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DA EVIDÊNCIA CIENTÍFICA À AÇÃO REGULATÓRIA: CONTAMINANTES EMERGENTES E GOVERNANÇA ADAPTATIVA DA ÁGUA NO BRASIL

FROM SCIENTIFIC EVIDENCE TO REGULATORY ACTION: EMERGING CONTAMINANTS AND ADAPTIVE WATER GOVERNANCE IN BRAZIL

DE LA EVIDENCIA CIENTÍFICA A LA ACCIÓN REGULATORIA: CONTAMINANTES EMERGENTES Y GOBERNANZA ADAPTATIVA DEL AGUA EN BRASIL

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Resumo

Contaminantes de preocupação emergente (CPEs), incluindo fármacos, hormônios sintéticos, substâncias per- e polifluoroalquiladas (PFAS), bisfenol A, determinantes de resistência a antibióticos e microplásticos, são cada vez mais relatados em ambientes aquáticos brasileiros, mas os instrumentos federais de qualidade da água aqui examinados os abordam apenas em parte. Esta revisão mapeia um conjunto estruturado e rastreável de evidências sobre a ocorrência de CPEs em águas brasileiras e examina em que medida essas evidências foram traduzidas em monitoramento, padrões e exigências de tratamento. A busca abrangeu Scopus, Web of Science, PubMed, ScienceDirect e Google Scholar e foi complementada por fontes regulatórias e institucionais oficiais e por uma análise exploratória no Bibliometrix/Biblioshiny de um corpus mais amplo da Web of Science. As evidências foram priorizadas segundo relevância temática, rastreabilidade, ocorrência ambiental, relevância para a resistência antimicrobiana, desempenho de tratamento e significância regulatória. Fármacos, antibióticos, compostos com atividade endócrina, PFAS, genes de resistência antimicrobiana (ARGs) e microplásticos foram documentados em águas superficiais, mananciais, estuários, ambientes costeiros e algumas matrizes de água para consumo humano no Brasil. Para alguns compostos, as concentrações locais se sobrepõem ou excedem benchmarks baseados em efeito ou de seleção de resistência; para outros, a conclusão mais defensável é a ocorrência recorrente sem exigência brasileira correspondente de monitoramento rotineiro. A União Europeia, em contraste, articulou progressivamente listas de observação, revisão periódica, padrões de potabilidade, vigilância da resistência antimicrobiana e tratamento quaternário de esgotos. Esse descompasso é descrito aqui como uma lacuna de tradução entre ciência e regulação (science-to-regulation translation gap) e fundamenta uma proposta regulatória adaptativa em cinco eixos para o Brasil, centrada em uma lista nacional dinâmica de observação, revisão periódica, priorização baseada em risco, monitoramento costeiro e estuarino e integração em Saúde Única (One Health) para os riscos associados aos ARGs.

Palavras-chave: contaminantes de preocupação emergente; regulação ambiental; interface ciência-política; monitoramento baseado em risco; regulação adaptativa.

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Abstract

Contaminants of emerging concern (CECs), including pharmaceuticals, synthetic hormones, per- and polyfluoroalkyl substances (PFAS), bisphenol A, antibiotic-resistance determinants, and microplastics, are increasingly reported in Brazilian aquatic environments, yet the federal water-quality instruments examined here address them only in part. This review maps a structured, traceable body of evidence on CEC occurrence in Brazilian waters and examines how far that evidence has been translated into monitoring, standards, and treatment requirements. The search covered Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar, and was complemented by official regulatory and institutional sources and by an exploratory Bibliometrix/Biblioshiny analysis of a broader Web of Science corpus. Evidence was prioritised according to thematic relevance, traceability, environmental occurrence, relevance to antimicrobial resistance, applied treatment performance, and regulatory significance. Pharmaceuticals, antibiotics, endocrine-active compounds, PFAS, antimicrobial resistance genes (ARGs), and microplastics have been documented in specific Brazilian surface waters, source waters, estuaries, coastal environments, and some drinking-water matrices. For some compounds, site-specific concentrations overlap with or exceed effect-based or resistance-selection benchmarks; for others, the more defensible conclusion is recurrent occurrence with no corresponding Brazilian requirement for routine monitoring. The EU, by contrast, has progressively connected watch lists, periodic review, drinking-water standards, antimicrobial-resistance surveillance, and quaternary wastewater-treatment requirements. This mismatch is described here as a science-to-regulation translation gap, and it frames a five-axis adaptive regulatory proposal for Brazil centred on a dynamic national watch list, periodic review, risk-based prioritisation, coastal and estuarine monitoring, and One Health integration for ARG-related hazards.

Keywords: contaminants of emerging concern; environmental regulation; science-policy interface; risk-based monitoring; adaptive regulation.

Resumen

Los contaminantes de preocupación emergente (CPE), incluidos fármacos, hormonas sintéticas, sustancias per- y polifluoroalquiladas (PFAS), bisfenol A, determinantes de resistencia a antibióticos y microplásticos, se reportan cada vez más en ambientes acuáticos brasileños, pero los instrumentos federales de calidad del agua examinados aquí solo los abordan parcialmente. Esta revisión mapea un conjunto estructurado y trazable de evidencias sobre la presencia de CPE en aguas brasileñas y examina en qué medida dichas evidencias se han traducido en monitoreo, normas y exigencias de tratamiento. La búsqueda abarcó Scopus, Web of Science, PubMed, ScienceDirect y Google Scholar, y se complementó con fuentes regulatorias e institucionales oficiales y con un análisis exploratorio en Bibliometrix/Biblioshiny de un corpus más amplio de Web of Science. Las evidencias se priorizaron según relevancia temática, trazabilidad, presencia ambiental, relevancia para la resistencia antimicrobiana, desempeño de tratamiento e importancia regulatoria. Se han documentado fármacos, antibióticos, compuestos con actividad endocrina, PFAS, genes de resistencia antimicrobiana (ARG) y microplásticos en aguas superficiales, fuentes de abastecimiento, estuarios, ambientes costeros y algunas matrices de agua potable en Brasil. Para algunos compuestos, las concentraciones locales se superponen o superan umbrales basados en efectos o de selección de resistencia; para otros, la conclusión más defendible es la presencia recurrente sin una exigencia brasileña correspondiente de monitoreo rutinario. La Unión Europea, en cambio, ha articulado progresivamente listas de observación, revisión periódica, normas de agua potable, vigilancia de la resistencia antimicrobiana y tratamiento cuaternario de aguas residuales. Este desajuste se describe aquí como una brecha de traducción entre ciencia y regulación (science-to-regulation translation gap) y sustenta una propuesta regulatoria adaptativa de cinco ejes para Brasil, centrada en una lista nacional dinámica de observación, revisión periódica, priorización basada en riesgo, monitoreo costero y estuarino e integración en Una Salud (One Health) para los riesgos asociados a los ARG.

Palabras clave: contaminantes de preocupación emergente; regulación ambiental; interfaz ciencia-política; monitoreo basado en riesgo; regulación adaptativa.

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1. Introduction

Water quality underpins environmental sustainability, public health, and the ecosystem services on which aquatic and terrestrial life depend. Urbanisation, rising pharmaceutical consumption, agricultural intensification, and the growth of industrial chemistry have nonetheless introduced into aquatic environments a wide range of substances that conventional regulatory systems and treatment technologies were not designed to handle (Schwarzenbach et al., 2006; Geissen et al., 2015). These substances, commonly grouped as contaminants of emerging concern (CECs), are chemically heterogeneous and have been documented in water for decades, yet most of them remain outside mandatory monitoring and current Brazilian environmental and sanitary regulation.

Concern about these compounds is not new. Daughton and Ternes (1999) drew early attention to pharmaceuticals and personal-care products in aquatic environments and to the limits of existing regulatory frameworks, and evidence has since accumulated across several CEC classes. Pharmaceuticals and hormones can affect endocrine, reproductive, and behavioural processes in non-target organisms at low concentrations (Kümmerer, 2009; Johnson and Sumpter, 2001). Antibiotics at sub-lethal concentrations can select for resistant microbial populations and favour the spread of antimicrobial resistance genes (ARGs) through horizontal gene transfer (Bengtsson-Palme and Larsson, 2016; Manaia et al., 2018). PFAS occur across environmental compartments and are associated with hepatic, immune, and carcinogenic effects (Cousins et al., 2020). Microplastics can carry sorbed contaminants and release additives such as plasticisers into aquatic organisms (Eerkes-Medrano et al., 2015). Meanwhile, advances in analytical chemistry, especially liquid chromatography coupled to tandem mass spectrometry (LC-MS/MS), have made detection at nanogram-per-litre levels routine, bringing previously hard-to-measure contamination into view (Montagner et al., 2017).

Across these classes, exposure tends to follow a similar chain: human or veterinary use, industrial or agricultural application, excretion or release, sewered or diffuse discharge, incomplete removal during treatment, and transport through receiving waters. This sequence can connect inland sources to source waters,

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estuaries, and coastal environments (Ternes, 1998; Kümmerer, 2009; Verlicchi et al., 2010), and that continuity matters for governance. Regulation that looks only at end-point compliance can miss what happens upstream, where contaminants are generated and treated, and downstream, where they are redistributed through connected aquatic systems. For this reason, occurrence, treatment, and regulatory response are examined here as parts of a single pathway.

This raises a question that remains only partly answered in Brazil: why do compounds with documented occurrence and recognised toxicity remain outside dedicated CEC-specific parameters or routine monitoring requirements in the federal instruments examined here? I approach this question by mapping a traceable body of evidence and examining what I call the science-to-regulation translation gap, that is, the lack of a systematic institutional pathway through which scientific evidence becomes a binding requirement for monitoring, control, or accountability. The term is used as an operational concept for this study, not as an established regulatory category. It should also be stressed that the absence of a regulatory parameter is not evidence that the contaminant itself is absent.

The two principal federal instruments examined here are CONAMA Resolution No. 357/2005 and Ordinance GM/MS No. 888/2021, for surface-water quality and drinking-water quality, respectively. CONAMA 357/2005 classifies surface water bodies and sets environmental quality standards for the aquatic environment, whereas the drinking-water standard for human consumption is consolidated in Annex XX of Consolidation Ordinance No. 5/2017, as updated by Ordinances GM/MS No. 888/2021 and No. 2,472/2021. The two instruments regulate different objects and are not functionally equivalent. Neither instrument comprehensively incorporates the contemporary CEC agenda examined here, neither embeds a formal periodic, CEC-specific evidence-review cycle for its parameters, and neither sets maximum allowable values for pharmaceuticals, synthetic hormones, PFAS, microplastics, or ARGs. As a result, biologically active compounds reported in Brazilian rivers, source waters, estuaries, and even treated drinking water generally fall outside routine mandatory monitoring under these instruments. Compliance therefore confirms conformity with

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the listed parameters; it does not demonstrate chemical safety with respect to substances that are not listed.

The EU has taken a different path. Over the past two decades, the Water Framework Directive (WFD, 2000/60/EC) introduced priority-substance lists subject to mandatory review; the watch-list mechanism, beginning with Decision (EU) 2015/495, allowed precautionary monitoring before formal regulation; the Drinking Water Directive (DWD, (EU) 2020/2184) set parametric values for PFAS and bisphenol A; and the recast Urban Wastewater Treatment Directive (UWWTD, (EU) 2024/3019) added quaternary treatment requirements for large plants, an extended-producer-responsibility (EPR) scheme, and public-health monitoring provisions (European Union, 2020, 2024). This trajectory is used here as a comparative reference rather than as a model for direct transplantation, since administrative structures, analytical capacity, sanitation coverage, and enforcement differ substantially between the EU and Brazil.

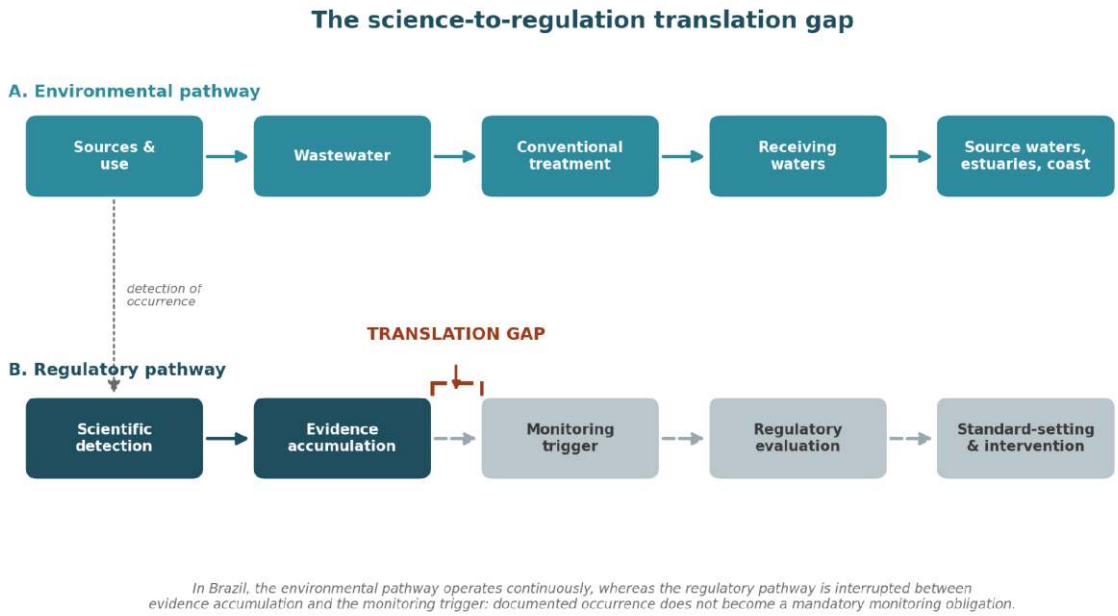
With this background, the review has four objectives: (i) to map the extent and nature of evidence on CEC occurrence in Brazilian water bodies; (ii) to identify structural gaps in Brazilian regulatory instruments; (iii) to compare the Brazilian framework with EU, EPA, and WHO approaches; and (iv) to develop an adaptive national regulatory proposal. Figure 1 sets out the conceptual logic that links these objectives.

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Figure 1. Conceptual representation of the science-to-regulation translation gap for contaminants of emerging concern in Brazil.



The environmental pathway (A) operates continuously, whereas the regulatory pathway (B) is interrupted between evidence accumulation and the monitoring trigger, so documented occurrence does not become a mandatory monitoring obligation. Source: prepared by the author.

Figure 1 locates the key break in the institutional pathway rather than in the environmental one. Sources, releases, incomplete treatment, and transport to receiving waters continue to operate, but the step from accumulated evidence to a formal monitoring trigger is not systematically built into the Brazilian instruments examined here. This distinction guides the comparisons between occurrence, monitoring requirements, and regulatory response that follow.

2. Methods

2.1 Review design and analytical framework

The study combines a structured evidence review with comparative regulatory analysis. Its purpose was not to estimate national prevalence or to produce a meta-analytic effect measure, but to assemble traceable evidence on CEC occurrence, treatment relevance, antimicrobial resistance, and water governance, and to examine how that evidence is reflected in regulatory instruments. This design suits a heterogeneous evidence base that spans environmental chemistry, microbiology, engineering, ecotoxicology, and public policy, where quantitative pooling would be neither methodologically consistent nor necessary to answer the regulatory question.

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The analytical question was organised around three dimensions: (i) Brazilian aquatic environments, including water bodies, source waters, estuaries, and coastal zones; (ii) contaminants of emerging concern, with emphasis on documented occurrence, measured concentrations, antimicrobial resistance, treatment performance, and effect-based or resistance-selection benchmarks; and (iii) the Brazilian regulatory context in comparison with EU, U.S. EPA, and WHO frameworks. Evidence was assessed for relevance to one or more of these dimensions and for traceability to a peer-reviewed or primary official source.

2.2 Search strategy and information sources

The core indexed search covered Scopus, Web of Science, and PubMed for publications from 2014 to 2026. ScienceDirect was consulted as an additional full-text publisher platform and was not treated as methodologically equivalent to the indexed bibliographic databases. Google Scholar served as a supplementary cross-disciplinary and full-text discovery source. The main multi-source search was completed on 22 May 2026, and a documented Google Scholar update was run on 15 August 2026 with the exact query "emerging contaminants" + "aquatic matrices" + "Brazil" + "monitoring" + "treatment" + "regulation" + "governance". This query returned 22 relevance-ranked records; all 22 were screened, five peer-reviewed sources were incorporated, and 17 were excluded, with record-level reasons given in Supplementary Table S4. Across sources, the search combined concepts related to emerging contaminants, aquatic matrices, Brazil, occurrence/monitoring, treatment, regulation/governance, and environmental antimicrobial resistance, with syntax adapted to each database. Seminal works of established relevance (Ternes, 1998; Daughton and Ternes, 1999; Johnson and Sumpter, 2001) and official regulatory and institutional sources were added to the database results. Screening, data extraction, numerical verification, and regulatory checking were carried out by the author, and every quantitative or regulatory claim was checked against the cited primary source whenever one was available.

2.3 Eligibility criteria

Inclusion criteria: (i) peer-reviewed articles indexed in the listed databases; (ii) studies reporting quantitative environmental concentrations of CECs; (iii) studies on environmental antimicrobial resistance and ARGs; (iv) studies on removal efficiency in

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wastewater treatment; (v) official regulatory and normative documents; and (vi) studies relevant to water management and public policy. Exclusion criteria: duplicates; non-peer-reviewed items (for primary occurrence data); items without central thematic relevance; and items with non-verifiable data.

2.4 Evidence selection and verification

Evidence selection followed a transparent, claim-oriented process in which the analytical domains were defined a priori, before the interpretive synthesis: Brazilian occurrence, environmental antimicrobial resistance, applied treatment performance, effect-based or resistance-selection benchmarks, and regulatory/governance analysis. Sources were assigned to these pre-established domains rather than selected to fit individual claims. Primary occurrence studies received a minimum reliability appraisal covering temporal design (single versus repeated campaigns), number of sampling campaigns and sites, spatial representativeness, analytical QA/QC (including blanks and recoveries where reported), LOD/LOQ, instrumental method, matrix, and consistency of units. Sparse or single-campaign evidence was treated as site-specific and indicative, not as nationally representative. Treatment studies were appraised separately; where reported, data were extracted on influent and effluent characterisation, treatment technology, matrix, hydraulic and/or solids retention time, influent concentration or loading, number of replicates or sampling events, reactor/process configuration, removal efficiency, and variability or uncertainty. Missing methodological fields were not imputed. Keeping the two appraisals apart prevents a short bench-scale experiment from carrying the same interpretive weight as repeated full-scale or field monitoring. The framework is summarised in Table 1 and detailed in Supplementary Table S6.

Table 1. Evidence selection and verification framework.

Stage	Purpose	Operational criterion
Evidence identification	Assemble a broad discovery corpus	Peer-reviewed and official sources relevant to CECs, aquatic environments, treatment, AMR, regulation, or governance
Relevance screening	Remove clearly off-scope material	Title/abstract adherence to the CEC-in-water axis or direct regulatory relevance
Primary-evidence prioritisation	Identify evidence supporting environmental claims	Traceable occurrence, concentration, AMR, or applied treatment information

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Stage	Purpose	Operational criterion
Contextual evidence	Support interpretation and comparison	Reviews, mechanistic studies, benchmarks, and international evidence used without substituting for Brazilian primary occurrence data
Quantitative verification	Prevent unsupported numerical claims	Matrix, unit, concentration/range, benchmark type, and cited source must be mutually traceable
Regulatory verification	Separate binding and non-binding instruments	Primary official texts used to distinguish standards, proposed EQS, watch lists, guidance, and effect-based benchmarks
Evidence register	Maintain auditability	All sources used in the manuscript are cross-referenced in the supplementary evidence workbook
Occurrence-study robustness	Qualify the strength of site-specific occurrence evidence	Temporal design; sampling campaigns/sites; spatial representativeness; matrix; QA/QC; blanks/recoveries; LOD/LOQ; instrumental method; units and detection frequency/central tendency where available
Treatment-study robustness	Qualify engineering performance evidence separately from occurrence evidence	Influent/effluent; technology; matrix; hydraulic/solids retention time; initial concentration/loading; n/replicates or sampling events; process configuration; removal efficiency and variability/uncertainty where available

Source: Author's elaboration.

Throughout, traceability took precedence over retrospective numerical reconstruction. The resulting synthesis is the body of evidence used directly to support the environmental, engineering, microbiological, and regulatory claims of the manuscript; the complete reference list and an auditable source register are provided in the supplementary material.

2.5 Data extraction

For each source used in the synthesis, information was extracted where available on author and year, geographic context, Brazilian location, environmental matrix, contaminant or class, analytical method, measured concentration or range, central tendency (mean/median), detection frequency, sampling period/season, number of campaigns and sites, and regulatory relevance. For treatment studies, the engineering fields listed in Section 2.4 were extracted separately. Temporal or event-related information (for example, wet or dry season, high-flow conditions, or an extreme event) was retained when the source reported it, because a maximum concentration without its sampling context can be misleading. Extraction was

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qualitative and interpretive rather than a pooled meta-analysis, and no value was generated where the original study did not report one.

2.6 Exploratory bibliometric context and descriptive evidence mapping

A bibliometric exploration was carried out in Bibliometrix/Biblioshiny using Web of Science records retrieved while the search strategy was being developed. The raw tagged Web of Science export (savedrecs.txt) contains 300 records, and the processed Bibliometrix/Biblioshiny dataset used for the exploratory maps contains 145. In the collaboration output, SCP denotes single-country publications and MCP multiple-country publications. These counts describe the exploratory bibliometric dataset; they are not the inclusion count of the review. The substantive synthesis rests on the source-level evidence register in Supplementary Table S1, which lists 59 traceable sources (39 peer-reviewed and 20 regulatory/institutional). Supplementary Tables S2–S4 document the search and export metadata, the recovered Web of Science records, and the screening decisions for the Google Scholar update, respectively.

Publication-frequency counts from earlier exploratory groupings were not used, because they could not be reliably linked to a single auditable evidence set. The Bibliometrix figures presented below are labelled exploratory and describe only the broader discovery corpus.

2.7 Comparative regulatory analysis

The comparative analysis took as its units of analysis the presence or absence, for each compound class, of a dedicated parametric value or environmental quality standard (EQS), a formal periodic-review mechanism, a monitoring or candidate-list instrument, and a mandatory treatment or surveillance obligation. Brazilian instruments were compared with EU instruments (WFD; DWD (EU) 2020/2184; UWWTD (EU) 2024/3019), U.S. EPA instruments (including the CCL, the UCMR, and the PFAS drinking-water rule), and WHO guidance and hazard assessments. Binding standards, candidate or watch lists, monitoring rules, proposed values, and non-regulatory effect benchmarks were kept analytically separate. Regulatory status was checked against primary official sources up to 15 August 2026, the regulatory cut-off date of this study.

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3. Results

3.1 Evidence landscape

The literature reviewed shows sustained attention to CECs over the past decade, particularly PFAS, antimicrobial resistance, endocrine-active compounds, and microplastics. For several contaminant classes, Brazilian studies are concentrated in the South-East and South, while the North, the Amazon, and several coastal and estuarine settings remain under-represented. The spatial pattern, however, varies by contaminant class and environmental matrix. For microplastics, Escrobot et al. (2024) identified 102 Brazilian coastal studies published between 2018 and 2023; institutions from the South-East accounted for 37.3% and those from the North-East for 34.3%, whereas estuaries and coral reefs made up only a small share of the environments studied. This uneven spatial and ecosystem coverage rules out any inference of national prevalence from site-based datasets.

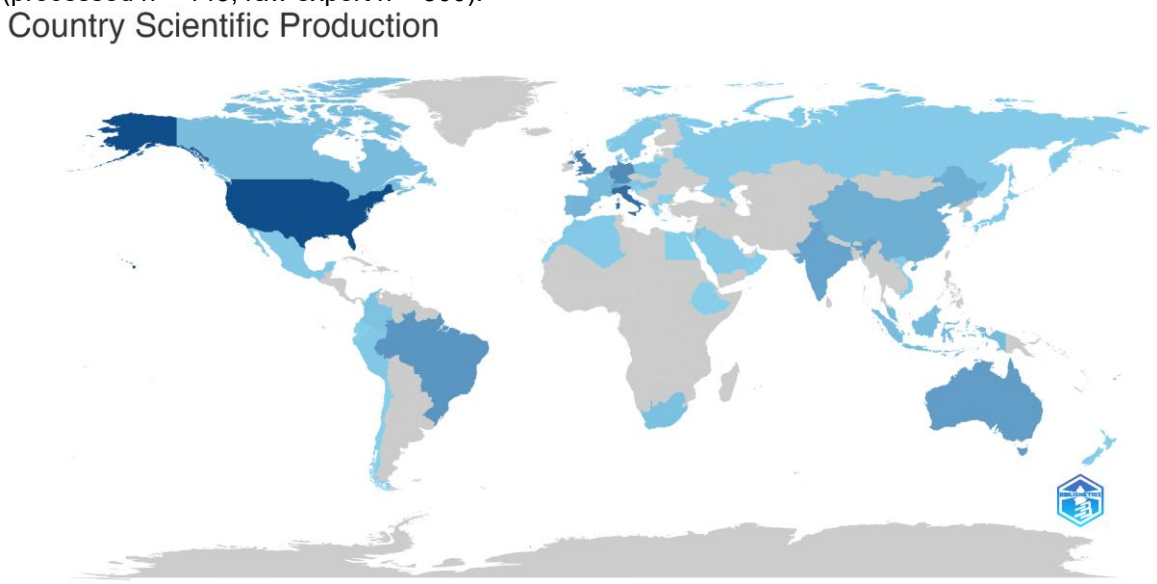
The exploratory Bibliometrix analysis offers a wider view of the processed Web of Science dataset (n = 145) described in Section 2.6. The country scientific-production map (Figure 2A) shows research activity across North America, Europe, Asia, Oceania, and Brazil, and the corresponding-author analysis (Figure 2B) shows both single-country (SCP) and multiple-country (MCP) publications.

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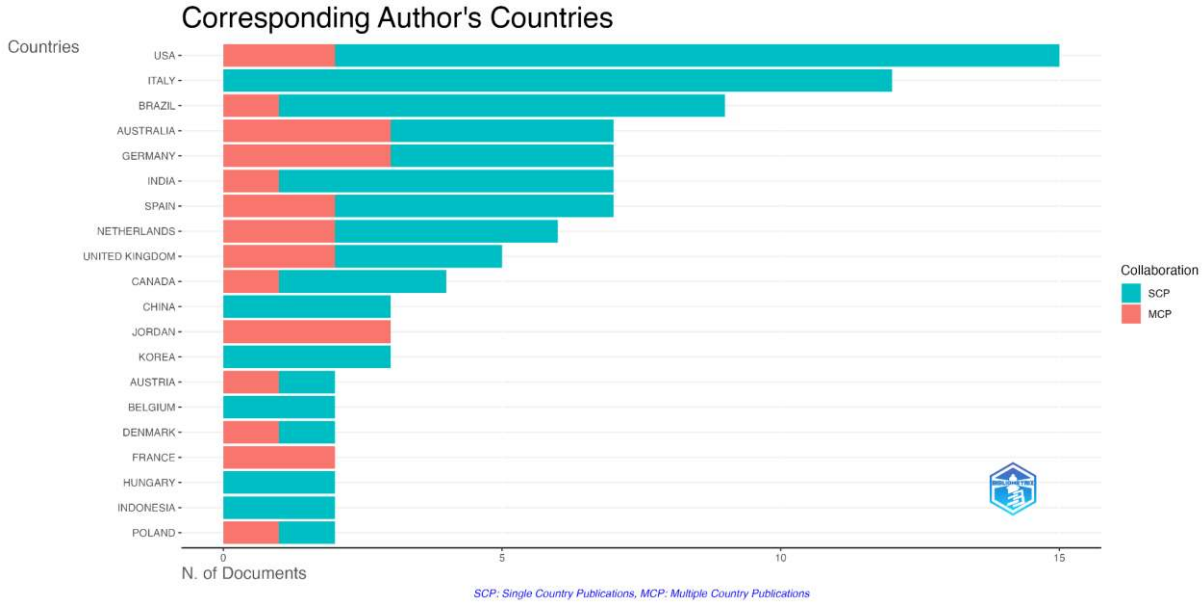
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Figure 2A. Country scientific production in the exploratory Web of Science bibliometric dataset (processed n = 145; raw export n = 300).



This dataset is distinct from the evidence base of the review (Supplementary Table S1, n = 59). Source: Author's elaboration using Bibliometrix/Biblioshiny.

Figure 2B. Corresponding-author countries and collaboration pattern (SCP/MCP) in the exploratory Web of Science bibliometric dataset (processed n = 145; raw export n = 300).



This dataset is distinct from the evidence base of the review (Supplementary Table S1, n = 59). Source: Author's elaboration using Bibliometrix/Biblioshiny.

Taken together, Figures 2A and 2B place the Brazilian regulatory discussion within a broad international research landscape. The geographic breadth of the corpus supports cross-jurisdictional comparison, while the predominance of single-country production underlines the weight of institutional and territorial context. Regulatory

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approaches developed elsewhere therefore cannot be assumed to transfer directly to Brazil, given differences in monitoring capacity, analytical infrastructure, governance arrangements, environmental conditions, and regulatory maturity.

More broadly, the results of this review should be read as site-specific evidence, not as estimates of national prevalence. Maximum concentrations reported in individual studies are treated as screening signals rather than national distributions. Where studies reported detection frequency, repeated campaigns, central tendency, or seasonal patterns, those descriptors were given priority; where they were not reported, they were not inferred retrospectively. Ratios between reported concentrations and benchmarks were calculated only when substance, matrix, unit, benchmark type, and source were sufficiently comparable.

3.2 Pharmaceuticals and antibiotics

Pharmaceuticals are reported in surface waters worldwide (aus der Beek et al., 2016) and have a substantial evidence base in Brazil, but they remain weakly represented in compound-specific regulatory requirements. Their occurrence reflects therapeutic use and excretion, incomplete removal in conventional wastewater treatment, and the absence of routine monitoring obligations. Carbamazepine, for example, is an antiepileptic with low removal in conventional secondary treatment and is widely used as a marker of domestic-sewage contamination (Miège et al., 2009). Cunha et al. (2019) compiled more than 80 pharmaceutical compounds reported in Brazilian water bodies, none of which has a specific parametric value under CONAMA 357/2005 or Ordinance 888/2021.

A recurring pathway links human and veterinary use to excretion, sewered or diffuse release, incomplete wastewater treatment, and discharge into receiving waters, and it carries more weight where sanitation coverage and advanced treatment are uneven. Brazilian studies should therefore be read as evidence of occurrence at monitored sites, not as a national concentration distribution. Reviews by Montagner et al. (2017), Cunha et al. (2019), and Marson et al. (2022) point in the same direction: analytical detection has advanced faster than routine monitoring requirements. A recent review that integrates pharmaceutical occurrence, fate, treatment performance, and governance likewise argues for linking monitoring evidence to lifecycle

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management and adaptive regulation, rather than treating treatment technology as an isolated endpoint (Arumugam et al., 2026).

Diclofenac is one of the pharmaceuticals for which an EQS has been developed under the WFD. The European Commission/SCHEER supported a proposed annual-average EQS of 0.04 µg/L (40 ng/L) for inland surface waters (MAC-EQS 250 µg/L); this value remains proposed and non-binding, and has been discussed and re-derived by Peters et al. (2022). Diclofenac was included in the first EU watch list for Union-wide monitoring (Decision (EU) 2015/495) and removed in 2018 after data review (Commission Implementing Decision (EU) 2018/840). For antibiotics, Bengtsson-Palme and Larsson (2016) proposed predicted no-effect concentrations for resistance selection (PNEC-res), acknowledging method-dependent variation. Ciprofloxacin, for example, has a PNEC-res of 0.064 µg/L (64 ng/L) and has been reported at concentrations in the low thousands of ng/L in Brazilian rivers, whereas sulfamethoxazole has a broader, method-dependent PNEC-res range (0.6–16 µg/L), so its interpretation depends on the estimate chosen.

Table 2 sets reported concentrations from specific Brazilian studies beside the most relevant regulatory or effect-based benchmarks. These comparisons call for caution because the comparators do not share the same legal or scientific status. An EQS may be proposed, derived, or legally binding depending on the instrument, whereas PNEC-res values are effect-based thresholds below which selection for antimicrobial resistance is not expected; they are therefore used here as resistance-selection benchmarks, not as legal limits. Ratios are calculated only when substance, matrix, unit, and benchmark are sufficiently comparable and the underlying sources are traceable; otherwise, values are presented qualitatively.

Table 2. Pharmaceuticals and antibiotics: reported occurrence in specific Brazilian studies and comparison with benchmarks.

Compound	Reported conc. (ng/L) — site, source	BR status	Benchmark (type; source)	Comparison / caveat
Diclofenac	Up to ~2,150 (Rio Piracicaba, SP; Madeira et al., 2023); Rio Doce, MG (Gomes et al., 2022)	No dedicated federal CEC parameter*	Proposed AA-EQS 0.04 µg/L (40 ng/L), inland surface water; non-binding (EC/SCHEER, 2022; Peters et al., 2022)	Reported max ≈54× the proposed inland AA-EQS at the reported site; benchmark is proposed, not binding

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Compound	Reported conc. (ng/L) — site, source	BR status	Benchmark (type; source)	Comparison / caveat
Carbamazepine	Reported in SP and RJ rivers (Oliveira et al., 2024)	No dedicated federal CEC parameter*	Watch-list marker; secondary-treatment removal <15% (Miège et al., 2009)	Marker of sewage contamination; no numeric EU EQS
Sulfamethoxazole	Up to ~9,640 (Rio Doce, MG; Gomes et al., 2022; Oliveira et al., 2024)	No dedicated federal CEC parameter*	PNEC-res 16 µg/L; method range 0.6–16 µg/L (Bengtsson-Palme and Larsson, 2016; Le Page et al., 2018)	Reported max below the 16 µg/L PNEC-res but within lower method-dependent estimates
Ciprofloxacin	Up to ~4,854 (Rio Doce, MG; Curitiba; Gomes et al., 2022)	No dedicated federal CEC parameter*	PNEC-res 0.064 µg/L (64 ng/L) (Bengtsson-Palme and Larsson, 2016)	~76× above the PNEC-res at the reported maximum site (effect-based benchmark, not a regulatory limit)
Ibuprofen	Reported in heavily impacted rivers (Cunha et al., 2019)	No dedicated federal CEC parameter*	No fixed EQS; secondary-treatment removal 65–90%	No comparable numeric benchmark

Note: EQS = environmental quality standard; PNEC-res = predicted no-effect concentration for resistance selection. * “No dedicated federal CEC parameter” means no dedicated CEC-specific parametric value in CONAMA Resolution 357/2005 or in the federal drinking-water instrument examined; it does not imply absence of broader environmental, sanitary, licensing, liability, or subnational law. Source: Author’s synthesis based on Gomes et al. (2022), Madeira et al. (2023), Oliveira et al. (2024), Cunha et al. (2019), Bengtsson-Palme and Larsson (2016), and Peters et al. (2022).

The regulatory significance of an apparent exceedance thus depends not only on the numerical ratio but also on the status, intended matrix, and purpose of the comparator. Proposed EQS values and PNEC-res benchmarks are not equivalent to binding Brazilian standards.

3.3 Endocrine-active compounds

Synthetic hormones and industrial endocrine disruptors can produce adverse effects at very low concentrations, sometimes below 1 ng/L, and often follow non-monotonic dose–response patterns (Johnson and Sumpter, 2001). The most studied compound of this class is 17α-ethinylestradiol (EE2): laboratory concentrations of roughly 0.1–2 ng/L are enough to induce feminisation in male fish, and field studies

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have linked intersex fish populations in sewage-receiving rivers to EE2 exposure. The European Commission's Scientific Committee on Health, Environmental and Emerging Risks (SCHEER) proposed annual-average EQS values of the order of 0.035 ng/L for EE2 and 0.4 ng/L for 17β-estradiol (E2) in surface waters (SCHEER, 2022). These are among the most stringent values proposed for any CEC, but they are proposals, not binding limits.

In Brazil, hormones have been detected by LC-ESI-MS/MS in surface water and treated drinking water (Santos et al., 2015), and estuarine-sediment studies show that endocrine-active contamination also reaches coastal receiving environments (Maranho et al., 2019). Because effects can occur at very low concentrations, and mixture effects and non-monotonic dose responses complicate threshold-based interpretation, these findings support surveillance based on occurrence, effect relevance, and matrix-specific benchmarks rather than the direct transfer of drinking-water values to surface-water risk assessment. At the regional scale, a Latin American synthesis reports widespread detection of bisphenol A (BPA) in surface water, groundwater, wastewater, and occasionally drinking water, together with persistent gaps in harmonised monitoring and treatment (Mahlknecht, 2026). Synthetic progestins offer a related example: their occurrence in waste and surface waters and their ecological effects justify continued attention to hormonally active contaminants beyond the better-known estrogens (Rocha and Rocha, 2022).

For drinking water, the DWD (EU) 2020/2184 sets a binding parametric value for bisphenol A of 2.5 µg/L (2,500 ng/L) (Annex I, Part B), applicable from 12 January 2026 (European Union, 2020). E2 and nonylphenol were added to the DWD watch list (Commission Implementing Decision (EU) 2022/679) for monitoring, not as binding limits. Endocrine-active compounds are reported at ng/L concentrations in specific Brazilian surface waters and estuarine sediments (Santos et al., 2015; Maranho et al., 2019; Oliveira et al., 2024). Where numerical values are reported, as for EE2 and E2 in Santos et al. (2015), site-specific concentrations exceed sub-ng/L endocrine-effect thresholds and the proposed surface-water EQS for the compounds concerned, yet no Brazilian parametric value applies. In the Santos–São Vicente estuarine system,

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Maranho et al. (2019) found estrogen levels in sediments that suggest chronic accumulation.

Table 3 brings the main endocrine-active compounds into a common frame, pairing reported Brazilian occurrence with the relevant international benchmark and its regulatory status. Keeping these categories apart matters, because an effect threshold, a proposed EQS, a watch-list entry, and a binding drinking-water value do not carry the same scientific or legal meaning.

Table 3. Endocrine-active compounds: benchmark types and Brazilian status.

Compound	Reported occurrence (Brazil)	Benchmark	Benchmark type / jurisdiction	BR status
EE2	ng/L levels in SP/RJ rivers and estuaries (Santos et al., 2015; Oliveira et al., 2024)	~0.035 ng/L (surface water); feminisation 0.1–2 ng/L	Proposed EQS (SCHEER, 2022); effect threshold (Johnson and Sumpter, 2001)	No dedicated federal CEC parameter*
E2 (17β-estradiol)	Surface water and treated drinking water (Santos et al., 2015)	~0.4 ng/L; DWD watch list	Proposed EQS (SCHEER, 2022); watch list (Decision (EU) 2022/679)	No dedicated federal CEC parameter*
Bisphenol A	Surface waters and treated drinking water	2.5 µg/L (2,500 ng/L), drinking water	Binding parametric value, DWD (EU) 2020/2184	No dedicated federal CEC parameter*
4-nonylphenol	Brazilian water bodies	300 ng/L, surface-water EQS (Dir. 2013/39/EU); separately, DWD drinking-water watch list, guide value 300 ng/L (Decision (EU) 2022/679)	EQS (binding, surface water) / watch list	No dedicated federal CEC parameter*

Sources: European Union (2020); SCHEER (2022); Santos et al. (2015); Maranho et al. (2019); Oliveira et al. (2024). * “No dedicated federal CEC parameter” means no dedicated CEC-specific parametric value in CONAMA Resolution 357/2005 or in the federal drinking-water instrument examined; it does not imply absence of broader environmental, sanitary, licensing, liability, or subnational law.

The pattern in Table 3 is mixed. Brazil has no compound-specific parameter for any of the endocrine-active substances listed, whereas the EU uses several levels of response, from watch-list monitoring for E2 to a binding drinking-water value for bisphenol A. The table also shows why Brazilian occurrence data should not be judged against a single universal threshold: the appropriate comparator changes with both the compound and the matrix.

3.4 PFAS

PFAS are a large family of synthetic compounds characterised by the exceptional stability of the carbon–fluorine bond, which makes them highly resistant to

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biological, chemical, and photolytic degradation; they are detected across environmental compartments worldwide (Cousins et al., 2020). The International Agency for Research on Cancer (IARC) has classified PFOA as carcinogenic to humans (Group 1) and PFOS as possibly carcinogenic to humans (Group 2B) (IARC Monograph 135; Working Group evaluation 7–14 November 2023, monograph published 2025).

In Brazil, the more important signal is not any single extreme concentration but the repeated detection of multiple PFAS in surface- and groundwater systems influenced by urban, industrial, and agricultural activity. Madeira et al. (2023) reported several PFAS in the Piracicaba–Capivari–Jundiaí basin, a major public-supply basin, and Stefano et al. (2023) documented PFAS in surface water and groundwater in southern Brazil. These studies also show why analytical definitions matter: a research value reported as ‘total PFAS’ is not automatically equivalent to the EU Drinking Water Directive categories ‘PFAS Total’ or ‘Sum of PFAS’.

International benchmarks must be distinguished carefully. The DWD (EU) 2020/2184 sets two drinking-water parametric values, PFAS Total = 0.50 µg/L (500 ng/L) and Sum of PFAS = 0.10 µg/L (100 ng/L), the latter covering a defined list of 20 PFAS; the two are not interchangeable (European Union, 2020). The EPA’s April 2024 National Primary Drinking Water Regulation set maximum contaminant levels of 4 ng/L each for PFOA and PFOS, with further limits for PFHxS, PFNA, HFPO-DA (GenX), and a hazard-index mixture. The 4 ng/L limits for PFOA and PFOS remain in force, but the EPA has proposed extending their compliance deadline from 2029 to 2031 and rescinding the limits for the other four PFAS; these proposals were announced on 18 May 2026 and remained non-final at the regulatory cut-off date (US EPA, 2024, 2026). PFOS and PFOA are also listed under the Stockholm Convention. In Brazil, no PFAS parametric value exists in CONAMA 357/2005 or Ordinance 888/2021. Surface-water concentrations should not be compared directly with drinking-water parametric values, and a ‘total PFAS’ figure based on an analytical list different from the 20 PFAS of the DWD cannot be compared like-for-like with the 100 ng/L Sum-of-PFAS value.

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Because definitions and regulatory functions differ across jurisdictions, Table 4 sets out the main verified PFAS benchmarks used in this review, separating binding drinking-water values, regulatory proposals, and hazard classifications.

Table 4. PFAS: verified benchmarks and Brazilian status.

Benchmark	Value	Type / jurisdiction (verified source)
DWD 'PFAS Total'	0.50 µg/L (500 ng/L)	Binding drinking-water parametric value, EU (European Union, 2020)
DWD 'Sum of PFAS'	0.10 µg/L (100 ng/L)	Binding, EU; covers a defined list of 20 PFAS (European Union, 2020)
EPA MCL, PFOA / PFOS	4 ng/L each	In force; compliance deadline under a proposed extension from 2029 to 2031 (proposal of 18 May 2026, non-final at cut-off; US EPA, 2024, 2026)
EPA MCLs, PFHxS/PFNA/ GenX/HI	Rule-specific	Under proposed rescission as of 2026 (US EPA, 2026)
IARC classification	PFOA Group 1; PFOS Group 2B	Carcinogenic / possibly carcinogenic to humans (IARC Monograph 135; evaluated 2023, published 2025)

MCL = maximum contaminant level; HI = hazard index. Sources: European Union (2020); US EPA (2024, 2026); IARC (2025; Working Group evaluation 2023); Madeira et al. (2023); Stefano et al. (2023); Cousins et al. (2020).

Table 4 also shows why PFAS regulation cannot be reduced to a single number. The EU and U.S. frameworks use different analytical definitions and regulatory values, and the IARC classification concerns hazard rather than water-quality compliance. For Brazil, the clearest regulatory finding is the absence of a dedicated PFAS parameter; exceedance calculations across non-equivalent standards would be misleading.

3.5 Antimicrobial resistance and ARGs

ARGs occupy a distinctive position among CECs. As transmissible biological elements, they can move horizontally between bacteria of different species and genera via plasmids, transposons, and integrons (Pruden et al., 2006; Manaia et al., 2018). The WHO lists antimicrobial resistance (AMR) among the top global public-health threats (WHO, 2021). Analysing data from 204 countries, Murray et al. (2022) estimated 1.27 million deaths attributable to bacterial AMR and 4.95 million associated deaths in 2019, two distinct metrics that should not be conflated. The widely cited projection of 10 million deaths per year by 2050 comes from the most alarming scenario of the O'Neill Review (2016); a more recent forecast (Naghavi et al., 2024) projects about 1.9 million attributable and 8.2 million associated deaths in 2050.

ARGs also differ conceptually from conventional chemical contaminants. A gene copy number is not directly comparable with a chemical concentration, and there is no

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generally accepted environmental ‘safe concentration’ for ARGs that could serve as a universal regulatory threshold. Risk interpretation depends instead on the co-occurrence of resistance determinants, mobile genetic elements, antibiotic residues, host bacteria, and exposure pathways. The regulatory comparison in this review therefore treats ARG monitoring as a surveillance and One Health issue, rather than forcing onto a biological hazard a framework designed for chemical maximum allowable values or EQS.

Aquatic environments receiving domestic and hospital effluents act as reservoirs and amplifiers of ARGs, because sub-lethal antibiotic concentrations exert selective pressure on microbial communities; under some conditions, conventional biological treatment can select for resistant populations rather than eliminate them (Manaia et al., 2018). A One Health approach is essential, since ARGs circulate among environmental, animal, and human compartments (Rodriguez-Mozaz et al., 2016; Larsson and Flach, 2022). Brazilian studies report ARGs in surface waters and hospital effluents, including sulfonamide (sul1) and β-lactam resistance determinants and carbapenemase genes such as blaKPC and NDM-1 (Gomes et al., 2022; Starling et al., 2019). Carbapenemases confer resistance to last-line antibiotics, so their presence in Brazilian surface waters is of particular concern. None of these determinants is addressed by the federal water-quality instruments examined here.

The UWWTD (EU) 2024/3019 introduced monitoring of public-health parameters, including antimicrobial resistance, in urban wastewater for agglomerations of 100,000 p.e. or more (once the Commission has established a harmonised methodology), and it mandates quaternary treatment for large plants (Section 3.7). This is AMR surveillance rather than mandatory monitoring of specific ARGs, and the two should not be equated. Even so, it brings AMR into the wastewater-regulation framework, marking a shift from AMR as a research topic to AMR as an object of regulatory surveillance (European Union, 2024).

3.6 Microplastics and coastal evidence

Microplastics (< 5 mm) reach Brazilian aquatic environments through wind and rain, storm-water and sewage outfalls, and river transport, and they occur in fresh water, estuaries, mangroves, beaches, and coastal sediments. Because sampling and

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quantification methods differ widely, with results reported per kilogram of sediment, per square metre, or per litre, comparability across Brazilian studies is limited. Moreover, neither the federal instruments examined nor the ecotoxicological literature provides a generally accepted threshold against which a Brazilian regulatory 'exceedance' could be defined. The relevant international instruments (the DWD monitoring methodology for drinking water and the Marine Strategy Framework Directive) establish monitoring frameworks rather than binding numerical thresholds.

A large standardised national survey, the MICROMar project, analysed 4,134 sandy-sediment samples from 1,024 beaches along approximately 7,500 km of the Brazilian coastline and detected microplastics on 69.3% of beaches. The study identified 24,549 microplastic particles and derived a study-based national reference baseline estimate of 27.09 particles kg−1 for sandy beach sediment; this value is descriptive of that standardised survey design, not a legal threshold or a universal baseline for all Brazilian matrices. The result provides unusually broad spatial coverage, but it remains matrix- and method-specific and should not be extrapolated to water, biota, sludge, or other sediment protocols (Luz et al., 2025).

Table 5 brings together two complementary aspects of the Brazilian microplastic literature: measured coastal occurrence and the geographic and ecosystem distribution of published studies.

Table 5. Microplastics: reported Brazilian occurrence and regulatory context.

Setting	Reported occurrence	Source	Regulatory context
National coastal survey	69.3% of 1,024 beaches; 4,134 sandy-sediment samples; study-derived reference baseline estimate 27.09 particles kg^{-1}; 17 coastal states	Luz et al. (2025)	No Brazilian numeric threshold; descriptive, method- and matrix-specific survey baseline, not a regulatory standard
Systematic coastal evidence base	102 studies (2018–2023); 70% beaches, 26% mangroves, 2% estuaries, 2% coral reefs	Escrobot et al. (2024)	Evidence distribution, not a numeric standard
Regional research distribution	South-East 37.3%; North-East 34.3% of reviewed coastal studies	Escrobot et al. (2024)	Geographic asymmetry in evidence

Units differ across studies (per kg, per m^2, per L), limiting direct comparability; values describe occurrence, not exceedance of a standard. Source: Author's synthesis based on Luz et al. (2025) and Escrobot et al. (2024).

These entries point to two related gaps. Microplastics are widely reported along the Brazilian coast, but research coverage remains uneven across regions and ecosystem types, and there is no national numerical threshold against which these

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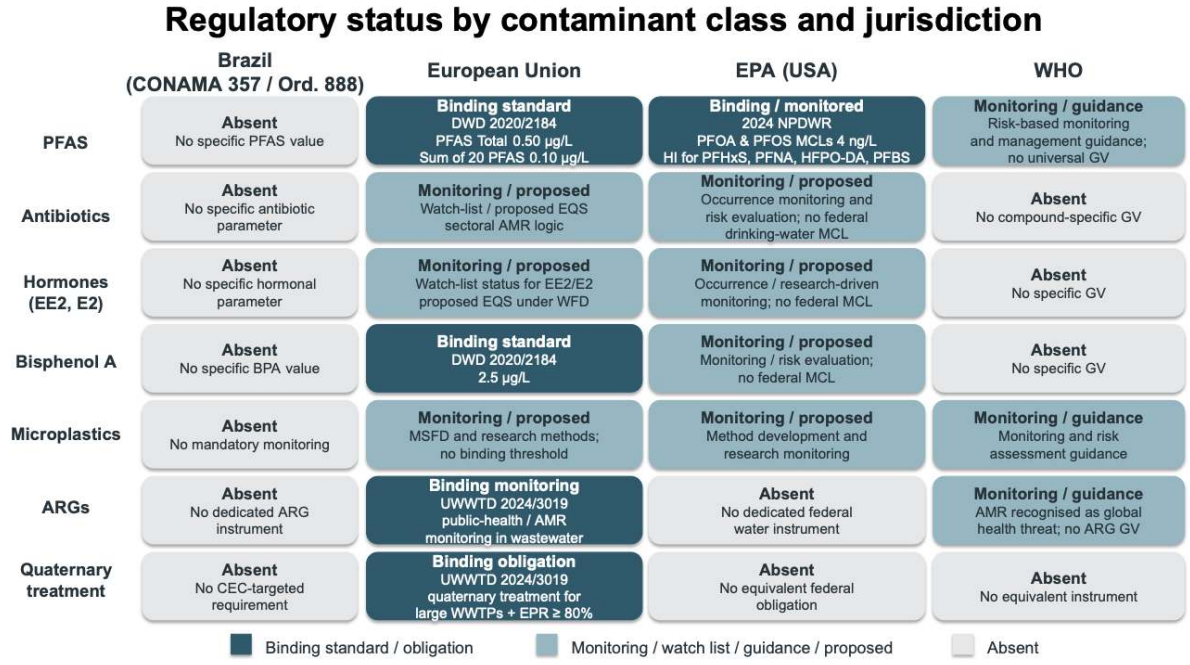
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concentrations could be classified as regulatory exceedances. At this stage, harmonised methods and systematic monitoring are more defensible priorities than a single concentration limit.

3.7 Comparative regulatory mapping

Brazil and the EU differ not only in which contaminants they regulate, but also in how their institutions respond to scientific uncertainty. The WFD established priority-substance lists with mandatory periodic review, and the watch-list mechanism introduced monitoring before formal standard-setting, which is the step that links emerging evidence to regulatory action (Carvalho et al., 2015). To make this institutional contrast explicit, Figure 3 compares the type of response adopted for each contaminant class in Brazil, the European Union, the U.S. EPA, and WHO. The comparison deliberately separates binding standards from monitoring and watch-list mechanisms, guidance, surveillance requirements, and the absence of a dedicated instrument, because these represent different stages and levels of regulatory intervention.

Figure 3. Comparative regulatory and guidance status by contaminant class.



Source: Author's elaboration based on verified primary regulatory texts from Brazil, the European Union, U.S. EPA, and WHO. Note: DWD = Drinking Water Directive; UWWTD = Urban Wastewater Treatment Directive; MCL = maximum contaminant level; HI = hazard index; MSFD = Marine Strategy Framework Directive; EPR = extended producer responsibility. In the figure, 'Absent' means that no dedicated CEC-specific parameter, monitoring requirement, or comparable class-specific instrument was identified

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within the federal/regulatory framework examined for that cell; it does not mean absence of broader environmental or public-health law.

Figure 3 reveals a marked asymmetry in regulatory architecture. For the CEC classes examined, the Brazilian column is defined by the absence of dedicated parameters or monitoring instruments, whereas the European framework combines binding standards, watch-list monitoring, AMR surveillance, and treatment obligations. The EPA adopts binding values for selected compounds, particularly PFAS, and relies on monitoring or candidate-list mechanisms for others, while WHO mainly provides guidance and risk-based recommendations (WHO, 2022). The figure is not meant to rank jurisdictions. What it shows is that the regulatory difference lies in the range of institutional tools available to respond to emerging evidence, and in the capacity to move from scientific detection to progressively stronger forms of regulatory action.

Figure 3 gives the overall regulatory pattern but not the compound-specific detail behind each cell. Table 6 therefore disaggregates the comparison by CEC class, so that the status of PFAS, antibiotics, hormones, bisphenol A, microplastics, ARGs, and quaternary treatment can be examined across three regulatory systems and the WHO guidance framework.

Table 6. Comparative regulatory, monitoring, and guidance status for CEC classes (verified to 15 August 2026).

Class	Brazil — federal instruments examined	European Union	U.S. EPA	WHO guidance/status
PFAS	No dedicated federal CEC-specific parameter/requirement in CONAMA 357/2005 or the drinking-water instrument examined	DWD: Sum of PFAS 0.10 µg/L (20 PFAS); PFAS Total 0.50 µg/L	PFOA/PFOS MCLs 4 ng/L each remain in force; compliance extension to 2031 proposed 18 May 2026; PFHxS/PFNA/GenX/HI provisions under proposed rescission (non-final at cut-off)	No binding WHO national standard; WHO health guidance/hazard assessments are non-binding internationally
Antibiotics	No dedicated federal CEC-specific parameter/requirement in CONAMA 357/2005 or the drinking-water instrument examined	Union watch-list monitoring has included macrolide antibiotics; UWWTD adds broader wastewater monitoring architecture	Draft CCL 6 includes a pharmaceuticals group (2026); CCL is a candidate-list step, not mandatory occurrence monitoring or a concentration standard	AMR is a major public-health concern; no WHO binding water parametric value for antibiotics
Hormones (EE2, E2)	No dedicated federal CEC-specific	Proposed EQS ~0.035 ng/L (EE2) and ~0.4 ng/L (E2); E2 on DWD watch list	Historical UCMR 3 screening-survey monitoring of hormones	Endocrine-disruptor concern addressed

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Class	Brazil — federal instruments examined	European Union	U.S. EPA	WHO guidance/status
	parameter/requirement in CONAMA 357/2005 or the drinking-water instrument examined		(2013–2015); UCMR generated occurrence data, not compliance limits; no current federal hormone MCL	through guidance/assessment, not binding national water standards
Bisphenol A	No dedicated federal CEC-specific parameter/requirement in CONAMA 357/2005 or the drinking-water instrument examined	DWD binding parametric value 2.5 µg/L for drinking water	Bisphenol A is listed individually on Draft CCL 6 (2026); no federal drinking-water MCL at cut-off	Recognised endocrine-disrupting chemical; WHO guidance is non-binding
Microplastics	No dedicated federal CEC-specific parameter/requirement in CONAMA 357/2005 or the drinking-water instrument examined	DWD requires a methodology for measuring microplastics; MSFD supports marine monitoring	Draft CCL 6 includes microplastics as a contaminant group (2026); this is not a current UCMR requirement or compliance standard	Active scientific/health assessment; no binding WHO water threshold
ARGs	No dedicated federal CEC-specific parameter/requirement in CONAMA 357/2005 or the drinking-water instrument examined	UWWTD (EU) 2024/3019: AMR surveillance in urban wastewater for agglomerations ≥100,000 p.e. after harmonised methodology; not equivalent to mandatory monitoring of specified ARGs	No federal drinking-water ARG standard; research/surveillance endpoints remain distinct from chemical MCLs	AMR recognised as a major health threat; environmental surveillance fits One Health rather than a chemical concentration threshold
Quaternary treatment	No CEC-specific federal quaternary-treatment requirement identified in the instruments examined	UWWTD (EU) 2024/3019: quaternary treatment for ≥150,000 p.e. phased to 2033/2039/2045; risk-based application for agglomerations ≥10,000 p.e.; ≥80% average removal across specified indicator substances; EPR finances at least 80% of relevant quaternary-treatment/monitoring costs for human medicines and cosmetics	No analogous federal SDWA quaternary-treatment mandate	Treatment guidance/recommendations are non-binding and context dependent

Note: p.e. = population equivalent; EPR = extended producer responsibility; CCL = Contaminant Candidate List; UCMR = Unregulated Contaminant Monitoring Rule; MSFD = Marine Strategy Framework Directive. CCL identifies candidates for possible future regulation; UCMR is an occurrence-monitoring rule and does not establish compliance concentration limits. WHO is presented as a guidance/hazard-assessment framework, not as a regulatory jurisdiction. Regulatory status verified against primary official sources through 15 August 2026. Brazilian entries are limited to the federal instruments examined and do not imply that no subnational, sectoral, licensing, liability, or other legal

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mechanisms exist. Sources: primary regulatory texts of Brazil, the European Union (2013, 2015, 2018, 2020, 2022, 2024), US EPA (2012/2016, 2024, 2026), and WHO (2021, 2022).

Table 6 shows that the Brazilian gap is broader than the absence of numerical limits. Other jurisdictions use several intermediate instruments (candidate lists, monitoring programmes, watch lists, guidance, and targeted treatment requirements) that allow evidence to enter the regulatory process before a definitive standard is set. This matters for CECs because scientific uncertainty is often greatest precisely when routine monitoring is still absent, and without an intermediate monitoring mechanism the evidence needed for later standard-setting may be slow to emerge.

Table 6 shows where each jurisdiction stands, but not how such regulatory structures develop. Table 7 adds this temporal dimension by tracing how the EU progressively brought priority-substance review, precautionary watch lists, drinking-water parameters, treatment requirements, extended producer responsibility, and antimicrobial-resistance surveillance into water policy.

Table 7. Chronology of EU regulatory instruments for CECs (2000–2024).

Year	Instrument	Main provision relevant to CECs/ARGs
2000	WFD 2000/60/EC	Priority-substance lists; framework for water-quality monitoring and mandatory review
2013	Directive 2013/39/EU	Amended the priority-substances regime and established the Union watch-list mechanism, under which diclofenac, 17β-estradiol (E2) and 17α-ethinylestradiol (EE2) were subsequently placed on the first watch list for monitoring (not as binding priority-substance standards)
2015	Decision (EU) 2015/495 (1st watch list)	First watch list including diclofenac, E2 and EE2 for Union-wide precautionary monitoring before formal regulation
2018	Commission Implementing Decision (EU) 2018/840 (2nd watch list)	Removed diclofenac following data review; added neonicotinoids and macrolide antibiotics (azithromycin, erythromycin, clarithromycin)
2020	DWD (EU) 2020/2184	Parametric values incl. PFAS Total 0.50 µg/L, Sum of PFAS 0.10 µg/L, and bisphenol A 2.5 µg/L; mandatory review; water-safety plans
2022	Decision (EU) 2022/679; SCHEER opinion	DWD watch list (incl. E2, nonylphenol); proposed EQS for EE2 (~0.035 ng/L) and E2 (~0.4 ng/L)
2024	UWWTD (EU) 2024/3019	Recast UWWTD separates tertiary nutrient removal from quaternary micropollutant treatment. Quaternary treatment is required for plants ≥150,000 p.e. with phased coverage (20% by 2033, 60% by 2039, 100% by 2045) and is risk-based for agglomerations ≥10,000 p.e. in sensitive/risk areas. Annex I requires ≥80% average removal calculated across specified indicator substances, not 80% removal of every CEC. EPR for human medicines and cosmetics must cover at least 80% of relevant quaternary-treatment and micropollutant-monitoring costs. AMR monitoring applies to agglomerations ≥100,000 p.e. after the Commission establishes a harmonised methodology; it is not synonymous with a mandatory list of ARGs.

Source: EUR-Lex primary texts.

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Taken together, Figure 3 and Tables 6–7 support the central interpretation of this review: the relevant difference is not simply the number of contaminants currently regulated, but the existence of an institutional pathway through which evidence can trigger monitoring, monitoring can inform review and prioritisation, and these processes can eventually lead to standards or treatment obligations. The EU chronology shows that this architecture was built incrementally over more than two decades, not through a single regulatory change. The Brazilian instruments assessed here do not yet contain an equivalent CEC-specific sequence, while the EPA and WHO occupy intermediate positions, combining selected binding values with monitoring, candidate listing, guidance, and risk-based assessment. This comparison provides the empirical basis for the discussion of the science-to-regulation translation gap that follows.

4. Discussion

4.1 The science-to-regulation translation gap

Across the CEC classes reviewed, the same broad pattern emerges: compounds are documented in specific Brazilian water bodies, yet the two principal federal instruments examined here contain no dedicated CEC-specific parametric values, EQS, or mandatory monitoring requirements for them (Figure 3). This is best described as the absence, in these instruments, of CEC-specific parametric values and routine monitoring requirements, not as a general absence of environmental regulation or legal accountability, both of which exist through other instruments. It should also be read against ongoing regulatory activity: in 2026, CONAMA has an active process to revise Resolution 357/2005 and its effluent-discharge conditions and standards (CONAMA, 2026). Such ad hoc revision, however, is not equivalent to an embedded, periodic, CEC-specific evidence-review cycle of the kind proposed here. The gap is best understood as institutional and regulatory lag, that is, the absence of a routine mechanism that turns documented exposure into monitoring obligations, and not as a lack of scientific activity or technical capacity. This lag is not attributed here to any particular political intention, which was not investigated; the more limited claim is that the Brazilian instruments examined do not yet include mechanisms comparable to the EU watch-list approach. These conclusions are restricted to the federal level and to

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the national instruments examined; subnational (state and municipal) rules and agency-level measures were not reviewed and are not claimed to be absent. Seen in this way, the different CEC classes point to a common governance problem: regulation lacks an established pathway for incorporating what the scientific evidence continues to document.

4.2 Treatment limitations and regulatory implications

Conventional wastewater treatment relies mainly on primary and secondary processes designed to remove suspended solids, biodegradable organic load, and pathogens, not the broad range of CECs (Johnson and Sumpter, 2001; Verlicchi et al., 2010; Manaia et al., 2018). Removal depends on the compound, technology, matrix, dose, and contact time, so universal percentages are not scientifically defensible. Carbamazepine and many PFAS are comparatively persistent in conventional treatment, whereas ozonation, activated carbon, advanced oxidation, and membrane processes can achieve substantially higher, though still configuration-dependent, removal (Miège et al., 2009; Cousins et al., 2020).

This technological variability has direct regulatory implications. Monitoring, risk assessment, treatment objectives, and performance verification should form a causal sequence: monitoring identifies the compounds and matrices of concern; risk and persistence evidence define the intervention objective; the treatment train is selected against that objective; and post-treatment monitoring verifies performance. Without CEC-specific monitoring or performance requirements, utilities and regulators lack a formal trigger for targeted advanced treatment. The recast EU UWWTD illustrates this architecture by linking specified micropollutant-removal performance to quaternary treatment and to a financing mechanism (European Union, 2024), but it should be read as an institutional precedent, not as a technology or population-threshold template for Brazil.

Treatment policy also needs to look beyond end-of-pipe solutions. Advanced processes can remove many micropollutants, but they add capital, energy, operational, and analytical demands for utilities. Source reduction and producer-responsibility measures can therefore complement treatment rather than replace it. Their suitability is class-specific. The EU UWWTD targets human medicines and cosmetics because

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these product groups are major identifiable sources of micropollutants in urban wastewater, whereas diffuse or multi-source classes such as PFAS and microplastics raise harder source-attribution questions, and ARGs, as transmissible biological endpoints, do not map naturally onto product-based EPR. A Brazilian financing approach should therefore assess source attribution, market incidence, affordability, and administrative feasibility before assigning producer responsibility.

The regulatory implications of this variability become clearer when the available technologies are considered side by side. Table 8 compares the main treatment options relevant to CEC control, not to identify a universally superior process, but to show how performance, operational constraints, and regulatory relevance differ among conventional treatment, oxidation processes, activated carbon, membranes, and biological or nature-based polishing.

Table 8. Treatment technologies relevant to CEC control and the principal interpretation caveats for regulatory use.

Treatment stage / technology	Typical relevance to CECs	Major strengths	Key caveats for interpretation
Conventional primary/secondary treatment	Variable; often limited for persistent or poorly biodegradable compounds	Established infrastructure; organic-load and pathogen control	Removal is compound-specific; low removal of one compound cannot be generalised to all CECs.
Ozonation / advanced oxidation	Effective for many oxidisable organic micropollutants	High transformation capacity; compatible with tertiary/quaternary treatment	By-products and transformation products require assessment; performance depends on ozone dose and matrix.
Activated carbon (PAC/GAC)	Broad adsorption of many organic micropollutants	Mature process; flexible integration	Capacity is finite; natural organic matter competes for sites; replacement/regeneration affects cost.
Membranes / reverse osmosis	High rejection for many dissolved micropollutants, including several PFAS	Strong physical separation	Energy, concentrate management, membrane fouling, and cost can be limiting.
Biological optimisation / nature-based polishing	Potential additional removal for selected biodegradable CECs	Lower energy demand; can complement conventional treatment	Highly compound- and condition-dependent; not a substitute for targeted treatment where persistent CECs dominate.

Source: Author's synthesis based on Miège et al. (2009), Verlicchi et al. (2010), Manaia et al. (2018), Cousins et al. (2020), and Directive (EU) 2024/3019.

Performance varies substantially by compound, treatment configuration, and operating conditions, which is why Table 8 emphasises relative relevance, strengths, and caveats instead of fixed removal efficiencies. No single technology can be

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prescribed without reference to the contaminant profile and operating context. Processes that work well for one group of compounds may be less suitable for another, and advanced options bring trade-offs involving energy demand, transformation products, adsorbent replacement, membrane fouling, concentrate management, and cost. The governance implication is that technology requirements should follow, not precede, evidence on occurrence and prioritisation, in the sequence described above: monitoring identifies what is present, risk and persistence indicate which compounds require intervention, and only then can treatment objectives and performance criteria be defined in a technically and economically defensible way.

4.3 River–estuary–coast continuum

The regulatory gap is not confined to inland rivers and source waters. Treated and untreated effluent, storm-water discharges, agricultural and urban runoff, and river transport can move CECs along a river–estuary–coast continuum. Estuaries are particularly informative because they integrate upstream basin loads, wastewater discharges, tidal exchange, and coastal exposure. Brazilian coastal evidence is less systematic than inland monitoring, but site-specific studies document estrogens in the Santos–São Vicente estuarine system (Maranho et al., 2019), pharmaceuticals along the São Paulo coast (Roveri et al., 2022), and microplastics in a national beach survey (Luz et al., 2025). CONAMA 357/2005 provides the general classification framework for coastal and estuarine waters but does not establish the CEC-specific parameters examined here, and the drinking-water instrument addresses a different regulatory object. Coastal prioritisation should therefore not rest on ecological value alone; it should be driven by catchment load, anthropogenic pressure, hydrological connectivity, water use, vulnerability, and plausible exposure. Using the river basin as the unit of governance and data integration can connect inland sources with estuarine and coastal sentinel sites and avoid treating the coast as an isolated monitoring compartment.

4.4 The EU architecture as a comparative reference

The EU experience is useful because its framework developed incrementally rather than through a single regulatory shift. The WFD established a monitoring base, watch lists enabled monitoring before standard-setting, and later sectoral directives

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such as the DWD and the UWWTD linked monitoring to standards, treatment, and cost allocation. Watch lists, periodic review, risk-based prioritisation, monitoring before standard-setting, extended producer responsibility, and adaptive regulation are all potentially relevant to Brazil. They are treated here as reference mechanisms, not as measures that can be transferred unchanged, given the marked differences in administrative capacity, laboratory infrastructure, sanitation coverage, financing, and enforcement.

Two features are especially relevant to Brazil. First, the watch-list approach allows monitoring to begin before a binding limit is set, which keeps uncertainty itself from becoming a reason for inaction and generates comparable data for later prioritisation (Carvalho et al., 2015; European Union, 2015, 2018, 2022). Second, the recast UWWTD links micropollutant monitoring and quaternary-treatment performance to financing through EPR for human medicines and cosmetics, while separately introducing public-health surveillance provisions, including AMR, for large agglomerations (European Union, 2024). These are distinct regulatory functions and should not be collapsed into a single instrument.

4.5 Implications for Brazilian water governance

For the classes examined, the practical implication of the federal regulatory gap is not that CECs are legally irrelevant, but that the two federal instruments analysed provide neither dedicated CEC-specific monitoring requirements nor compound-specific compliance parameters. General environmental-liability, licensing, discharge-control, public-health, and subnational instruments may still apply and were not exhaustively reviewed. The absence of a compound-specific parameter therefore complicates direct compliance assessment for that substance and weakens any routine path from evidence to prioritisation; it does not mean that legal accountability is absent. The precautionary principle is present in Brazilian environmental law and policy, but its operationalisation for CECs, through a recurring national sequence of horizon scanning, watch-list monitoring, evidence review, and class-specific regulatory decisions, has not yet been embedded in the federal instruments examined here.

For Brazil, then, the issue is broader than adding new numerical limits. An adaptive system would need to connect prioritisation, harmonised monitoring,

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laboratory capacity, public reporting, and periodic revision. Published studies remain concentrated in a relatively small number of regions (Montagner et al., 2017; Escrobot et al., 2024), and sanitation infrastructure and operational capacity are also uneven (SNIS, 2022). A phased, territorially differentiated approach is therefore likely to be more realistic than a simultaneous nationwide mandate. Recent comparative studies support this institutional reading. A systematic review centred on Portugal highlights the same coupling of monitoring gaps, treatment limitations, and governance readiness (Esperanço et al., 2026), and an analysis of U.S. public water systems documents marked state-level differences in monitoring, enforceable standards, treatment investment, and regulatory capacity (Siame et al., 2026). These comparisons support using international experience as evidence about governance mechanisms and implementation constraints, not as a basis for transferring foreign thresholds directly to Brazil.

4.6 Proposed adaptive regulatory framework

Building on the mapped evidence and regulatory gaps, I propose a five-axis adaptive framework for Brazil (Figure 4; Table 9). The proposal draws on operational features of the EU and U.S. systems, namely horizon scanning and candidate nomination, monitoring before standard-setting, periodic evidence review, and differentiated treatment and source-control instruments, but adapts them to Brazilian conditions. A ‘stage zero’ horizon-scanning step precedes formal watch listing, and the watch list itself is defined as an evidence-generation instrument, not as a list of substances already judged hazardous or regulated. The proposed review intervals, institutional arrangements, monitoring tiers, and laboratory requirements are the author’s recommendations, not obligations derived from the evidence or from existing Brazilian law.

The framework draws together the recurring gaps identified in the review rather than treating them as separate recommendations. Figure 4 presents it as an integrated cycle in which the five axes depend on one another: the watch list sets monitoring priorities; monitoring produces evidence for review; review supports prioritisation; prioritisation directs where monitoring capacity should be concentrated; and One

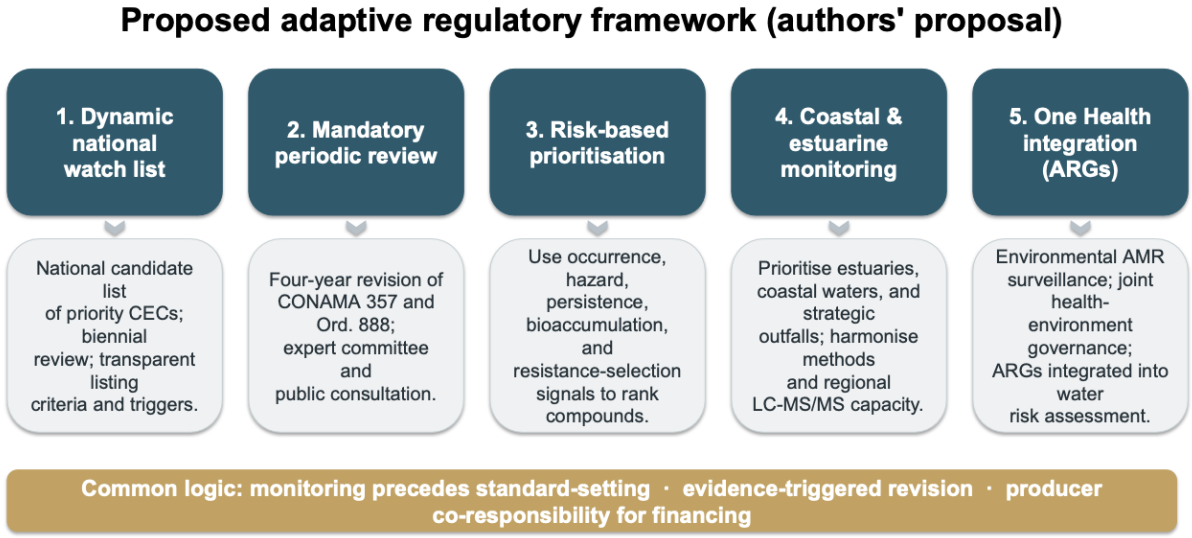
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Health integration keeps antibiotics and ARGs within broader water-governance decisions.

Figure 4. Proposed five-axis adaptive regulatory framework for CECs in Brazil.



Source: Author's proposal based on the reviewed scientific evidence and on regulatory precedents from Brazil, the European Union, WHO, and the U.S. EPA.

The first three axes form the decision pathway through which a contaminant can move from scientific concern to regulatory consideration, while the fourth and fifth extend that pathway spatially, to estuarine and coastal systems, and institutionally, to environmental, human, and animal health. Monitoring is the connecting element across the framework: without comparable occurrence data, periodic review and risk-based prioritisation cannot operate consistently. Table 9 translates this sequence into operational terms, separating the evidence or regulatory precedent behind each axis from the adaptations proposed specifically for Brazil.

Table 9. Proposed five-axis adaptive regulatory framework (author's proposal).

Axis	Objective and mechanism	Evidence trigger / precedent	Brazilian adaptation
1. Dynamic national watch list	Evidence-generation instrument preceded by stage-zero horizon scanning. Candidates may be nominated from peer-reviewed occurrence evidence, regulatory alerts, monitoring programmes, health/environment agencies, and transparent stakeholder submissions. Listing is decided using predefined entry criteria; it does not itself create a water-quality limit. Proposed minimum biennial review and public publication of monitoring results are	Scientific signal + occurrence/detection frequency + persistence/mobility + hazard/exposure evidence; EU watch list and EPA candidate-list logic as functional precedents	Start with a small class-specific list and sentinel matrices/regions; move to confirmatory monitoring before national regulatory assessment

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Axis	Objective and mechanism	Evidence trigger / precedent	Brazilian adaptation
	author-proposed implementation parameters.		
2. Mandatory periodic review	Formal evidence-review stage proposed for the federal instruments examined, with a four-year cycle as an author proposal. Review would assess watch-list data, detection frequency, temporal/spatial coverage, benchmark/risk evidence, analytical feasibility, treatment implications, and whether a substance should be retained, escalated, delisted, or transferred to a stronger instrument. A technical-scientific committee and public consultation are proposed arrangements, not existing joint competences.	Need for an embedded periodic CEC-specific review cycle; contrast with ad hoc regulatory revisions and DWD/WFD review mechanisms	Use existing legal competences of each institution; coordination mechanism would require formal definition rather than presuming new authority
3. Risk-based prioritisation	Multi-criteria prioritisation by persistence, mobility, bioaccumulation where relevant, toxicity/endocrine activity, exposure, detection frequency, resistance-selection relevance, mixture contribution, treatability, and matrix/territorial vulnerability. PBT is one criterion set, not a universal classifier for every CEC.	Effect-based benchmarks, AMR selection evidence, repeated occurrence, vulnerable uses/matrices, and mixture signals	Matrix-specific and class-specific prioritisation; foreign thresholds are comparators, not automatically imported Brazilian limits
4. Coastal and estuarine monitoring	Tiered, matrix-specific monitoring linking hydrographic basins to source waters, groundwater where vulnerable, wastewater, estuaries/coasts, and selected drinking-water points. Territorial priority should reflect load, source pressure, connectivity, water use and vulnerability rather than a single national protocol. Analytical capacity must be class-specific: LC-MS/MS where appropriate; dedicated PFAS QA/QC and methods; spectroscopic/microscopic microplastic protocols; and microbiological/qPCR/metagenomic approaches for AMR/ARG endpoints.	Uneven territorial evidence; matrix-specific exposure pathways; need for harmonised QA/QC, detection limits, interlaboratory comparison and intercalibration	Sentinel → confirmatory → regional/national prioritisation → regulatory assessment, with repeated seasonal/event sampling where relevant
5. One Health integration of ARGs	One Health integration keeps antibiotic residues, resistant organisms, ARG abundance/composition, mobile genetic elements, and relevant exposure pathways as linked but non-equivalent endpoints. Environmental surveillance should connect with human/animal-health data without treating PNEC-res values for antibiotics as thresholds for ARGs.	Environmental AMR evidence; UWWTD AMR surveillance precedent; causal chain from antimicrobial residues/selection pressure to resistant organisms and genes	Define endpoints, matrices, methods, interpretation rules and data-sharing responsibilities before scaling surveillance

Note: PBT = persistent, bioaccumulative and toxic; PBT is one component of a broader multi-criteria prioritisation and does not apply in the same way to all CEC classes. Quantitative cycles, institutional arrangements, monitoring tiers, and implementation parameters are the author's proposals, not evidence-derived or existing legal obligations. Source: Author's proposal based on the reviewed evidence and regulatory precedents.

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Table 9 draws an important line between what the reviewed evidence supports and what remains a policy proposal. The need for better monitoring, periodic review, attention to basin–estuary–coast connectivity, and integration of environmental AMR surveillance is grounded in the evidence mapped here and in existing international precedents. The proposed review intervals, institutional arrangements, and phased deployment of analytical capacity, by contrast, are implementation choices suggested by the author. The proposed watch list has a deliberately limited legal function: it generates harmonised evidence for later decision-making and does not itself establish a binding standard. Stage-zero horizon scanning specifies nomination routes, and entry criteria include repeated occurrence or credible exposure potential, persistence/mobility, toxicity or endocrine activity, relevance to resistance selection, vulnerable uses and matrices, analytical measurability, and policy significance. Exit criteria include sufficient evidence to establish a stronger standard or monitoring obligation, evidence supporting low priority or delisting, lack of meaningful occurrence after adequate monitoring, or replacement by another regulatory instrument. Because ARGs, hormones, PFAS, microplastics, pharmaceuticals, and pesticides differ markedly, the framework rejects a one-size-fits-all protocol: prioritisation, matrix, method, sampling frequency, and policy instrument are class-specific. Mixture effects remain a cross-cutting assessment dimension rather than being reduced to single-substance thresholds.

4.7 Implementation challenges

Implementation will have to contend with uneven analytical capacity and laboratory infrastructure, financing constraints, and strong regional asymmetries. A phased approach is more realistic than an immediate comprehensive mandate: standardise methods and data fields first; validate class-specific QA/QC through interlaboratory comparison and intercalibration exercises; begin with a limited sentinel network; confirm recurrent detections with repeated sampling; and expand territorial coverage only once the data are comparable. Laboratory expansion should therefore follow method standardisation, not precede it. LC-MS/MS is important for many organic micropollutants but is not a proxy for universal CEC capacity. PFAS require contamination-controlled targeted methods with stringent blanks and LOQs,

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microplastics require size- and polymer-specific sampling and spectroscopic or microscopic identification, and AMR/ARG surveillance requires microbiological and molecular endpoints.

Tiered monitoring offers a practical starting point. Tier 1 would use sentinel basins and source–receptor systems to screen a small set of class-specific analytes or endpoints. Tier 2 would confirm detections through repeated sampling with adequate seasonal and hydrological coverage. Tier 3 would use confirmed frequency, concentration distributions, temporal persistence, matrix relevance, and exposure to prioritise regional or national assessment. Tier 4 would support a regulatory decision (retain on the watch list, delist, establish a stronger monitoring or standard-setting instrument, or define a treatment or source-control objective), followed by verification monitoring. Not every CEC needs nationwide sampling. PFAS may warrant groundwater and source-area designs around industrial, firefighting, or contaminated sites; hormones and pharmaceuticals may be prioritised around wastewater-impacted source waters; microplastics need separate protocols for water, sediment, sludge, and coastal matrices; and AMR surveillance should target wastewater, hospital- or livestock-influenced systems, and receiving waters, using endpoints that are not interchangeable with antibiotic-residue concentrations.

Antimicrobial resistance requires an additional layer of coordination. Environmental surveillance should not be separated from human- and animal-health governance. A One Health approach would connect antibiotic residues and selection pressure with resistant organisms, ARG abundance/composition, mobile genetic elements, and relevant exposure pathways, while keeping these endpoints analytically distinct (Rodriguez-Mozaz et al., 2016; Larsson and Flach, 2022). PNEC-res values apply to antibiotic concentrations and resistance-selection potential; they are not concentration thresholds for ARGs. A causal chain—antimicrobial use/release → environmental residues and other selective pressures → resistant organisms/genes and horizontal transfer → exposure—provides a more defensible basis for integrated interpretation than collapsing chemical and genetic measurements into one metric.

Data interoperability is a prerequisite for scaling up this system. A national repository should require a minimum metadata schema covering the

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contaminant/analyte or biological endpoint, environmental matrix, site and basin identifier, sampling date and hydrological or seasonal context, unit, analytical method, LOD/LOQ, QA/QC indicators, treatment configuration where relevant, detection or non-detection, concentration or gene-copy result, and laboratory identifier. Where the source data allow, reporting should include detection frequency and central tendency in addition to maxima. Open-data governance with machine-readable records, versioned methods, and explicit handling of non-detects would allow agencies, researchers, and utilities to compare results without erasing methodological differences.

Sampling frequency should be set by the process being observed, not fixed uniformly across CECs. Repeated wet- and dry-season sampling may be needed where dilution, runoff, or wastewater contributions vary seasonally, and event-triggered sampling may be justified after floods, droughts, treatment failures, spills, or other extreme conditions that alter contaminant mobilisation. These temporal requirements are part of evidence quality: an isolated maximum is useful as a signal, but it should not stand in for detection frequency, distribution, and persistence when regulatory prioritisation is at stake.

Table 10. Proposed class- and matrix-specific monitoring architecture within the adaptive framework (author's proposal).

Class / endpoint	Priority matrices and territorial logic	Primary analytical / measurement logic	Temporal / tiered monitoring emphasis	Potential regulatory response
Pharmaceuticals, hormones, BPA	Wastewater influent/effluent; receiving and source waters; drinking water where exposure is plausible	Targeted LC-MS/MS or validated equivalent; matrix-specific recoveries, blanks and LOQs	Sentinel wastewater-impacted basins → repeated confirmation; seasonal coverage where flow/use changes; report detection frequency and central tendency when available	Watch-list evidence → risk/benchmark assessment → treatment objective or drinking-/surface-water decision as appropriate
PFAS	Groundwater, source water, surface water and drinking water; prioritise industrial/firefighting/source-area vulnerability and hydrological connectivity	PFAS-specific targeted methods with contamination-controlled sampling, field/lab blanks, low LOQs and interlaboratory comparability; analytical	Source-area and sentinel screening → confirmatory spatial delineation → exposure-oriented assessment; repeated sampling	Class/compound-specific monitoring or standard-setting; source control and treatment selected to the

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Class / endpoint	Priority matrices and territorial logic	Primary analytical / measurement logic	Temporal / tiered monitoring emphasis	Potential regulatory response
		definitions must match the regulatory comparator	where plume/source dynamics justify it	relevant PFAS definition
Antibiotic residues / AMR / ARGs	Wastewater, hospital/livestock-influenced effluent, receiving waters; human/animal/environment interfaces	Antibiotics by chemical analysis; resistant organisms by culture/phenotype where relevant; ARGs/mobile elements by qPCR/metagenomics or validated molecular methods; endpoints kept separate	Repeated surveillance with One Health linkage; antibiotic concentrations and PNEC-res do not substitute for ARG/organism endpoints	AMR surveillance, source stewardship and wastewater controls; chemical benchmarks and biological surveillance interpreted through a causal chain
Microplastics	Water, sediment, beach sediment, sludge/biota as question-specific matrices; river–estuary–coast connectivity	Matrix-specific sampling plus size-range definition and polymer/particle identification by validated spectroscopic/microscopic approaches; not treated as LC-MS/MS chemistry	Standardised sentinel protocols first; temporal/event sampling where runoff and hydrodynamics matter; never pool non-equivalent units/matrices	Monitoring-method harmonisation and risk assessment before any numeric threshold; source-reduction instruments may differ from chemical CECs
Mixed CEC signals	Matrices selected by co-exposure pathway and basin/source pressure	Compatible multi-residue methods where valid plus effect-based tools when scientifically justified; preserve analyte-specific QA/QC	Use repeated co-occurrence and effect signals to identify mixtures requiring targeted assessment	Mixture effects inform prioritisation and risk assessment; do not infer a legal mixture exceedance without an applicable instrument

Note: the table is a policy-design proposal derived from the evidence synthesis and does not describe existing Brazilian legal obligations. Monitoring frequency, methods, and territorial scope should be validated for each class and matrix before regulatory use.

Table 10 shows that the monitoring architecture is not uniform across contaminant classes. Each class combines its own priority matrices, measurement logic, and tiered sequence of screening, confirmation, and prioritisation, so the regulatory response depends on the evidence generated at each tier rather than on a single national protocol.

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4.8 Limitations

The findings should be read with several limitations in mind. Methods varied across the cited studies, including analytical techniques, limits of quantification, sampling protocols, and reporting units, which limits direct comparison of reported concentrations. Brazil also lacks a standardised national CEC monitoring programme, so the available evidence comes from geographically concentrated research initiatives rather than systematic territorial coverage, and national prevalence cannot be inferred; the North and some coastal and estuarine settings remain under-represented. The Bibliometrix visualisations derive from a broader Web of Science discovery export and serve only as exploratory context. Cross-jurisdictional benchmark comparisons are further constrained by differences in matrix, benchmark status, analytical definitions, and policy purpose. This study is a structured evidence synthesis with comparative regulatory analysis, not an exhaustive systematic review or meta-analysis. The evidence base can be audited through the source register in Supplementary Table S1 and the complete reference list, and the screening decisions for the 22-record Google Scholar update are documented in Supplementary Table S4. Because the original multi-database screening history was not preserved as a single deduplicated study-flow file, retrospective PRISMA-style flow counts were not reconstructed; this affects claims of search completeness, not the traceability of the evidence actually used. Screening, extraction, and verification were carried out by a single reviewer (the author), which may introduce selection bias despite the predefined evidence domains and source-level verification, and primary occurrence studies were appraised for basic reliability but not formally scored. These limitations restrict quantitative generalisation but do not alter the gaps in monitoring and regulation that can be observed directly in the Brazilian instruments reviewed.

5. Conclusions

This review shows that CECs are repeatedly reported in specific Brazilian aquatic environments, while their incorporation into the two principal federal instruments examined, for surface-water quality and drinking-water quality, respectively, remains limited and class-specific. The evidence covers pharmaceuticals, antibiotics, endocrine-active compounds, PFAS, ARGs, and microplastics in rivers,

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source waters, groundwater, estuaries, treated water, and coastal environments. Because the underlying studies are heterogeneous and geographically uneven, these findings should not be read as national prevalence estimates. Their regulatory relevance lies instead in recurrent, traceable occurrence and in the absence, within the federal instruments examined, of an embedded CEC-specific sequence linking horizon scanning, harmonised monitoring, periodic evidence review, prioritisation, and eventual regulatory or treatment decisions.

For some compounds, site-specific concentrations overlap with or exceed effect-based or resistance-selection benchmarks; for others, documented occurrence is the stronger conclusion and an exceedance ratio would not be defensible. The review therefore keeps binding values, proposed EQS, watch-list status, and non-regulatory effect benchmarks separate, and avoids comparing non-equivalent matrices or PFAS definitions. This distinction underpins the central concept of the paper: the science-to-regulation translation gap is the absence of a systematic route by which accumulating evidence can trigger coordinated monitoring, periodic review, and, when justified, standard-setting or treatment requirements.

The study makes four related contributions. It synthesises a traceable Brazilian evidence base; places that evidence within an exploratory international bibliometric context without conflating the discovery dataset with the evidence register; compares Brazilian instruments with verified EU, U.S. EPA, and WHO frameworks; and proposes an adaptive architecture suited to Brazilian institutional and analytical constraints. The proposed pathway (stage-zero horizon scanning, dynamic watch listing, tiered and matrix-specific monitoring, periodic evidence review, multi-criteria risk prioritisation, class-specific regulatory or treatment responses, and One Health integration of AMR) is intended as a staged governance framework rather than a prescriptive legal model. Future work should prioritise harmonised methods, open and interoperable occurrence datasets, seasonal and event-aware monitoring, mixture-effect assessment, class-specific analytical capacity, interlaboratory comparison, and studies of the feasibility and cost of treatment and source-control instruments.

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