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A review on pesticide contamination in Indian water bodies

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Abstract
India is facing a concerning environmental challenge driven by rapid population growth, industrialization, and intensive agricultural practices. This issue is even more worsened by the widespread use of pesticides, which poses significant toxicity risks. Several categories of pesticides, which includes organochlorines, organophosphates, carbamates, and pyrethroids have become essential and used vastly in Indian agriculture. One of the critical consequences of uncontrolled use of pesticides is the pollution of India's mainstream rivers. Pesticide pollution has been evident and studied in mainstream rivers of India, such as the Ganges, Yamuna, Cauvery and Gomti posing risks via leaching and runoff from the crop fields. This review sheds light on the depth of the crisis, highlights the critical extent of pesticide residues present in mainstream waterbodies. Ultimately, the goal is to ensure the longevity of the Indian waterbodies and ecosystem, also to secure a sustainable environment for present and future generations.

Keywords: Pesticide, mainstream rivers, water pollution, Indian scenario

1. Introduction
Pesticides, a prominent class of pollutants in aquatic systems, often arise from human activities and migrate from application sites to diverse ecosystems (De Araújo *et al*. 2022) [13]. These toxic residues bio-accumulate through the food chain, impairing flora and fauna at various levels (Arslan *et al*. 2021) [6] with proven endocrine-disrupting properties, they even impact reproductive behaviour. This bioaccumulation disrupts ecological balance and biodiversity, a critical concern given the significant consumption of riverine fish by human populations, posing potential food safety risks (Schwarzenbach *et al*. 2006) [46].

Mainly there are four different groups of pesticides organochlorines (OCPs), organophosphates (OPs), carbamates (CAR), and pyrethroids (PYR). OCPs constitute an early pesticide group with broad-spectrum insecticidal properties for agricultural and domestic pest control. These compounds endure in the environment due to their slow degradation. They disrupt insect nervous systems, inducing convulsions and paralysis that lead to mortality. Examples include DDT, lindane, endosulfan, aldrin, dieldrin, and chlordane. Despite bans in developed nations, DDT remains in use for malaria control in many tropical countries, including India. Organophosphates, another broad-spectrum group, function as stomach, contact, and nervous poisons. Parathion, Malathion, diazinon, and glyphosate are commonly employed pesticides that come under organophosphate family (Karunarathne *et al*., 2021) [27]. Carbamates group of pesticides that include carbaryl, carbofuran, propoxur, and aminocarb etc. share similarities with organophosphates in structure and action, although originating differently (Drum *et al*., 1990) [16]. Pyrethroids and neonicotinoids stand out as prominent pesticides with heightened toxicity towards insects and fish, yet they exhibit relatively lower levels of toxicity when it comes to mammals and birds. As a result, synthetic pyrethroids and neonicotinoids are regarded as some of the safest insecticides for use in food production. Among synthetic pyrethroids, cypermethrin and permethrin stand out as the most extensively utilized pesticides (Rehman *et al*. 2014) [44]. Despite India's minimal pesticide use per hectare, residues from these chemicals persist in both terrestrial and aquatic ecosystems. Significantly pesticide residues can be found in the water and sediments of major rivers such as the Ganges, Yamuna, and Cauvery, which bioaccumulate in the food chain. Agricultural runoff intensifies non-target species and negatively impact ecosystems.

This review comprehensively examines the various classifications of pesticides and their presence in the major river bodies of India. It offers a comparative analysis of each group of pesticides across the major rivers and lakes that have been studied so far. Additionally, the review discusses the hazardous impact that pesticides have been reported and explores potential measures to control the uncontrolled usage of these pesticides overall, the review provides a thorough overview of the pesticide situation in India, focusing on its implications for water bodies, particularly major rivers. It highlights the need for a better understanding of pesticide contamination and its effects on aquatic ecosystems and human health. Furthermore, it highlights the importance of implementing strategies to mitigate the adverse effects of pesticides and promote sustainable pesticide management practices in order to safeguard both the environment and public health.

2. Pesticide consumption in India

Global consumption of pesticides is around 2 million tons with the highest consumption of usage in Europe for 45%, USA 24%, and rest of the world for 25% of consumption (Abhilash *et al*., 2009) [1]. This highlights that the most developed regions, including North America, Western Europe, and Japan, where pesticide use is extensive, collectively consume three-quarters of the world's total pesticide supply (USEPA. 2009) [52]. In many developing countries, including India, the scenario is different, with a greater emphasis on the use of insecticides, leading to elevated levels of acute risks.

India initiated pesticide usage in 1948 by introducing DDT to combat malaria and benzene hexachloride (BHC) for locust control (Gupta., 2004) [22]. Its application was later extended to agriculture in 1949. Presently, India's contribution to the global pesticide consumption stands at around 3%, experiencing an annual growth rate of 2-5% (Bhadbhade *et al*., 2002) [7]. These pesticides are overall (67%) utilized in agriculture and horticulture (Puri, 1998) [40], and with respect to public health accounting for approximately (8.5%) (World Bank, 1997) [53]. Despite this substantial increase, India's per-hectare domestic pesticide usage remains relatively modest at just 0.5 kg, diverging notably from countries like Taiwan, China, Japan, the Netherlands, the USA, and the United Kingdom, where it ranges from 5.0 kg to 17.0 kg per hectare (Chauhan and Singhal, 2006) [12].

Pesticide usage in India diverges significantly from global trends. In India, the majority of pesticide consumption, at 76%, is attributed to insecticides, while herbicides make up 10%, and fungicides 13%. This stands in contrast to the rest of the world, where herbicides (30%) and fungicides (21%) consumption has a larger share (Mathur, 1999) [35]. Some noteworthy pesticides commonly used in India are Monocrotophos, endosulfan, glyphosate, chlorpyriphos, methyl parathion, cypermethrin, mancozeb, paraquat, butachlor (Bhushan *et al*., 2013) [8]. Hexachlorocyclohexanes (HCHs) and (Dichloro-diphenyl-trichloroethane) DDTs together constitute a substantial portion, comprising two-thirds of India's overall pesticide usage, serving both agricultural and public health purposes (Kumari *et al*., 2001) [32].

In terms of volume, OCPs constitute 40% of pesticide consumption, trailed by organophosphates at 30%, carbamates at 15%, synthetic pyrethroids at 10%, with the remaining 5% spread across various other categories. When considering value, organophosphates hold the largest share at 50%, followed by synthetic pyrethroids at 19%, OCPs at 16%, carbamates at 4%, and bio-pesticides at 1% (SEEP, 2010) [47].

3. Methodology

This review article is focused on assessing the extent of pesticide pollution in major river bodies and lakes across India. To achieve this objective, a systematic approach was adopted. Initially, keywords like "pesticide pollution in Indian rivers and lakes" is used to search the literature reviews in databases such as Google Scholar, PubMed, and Science Direct within the timeframe from 2002-2023. The search approach originally yielded a total of 108 articles. After conducting a screening process to determine relevance, a total of 53 articles were chosen for the current study.

Data regarding pesticide occurrence in major rivers and lakes were precisely collected from the above-mentioned sources. This included information on the total amount of pesticides detected, specific pesticide groups identified, and the particular sites within the river or lake where the studies were conducted. In cases where multiple studies examined pesticide accumulation at different sites within the same river or lake, the average values of pesticide

systems is concerning, particularly due to the proximity of fertile agricultural lands along riverbanks. This increases the risk of agricultural runoff contaminating water bodies. Notably, Chilika Lake in Odisha, Asia's largest coastal lagoon, faced significant pesticide contamination with 25% of OCPs including HCH isomers, DDD, DDE, and heptachlor. Similarly, the Tamiraparani River basin in Tamil Nadu exhibited heavy OCP contamination, characterized by compounds like heptachlor, OP′-DDE, dieldrin, OP′-DDD, and mirex. Their persistence in the environment, due to chemical properties like fat solubility and stability, exacerbates their impact. Concentrations of 17 targeted OCPs in surface water samples ranged from 0.1-79.9 ng/l (Agarwal *et al*., 2015; Nag *et al*., 2020) [2, 38].

A study was conducted to estimate the concentrations were calculated to ensure comprehensive analysis. Furthermore, when studies were conducted across various seasons, preference was given to the most recent data on pesticide detection. This study aimed to provide an up-to-date representation of pesticide pollution levels in Indian water bodies. The results were then analysed, data are normalized and presented graphically. The concentration of pesticides is expressed in units of micrograms per liter (μg/L) for clear interpretation and comparison of pesticide concentrations across different locations and time frames.

4. Occurrence of pesticide pollution on mainstream Indian rivers and lakes

Pesticide pollution in Indian river levels of surfactants and pesticide residues in groundwater and surface water on the western Ganga delta in Greater Kolkata. It contains 54 samples, during the post-monsoon period (groundwater: 27, tanks and other surface water accumulations: 16, and rivers: 11). The findings are as follows- Concentration of pesticides in seasonal variations at Kolkata Surfactant concentrations exhibit significant variation across water sources in the studied regions. Surface water of the Hugli River near Howrah Bridge displays the highest surfactant level (0.425 mg/l), while Chetla's central Kolkata groundwater records the lowest (0.015 mg/l) from a 75m deep hand pump. Groundwater generally maintains lower surfactant levels compared to surface water, with the highest groundwater concentration in Mathurapur (0.084 mg/l), a rural area in the southern South 24 Paraganas district. The Hugli River showcases a surfactant range of 0.013 to 0.425 mg/l, while ponds and tanks range from 0.017 to 0.250 mg/l. India's adopted standards set a desirable limit of 0.2 mg/l and a maximum permissible limit of 1.0 mg/l for surfactants in water. Anionic surfactant levels in Calcutta Metropolitan District's surface and groundwater sometimes surpass the desirable limit.

In the Tamiraparani river basin, South India, a study assessed the contamination and risk posed by 17 OCPs in surface water and sediments. Over 2008–2009, 96 samples were collected at 12 sites across four seasons. OCP concentrations ranged from 0.1 to 79.9 ng l^{-1} in water. Key OCPs in water included heptachlor, OP′-DDE, dieldrin, OP′-DDD, and mirex, with varied contamination sources across seasons. In the river, the highest HCH concentration was 0.78 ng l^{-1} (S9) during premonsoon, while dieldrin (7.53 ng l^{-1}, S5) and endrin (58.0 ng l^{-1}, S2) were highest during monsoon. Other OCPs (aldrin, heptachlor, chlordane isomers, mirex) were detected in small amounts across sites and seasons, particularly endrin and dieldrin found frequently (Kumarasamy *et al*., 2012) [31].

4.1 River Brahmaputra & Hooghly

The assessment of two different classes of pesticides, Polychlorinated biphenyls (PCBs) which belongs to pyrethroid (PYR) group and OCPs on the River Brahmaputra (RB) and River Hooghly (RH) was carried out by (Chakraborty *et al*., 2016) [11].

In the RB, PCB concentrations ranged from 39 to 161 ng/L (average ± SD: 83 ng/L ± 32), while in the RH, they ranged from 57 to 233 ng/L (average ± SD: 116 ng/L ± 46). OCP levels varied from 2 to 245 ng/L (average ± SD: 47 ng/L ± 67) in RB and 12 to 154 ng/L (average ± SD: 62 ng/L ± 35) in RH. High OCP detection rates of 88% in RB and 100% in RH were noted. Interestingly, HCHs, DDTs, endosulfan, and heptachlor contamination in surface waters of RB and RH were lower than those in the upper Ganges River. Specific Hooghly River areas, such as Namkhana Port, Belurmath, and Chinsura, displayed elevated PCBs levels, consistently present across all sites in both RB and RH.

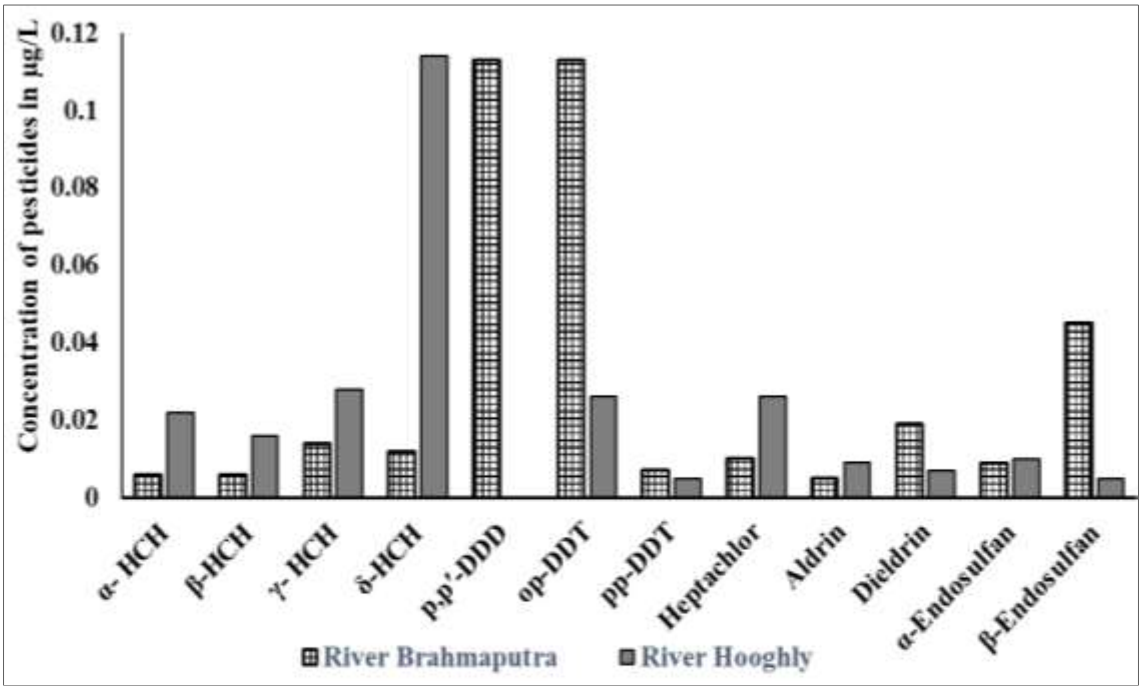

Fig 1: Contamination of pesticides at river Brahmaputra and Hooghly (µg/L)

Surface riverine water is extensively polluted with OCPs. RB is contaminated highly with δ-HCH residues, posing environmental and health concerns.

4.2 River Ganga

Pesticide studies conducted across various sections of the Ganga River aimed to evaluate ecological risk and pollution toxicity monitoring. Analysis revealed that aldrin and DDT posed a significant risk at the mid-section of the river. Conversely, the upper stretch showed elevated risk levels for HCH, and the lower section indicated increased risk associated with heptachlor. This assessment highlights notable ecological risks from specific pesticides in distinct areas of the Ganga River (Shah *et al*., 2021) [48]

Another study was conducted by assessing 13 banned organochlorine pesticides (OCPs) in Ganga River surface water across seasons and zones. Sampling at 43 sites revealed higher ΣOCP concentrations in the wet season (0.126-10.402 µg/L, mean: 2.482 µg/L) than in the dry season (0.053-3.010 µg/L, mean: 0.765 µg/L). Lindane was dominant, suggesting ongoing agricultural use despite the ban. OCP distribution didn't significantly differ between zones, indicating potential open drain pollution influence. Ratio analysis identified fresh lindane and chlordane inputs, historical DDT usage, even in the pristine Upper zone (Sah *et al*., 2020) [45].

The Ganga is severely contaminated with banned OCPs, notably Hexachlorocyclohexane (HCH) isomers. Additionally, Cypermethrin (PYR group) and organophosphate (OP) residues surpass permissible safe limits for pesticides, Posing a serious threat to water quality and residents dependent on the river.

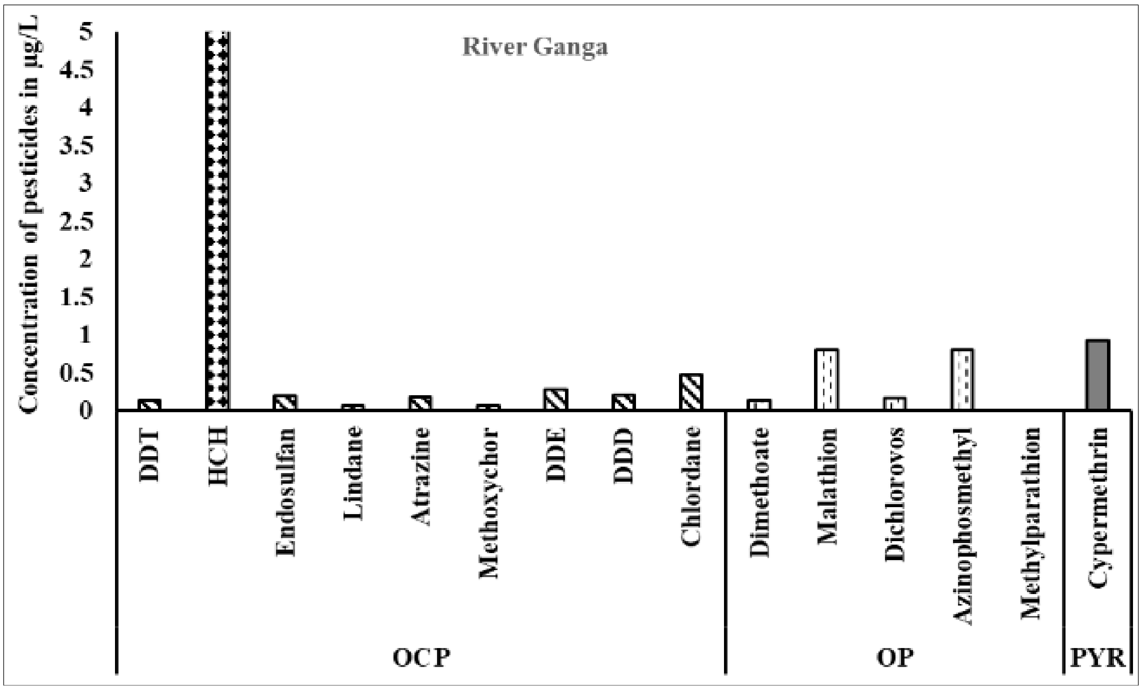

Fig 2: Contamination of the pesticides at ganga river (ug/l)

4.3 Chilika Lakes

Assessment of pesticide pollution at Chilika was done From 2012 to 2016, subsurface water samples (n = 90) were collected across three high-pollution risk sites in Chilika Lake: Palur Bridge (CS-1), Daya-Makara River Estuary (CS-2), and Daya River (CS-3). In the study it was found Organochlorinated (OC) residues were detected in 31% of samples, including HCH isomers, DDD, DDE, and heptachlor. γ-HCH was found twice, varying from 0.03–6.08 µg/l. α and δ-HCH appeared in 2015 and 2013. DDD and DDE isomers were detected, with DDD in 2012 (8.99–23.4 µg/l) and DDE in 2013 (0.017–0.062 µg/l). Heptachlor (0.04–1 µg/l) was found in 2012 and 2013. Pesticides likely entered from rivers into the lake. No targeted Synthetic pyrethroids (SPs) were found. Chlorpyrifos residue was detected in the Daya River and Palur Bridge sites (February 2015, June 2016), ranging from 0.019 to 2.73 µg/l. Dichlorvos (0.647 µg/l) was found in Daya-Makara River Estuary (CS-2, March 2016). No other Organophosphate (OP) residues were detected (Nag *et al*., 2020) [38].

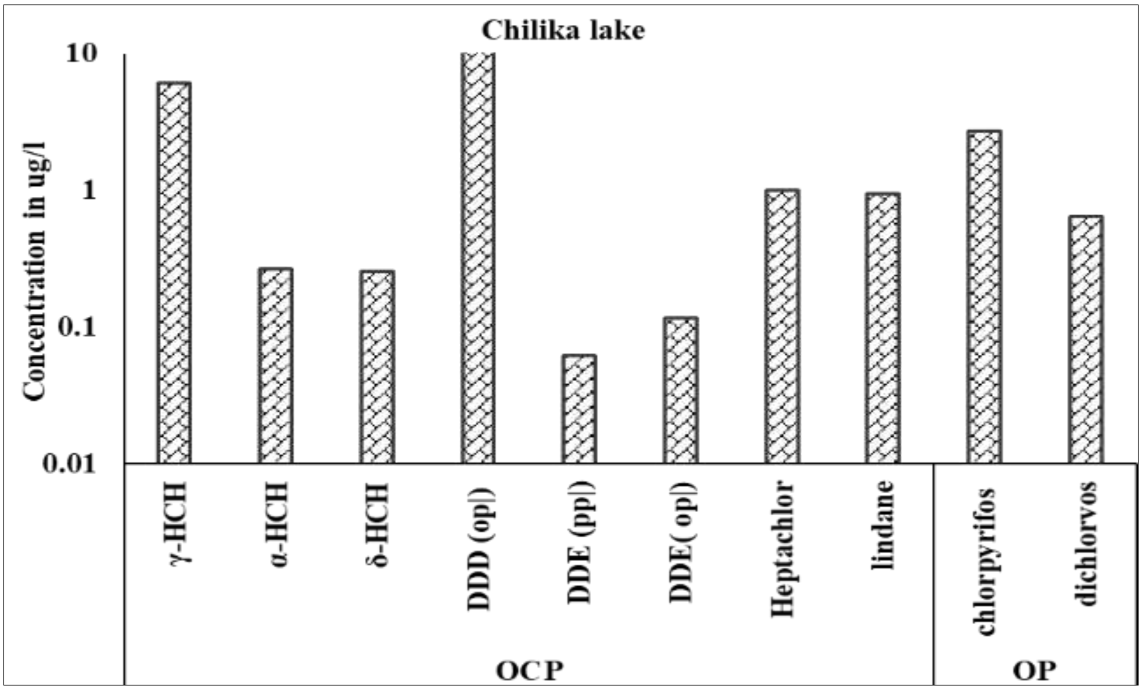

Fig 3: Contamination of the pesticides at Chilika lake (ug/l).

The contamination at the lake Chilika is significant, primarily due to the presence of isomers of OCP and OP group of pesticides. Specifically, with the isomers γ-HCH and DDD-op′, belonging to the OCP group, have been found to exceed the standard safety limits in the sampled water sites.

4.4 River Tapi

A study was conducted for the assessment of pesticide pollution at one of the major rivers of Gujrat, India. The results of surface water in the river contained endosulfan (37.56 µg/L), chlorpyrifos (0.86 µg/L), and methyl parathion

(0.43 µg/L) which conclude that river water samples exhibit contamination by both organochlorine and organophosphorus pesticides, pointing to potential sources of pollution. Surat's industrial activity and agricultural runoff contribute to this contamination. Notably, endosulfan is the prevalent residue across samples. The river ecosystem is significantly impacted, particularly during summer and monsoon seasons, due to heightened pollution levels (Hashmi *et al*., 2020) [24]. In the study of the Tapi River, the predominant pesticide identified is Endosulfan of OCP group, pesticides from the OP group, specifically Chlorpyrifos and Methyl Parathion as well detected in the surface water at the study locations.

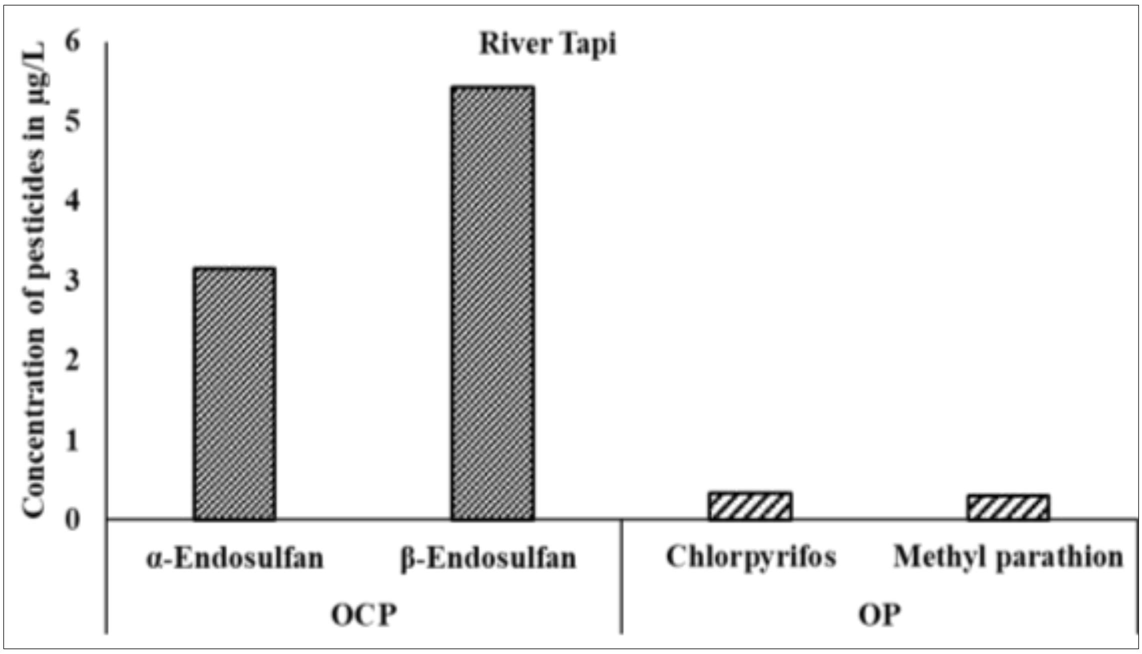

Fig 4: Contamination of the pesticides at Tapi river (ug/l)

4.5 Sabarmati river

The Sabarmati River originates from Rajasthan's Aravali hills and traverses 371 km before reaching Arabian Sea at the Gulf of Cambay. Flowing through both Rajasthan (48 km) and Gujarat (323 km), the the river starts at an elevation of 762 meters in Tepur village. Industrial wastewater discharge is the primary pollution source, rendering it one of India's most polluted rivers. Despite this, Sabarmati is vital for Gujarat's water supply, flowing through both states but facing the worst pollution in Gujarat (Khan *et al*., 2021) [28].

A study reveals the contamination status of Sabarmati River in Ahmadabad, Gujarat, India. All samples indicated the presence of pesticide residues, primarily HCH, in high levels, rendering the water unsafe for drinking and harmful to aquatic life. DDT and endosulfan were also prevalent. Organochlorine pesticides, major environmental pollutants, result from illegal waste disposal by pesticide manufacturers and industries, as well as urban sewage runoff. Despite restrictions under the Insecticide Act, 1968, their detection underscores ongoing use for agricultural or industrial purposes in violation of regulations (Hashmi *et al*., 2015) [23].

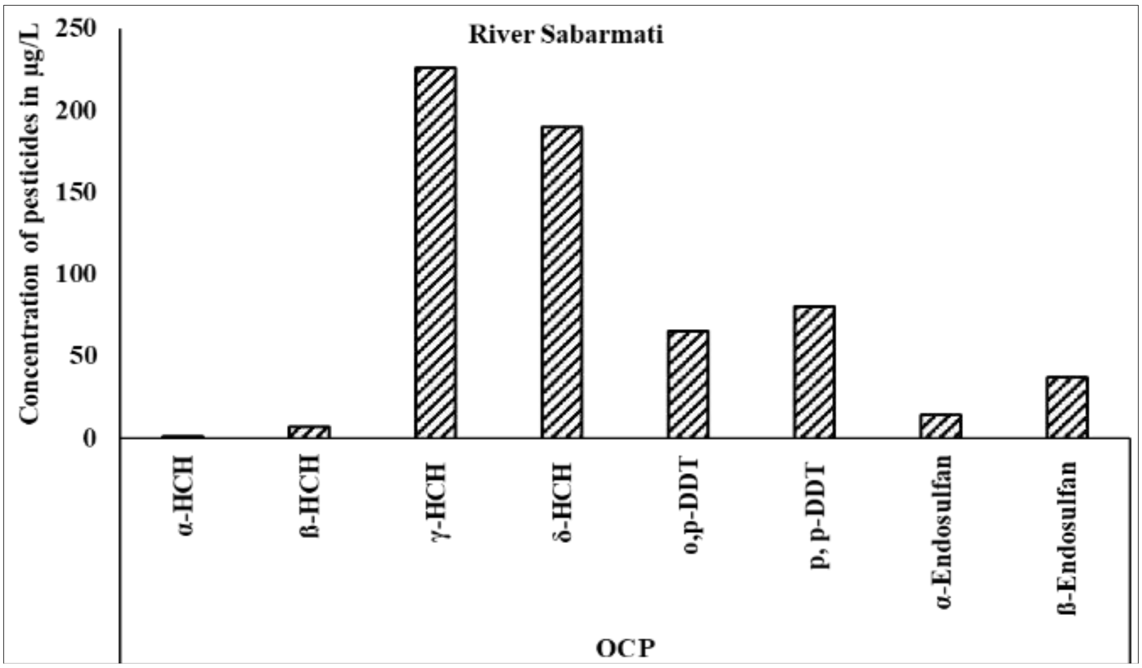

Fig 5: Contamination of pesticides at Sabarmati River (ug/l)

OCPs, notably HCH, DDT, and endosulfan, are prominent environmental pollutants detected in samples collected from the Sabarmati River.

4.6 River Gomti
A study was conducted to evaluate the presence of pesticide residues in the Gomti River, which serves as a tributary of the Ganga River and traverses through Uttar Pradesh, India. The study encompassed the analysis of water, sediment, and fish samples obtained from different points along the river. Specifically, researchers targeted 34 pesticide compounds, which included members from the OCP, OP, and PYR groups.

The residues of Hexachlorohexane (HCH isomers -α, β, γ&δ), Dichloro-diphenyl- trichloroethane (DDT -op$^{|}$,pp$^{|}$), and its metabolites Dichloro diphenyl dichloro ethylene (DDE- op$^{|}$, pp$^{|}$) and dichloro diphenyl dichloro ethane (DDD- op$^{|}$, pp$^{|}$), endosulfan (α,β, sulfate), chlorpyrifos, and methyl parathion were detected in Gomti river. HCH isomers were identified mainly in the middle and lower stretches, such as Gosia Mou (Hydergarh), Wallipur (Sultanpur), Surajghat (Jounpur), and Rajepur sites. Among these, α-HCH was found in 9 of 63 samples, ranging from 0.03–0.3 µg/l. Comparable global α-HCH levels ranged from 0.003–0.004 µg/l in Tanzania, 0.007–0.013 µg/l in China, 0.2 µg/l in Nigeria, to 26.8 µg/l in an Indian river. β-HCH occurrence was minimal, detected in just two samples at an average 0.05 µg/l concentration.

Residues of various pesticide compounds, including HCH isomers (α, β, γ, δ), DDT (op$^{|}$, pp$^{|}$), DDE (op$^{|}$, pp$^{|}$), DDD (op$^{|}$, pp$^{|}$), endosulfan (α, β, sulfate), chlorpyrifos, and methyl parathion, were identified in the waters of the Gomti River. Specifically, HCH isomers were predominantly detected in the middle and lower segments of the river, notably at locations such as Gosia Mou (Hydergarh), Wallipur (Sultanpur), Surajghat (Jounpur), and Rajepur sites. Among these isomers, α-HCH was found in 9 out of 63 samples, with concentrations ranging from 0.03–0.3 µg/l. This finding falls within a range of comparable global α-HCH levels, which have been reported at varying concentrations in different regions. For instance, levels ranged from 0.003–0.004 µg/l in Tanzania, 0.007–0.013 µg/l in China, 0.2 µg/l in Nigeria, and up to 26.8 µg/l in another Indian river. β-HCH occurrence was minimal in the Gomti River, with detection in only two samples at an average concentration of 0.05 µg/l. Such findings shed light on the distribution and concentration levels of these pesticide residues within the Gomti river.

This study identified various residues of OCP and OP pesticides in water, and no residues of SP detected. The river's catchment area included extensive agricultural land as well as urban and industrial zones where it flowed through cities and towns. Run-off from pesticide-treated agricultural fields emerged as a major contamination source. Despite bans or restrictions in agriculture, these chemicals, due to their persistence and bio-accumulative traits, posed contamination risks (Nag *et al.*, 2023) [39].

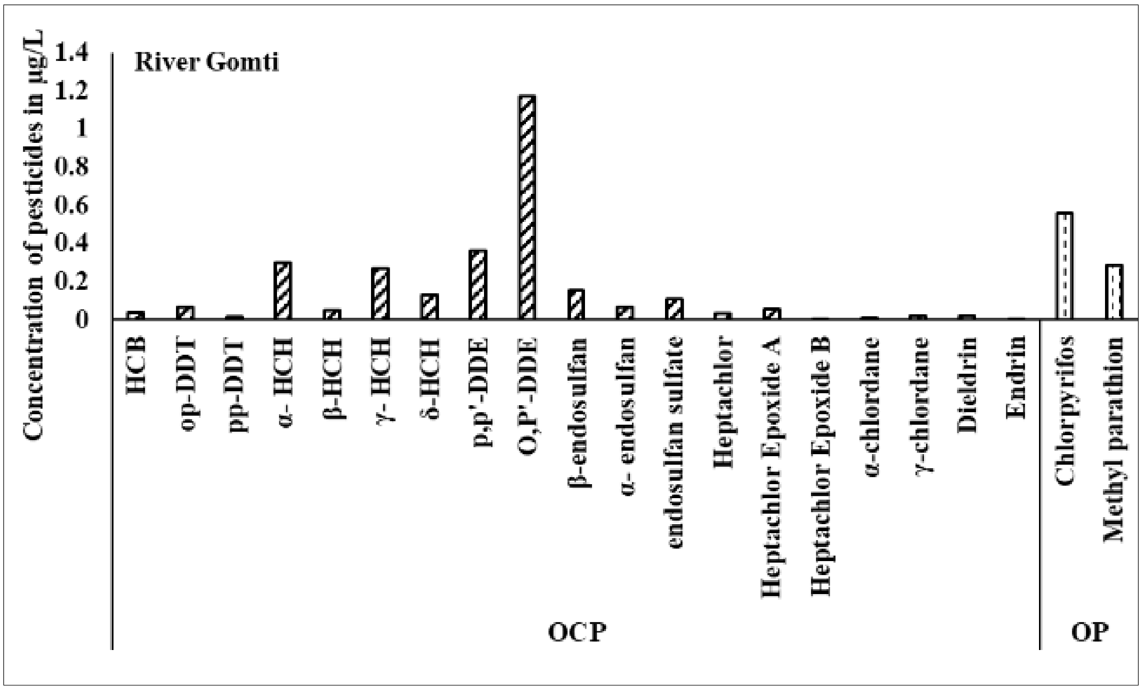

Fig 6: Values of OCP & OP group of pesticides in the river Gomti (ug/l).

Water samples contained residues of various HCH isomers (α, β, γ, δ), DDT (op$^{|}$, pp$^{|}$), its metabolites DDE (op$^{|}$, pp$^{|}$), and DDD (op$^{|}$, pp$^{|}$), as well as endosulfan (α, β, sulfate) among the Organochlorines (OCPs), Chlorpyrifos and methyl parathion among the Organophosphates (OPs) were detected in water. The presence of HCH & DDE residues of (OCP) as well as Chlorpyrifos and methyl parathion of (OP) group is significantly higher in the Gomti river.

4.7 Comparative analysis of the group of pesticide accumulated in Indian major rivers

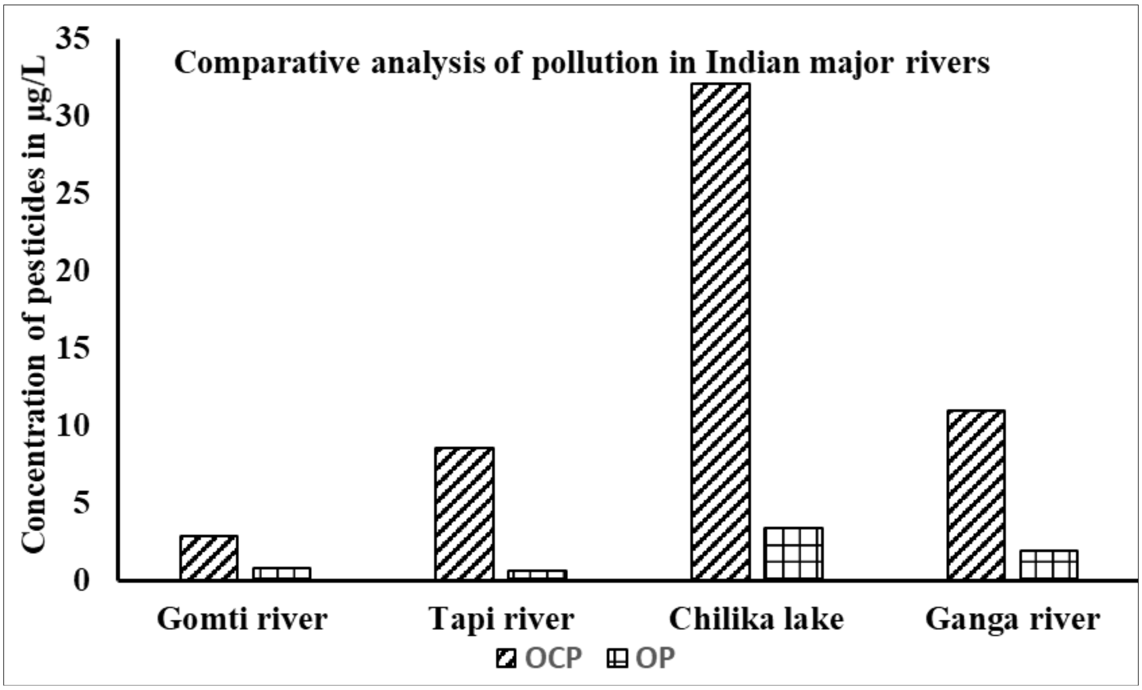

Fig 7: Values of the most persistent group of pesticides in the mainstream Indian rivers and lakes (ug/l).

Elevated levels of pesticide residues from OCPs persist in India's major rivers and lakes, despite some of these chemicals being restricted or banned under Section 5 of the Insecticide Act, 1968. This indicates continued usage in agricultural or industrial activities.

5. Health impact and ecological toxicity

Pesticides play a pivotal role in India, serving both agricultural and public health purposes. Its application is crucial for ensuring food production. However, the uncontrolled widespread use raises significant health and environmental concerns, as highlighted in various studies In India, pesticides play a important role in advancing agriculture and safeguarding public health. But it has been associated with approximately 20 major diseases in India, including malaria, filariasis, dengue, Japanese encephalitis, cholera, and louse-borne typhus (Forget *et al*.,1993, Jeyaratnam *et al*., 1985) [18, 26].

One of the key concerns with pesticides, especially with Organochlorine Pesticides (OCPs), is their persistence in the environment. OCPs decompose slowly, have a long lifespan, and can accumulate in the food chain, posing a threat to ecosystems and human health (Gallo *et al*., 1991; Kocan *et al*., 1989; Raju *et al*., 1982) [19, 30, 42]. Even mild cases of pesticide poisoning can result in a range of health issues, such as headaches, gastrointestinal problems, numbness, and anxiety. Some pesticides can disrupt the endocrine system, mimicking or interfering with natural hormones. Tragically, pesticide-related suicides are prevalent in India, where they constitute a significant portion of the overall suicides in the South-eastern Asia region (Gunnell *et al*., 2007) [21]. The potential health risks associated with pesticide contamination by not just on the toxicity of the chemicals involved, but also on the level of exposure (Kim *et al*., 2017) [29]. While pesticides are widely proven in studies for their capacity to cause severe conditions like various forms of cancer, they are also implicated in a range of other illnesses. These ailments, if left untreated, can prove fatal and significantly diminish one's quality of life particularly organochlorines and their byproducts, has been associated with an increased likelihood of developing type 2 diabetes and its accompanying health complications (Bonner *et al*., 2017) [9], (DelValls *et al*., 2017) [14].

Exposure to pesticides also linked to the worsening of asthma symptoms due to factors such as inflammation and suppression of the immune system. Numerous studies had found the potential correlation between pesticide exposure and Parkinson's disease (PD). Additionally, paraquat has been identified evidently linked to an elevated risk of developing PD. Researchers such as (Freire *et al*., 2012) [17] and (Brouwer *et al*,. 2017) [10] have documented a relationship between PD and the use of various pesticides, including most commonly used herbicide paraquat, few organophosphate insecticides, and fungicides like cyprodinil, fenhexamid, and thiophanate-methyl. Exposure to these pesticides at certain levels has been associated with increased incidences of sperm abnormalities, decreased fertility, miscarriages, and birth defects as well.

6. Discussion

Water pollution with pesticides poses a serious threat globally, affecting both advanced and developing nations. Assessing the pollution levels and understanding their impact on aquatic life and human health is challenging. In the present work, an attempt was made to determine the pollution levels in India's major rivers highlighting the extent of this environmental hazard. India faces a severe environmental crisis as major water bodies, including the Ganga, Chilika Lake, Tapi River, Sabarmati River, Tamirapani river, Gomti River, and other mainstream rivers, exhibit alarming contamination along with few banned pesticides. The Ganga is tainted with Hexachlorocyclohexane (HCH) isomers, Cypermethrin, and few OP group of pesticides, surpassed the safe limits, endangering water quality and the livelihoods of river-dependent residents. Chilika Lake suffers significant pollution, notably from OCP and OP isomers like γ-HCH and DDD- op|, exceeding safety standards. In the Tapi River, Endosulfan dominates, while Chlorpyrifos and Methyl Parathion belonging of the OP group are detected. The Sabarmati River faces contamination with HCH, DDT, and endosulfan. Even though, there is no specific standard value for safe pesticide levels in water for aquatic life in India, but guidelines established by the USEPA can be referenced for guidance. Gomti river water showed elevated levels of OCP and OP pesticides, surpassing USEPA standards. Frequent detection of HCH isomers, DDT, DDE, DDD, Endosulfan, Chlorpyrifos, and Methyl Parathion denotes severe contamination, posing a threat to aquatic life. River Hooghly and Brahmaputra also exhibited significant pollution with specific pesticides. Despite regulations, pesticides continue to linger in India's rivers and lakes. It's crucial to make stricter clauses and support eco-friendly options to protect the environment and people's health from the pesticide pollution in these important water sources.

7. Conclusion

The analysis within Indian rivers reveals a concerning pattern in the occurrence of different pesticide groups. OCP consistently exhibit the highest levels among these groups, with their presence detected across multiple river sites. They are followed in terms of highest concentration by OP and PYR. It's worth noting that the Chilika lake of Odisha stands out with the highest concentration of accumulated OCPs found amongst the examined sites. Current review highlights the widespread and persistent presence of OCPs in aquatic environments, highlighting the urgent need for further investigation and management to address their potential environmental and health impacts.

8. Preventive measures

The Government of India has taken few proactive measures to address the problems of pest management, to mitigate health risks associated with pesticides, and prevent from pollution of rivers and lakes. These measures include the adoption of Integrated Pest Management (IPM), the prohibition of highly hazardous pesticides, restrictions on the use of toxic compounds, and the development of a National Implementation Plan (NIP) (Swaminathan, 1975) [50]. Another important initiative involves strategically positioning of monitoring stations to assess river water pollution (Alvarez *et al*., 2005) [4]. This approach relies on mathematical and numerical optimization techniques to find the best spots for water treatment stations and figure out the most effective ways to clean polluted river areas, like adding clean water from reservoirs. (Martínez *et al*., 2010) [32]. Advanced techniques like Paretian analysis is a smart method to decide how to use and clean water. It helps design systems for sewage disposal that clean the water a lot but cost less and don't harm the environment much. (Gros 1975) [20].

9. Future perspective

In India, the Insecticide Act of 1968 regulates pesticides. Yet, some prohibited pesticide residues found indicates the loopholes in enforcing rules. Without standards for water and soil policies need strengthening to combat present and future pesticide risks (Devi *et al*., 2015) [15]. Continuous monitoring of residues across fields, environments, and commodities is essential. Encouraging biopesticides and traditional methods, like traps, can reduce chemical dependency on 7-8% of agricultural land. Embracing organic farming, integrated pest management, and other approaches will also help. Farmers require education on banned pesticides, proper usage, protective gear, dosages, and disposal to prevent harm. Persistent pesticide residues require both regulatory measures and environmental cleanup. Various methods – physical (Nanocomposites, activated carbon), chemical (Oxidation), physicochemical (UV light, photocatalysis), and biological (Bioremediation) – have been explored for residue removal. However, limitations in efficiency and scalability persist. Further research should prioritize cost-effective, widely applicable techniques. Additionally, for future prevention, eco-friendly pesticides and efficient crop varieties should be crucial goals (Marian *et al*., 2018, Rajmohan *et al*., 2020) [33, 41].

Plants like wetlands and algae can helps to clean water, preventing pesticide pollution in rivers. This is an eco-friendly method, like phytoremediation, one of the powerful tool for treating wastewater (AI-Jawhari *et al*., 2021) [3]. These innovative methods excel at extracting nutrients and toxic metals from wastewater before it flows into natural water bodies. By implementing these cost-effective and sustainable technologies at pollution sources, we can effectively thwart surface water pollution and even recycle treated water for agricultural use (Singh *et al*., 2019) [49]. Introduction of tiny nanoparticles can make plant-based cleaning (Phytoremediation) works better. This helps to remove pollutants like heavy metals from soil and water, making the cleaning process faster and more effective. (Hüesker *et al*., 2022) [25]. Through the combined adoption of these plant-based and nanotechnology-driven approaches, the prevention of pesticide pollution can be ensured (Tripathy *et al*., 2014) [51].

10 Conflict of interest

The author declares that there is no conflict of interest.

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