

Prioritisation of Emerging Contaminants for Monitoring in Indian Aquatic Environments Based on Occurrence, Treatment Persistence and Ecological Risk

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Abstract— Emerging contaminants are increasingly reported in Indian wastewater and receiving waters, but routine monitoring is constrained by the large number of substances that may require analytical attention and by evidence that is distributed unevenly across occurrence, treatment behaviour and ecological risk. This study develops a quantitative framework for prioritising contaminants for monitoring by integrating these three dimensions. Seventeen primary Indian studies were retained in the quantitative evidence base. Nine contaminants—ibuprofen, carbamazepine, diazepam, ciprofloxacin, diclofenac, bisphenol A, paracetamol, triclosan and caffeine—had sufficient evidence for integrated scoring. Occurrence was represented by the number of independent Indian studies reporting each contaminant; treatment persistence was represented by an operational persistence score based on reported or evidence-supported removal behaviour; and ecological risk was represented by a relative score derived from reported hazard or risk quotients. The three components were combined using weights of 40%, 30% and 30%, respectively. Ibuprofen obtained the highest Overall Priority Score (OPS, 85.9), followed by ciprofloxacin (78.5), carbamazepine (78.3), diclofenac (73.5) and triclosan (72.3). Caffeine had the highest occurrence coverage, with 13 independent studies, but the lowest OPS (56.2) because of comparatively lower persistence and risk contributions. Sensitivity analysis showed that ibuprofen, ciprofloxacin and carbamazepine remained within the upper part of the ranking across alternative weighting schemes, although the exact order changed. The framework provides a transparent and updateable screening approach for monitoring prioritisation while explicitly recognising heterogeneity, geographic imbalance and incomplete treatment and risk evidence in the Indian literature.

Keywords— Emerging Contaminants, Environmental Monitoring, Indian Aquatic Environments, Wastewater Treatment, Treatment Persistence, Ecological Risk, Prioritisation, Pharmaceuticals, Water Quality.

I. INTRODUCTION

Emerging contaminants (ECs) comprise a heterogeneous group of substances that are not routinely addressed within conventional environmental monitoring programmes but may enter aquatic systems and exert ecological or other environmental effects. Pharmaceuticals, personal-care products, endocrine-disrupting chemicals, antibiotics and related compounds are of particular interest because their continuous use and discharge can create repeated inputs to wastewater and receiving waters. Their environmental significance cannot be inferred from concentration alone because persistence, biological activity and toxicity vary substantially among compounds (Fent et al., 2006; Tang et al., 2020; Ortúzar et al., 2022).

Wastewater is an important pathway for the transfer of ECs to aquatic environments. Conventional wastewater treatment plants were designed primarily for removal of conventional organic matter, nutrients and pathogens, rather than the broad range of trace organic micropollutants now routinely detectable by modern analytical methods. Consequently, treatment performance varies markedly among contaminants and treatment configurations. Indian investigations have documented both substantial removal for some compounds and limited, negligible or even negative apparent removal for others (Subedi et al., 2015, 2017; Singh & Suthar, 2021b; Dubey et al., 2023).

Occurrence is therefore only one dimension of monitoring relevance. A contaminant detected repeatedly may warrant attention because of widespread environmental presence, whereas another compound with fewer occurrence observations may warrant attention because its reported ecological-risk quotient is substantially higher. Multi-criteria approaches have been used internationally to address this problem by combining occurrence, persistence, hazard and other characteristics rather than relying on a single indicator (Gaston et al., 2019; Wielens Becker et al., 2021).

The Indian evidence base is sufficiently developed to demonstrate widespread occurrence, but it remains heterogeneous in geographical coverage, environmental matrix, analytical target list, wastewater-treatment technology and ecological-risk methodology. Studies have investigated the Yamuna, Ganges and Cauvery river systems, urban lakes, municipal wastewater, sewage treatment plants and decentralized greywater systems, but the resulting evidence is fragmented across individual contaminants and evidence dimensions (Ramaswamy et al., 2011; Mutiyar et al., 2018; Singh & Suthar, 2021a,b; Biswas & Vellanki, 2021; Renganathan et al., 2021; Biswas et al., 2024).

The present study addresses this gap by developing a transparent quantitative framework for monitoring prioritisation in Indian aquatic environments. The framework integrates occurrence, treatment persistence and ecological risk, assigns explicit weights to the three dimensions, and tests the sensitivity of the resulting priorities to alternative weighting assumptions. The objective is not to establish a definitive national ranking of environmental hazard, but to provide a reproducible screening tool that converts fragmented Indian evidence into a practical set of monitoring priorities.

II. METHODS

2.1 Study Design

The study followed a sequential evidence-synthesis and scoring workflow consisting of literature identification, eligibility screening, data extraction, evidence standardisation, candidate selection, contaminant-level scoring, integrated prioritisation and sensitivity analysis. The analytical workflow is shown in Figure 1. The analysis was designed around three evidence dimensions: occurrence in Indian aquatic or wastewater systems, behaviour during wastewater treatment, and ecological risk.



FIGURE 1: Overall workflow used for evidence identification, data extraction, standardisation and contaminant prioritisation

2.2 Evidence Identification and Study Selection

Relevant literature was identified from major bibliographic databases and supplemented by backward and forward citation tracking. Search terms combined concepts related to emerging contaminants, pharmaceuticals, personal-care products, antibiotics, wastewater, sewage treatment, rivers, surface water, ecological risk and India. Studies published after the date of the locked quantitative dataset were excluded from the evidence base regardless of their relevance.

Studies were eligible when they (i) presented original quantitative observations from Indian aquatic environments or wastewater systems; (ii) reported at least one contaminant relevant to the study framework; and (iii) provided extractable information for occurrence, treatment behaviour or ecological risk. Review articles, editorials, secondary analyses, purely laboratory studies without Indian environmental observations, and studies outside India were excluded from the quantitative evidence base. Seventeen primary studies satisfied the eligibility criteria and formed the final evidence base (Table 1).

The quantitative evidence base was deliberately restricted to primary studies so that occurrence counts represented independent Indian investigations rather than repeated citations of the same underlying evidence. Reviews and regional prioritisation studies were used only as contextual sources where appropriate.

TABLE 1
CHARACTERISTICS OF THE 17 PRIMARY STUDIES INCLUDED IN THE QUANTITATIVE EVIDENCE BASE

ID	Study	Year	Location	Matrix	Treatment Evidence	Risk Evidence
S1	Subedi et al.	2015	Five Indian STPs	Influent, effluent, sludge	Yes	No
S2	Ramaswamy et al.	2011	Kaveri, Vellar, Tamiraparani; Pichavaram	River water/sediment	No	Yes
S3	Mutiyar et al.	2018	Yamuna, Delhi	River water	No	Yes
S4	Shipingana et al.	2022	Mysuru, Karnataka	Municipal wastewater	Yes	Yes
S5	Puri et al.	2024	Nagpur, Maharashtra	Sewerage/WWTP influent-effluent	Yes	Yes
S6	Subedi et al.	2017	Southern India; two STPs	Influent, effluent, sludge	Yes	No
S7	Archana et al.	2017	Nagpur, Maharashtra	STP and lakes	Yes	Yes
S8	Kachhawaha et al.	2021	Nagpur, Maharashtra	Six lakes and River Nag	No	No
S9	Singh & Suthar	2021a	Rishikesh and Haridwar	River Ganges	No	Yes
S10	Singh & Suthar	2021b	Upper Ganges basin	Four STPs	Yes	No
S11	Ravichandran et al.	2021	Vichoor, Tamil Nadu	Greywater/VFCW	Yes	Yes
S12	Renganathan et al.	2021	Cauvery and tributaries	River water	No	Yes
S13	Kumar et al.	2019	Guwahati, Assam	Ambient waters	No	Yes
S14	Sharma et al.	2019	Ganges River basin	Surface and groundwater	No	Yes
S15	Dubey et al.	2023	North India; 10 WWTPs	Influent and effluent	Yes	Yes
S16	Biswas & Vellanki	2021	Yamuna and tributaries	River water	No	No
S17	Biswas et al.	2024	Yamuna River basin	Multiple aquatic matrices	Yes	Yes

Notes: WWTP = wastewater treatment plant; STP = sewage treatment plant; VFCW = vertical-flow constructed wetland. "Treatment evidence" indicates that the study contained influent-effluent or other treatment-fate information relevant to the persistence component. "Risk evidence" indicates that an ecological-risk assessment was reported.

2.3 Data Extraction

A structured extraction template was used to record bibliographic information, study location, environmental matrix, contaminant identity, treatment configuration, occurrence information, influent and effluent concentrations where available, treatment removal, and ecological-risk metrics. Risk Quotients (RQ), Hazard Quotients (HQ), Predicted No-Effect Concentrations (PNECs) and Measured Environmental Concentrations (MECs) were retained when reported. Original values and units were preserved for traceability. Where removal could be calculated directly from influent and effluent concentrations, the calculated value was recorded separately. Values that could not be extracted unambiguously were not estimated.

2.4 Data Standardisation

Concentration values were converted to a common unit where conversion was unambiguous, while original reporting was retained in the source records. Occurrence was standardised to the number of independent Indian studies reporting each contaminant rather than the number of samples or detections. This reduced the influence of studies with unusually intensive sampling designs. Ecological-risk metrics were retained in their original RQ or HQ form because the underlying studies differed in organisms, exposure scenarios and toxicity thresholds; they were subsequently normalised only for relative scoring. Missing information was recorded as not reported, and no missing values were imputed.

2.5 Candidate Contaminants

Candidate contaminants were retained for integrated prioritisation when sufficient evidence existed to derive the three component scores. Nine contaminants met the final quantitative criteria: ibuprofen, carbamazepine, diazepam, ciprofloxacin, diclofenac, bisphenol A (BPA), paracetamol, triclosan and caffeine. Lorazepam was retained as contextual evidence because it was reported in Indian treatment studies, but it was not included in the final ranking because a sufficiently comparable ecological-risk value was not available in the locked quantitative dataset.

2.6 Development of the Prioritisation Framework

The framework combined occurrence, treatment persistence and ecological risk into a single Overall Priority Score (OPS). The three dimensions were selected because they were sufficiently represented across the assembled Indian literature and address complementary aspects of monitoring relevance. Occurrence reflects the breadth of independent Indian evidence; treatment persistence reflects the extent to which a contaminant may remain associated with treated wastewater; and ecological risk reflects the magnitude of reported risk relative to the other candidates.

$$\text{Occurrence Score (OS)} = 100 \times \log(n + 1) / \log(n_{\max} + 1) \quad (1)$$

where n is the number of independent Indian studies reporting a contaminant and $n_{\max}$ is the maximum study count among the nine ranked contaminants.

$$\text{Persistence Score (PS)} = 100 - \text{Removal (\%)} \quad (2)$$

where Removal (%) is the reported or directly calculated wastewater treatment removal efficiency. When comparable numerical removal data were unavailable but Indian evidence consistently indicated poor, negligible or negative removal, PS was assigned as 100 as an operational treatment-resistance indicator. Such values are not interpreted as measured universal removal percentages or as intrinsic physicochemical persistence.

$$\text{Risk Score (RS)} = 100 \times R_i / R_{\max} \quad (3)$$

where R_i is the reported HQ or RQ used for the contaminant and $R_{\max}$ is the highest risk value in the final candidate dataset. Because the underlying HQ and RQ assessments were heterogeneous, RS is interpreted as a relative evidence score within this dataset rather than as an absolute toxicity scale.

$$\text{OPS} = 0.40(\text{OS}) + 0.30(\text{PS}) + 0.30(\text{RS}) \quad (4)$$

The primary weighting assigned 40% to occurrence, 30% to treatment persistence and 30% to ecological risk. Higher OPS values indicate greater monitoring priority within the defined evidence base.

2.7 Sensitivity Analysis

Sensitivity was evaluated by recalculating contaminant ranks under four weighting schemes: (1) primary weighting, 40% occurrence/30% persistence/30% risk; (2) equal weighting, 33.3% for each dimension; (3) persistence emphasis, 30% occurrence/50% persistence/20% risk; and (4) risk emphasis, 30% occurrence/20% persistence/50% risk. An additional

occurrence-emphasis scenario (50% occurrence/25% persistence/25% risk) was also evaluated to test the effect of greater weight on evidence coverage. The resulting ranks were compared to determine whether the main prioritisation pattern depended strongly on the selected weights.

III. RESULTS

3.1 Evidence Base and Candidate Selection

Seventeen primary Indian studies formed the quantitative evidence base. The studies covered wastewater treatment plants, municipal wastewater, decentralized greywater, rivers, lakes and other receiving waters across northern, central and southern India. The evidence was heterogeneous: some studies focused primarily on occurrence, whereas others also reported treatment behaviour and ecological-risk metrics (Table 1).

Nine contaminants had sufficient evidence for integrated scoring. The occurrence matrix contained 13 independent study reports for caffeine, 12 for triclosan, 10 for carbamazepine, 9 each for ibuprofen and paracetamol, 8 for ciprofloxacin, 7 for diclofenac, and 3 each for diazepam and BPA. These counts represent the number of independent Indian studies in which the contaminant was included and reported, not the number of samples or concentration measurements.

3.2 Occurrence Patterns

Caffeine had the broadest occurrence coverage, appearing in 13 of the 17 primary studies. Triclosan and carbamazepine were also widely represented, with 12 and 10 studies, respectively. Ibuprofen and paracetamol were each reported in 9 studies, while ciprofloxacin and diclofenac were reported in 8 and 7 studies. Diazepam and BPA had the narrowest occurrence coverage, with three independent studies each.

The distribution of evidence across Indian regions and matrices indicates that high study counts should not be interpreted as nationally representative prevalence estimates. For example, the Yamuna, Ganges and southern Indian river systems have received repeated investigation, while other regions remain comparatively underrepresented. The occurrence score therefore measures evidence coverage rather than national concentration or exposure.

3.3 Treatment Persistence

Treatment evidence showed marked differences among the candidate contaminants. The locked persistence scores ranged from 34.0 for caffeine to 100.0 for ibuprofen, carbamazepine, diazepam and diclofenac. Intermediate scores were assigned to ciprofloxacin (50.5), paracetamol (55.0), triclosan (41.5) and BPA (38.5). These values integrate reported removal behaviour across the assembled evidence and, for several compounds, reflect qualitative or negative-removal evidence rather than a single universal removal percentage.

The treatment literature illustrates why persistence cannot be inferred solely from occurrence. Indian STP studies have reported poor or negative apparent removal for compounds such as carbamazepine and diazepam, while other contaminants show more variable or substantial removal depending on the treatment system (Subedi et al., 2015, 2017; Singh & Suthar, 2021b; Dubey et al., 2023). Treatment removal is consequently treated here as context-dependent evidence supporting a screening-level persistence score.

3.4 Ecological-Risk Patterns

The risk component showed a different pattern from occurrence. BPA received the maximum relative risk score (RS = 100), based on the highest numerical risk value retained in the final dataset. Ciprofloxacin also received RS = 100 because of its high reported risk relative to the other ranked contaminants. Ibuprofen and triclosan received RS = 70, whereas carbamazepine, diazepam, diclofenac and paracetamol received RS = 40. Caffeine received the lowest relative risk score (RS = 20).

The ecological-risk values were not treated as directly interchangeable toxicity measurements because the source studies used different organisms, endpoints, exposure conditions and reference thresholds. The RS therefore preserves relative differentiation while avoiding the stronger claim that a risk quotient from one study is directly equivalent to a risk quotient from another.

3.5 Integrated Prioritisation

The integrated results are presented in Table 2 and Figure 2. Ibuprofen obtained the highest OPS (85.9), followed by ciprofloxacin (78.5), carbamazepine (78.3), diclofenac (73.5) and triclosan (72.3). Paracetamol, diazepam and BPA formed an intermediate group with OPS values of 63.4, 63.0 and 62.6, respectively. Caffeine received the lowest OPS (56.2).

The ranking illustrates the effect of combining evidence dimensions. Ibuprofen benefited from strong occurrence coverage and a maximum persistence score, while ciprofloxacin combined high occurrence coverage with the maximum risk score despite a lower persistence score. Carbamazepine had the second-highest occurrence score and maximum persistence score, but its lower risk score reduced its integrated position relative to ciprofloxacin. Triclosan had very high occurrence coverage but a lower persistence score, illustrating that broad occurrence alone did not determine the final priority.

TABLE 2
QUANTITATIVE PRIORITISATION OF THE NINE SELECTED EMERGING CONTAMINANTS

Rank	Contaminant	Independent Studies (n)	OS	PS	RS	OPS
1	Ibuprofen	9	87.3	100	70	85.9
2	Ciprofloxacin	8	83.3	50.5	100	78.5
3	Carbamazepine	10	90.9	100	40	78.3
4	Diclofenac	7	78.8	100	40	73.5
5	Triclosan	12	97.2	41.5	70	72.3
6	Paracetamol	9	87.3	55	40	63.4
7	Diazepam	3	52.5	100	40	63
8	Bisphenol A	3	52.5	38.5	100	62.6
9	Caffeine	13	100	34	20	56.2

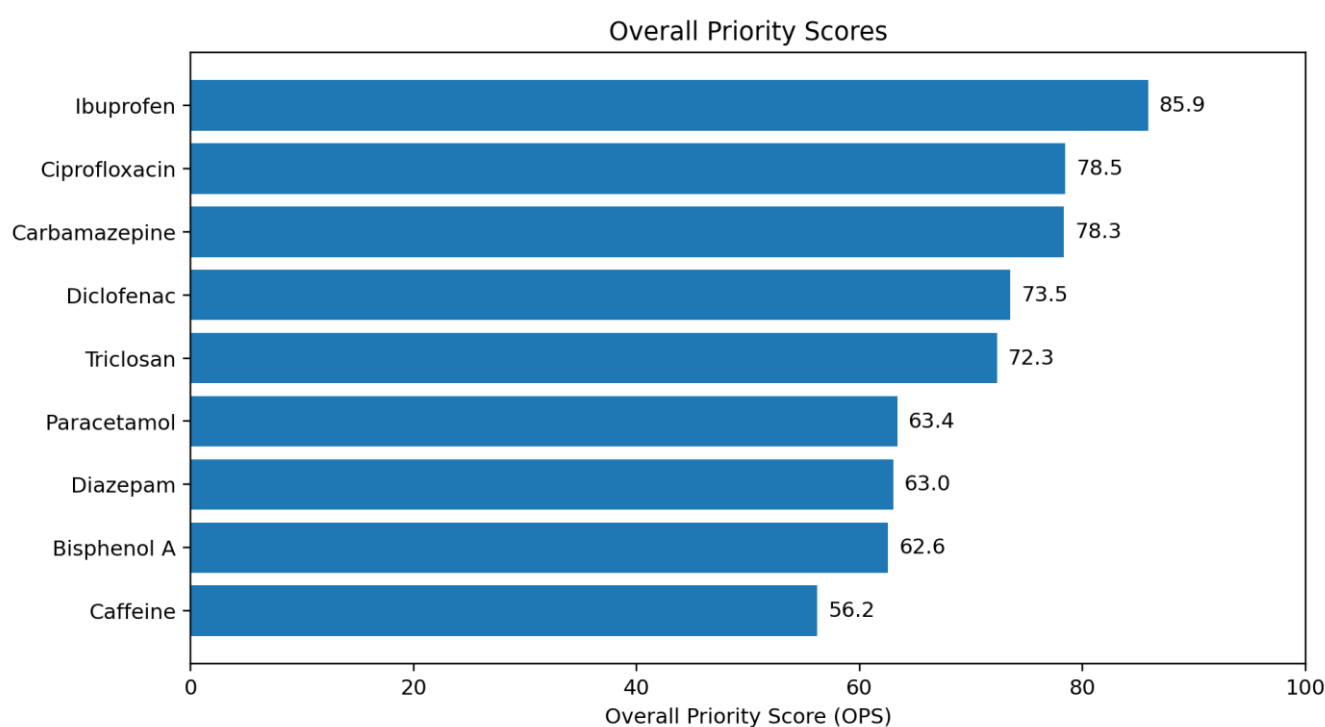


FIGURE 2: Overall Priority Scores (OPS) under the primary weighting scheme (40% occurrence, 30% persistence and 30% ecological risk)

3.6 Sensitivity of the Prioritisation

The alternative weighting scenarios changed the exact order of several contaminants but preserved a broadly similar upper group (Table 3; Figure 3). Ibuprofen ranked first under the primary, equal and persistence-emphasis schemes and second under risk emphasis. Ciprofloxacin ranked second under the primary and equal schemes, third when persistence was emphasised, and first when risk was emphasised. Carbamazepine ranked third under the primary and equal schemes, second under persistence emphasis and third under risk emphasis.

Diclofenac remained between fourth and fifth across the four scenarios, while triclosan remained between fourth and fifth. Paracetamol remained sixth under the first three schemes but fell to seventh under risk emphasis. Diazepam and BPA were more sensitive to weighting, reflecting their different combinations of occurrence, persistence and risk evidence. Caffeine remained ninth in all four scenarios. Thus, the analysis supports stability of the broad prioritisation pattern while showing that the exact order of intermediate contaminants depends on the relative importance assigned to the three evidence dimensions.

TABLE 3
RANKS OF THE NINE CONTAMINANTS UNDER ALTERNATIVE WEIGHTING SCHEMES

Contaminant	Primary	Equal	Persistence Emphasis	Risk Emphasis	Occurrence Emphasis
Ibuprofen	1	1	1	2	1
Ciprofloxacin	2	2	3	1	2
Carbamazepine	3	3	2	3	3
Diclofenac	4	4	4	5	4
Triclosan	5	5	5	4	5
Paracetamol	6	6	6	7	6
Diazepam	7	8	7	8	8
Bisphenol A	8	7	8	6	7
Caffeine	9	9	9	9	9

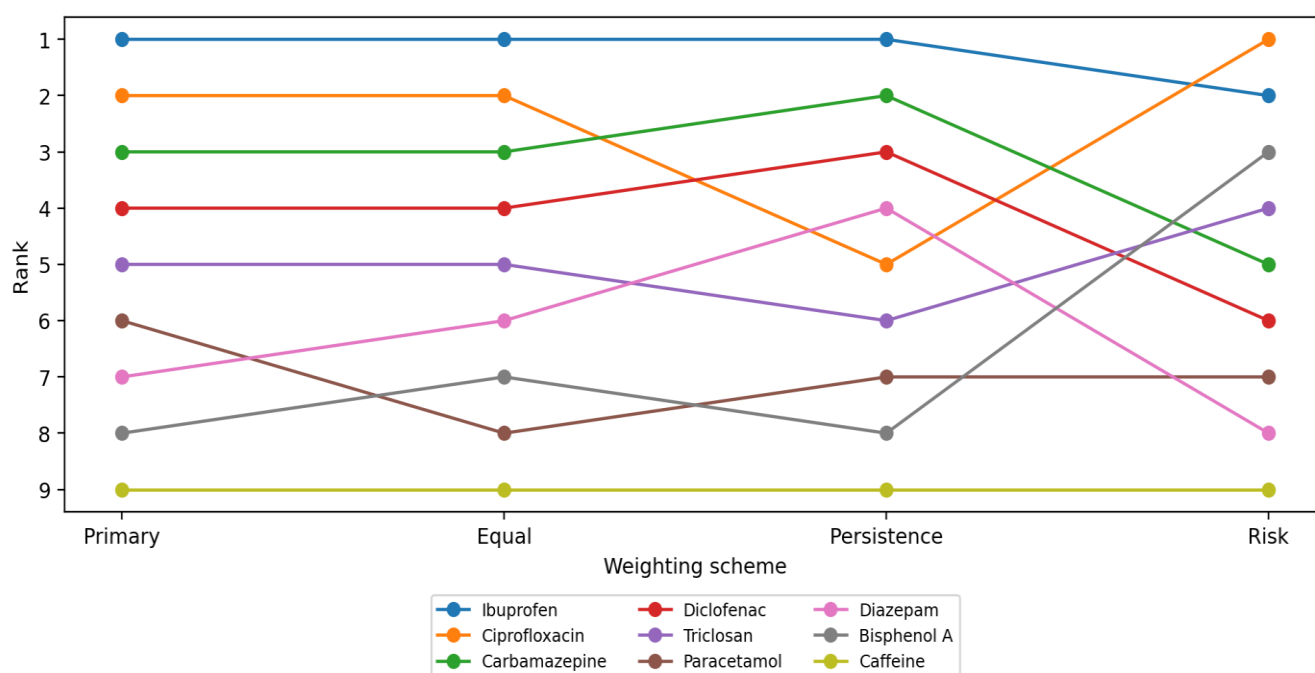


FIGURE 3: Sensitivity of contaminant ranks to alternative weighting schemes

3.7 Evidence Confidence and Data Limitations

Evidence strength was not uniform across the nine contaminants. Caffeine, triclosan and carbamazepine had the broadest occurrence coverage, whereas diazepam and BPA were represented by fewer independent studies. The treatment component was also uneven because some contaminants had direct influent-effluent evidence while others relied on repeated qualitative or negative-removal observations. The risk component was similarly heterogeneous because the reported HQ and RQ values came from different study designs.

These differences do not invalidate the screening framework, but they determine how the scores should be interpreted. The OPS values are relative priorities within the assembled evidence base, not national estimates of environmental hazard. The results also identify where additional Indian evidence would most directly improve the framework: repeated occurrence studies for less-studied contaminants, harmonised influent-effluent treatment studies, and comparable ecological-risk assessments.

IV. DISCUSSION

4.1 What the Integrated Ranking Indicates

The principal finding is that monitoring priority is produced by the combination of evidence dimensions rather than by a single characteristic. Ibuprofen, ciprofloxacin and carbamazepine occupied the first three positions under the primary weighting, but they reached those positions for different reasons. Ibuprofen combined broad occurrence evidence with strong treatment-persistence evidence and a moderate relative risk score. Ciprofloxacin was supported by broad occurrence coverage and a high risk signal, while its persistence score was intermediate. Carbamazepine combined high occurrence coverage and strong persistence evidence, with a lower risk contribution.

This distinction is important for monitoring design. A contaminant with high occurrence but comparatively low risk may still be relevant if it is persistent and repeatedly detected; while a less frequently investigated contaminant can move upward when strong ecological-risk evidence is available. The framework therefore separates the question of "how often has it been reported?" from "what happens during treatment?" and "what risk signal has been reported?" rather than treating these as interchangeable concepts.

4.2 Ibuprofen, Ciprofloxacin and Carbamazepine

Ibuprofen ranked first with an OPS of 85.9. Its occurrence was documented across nine independent Indian studies in the assembled matrix, and the treatment component assigned the maximum operational persistence score. Indian river and wastewater studies have repeatedly reported ibuprofen, including investigations of the Yamuna, Ganges and wastewater treatment systems (Subedi et al., 2015; Mutiyar et al., 2018; Singh & Suthar, 2021a,b; Renganathan et al., 2021; Biswas et al., 2024). The high OPS should be interpreted as a convergence of evidence rather than as a claim that ibuprofen is universally refractory to every treatment technology.

Ciprofloxacin ranked second (OPS 78.5). Its position was strongly influenced by the maximum relative risk score and substantial occurrence coverage. Indian studies have reported ciprofloxacin in river water, wastewater and treatment-plant investigations, including the Ganges, Cauvery, Yamuna and northern Indian WWTPs (Archana et al., 2017; Singh & Suthar, 2021a,b; Renganathan et al., 2021; Biswas & Vellanki, 2021; Dubey et al., 2023). Because ciprofloxacin is an antibiotic, environmental monitoring may also need to consider antimicrobial-resistance selection as a separate concern from conventional ecological toxicity. Shafi et al. (2023) highlighted the prominence of antibiotics in regional EC-prioritisation exercises, reinforcing the value of keeping antibiotic-specific environmental concerns visible in monitoring design.

Carbamazepine ranked third (OPS 78.3). It had the second-highest occurrence score and a maximum persistence score. Its repeated detection in Indian rivers and wastewater systems is consistent with the broader literature describing carbamazepine as relatively persistent through conventional wastewater treatment (Subedi et al., 2015, 2017; Ramaswamy et al., 2011; Mutiyar et al., 2018). The present result therefore illustrates how a contaminant can obtain high monitoring priority without having the maximum relative ecological-risk score.

4.3 Diclofenac and Triclosan: High Occurrence and Treatment Effects

Diclofenac ranked fourth with an OPS of 73.5. Seven independent Indian studies contributed occurrence evidence, while the persistence component was assigned the maximum operational score. Diclofenac has been reported in Indian rivers and wastewater studies, including the Ganges, Yamuna and Cauvery systems (Mutiyar et al., 2018; Singh & Suthar, 2021a,b; Renganathan et al., 2021; Biswas & Vellanki, 2021; Biswas et al., 2024). Treatment performance for diclofenac is known to vary with process configuration, and the present score should therefore be interpreted as evidence-supported treatment resistance within the assembled dataset rather than a universal removal property.

Triclosan ranked fifth (OPS 72.3), despite having the second-highest occurrence coverage in the matrix. This combination demonstrates the effect of treatment and risk dimensions on the integrated result. Indian studies have documented triclosan in river water, lakes, sewage treatment systems and the Cauvery/Ganges systems (Ramaswamy et al., 2011; Archana et al., 2017; Kachhawaha et al., 2021; Singh & Suthar, 2021a,b; Renganathan et al., 2021; Dubey et al., 2023). Its intermediate persistence score prevents the very high occurrence score from translating directly into the highest OPS.

4.4 Paracetamol, Diazepam and Bisphenol A

Paracetamol ranked sixth (OPS 63.4). It had nine occurrence studies and an intermediate persistence score, but a lower relative risk score. Indian studies have repeatedly detected paracetamol in wastewater and surface-water systems, including the

Yamuna, Nagpur and Ganges-related investigations (Mutiya et al., 2018; Shipingana et al., 2022; Archana et al., 2017; Singh & Suthar, 2021a,b; Kachhawaha et al., 2021). The result illustrates why high occurrence does not automatically imply the highest integrated priority when treatment and risk evidence provide countervailing information.

Diazepam ranked seventh (OPS 63.0). Its occurrence coverage was comparatively limited at three studies, but the persistence component was maximal. The compound was reported in Indian STP and river evidence, including the Yamuna and southern Indian wastewater studies (Subedi et al., 2015, 2017; Mutiya et al., 2018). The result is best interpreted as identifying diazepam as a monitoring candidate for which additional Indian occurrence and ecological-risk data would be particularly valuable, rather than as evidence that it poses a greater absolute hazard than every lower-ranked compound.

BPA ranked eighth (OPS 62.6). It had only three occurrence studies in the locked matrix, but it received the maximum risk score. The Nagpur wastewater study by Puri et al. (2024), first published online in 2023, reported BPA in influent and effluent and a high risk quotient for the aquatic insect endpoint used in that study. BPA therefore demonstrates how a strong risk signal can compensate for limited occurrence-study coverage within a multi-criteria framework. Its relatively low persistence score, however, moderated the final OPS.

4.5 Caffeine and Interpretation of Lower Priority

Caffeine ranked ninth (OPS 56.2) even though it had the broadest occurrence coverage, with reports from 13 independent studies. Its lower integrated position was driven mainly by the lowest persistence and risk scores in the locked dataset. Caffeine is frequently used as an indicator of anthropogenic wastewater influence, and its widespread detection should not be interpreted as environmental irrelevance. Rather, the result demonstrates that the present framework distinguishes frequent occurrence from the combined persistence and ecological-risk evidence used for monitoring prioritisation.

Similarly, a lower OPS should not be read as evidence of absence of environmental effects. Monitoring priority is a relative decision-support output. It depends on the evidence dimensions included, their weights and the quality and coverage of the underlying literature.

4.6 Comparison with Existing Prioritisation Approaches

Previous prioritisation approaches have used combinations of occurrence frequency, environmental concentrations, toxicity, persistence, exposure and physicochemical properties. For example, Gaston et al. (2019) reviewed prioritisation approaches for substances of emerging concern in groundwater, while Wielens Becker et al. (2021) combined multi-criteria decision-making with risk assessment for surface-water contaminants. Shafi et al. (2023) developed a regional prioritisation approach for surface waters in India and neighbouring South Asian countries. The present framework differs in scope by focusing specifically on Indian primary evidence and by integrating three dimensions that can be populated from the available Indian treatment and occurrence literature.

The framework is intentionally simpler than a full chemical-specific risk assessment. Its purpose is to support the first stage of monitoring design: narrowing a large candidate list to a manageable set for further investigation. The use of transparent component scores also makes the framework updateable when new Indian data become available.

4.7 Uncertainty and Limitations

Several limitations should be considered when interpreting the results. First, the number of studies contributing to occurrence scores reflects both environmental occurrence and research effort. A low study count can indicate limited environmental importance, but it can equally indicate that a contaminant has simply received less analytical attention. Second, geographical coverage is uneven, with repeated investigation of selected river basins and urban centres and comparatively limited coverage elsewhere. The occurrence scores therefore should not be interpreted as national prevalence estimates.

Third, treatment removal is strongly dependent on treatment technology, operating conditions, wastewater composition and the specific study design. The operational PS=100 assignments for compounds with poor, negligible or negative-removal evidence are therefore screening indicators, not measured universal persistence values. Fourth, HQ and RQ values are heterogeneous across studies. Different organisms, endpoints, exposure assumptions and reference concentrations mean that the normalised RS should be interpreted as a relative evidence score rather than an absolute toxicity scale.

Finally, publication and reporting bias may affect the evidence base. Compounds associated with notable contamination or risk may be more likely to be investigated, while the absence of studies for another compound does not demonstrate environmental

absence. These limitations are not reasons to discard the framework; rather, they define the level of inference that can reasonably be drawn from it.

4.8 Implications for Monitoring and Future Research

The results support a tiered monitoring strategy in which the highest-scoring contaminants are considered for more consistent occurrence surveillance, while intermediate contaminants are retained where risk or treatment evidence indicates a specific concern. For the current evidence base, ibuprofen, ciprofloxacin, carbamazepine, diclofenac and triclosan form the upper portion of the integrated ranking, but the sensitivity analysis indicates that the exact order is weight-dependent.

Future Indian studies should prioritise harmonised influent-effluent sampling across treatment technologies, repeated seasonal sampling across underrepresented regions, and consistent ecological-risk endpoints. Antibiotic monitoring should additionally distinguish conventional ecotoxicity from antimicrobial-resistance selection pressure, following the framework proposed by Larsson et al. (2018). For contaminants such as diazepam and BPA, additional independent occurrence studies would be particularly useful because the present scores are based on relatively limited occurrence coverage. The framework can be updated as new evidence accumulates without changing its basic structure.

V. CONCLUSIONS

A quantitative framework was developed to prioritise emerging contaminants for monitoring in Indian aquatic environments using occurrence, treatment persistence and ecological risk. The final evidence base contained 17 primary Indian studies and supported integrated scoring of nine contaminants. Under the primary 40:30:30 weighting, ibuprofen obtained the highest OPS (85.9), followed by ciprofloxacin (78.5), carbamazepine (78.3), diclofenac (73.5) and triclosan (72.3). Caffeine was the most widely reported contaminant in the occurrence matrix but received the lowest integrated score because its persistence and risk contributions were comparatively low.

The sensitivity analysis showed that the broad upper group was relatively stable, while the exact order of several intermediate contaminants changed when persistence or ecological risk received greater weight. The results should therefore be used as a screening-level monitoring prioritisation rather than as a definitive national ranking of environmental hazard. The principal value of the framework is its transparency: new occurrence, treatment and ecological-risk evidence can be incorporated as the Indian evidence base expands. Continued harmonised monitoring and comparable treatment-fate and risk assessment will be necessary to refine these priorities and improve their national applicability.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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