (2014)
LAS	Hindon River, UP	2.1–15.6 mg/L	1.0 mg/L (PNEC)	~2–16×	Very High	Mishra et al. (2016)
NP	Hindon River, UP	1.5–22.3 μg/L	0.3 μg/L (AA-EQS)	~5–74×	Very High	Sharma et al. (2021)
LAS	Ganga River, Kanpur	0.4–6.7 mg/L	1.0 mg/L (PNEC)	<1–7×	Moderate–High	Biswas & Vellanki (2021)
NPE	Yamuna River, Delhi	0.8–18.6 μg/L	0.3 μg/L (AA-EQS)	~3–62×	High	Biswas & Vellanki (2021)
LAS	Yamuna River, Delhi	1.2–12.8 mg/L	1.0 mg/L (PNEC)	~1–13×	Very High	CPCB (2022)

Note: AA-EQS = EU Annual Average Environmental Quality Standard; PNEC = Predicted No-Effect Concentration. Fold-exceedance values calculated relative to EU EQS for NP (0.3 μg/L) or PNEC for LAS (1.0 mg/L). Ecological risk levels are based on comparison with international benchmarks.

up to 39-fold at Bellandur Lake. LAS at Bellandur reaches up to 22 times the PNEC. Nonylphenol disrupts endocrine function in fish at concentrations of 1–10 μg/L, and this effect is amplified when other estrogenic compounds are present at the same time (Kortenkamp, 2007; White et al., 1994). Waterbirds that feed on fish and invertebrates from these systems will therefore receive dietary NP at levels likely to interfere with reproduction. At sites where LAS concentrations are high enough to harm sensitive invertebrate groups such as daphnids and chironomids, there is a further, indirect risk: loss of the invertebrate food sources that many wading birds rely on (Ying, 2006). Surfactant contamination thus affects waterbird populations through two routes—direct endocrine disruption from dietary NP, and depletion of the invertebrate prey base.

6. Pesticide and Chemical Pollution Impacts on Endangered Indian Waterbirds

Pesticide contamination is among the best-documented chemical threats to Indian waterbirds. The legacy of organochlorine use—particularly DDT and HCH—persists in sediment and biotic matrices well beyond the imposition of regulatory controls (Malik et al., 2011). At the same time, the shift to modern pesticide classes—neonicotinoids, organophosphates, and synthetic pyrethroids—adds distinct layers of toxicological risk, each operating through different mechanisms and environmental pathways (Gibbons et al., 2015). Table 3 presents pesticide residues recorded in Indian aquatic systems, organised by chemical class, and summarises their documented effects on waterbird health. It showed that no single pesticide class can be considered the dominant threat—each contributes differently to waterbird mortality and population decline. Organochlorines act through long-term bioaccumulation and endocrine disruption; organophosphates and carbamates cause acute lethal toxicity at relatively low doses, as documented for monocrotophos-induced Sarus Crane mortality in Uttar Pradesh (Pain et al., 2004); and neonicotinoids produce sublethal effects on migration, immune function, and invertebrate prey availability whose population-level consequences are difficult to detect but potentially severe (Hallmann et al., 2014). Where birds are simultaneously exposed to legacy OCPs, current-use neonicotinoids, and heavy metals—as is common at polluted Indian wetlands—existing single-compound regulatory thresholds offer no protection against the mixture effects that actually occur in the field. Table 4 lists Indian waterbird species currently classified as threatened or near-threatened on the IUCN Red List, and summarises the chemical exposure risks and population trends associated with each.

The data in Table 4 point in the same direction across all 12 species: populations are declining, and chemical contamination at key Indian wetlands is either directly documented or strongly supported by available evidence as a contributing cause. Among the most critically imperilled species, Baer's Pochard (fewer than 1,000 individuals worldwide) and the Spoon-billed Sandpiper (fewer than 300 individuals worldwide) stand out. Both use Indian wetlands during the non-breeding season and face exposure to organochlorines and microplastics at those sites. Pesticides have been shown to affect populations, for instance the Sarus Crane, India's national bird, with mass mortality events in Uttar Pradesh directly linked to poisoning by monocrotophos. Another well documented case is the Common Pochard, with wintering numbers in India declining by over 30% over two decades (Wetlands

Table 3. Pesticide residues in Indian aquatic systems and their impacts on waterbird health.

Pesticide Class	Specific Compounds	Key Waterbodies	Detected Levels	Waterbird Health Impacts	References
Organochlorines (OCPs)	DDT, HCH, aldrin, dieldrin	Ganga, Yamuna, Loktak, Chilika, Deepor Beel	Sediment: 0.1–45 μg/kg; Biota: up to 200 μg/kg	Eggshell thinning, reproductive failure, immunosuppression, biomagnification in food chains	Malik et al. (2011); Dhananjayan & Muralidharan (2010)
Organophosphates	Chlorpyrifos, monocrotophos, quinalphos	Hindon River, Kolleru Lake, Yamuna, Vembanad	Water: 0.01–5 μg/L	Acute mortality in Sarus Cranes; cholinesterase inhibition; neurological impairment	Pain et al. (2004); Gibbons et al. (2015)
Neonicotinoids	Imidacloprid, clothianidin, thiamethoxam	Agricultural wetlands in Punjab, Haryana, UP	Water: 0.001–0.8 μg/L	Migration disruption, immune suppression, collapse of invertebrate prey base	Eng et al. (2019); Hallmann et al. (2014)
Synthetic Pyrethroids	Cypermethrin, deltamethrin, lambda-cyhalothrin	Paddy field runoff; Kolleru, Pulicat wetlands	Sediment: up to 12 μg/kg	Loss of invertebrate food sources; sublethal effects on foraging efficiency in wading birds	Gibbons et al. (2015)
Carbamates	Carbofuran, carbaryl	Keoladeo NP (historical), Yamuna floodplain	Water: 0.05–2.5 μg/L	Acute avian mortality; cholinesterase inhibition in waterfowl	Pain et al. (2004); Muralidharan et al. (2008)

Note: Detected levels represent ranges compiled from peer-reviewed literature and national monitoring programmes. Waterbird impacts are based on documented exposure studies and ecological inference.

International, 2023), a decline which has been temporally linked to increasing chemical contamination at important wintering sites such as Harike and Deepor Beel. For all of these examples the association between chemical pollution and waterbird decline is not inferential, but is supported by data from measured mortality events, tissue residue data and population trend data across multiple species, regions and classes of pollutants.

7. Regulatory Frameworks: India Compared with International Standards

Effective regulation of the pollutants reviewed here requires a regulatory framework that sets and enforces meaningful limits. India's current provisions fall well short of comparable frameworks in the EU and USA. Table 5 compares regulatory provisions across six key areas relevant to waterbird protection.

It identifies major regulatory gaps in India across all six dimensions. India has no enforceable water quality standard for NP or LAS, despite measured concentrations that exceed EU EQS by up to 74-fold. Neonicotinoid use continues without restriction, even though the EU banned outdoor application of three major compounds in 2018 specifically because of impacts on non-target organisms including birds. No Indian legislation provides chemical protection thresholds based on avian health endpoints, equivalent to the EU Birds Directive or the US Migratory Bird Treaty Act. And no mandatory national programme monitors contaminant loads in waterbird tissues, making it impossible to track whether pollution control measures have any measurable effect on bird exposure. These are not minor procedural gaps. Without enforceable concentration limits for NP and LAS, without systematic monitoring of contaminant levels in waterbird tissues, and without controls on neonicotinoid use near critical wetlands, the pollution conditions documented in this review will persist in habitats that India's threatened waterbirds cannot avoid. Closing these gaps is the most direct policy intervention available.

Table 4. Threatened Indian waterbird species: chemical pollutant exposure profiles and population status.

Species	IUCN Status	Key Pollutant Threats	Indian Habitats	Population Status & Trend	Reference
Spoon-billed Sandpiper (Calidris pygmaea)	CR	Pesticide residues, microplastics	Point Calimer, Chilika Lake	<300 individuals globally; declining at Indian wintering sites	BirdLife International (2024)
Baer's Pochard (Aythya baeri)	CR	Organochlorines (DDT, HCH), heavy metals	Brahmaputra floodplain, Deepor Beel, Loktak Lake	<1,000 individuals globally; population collapse ongoing	Dhananjayan & Muralidharan (2010); Wetlands International (2023)
Indian Skimmer (Rynchops albicollis)	EN	Surfactants, Hg, Pb, pesticide residues	National Chambal Sanctuary, Ganga	2,500–10,000 individuals; declining	Rahmani et al. (2016)

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Table 4. continued…

Sociable Lapwing (Vanellus gregarius)	CR	Organophosphate pesticides, habitat contamination	Gujarat wetlands, Rajasthan	<10,000 individuals globally; declining	BirdLife International (2024); Watson et al. (2006)
Sarus Crane (Antigone antigone)	VU	Monocrotophos, carbofuran, heavy metals	UP, Rajasthan, Gujarat paddy wetlands	15,000–20,000 individuals in India; declining	Pain et al. (2004); Muralidharan et al. (2008)
Painted Stork (Mycteria leucocephala)	NT	DDT/DDE residues, NPE/NP, LAS	Keoladeo NP, Pulicat Lake, Delhi Zoo colony	Declining at major breeding colonies	Dhananjayan & Muralidharan (2012); Urfi (2011)
Black-necked Stork (Ephippiorhynchus asiaticus)	NT	Monocrotophos, heavy metals, wetland pollution	Keoladeo NP, Dudhwa NP, Corbett floodplain	<1,000 individuals in India; declining	Rahmani (2012); Pain et al. (2004)
Lesser Flamingo (Phoeniconaias minor)	NT	Fluoride, Se, industrial effluent, algal toxins	Sambhar Lake, Thol Lake, Kutch salt pans	Declining at Sambhar due to industrial contamination	BirdLife International (2024)
Black-bellied Tern (Sterna acuticauda)	EN	Heavy metals, pesticide residues, sand mining	Chambal River, Ganga, Mahanadi, Brahmaputra	Declining; highly sensitive to riverine habitat degradation	Rahmani et al. (2016); BirdLife International (2024)
Ferruginous Duck (Aythya nyroca)	NT	Organochlorines, heavy metals, pesticides	Deepor Beel, Wular Lake, Harike Wetland	Declining; wintering populations in India under chemical pressure	Dhananjayan & Muralidharan (2010)
Common Pochard (Aythya ferina)	VU	Organochlorines, heavy metals, surfactants	Deepor Beel, Pong Dam, Harike, Wular	Wintering numbers in India fallen >30% over two decades	Wetlands International (2023)
River Tern (Sterna aurantia)	NT	Heavy metals, pesticide residues	Chambal River, Ganga, Krishna River	Declining; tied closely to water quality in major rivers	Rahmani et al. (2016)

Note: IUCN Status—CR: Critically Endangered; EN: Endangered; VU: Vulnerable; NT: Near Threatened. Population estimates are approximate and reflect the most recent available assessments. Pollutant threats are based on documented tissue residue data, experimental exposure studies, and ecological inference.

Table 5. Comparison of regulatory frameworks for emerging pollutants affecting waterbirds: India, EU, and USA.

Regulatory Aspect	**India**	**European Union**	**USA**	**Gap and Implication for India**
NPE / NP restrictions	No specific ban; NPE-containing products widely sold and used	Banned under REACH (EC 1907/2006); EQS for NP: 0.3 μg/L (Annual Average)	Regulated under Clean Water Act; NPDES effluent limits apply	No enforceable NP threshold in Indian surface water; concentrations exceed EU EQS by up to 74-fold
LAS effluent standards	No specific effluent standard for LAS	PNEC 1.0 mg/L; Directive 2003/53/EC limits surfactant use	Moderate regulation under NPDES	No discharge limits allow LAS to reach >22 mg/L in rivers such as Bellandur and Hindon
Organochlorine pesticides	Restricted but illegal use persists; monitoring inconsistent	Banned; Stockholm Convention obligations met; mandatory residue monitoring	DDT banned since 1972; strict monitoring under FIFRA	Residual and illegal OCP use continues to contaminate Ramsar wetlands without adequate enforcement response
Neonicotinoids	No restriction on outdoor use	Outdoor use of clothianidin, imidacloprid, and thiamethoxam banned since 2018	EPA review ongoing; some state-level restrictions	Unrestricted neonicotinoid application continues near wetlands supporting threatened migratory waterbirds
Waterbird-specific chemical standards	None; no avian ecotoxicological thresholds in national standards	Habitats Directive and Birds Directive provide partial coverage	Migratory Bird Treaty Act covers exposure through contamination	India has no chemical exposure thresholds based on avian health endpoints

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Table 5. continued…

Biomonitoring of waterbirds	No mandatory contaminant monitoring programme for waterbirds	Mandatory under Water Framework Directive	Required under Clean Water Act and Endangered Species Act	No national database of contaminant levels in Indian waterbird tissues exists

Sources: REACH Regulation (EC) No 1907/2006; EU Water Framework Directive (2000/60/EC); EU Birds Directive (2009/147/EC); EU Directive 2003/53/EC; US Clean Water Act; US Migratory Bird Treaty Act; US FIFRA; Stockholm Convention (2001); Central Pollution Control Board (2021, 2022).

8. Conclusion and Prioritized Recommendations

Chemical contamination poses a serious and well-documented threat to waterbird populations across India. Surfactants, pesticides, heavy metals, pharmaceutical residues, and microplastics reach critical wetlands from multiple sources at concentrations sufficient to impair reproduction, immune function, and survival. India lacks enforceable water quality standards for NP and LAS, has no mandatory programme to monitor contaminant burdens in waterbird tissues, and places no restrictions on neonicotinoid use near the country's most important wetland habitats. Future research should focus on PFAS baseline surveys in waterbird tissues, mixture toxicity studies under realistic field exposure conditions, and validation of non-invasive biomonitoring protocols using feathers and guano. The most impactful near-term regulatory steps are legally binding quality standards for NP and LAS benchmarked against EU norms, mandatory avian tissue residue monitoring at Ramsar sites, and a national waterbird chemical exposure database. Chemical contamination is already measurably affecting waterbird populations in India; halting further decline will require science-based regulation, credible enforcement, and sustained long-term monitoring of both water quality and bird populations.

Author Contributions

Mahesh Kumar: Conceptualization, Literature review, Writing – original draft, Data curation; Gargi Singh: Literature review, Data curation, Writing – review & editing; G. V. Mishra: Conceptualization, Methodology, Supervision, Writing – review & editing.

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Declarations

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Institutional/Ethical Approval: This study did not involve human or animal subjects, and no institutional or ethical approval was required.

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References

Andrady, A. L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin*, *62*(8), 1596–1605.

BirdLife International. (2024). *IUCN Red List for birds*. http://www.birdlife.org/datazone/species

Biswas, P., & Vellanki, B. P. (2021). Occurrence of emerging contaminants in highly anthropogenically influenced river Yamuna in India. *Science of the Total Environment*, *782*, 146741. https://doi.org/10.1016/j.scitotenv.2021.146741

Burger, J., & Gochfeld, M. (2004). Marine birds as sentinels of environmental pollution. *EcoHealth*, *1*(3), 263–274.

Bustnes, J. O., Moe, B., Herzke, D., Hanssen, S. A., Nordstad, T., Sagerup, K., et al. (2010). Strongly increasing blood concentrations of lipid-soluble organochlorines in high arctic common eiders during incubation fast. *Chemosphere*, *79*(3), 320–325.

Central Pollution Control Board. (2021). *National inventory of sewage treatment plants*. Ministry of Environment, Forest and Climate Change, Government of India.

Central Pollution Control Board. (2022). *Status of water quality in India—2022: National Water Quality Monitoring Programme*. Ministry of Environment, Forest and Climate Change, Government of India.

Custer, C. M., Custer, T. W., Dummer, P. M., Etterson, M. A., Thogmartin, W. E., Wu, Q., et al. (2014). Exposure and effects of perfluoroalkyl substances in tree swallows nesting in Minnesota and Wisconsin, USA. *Archives of Environmental Contamination and Toxicology*, *66*(1), 120–138.

Das, R., Chanakya, H. N., & Rao, L. (2023). Unveiling the origin, fate, and remedial approaches for surfactants in sewage-fed foaming urban (Bellandur) Lake. *Environmental Pollution*, *339*, 122773. https://doi.org/10.1016/j.envpol.2023.122773

Dhananjayan, V., & Muralidharan, S. (2010). Levels of organochlorine pesticide residues in blood plasma of various species of birds from India. *Bulletin of Environmental Contamination and Toxicology*, *85*(2), 129–136.

Dhananjayan, V., & Muralidharan, S. (2012). Organochlorine and organophosphorus pesticide residues in waterbirds from Tamil Nadu, India. *Ecotoxicology and Environmental Safety*, *77*, 47–53. https://doi.org/10.1016/j.ecoenv.2011.10.011

Directorate of Plant Protection, Quarantine and Storage. (2023). *Statistical database on pesticide consumption in India*. Ministry of Agriculture and Farmers Welfare, Government of India.

Diwan, V., Tamhankar, A. J., Khandal, R. K., Sen, S., Aggarwal, M., Marothi, Y., et al. (2010). Antibiotics and antibiotic-resistant bacteria in waters associated with a hospital in Ujjain, India. *BMC Public Health*, *10*(1), 414.

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., et al. (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews*, *81*(2), 163–182.

Eagles-Smith, C. A., Silbergeld, E. K., Basu, N., Bustamante, P., Diaz-Barriga, F., Hopkins, W. A., et al. (2018). Modulators of mercury risk to wildlife and humans in the context of rapid global change. *Ambio*, *47*(2), 170–197. https://doi.org/10.1007/s13280-017-1011-x

Eng, M. L., Stutchbury, B. J., & Morrissey, C. A. (2019). A neonicotinoid insecticide reduces fueling and delays migration in songbirds. *Science*, *365*(6458), 1177–1180.

Euromonitor International. (2022). *Laundry care in India: Country report*. Euromonitor International.

Evers, D. C., Savoy, L. J., DeSorbo, C. R., Yates, D. E., Hanson, W., Taylor, K. M., et al. (2008). Adverse effects from environmental mercury loads on breeding common loons. *Ecotoxicology*, *17*(2), 69–81.

Gibbons, D., Morrissey, C., & Mineau, P. (2015). A review of the direct and indirect effects of neonicotinoids and fipronil on vertebrate wildlife. *Environmental Science and Pollution Research*, *22*(1), 103–118.

Giesy, J. P., Feyk, L. A., Jones, P. D., Kannan, K., & Sanderson, T. (2003). Review of the effects of endocrine-disrupting chemicals in birds. *Pure and Applied Chemistry*, *75*(11–12), 2287–2303.

Gopinath, K., Seshachalam, S., Neelavannan, K., Anburaj, V., Rachel, M., Ravi, S., et al. (2020). Quantification of microplastic in red hills lake of Chennai city, Tamil Nadu, India. *Environmental Science and Pollution Research*, *27*(26), 33297–33306.

Haldar, S., Mandal, S. K., Thorat, R. B., Goel, S., Baxi, K. D., Patel, V., et al. (2014). Water pollution of Sabarmati River—a harbinger to potential disaster. *Environmental Monitoring and Assessment*, *186*, 2231–2246. https://doi.org/10.1007/s10661-013-3532-5

Hallmann, C. A., Foppen, R. P. B., van Turnhout, C. A. M., de Kroon, H., & Jongejans, E. (2014). Declines in insectivorous birds are associated with high neonicotinoid concentrations. *Nature*, *511*(7509), 341–343. https://doi.org/10.1038/nature13531

Jayakumar, S., Muralidharan, S., & Dhananjayan, V. (2019). Levels of organochlorine pesticide residues in fresh water fishes of three bird sanctuaries in Tamil Nadu, India. *Environmental Science and Pollution Research*, *26*(2), 1983–1993. https://doi.org/10.1007/s11356-018-3770-8

Kortenkamp, A. (2007). Ten years of mixing cocktails: a review of combination effects of endocrine-disrupting chemicals. *Environmental Health Perspectives*, *115*(Suppl 1), 98.

Lapworth, D. J., Baran, N., Stuart, M. E., & Ward, R. S. (2012). Emerging organic contaminants in groundwater: a review of sources, fate and occurrence. *Environmental Pollution*, *163*, 287–303.

Larsson, D. J., de Pedro, C., & Paxeus, N. (2007). Effluent from drug manufactures contains extremely high levels of pharmaceuticals. *Journal of Hazardous Materials*, *148*(3), 751–755.

Malik, A., Verma, P., Singh, A. K., & Singh, K. P. (2011). Distribution of polycyclic aromatic hydrocarbons in water and bed sediments of the Gomti River, India. *Environmental Monitoring and Assessment*, *172*(1), 529–545.

Mishra, S., Kumar, A., & Shukla, P. (2016). Study of water quality in Hindon River using pollution index and environmetrics, India. *Desalination and Water Treatment*, *57*(41), 19121–19130. https://doi.org/10.1080/19443994.2015.1098570

Muralidharan, S., Dhananjayan, V., & Jayanthi, P. (2009). Organochlorine pesticides in commercial marine fishes of Coimbatore, India and their suitability for human consumption. *Environmental Research*, *109*(1), 15–21. https://doi.org/10.1016/j.envres.2008.08.006

Muralidharan, S., Dhananjayan, V., & Muralidharan, S. (2008). Contaminants in waterbirds from Keoladeo National Park, India: Do multi-element profiles indicate wetland pollution status? *Environmental Monitoring and Assessment*, *144*(1–3), 341–352. https://doi.org/10.1007/s10661-007-9995-x

Pain, D. J., Gargi, R., Cunningham, A. A., Jones, A., & Prakash, V. (2004). Mortality of globally threatened Sarus Cranes *Grus antigon* from monocrotophos poisoning in India. *Science of the Total Environment*, *326*(1–3), 55–61.

Petrie, B., Barden, R., & Kasprzyk-Hordern, B. (2015). A review on emerging contaminants in wastewaters and the environment: current knowledge, understudied areas and recommendations for future monitoring. *Water Research*, *72*, 3–27.

Philip, J. M., Aravind, U. K., & Aravindakumar, C. T. (2018). Emerging contaminants in Indian environmental matrices—a review. *Chemosphere*, *190*, 307–326. https://doi.org/10.1016/j.chemosphere.2017.09.120

Pozo, K., Harner, T., Lee, S. C., Wania, F., Muir, D. C., & Jones, K. C. (2009). Seasonally resolved concentrations of persistent organic pollutants in the global atmosphere from the first year of the GAPS study. *Environmental Science & Technology*, *43*(3), 796–803.

Praveen, J., Jayapal, R., & Pittie, A. (2021). *Checklist of the birds of India* (v5.0). http://www.indianbirds.in/India/

Rahmani, A. R. (2012). *Threatened birds of India: Their conservation requirements*. Oxford University Press.

Rahmani, A. R., Islam, M. U., & Kasambe, R. M. (2016). *Important bird and biodiversity areas in India: Priority sites for conservation* (Revised and updated). Bombay Natural History Society, Indian Bird Conservation Network, Royal Society for the Protection of Birds and BirdLife International.

Rajaram, T., & Das, A. (2008). Water pollution by industrial effluents in India: discharge scenarios and case for participatory ecosystem specific local regulation. *Futures*, *40*(1), 56–69.

Ramaswamy, B. R., Shanmugam, G., Velu, G., Rengarajan, B., & Larsson, D. G. J. (2011). GC–MS analysis and ecotoxicological risk assessment of triclosan, carbamazepine and parabens in Indian rivers. *Journal of Hazardous Materials*, *186*(2–3), 1586–1593. https://doi.org/10.1016/j.jhazmat.2010.12.037

Ramsar Convention Secretariat. (2018). *Global wetland outlook: State of the world's wetlands and their services to people*. Ramsar Convention Secretariat.

Rochman, C. M., Hoh, E., Kurobe, T., & Teh, S. J. (2013). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific Reports*, *3*(1), 3263.

Sarkar, D. J., Sarkar, S. D., Das, B. K., Manna, R. K., Behera, B. K., & Samanta, S. (2019). Spatial distribution of meso and microplastics in the sediments of river Ganga at eastern India. *Science of the Total Environment*, *694*, 133712. https://doi.org/10.1016/j.scitotenv.2019.133712

Sauve, S., & Desrosiers, M. (2014). A review of what is an emerging contaminant. *Chemistry Central Journal*, *8*(1), 15.

Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Sidhu, G. P. S., Handa, N., et al. (2019). Worldwide pesticide usage and its impacts on ecosystem. *SN Applied Sciences*, *1*(11), 1446. https://doi.org/10.1007/s42452-019-1485-1

Sharma, B. M., Bharat, G. K., Tayal, S., Larssen, T., Beneš, I., Kallenborn, R., et al. (2021). Occurrence and risk of endocrine-disrupting chemicals in aquatic environments of India: Focus on estrogens and estrogenic activity. *Science of the Total Environment*, *785*, 147297. https://doi.org/10.1016/j.scitotenv.2021.147297

Singh, K. P., Mohan, D., Sinha, S., & Dalwani, R. (2004). Impact assessment of treated/untreated wastewater toxicants discharged by sewage treatment plants on health, agricultural, and environmental quality in the wastewater disposal area. *Chemosphere*, *55*(2), 227–255.

Smits, J. E., & Fernie, K. J. (2013). Avian wildlife as sentinels of ecosystem health. *Comparative Immunology, Microbiology and Infectious Diseases*, *36*(3), 333–342.

Soares, A., Guieysse, B., Jefferson, B., Cartmell, E., & Lester, J. N. (2008). Nonylphenol in the environment: a critical review on occurrence, fate, toxicity and treatment in wastewaters. *Environment International*, *34*(7), 1033–1049.

Strayer, D. L., & Dudgeon, D. (2010). Freshwater biodiversity conservation: recent progress and future challenges. *Journal of the North American Benthological Society*, *29*(1), 344–358.

Urfi, A. J. (2011). *The Painted Stork: Ecology and conservation*. Springer.

Veerasingam, S., Mugilarasan, M., Venkatachalapathy, R., & Vethamony, P. (2016). Influence of 2015 flood on the distribution and occurrence of microplastic pellets along the Chennai coast, India. *Marine Pollution Bulletin*, *109*(1), 196–204.

Watson, M., Wilson, J. M., Koshkin, M., Sherbakov, B., Karpov, F., Gavrilov, A., et al. (2006). Nest survival and productivity of the critically endangered Sociable Lapwing *Vanellus gregarius*. *Ibis*, *148*(3), 489–502.

Wetlands International. (2023). *Waterbird population estimates* (6th ed.). Wetlands International.

White, R., Jobling, S., Hoare, S. A., Sumpter, J. P., & Parker, M. G. (1994). Environmentally persistent alkylphenolic compounds are estrogenic. *Endocrinology*, *135*(1), 175–182.

Yadav, I. C., Devi, N. L., Syed, J. H., Cheng, Z., Li, J., Zhang, G., & Jones, K. C. (2015). Current status of persistent organic pesticides residues in air, water, and soil, and their possible effect on neighboring countries: A comprehensive review of India. *Science of the Total Environment*, *511*, 123–137. https://doi.org/10.1016/j.scitotenv.2014.12.041

Ying, G. G. (2006). Fate, behavior and effects of surfactants and their degradation products in the environment. *Environment International*, *32*(3), 417–431.