Review

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Emerging Contaminants in Water Resources: Monitoring Gaps, Treatment Limitations and Governance Challenges in a Global Context with Insights from Portugal

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Abstract

This paper provides a systematic and comparative review of emerging contaminants in water resources, examining global trends in occurrence, detection technologies, treatment strategies and regulatory responses, with a particular focus on the Portugal context. Following PRISMA 2020 guidelines, peer-reviewed studies published between 2020 and 2025 were critically assessed to identify patterns of contamination, monitoring gaps and technological readiness levels. Results indicate an increasingly frequent presence of pesticides, antibiotics, antidepressants and nutrients in surface water, groundwater and wastewater systems. Advanced analytical techniques, particularly liquid chromatography coupled with high-resolution mass spectrometry stands out as the main detection technique, allowing the identification of trace levels of compounds and the characterization of diffuse sources of contamination associated with agriculture, urban and industrial effluents. However, significant asymmetries persist between international and Portuguese research, especially regarding systematic monitoring networks and integrated risk assessment approaches. Conventional water/wastewater treatment plants show limited removal efficiency, while advanced oxidation processes, adsorption technologies and microalgae-based systems demonstrate promising but variable performance depending on scale and operational maturity. The findings highlight critical gaps between scientific advances and regulatory implementation, emphasizing the need for strengthened monitoring frameworks, technology scale-up strategies and improved integration between science, governance and sustainability policies to ensure resilient water resource management in line with the Sustainable Development Goals.

Keywords: water resources; antibiotics; nitrates; pesticides; PFAS; heavy metals; water treatment technology

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1. Introduction

Emerging contaminants (ECs) represent a global environmental and public health challenge, encompassing substances such as PFAS, pharmaceuticals, plastics, micro- and nano-plastics, and antimicrobial resistance genes. Pharmaceutical waste and personal care products represent another group of concern due to their action at low concentrations (endocrine effects, resistance) and multiple pathways of entry into the biosphere, urban sewage, agriculture, and improper disposal, which require integrated life cycle management strategies [1]. Microplastics and nanoplastics, in addition to acting as carriers of toxic additives (e.g., bisphenols, phthalates, PFAS), have been detected in human tissues and fluids, raising concerns about reproduction, immunotoxicity, and chronic effects that still require long-term studies and methodological standardization [2]. Intensive agriculture, long time recognized driver for soil and water contamination, shows different pesticides occurrence in water resources, nitrates and phosphorus, although classic contaminants are often addressed as EC, depending on where they occur and as accumulate addressing environmental pressures and evolving research priorities [3].

The historical limitation has been mainly analytical: many ECs occur in complex matrices and at extremely low concentrations, requiring advanced chromatography, mass spectrometry, and new sensors for broader and more agile surveillance [1].

Another emerging concern is the interaction between pollutant synergies between microplastics, PFAS, and organic contaminants that can alter bioavailability, transport, and toxicity, complicating risk assessments based on isolated substances.

On the regulatory and policy side, there is a growing movement to classify and limit priority substances, support monitoring, and fund improvements in water treatment, but global implementation is uneven and often lagging behind the rapid pace of environmental dispersion [4]. Promising mitigations include pre-screening of sources, advanced treatment technologies (activated carbon adsorption, advanced oxidation, membranes), circular waste management, and source reduction policies for high-risk products [1].

It should be noted that interdisciplinary research is crucial: ecotoxicology, exposomic epidemiology and exposure models must converge to define safe limits, biomarkers and preventive strategies that consider vulnerable populations and environmental justice [5]. From a public health perspective, incomplete scientific evidence should not be a barrier to taking preventive action; precautionary principles guide efforts to reduce emissions, improve labelling and increase transparency on industrial chemical formulations [6].

1.1. Legislative and Regulatory Overview of ECs

Regarding the legislative and regulatory framework of the European Commission (EU) on ECs, it has evolved incrementally and predominantly reactively, organized along three main fronts. Firstly, there is the update of the standard for water intended for human consumption, embodied in Directive (EU) 2020/2184 on the quality of water intended for human consumption, the so-called recast, which represents a significant milestone. This directive incorporates broader parameters of concern, including explicit references to endocrine disruptors and microplastics, and requires Member States to establish systematic monitoring and risk management programs, raising the minimum level of public health protection at European level [7].

Secondly, a monitoring system based on Community watch lists was established through Commission Implementing Decision (EU) 2022/679, which established a list of substances or compounds of concern for water intended for human consumption, as provided for in Article 13(8) of Directive (EU) 2020/2184. This tool is intended to detect in advance substances such as anti-inflammatories, antibiotics and new pesticides, which are successively included, evaluated and, where justified, subject to mitigation measures, reflecting an evidence-based regulatory strategy [8].

Thirdly, regulatory progress in the field of effluent reuse stands out, through requirements and incentives to improve treatment and use of treated water. The European Union has been progressively aligning itself with quality and risk management requirements, such as tertiary treatment, monitoring of biocontaminants and specific conditions for agricultural use or indirect use for human consumption. However, significant disparities remain between Member States in terms of infrastructure and technical capacity, creating gaps in the practical application of standards.

From a technical and regulatory point of view, these standards reflect the transition from a reactive control model to adaptive and integrated management, combining community monitoring, risk assessment and continuous regulatory review. This movement demonstrates Europe's effort to align environmental regulation with scientific advances and the need for a rapid response to new chemical risks [9].

In comparative terms, international regimes such as the United States Environmental Protection Agency (EPA) Contaminant Candidate List (CCL) follow a similar logic. The US list is based on five-year cycles of review and prioritization of contaminants, based on scientific evidence, including PFAS, cyanotoxins and disinfection by-products. However, institutional and technical differences result in different rates of conversion of watch lists into binding legal limits [10].

The implications for wastewater treatment and reuse are direct. Emerging contaminants tend to resist conventional treatment processes, requiring the adoption of advanced technologies such as ozonation, advanced oxidation and membranes, as well as permanent monitoring regimes. In the field of public health, the reuse of water for indirect drinking purposes requires cumulative exposure assessments, consideration of mixing effects, and the establishment of harmonized standards that reconcile health safety and water sustainability [9,10].

In short, the European framework offers a case of good regulatory practice based on harmonized monitoring, dynamic watch lists and recodified directives, the effectiveness of which, however, will depend heavily on national implementation capacity, continuous scientific updating and coordination with initiatives outside Europe to manage cross-border risks associated with emerging contaminants.

1.2. Portuguese Scenario

In recent years, Portugal has faced several growing challenges related to water quality, particularly regarding the presence of emerging contaminants [11]. These substances are chemical compounds or mixtures which, although generally found in low concentrations, are not yet properly regulated or systematically monitored. According to Sampaio [12], the absence of specific regulations does not diminish the relevance of the problem, as several studies demonstrate their potential to generate adverse impacts on both human health and aquatic ecosystems.

ECs include, in a very broad sense, drugs for hospital and domestic use, personal care products (such as preservatives or filters present in sunscreens), pesticides of different formulations, per- and polyfluoroalkyl substances (PFAS), paraben compounds, microplastics, nanomaterials, as well as metabolites and by-products resulting from the transformation of industrial chemicals [13,14]. The diversity of these contaminants also translates into different physical and chemical properties, with some characterized by high persistence, environmental mobility and toxicity, which implies considerable risks even at very low levels of occurrence [12].

National and international scientific literature has provided consistent evidence of the occurrence of these pollutants in Portuguese surface waters. A recent study, for example, identified the presence of PFAS in several rivers in the country, with significant seasonal variation, revealing their recurrent detection in river basins such as Ave, Leça, Antuã and Cértima [15]. This finding reinforces the idea that these substances not only accumulate in ecosystems but are also resistant to natural degradation processes.

At the same time, transnational studies involving Portugal, Spain and France have conducted a comparative analysis of a wide range of emerging contaminants in wastewater treatment plants (WWTPs), rivers and coastal areas. The results obtained point to a structural limitation in conventional treatment systems, since between 30 and 70% of the substances investigated remain detectable even after the treatment process. This data highlights a technological gap with direct implications for water quality management [16,17].

1.3. Legislative and regulatory framework of ECs in Portugal

The legislative and regulatory framework for ECs in Portugal is part of an increasingly demanding and comprehensive European context. The Water Framework Directive (WFD, 2000/60/EC) and the European list of priority substances laid the foundations for the identification and control of pollutants, while Directive 91/271/EEC on urban wastewater treatment and subsequent regulations have guided the modernization of sanitation and treatment infrastructure. More recently, the European Union has consolidated standards on the reuse of treated wastewater through Regulation (EU) 2020/741 and developed the Strategy on Pharmaceuticals in the Environment [COM (2019)128], reflecting growing concern about substances such as pharmaceuticals, PFAS, microplastics and disinfection by-products, now recognized as regulatory priorities [18,19].

In Portugal, the transposition of these European standards has been gradual, starting with legislation on wastewater (Decree-Law No. 152/97) and moving on to more recent legislation on reuse and effluent management, such as Decree-Law No. 119/2019, in addition to guidance documents issued by the Portuguese Environment Agency (APA) [20]. Technical guides on non-potable reuse and sectoral plans have sought to reconcile the principles of the circular economy with the requirements of public health protection. Despite these advances, various scientific and civil sectors have pointed out gaps and delays both in the full transposition of the WFD and in the effective implementation of measures associated with emerging contaminants [16].

Regarding the congruence between national and European standards, there has been significant formal assimilation: Portugal has adopted regulations and guidelines that reflect EU requirements for water quality and reuse. However, operational consistency is still only partial. Limitations remain in the individualized monitoring of compounds, technical resources at WWTPs are lacking, and there are no harmonized regulatory limits for various emerging substances, including safe concentrations of certain pharmaceuticals and PFAS mixtures. Recent studies highlight that the national capacity to assess risks associated with co-contaminants and mixtures is still insufficient to ensure full compliance with European Union objectives.

The implications of the presence of ECs in effluents are manifold. Of note are the ecotoxic effects on aquatic organisms, the potential for bioaccumulation, the formation of more toxic by-products during treatment, and the risks to human health in contexts of water reuse, whether for agriculture or for direct and indirect potable uses. Safe reuse, especially for consumption purposes, requires multiple treatment barriers, specific monitoring, and risk assessments based on mixing effects and chronic exposures. Regulation (EU) 2020/741 introduces minimum parameters for agricultural reuse, but allows Member States to adopt additional, more restrictive criteria, adapted to their environmental and health realities.

From a historical perspective, a trajectory can be traced from the classic regulation of effluents and sanitation in the 1990s and 2000s, through a phase of intensification of environmental policies and the inclusion of emerging contaminants on European agendas (2010–2020), to the consolidated regulatory framework on water reuse from 2020 onwards. In summary, there is robust regulatory harmonization between Portugal and the European Union. However, effective compliance with these standards requires institutional strengthening, expansion of national analytical capacity, updating of toxicological criteria, and the adoption of preventive policies throughout the production and consumption chain. In the absence of such advances, the reuse of effluents may continue to pose significant environmental and health risks, requiring an integrated, multidisciplinary and preventive approach.

Thus, conducting in-depth studies on ECs in Portugal is justified not only by their scientific relevance but also by their strategic relevance in the context of environmental sustainability, industrial development, and social well-being. Understanding the presence, behavior, and impacts of these pollutants is essential for designing effective public policies, promoting more responsible industrial practices, and driving more innovative treatment technologies. By guaranteeing the quality and safety of water, a vital resource that cuts across multiple sectors of society, we simultaneously ensure the protection of human health, the preservation of ecosystems and the competitiveness of economic activities that depend on the sustainable management of water resources. In this sense, advancing knowledge about emerging contaminants is a fundamental pillar for reconciling industrial growth, social justice and environmental sustainability, in line with European and global sustainable development goals.

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Despite the growing body of literature on emerging contaminants, significant gaps remain in the integration of monitoring data, technological readiness and regulatory implementation within a sustainability framework. Limited attention has been given to how national contexts align with international trends in detection capacity, treatment innovation and governance effectiveness.

Therefore, this study addresses three interconnected questions:

(i) What are the dominant trends in occurrence and detection of emerging contaminants in recent international and Portuguese literature?
(ii) How effective and technologically mature are current treatment solutions, considering their Technology Readiness Levels?
(iii) What governance and monitoring gaps hinder the transition towards sustainable wastewater management?

To answer this question, a systematic review (2020–2025) was conducted to comparatively analyze occurrence patterns, analytical methods, treatment technologies and governance instruments at both international and national levels.

2. Materials and Methods

2.1. Literature Review

The systematic review and comparative analysis presented here were developed according to the PRISMA 2020 guidelines, widely recognized for ensuring methodological rigor, transparency, and reproducibility in scientific synthesis studies. This framework allowed for the consistent structuring of the stages of identification, selection, evaluation, and synthesis of the literature, reducing bias and ensuring the traceability of decisions made throughout the process.

The central purpose of this investigation was to critically analyze current knowledge on ECs in water resources, with special attention to the Portuguese context in comparison with the international panorama. Considering the increase in environmental and health concerns, the review focused on compounds such as pharmaceuticals, personal care products, microplastics, pesticides and persistent industrial substances, recognized for their potential ecotoxicological and human health risks.

The research was organized into two complementary phases. The international phase brought together and critically analyzed review studies and experimental work on ECs in aquatic ecosystems in Europe and the Americas, including perspectives on legislation, analytical methods and implications for sustainable water management. The national stage focused on identifying and evaluating recent studies on the occurrence, environmental behavior and ecological risk of nitrates, pesticides and antibiotics in different Portuguese aquatic matrices, representing agricultural, urban and coastal realities.

A total of 408 articles were identified through database searches: 204 from MDPI, 77 from Scopus, and 127 from ScienceDirect. The search covered the period 2020–2025 and was conducted using Boolean operators with the terms: (“emerging contaminants” OR “micropollutants”) AND (“water resources” OR “surface water” OR “groundwater”) AND (“Europe” OR “America” OR “Portugal”), applied in different combinations. In ScienceDirect, additional filters were applied to refine the search to emerging contaminants, open access content, and review and research articles only. All retrieved records were exported to Zotero for reference management and further screening.

During the initial screening phase, 240 records were excluded because they were considered off-topic or not explicitly focused on the occurrence or treatment of emerging contaminants. Subsequently, a title screening excluded 70 articles, followed by an abstract screening that excluded 32 additional articles. A full-text assessment was then conducted, resulting in the inclusion of 24 eligible studies: 12 articles for the international review and 12 articles for the national review. The terms used allowed the identification of recent studies on the occurrence, concentration, environmental dynamics and management of ECs in European, American and Portuguese contexts.

Strict inclusion and exclusion criteria were applied: only indexed, peer-reviewed studies containing quantitative empirical data or systematic reviews published between 2020 and 2025 were considered. Opinion pieces, theoretical works without empirical validation, or those carried out in non-comparable environmental contexts were excluded, ensuring the consistency and scientific relevance of the synthesized results.

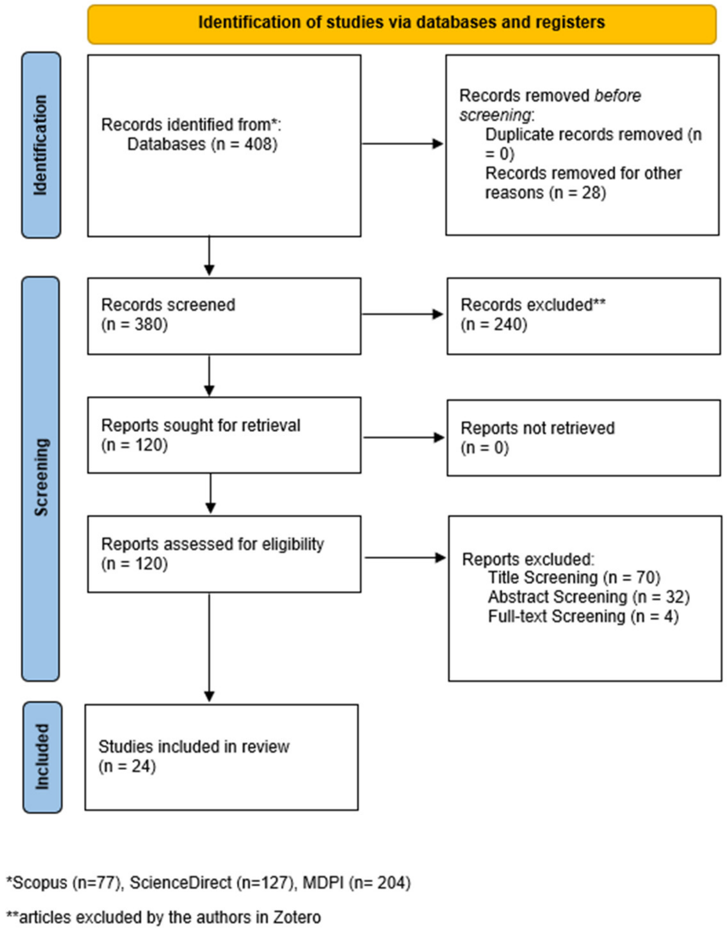

Figure 1. PRISMA 2020 flowchart built from a database of articles found. Adapted from PRISMA 2020 diagram [21], under the license CC BY 4.0.: Authors, 2025.

2.2. Gap Analysis

The gap analysis was conducted through a structured qualitative synthesis of the selected literature. Studies were evaluated according to methodological robustness, including clarity of experimental design, analytical validation procedures, reproducibility, and relevance to environmental application. Attention was given to sampling strategies, detection limits, treatment performance metrics, and consistency between reported concentrations and regulatory thresholds.

The synthesis followed a comparative and integrative framework organized into four analytical axes: (1) occurrence and environmental behavior of emerging contaminants; (2) ecological and human health risks associated with chronic exposure; (3) development, optimization, and validation of analytical and treatment technologies for trace-level detection and removal; and (4) regulatory frameworks and their implications for sustainable water management [19,22].

For each study, the following variables were extracted: target contaminants, environmental matrix, concentration range, analytical or treatment technology, operational scale (laboratory, pilot, or full-scale), and reported performance indicators. International studies (Table 1) were ranked according to citation frequency to reflect scientific visibility and thematic influence. Portuguese studies (Table 2) were analyzed in relation to contaminants prioritized under national and European legislation, including nitrates, pesticides, and antibiotics, with emphasis on analytical techniques, environmental matrices (surface water, groundwater, wastewater), and compliance with legal thresholds.

Representative case studies (Table 3) were further examined to compare experimentally tested concentrations with environmentally reported levels, highlighting potential discrepancies between laboratory research conditions and real-world scenarios. Treatment and detection technologies (Table 4) were classified according to operational scale and assigned an estimated Technology Readiness Level (TRL) based on the European Commission TRL framework, considering validation environment and degree of technological integration. This classification enabled assessment of technological maturity, scalability potential, and the translational gap between laboratory validation and full-scale implementation.

2.3. *Assessment of the Alignment between Technology and Policy*

To evaluate the degree of alignment between scientific research and regulatory priorities, a semi-quantitative content analysis was performed. Each selected study constituted a unit of analysis and was systematically coded according to predefined criteria.

A scoring system was applied in which each parameter received a value of 0 (absence), 0.5 (moderate mention or indirect relevance), or 1 (explicit focus and central objective of the study). Moderate mention (0.5) was assigned when the parameter was discussed but not constituting the primary research objective. The coding process was conducted through structured reading of the full texts, and discrepancies in classification were resolved through iterative review to ensure consistency.

The scoring framework encompassed four major parameter groups:

(i) Environmental matrix: wastewater, surface water, groundwater;
(ii) Target emerging contaminants: PFAS, antibiotics/pharmaceuticals, pesticides, nitrates, phosphorus, and metals;
(iii) Study typology: review, occurrence monitoring, or evaluation of treatment technologies;
(iv) Inclusion of risk assessment components.

Heatmaps were generated using R software (version 4.5.1) [23] with graphical visualization packages (pheatmap), representing the assigned scores on a color gradient ranging from light blue (low alignment) to dark blue (high alignment). All categories were weighed equally to allow comparative visualization without introducing preferential bias.

This exploratory visualization enabled identification of thematic concentration areas, research gaps, and potential misalignment between technological innovation and regulatory emphasis in both Portuguese and international contexts.

3. Results and Discussion

The analysis of international and national literature on ECs allowed us to identify convergent trends, significant methodological advances, and persistent challenges in the field of environmental governance. The evidence gathered reveals not only the expansion of scientific knowledge but also the increasing complexity of the problem, marked by the ubiquity of contaminants, the diversity of affected environmental matrices, and the sophistication of the analytical techniques employed.

Initially, the consolidation of scientific knowledge and the expansion of the spectrum of identified contaminants are examined. Next, the technological capacity demonstrated in the analyzed studies is evaluated, with special attention to the limitations associated with its systematic implementation. Subsequently, a critical analysis of the structural misalignment between scientific innovation and regulatory framework is carried out. Finally, implications for the development of more adaptive and integrated governance models are discussed.

The analysis of the twelve selected international articles, published between 2020 and 2025, highlights the comprehensive approach to emerging contaminants in different environmental matrices, including drinking water, effluents, and global monitoring systems. The studies range from reviews of risk profiles and regulatory policies to applied research involving advanced sensors and electrochemical degradation technologies. This methodological diversity allows for the assessment of both health and environmental impacts and the effectiveness of technological strategies for pollutant mitigation.

3.1. Occurrence and Detection Trends: International vs Portuguese Context

Following this integrated review, Figure 2 synthesizes the comparative distribution of contaminants, sample types and risk assessment approaches across international and Portuguese studies. The heatmap reveals clear thematic asymmetries that would be less evident through individual study description.

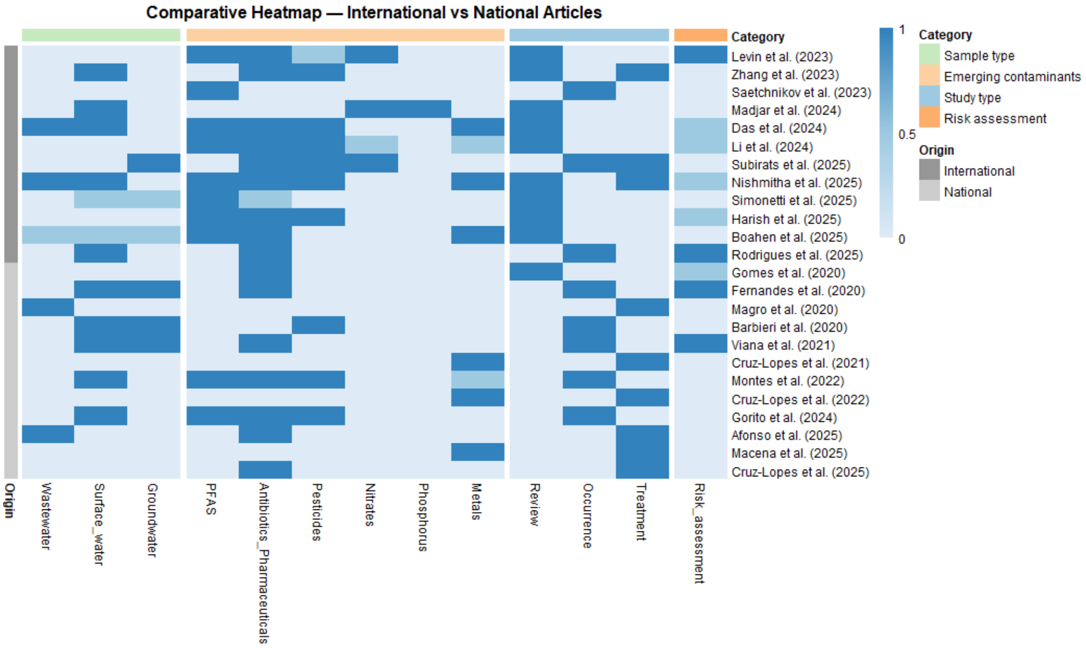

Figure 2. Comparative heatmap between selected international and national studies [1,24–46] and the categories evaluated were 0 – absence; 0.5 – moderate mention; 1 – high relevance. Source: Authors, 2025.

The comparative heatmap highlights clear differences and convergences between international and national studies in terms of sample type, contaminant focus, study design, and the incorporation of risk assessment. Overall, surface water emerges as the most frequently investigated matrix across both groups, indicating its central role in water quality research and environmental monitoring. Wastewater is also commonly addressed, particularly in international studies, reflecting interest in point sources and treatment system performance. In contrast, groundwater appears less frequently overall and is especially underrepresented in national studies. International publications demonstrate greater diversity in sampled matrices, often covering multiple water types within a single study, whereas national research tends to concentrate more narrowly on surface water systems. This suggests that international studies may adopt broader environmental surveillance approaches, while national investigations are more localized and context-specific.

With respect to contaminant type, a clear thematic distinction is evident. International studies show a strong emphasis on emerging contaminants, particularly PFAS and antibiotics/pharmaceuticals. These compounds are often linked to global regulatory debates and concerns regarding persistence, bioaccumulation, and long-term ecological and human health risks. Although nutrients (nitrates and phosphorus) and metals are still addressed in international research, they are comparatively less dominant. National studies, on the other hand, focus more heavily on conventional pollutants such as heavy metals. Emerging contaminants appear in national research, mainly antibiotics with pesticides also moderately represented, but with lower consistency than in the international literature, with a clear lack on PFAS. This asymmetry suggests differences in research priorities, funding availability, analytical capacity, and regulatory drivers, with international research more aligned with emerging global contaminant issues and national research more centered on established water quality parameters.

In terms of study type, occurrence-based investigations dominate across both international and national publications. This indicates that documenting the presence and distribution of contaminants remains the primary research objective. However, international studies display greater methodological diversity, including a higher proportion of review and treatment-focused research. Occurrence and treatment studies are more visible nationally, suggesting stronger engagement with mitigation strategies and technological development. Review articles are more prevalent internationally, reflecting a broader effort to synthesize existing knowledge and guide future research directions, and it is also evident a clear gap on review articles nationally, suggesting the need of consolidate existing knowledge.

Risk assessment is the least represented component overall. International studies more frequently incorporate risk assessment, particularly in investigations of emerging contaminants. This integration suggests an effort to link environmental occurrence data with potential ecological and human health implications, thereby increasing policy relevance, but studies rarely extend beyond contaminant detection and quantification to include formal risk evaluation. The limited integration of risk assessment indicates a gap between monitoring activities and decision-support frameworks, potentially constraining the translation of scientific findings into regulatory or management actions.

Taken together, the heatmap suggests that international research is characterized by broader thematic scope, greater methodological diversity, and stronger integration of risk-based perspectives. National research, while robust in occurrence, monitoring and treatment of conventional pollutants, appears more concentrated and less diversified in terms of contaminant range. These asymmetries highlight opportunities for strengthening national research frameworks through expanded attention to emerging contaminants, increased incorporation of risk assessment methodologies, and greater engagement with treatment and mitigation strategies. Conversely, international research may benefit from increased attention to groundwater systems and more localized, context-specific applications to enhance practical implementation.

The study reinforces that the trends observed in Portugal and other countries are not an isolated phenomenon, but are part of a continental framework that requires integrated responses aligned with the One Health perspective. Despite this technical and scientific advance, the extent and continuity of monitoring actions in the country remain limited. Unlike in Central European or North American countries, where there are systematic and widely institutionalized networks for the surveillance of emerging contaminants, the Portuguese reality is largely based on finite academic projects and isolated regional initiatives. This dependence compromises both the spatial representativeness and temporal consistency of the data collected, hindering an integrated assessment of the status of water bodies and limiting the capacity for regulatory response. Although national legislation is formally aligned with the Water Framework Directive (2000/60/EC), significant gaps remain. Decree-Law No. 69/2023, for example, while adopting a risk management approach for water intended for human consumption, does not incorporate most of the ECs among the mandatory monitoring parameters. Similarly, Decree-Laws No. 152/97 and 119/2019, which regulate the treatment and reuse of wastewater, still do not include specific indicators for pharmaceutical compounds and polar pesticides.

To further detail these patterns, Tables 1 and 2 summarize the methodological approaches and contaminant profiles of the selected studies. This synthesis allows us to identify global trends, monitoring gaps, and technological advances, establishing a solid basis for an integrated discussion of the impacts of emerging and classic contaminants in different contexts.

Table 1. International articles on emerging contaminants (references [1,24–34]).

Nº	Reference	Analytical Technique	Sample Type	Emerging Contaminants	Results
1	Levin *et al.* [24]	Review	–	Arsenic, Nitrate, PFAS, etc.	Risk profiles and health effects in the USA
2	Zhang *et al.* [25]	Review	Surface water and wastewaters	Pharmaceuticals, pesticides, endocrine disruptors	Emerging technologies reviewed
3	Saetchnikov *et al.* [26]	Optical sensor	Aqueous solutions	PFAS	Multiplexed detection of PFAS
4	Madjar *et al.* [27]	LC-MS/MS	Surface and wastewater	Nitrate, Phosphorous	Review of nutrient pollution and mitigation strategies
5	Das *et al.* [28]	Various techniques	Surface and wastewater	Pharmaceuticals, EDCs, PFAS, microplastics, heavy metals, pesticides	Identification of environmental impacts and main sources
6	Li *et al.*, [1]	Review	Review	pharmaceuticals, PPCPs, endocrine disruptors, nanomaterials, etc	Comprehensive review of sources, environmental and health impacts, analytical challenges, and regulatory limitations. Highlights the need for sensitive technologies, long-term monitoring, and innovation in treatment methods.
7	Subirats *et al.* [29]	UPLC-MS/MS	Groundwater	Nitrates, pesticides (triazines), antibiotics (sulphonamides, fluoroquinolones), resistance genes	Microalgae-biofilter system removed 15–98% of nitrates; low accumulation in biomass (<20 ng/g) allowing reuse
8	Nishmitha *et al.* [30]	Review	Surface and wastewater	Medicines, PFAS, microplastics, heavy metals, pesticides	Conventional technologies fail; need for advanced techniques; data gaps highlighted
9	Simonetti *et al.* [31]	Review	Different aquatic matrices	PFAS and other associated ECs	Comparison between classical methods and advanced technologies
10	Harish *et al.* [32]	Review	–	PFAS, pesticides, medicines	Analysis of global legal sources and measures
11	Boahen *et al.* [33]	Review	Diverse environmental matrices	PFAS, PPCPs, microplastics	Evidence of global occurrence, even in remote regions; significant regulatory gaps
12	Rodrigues *et al.* [34]	LC-MS/MS	Urban streams in five European cities	16 pharmaceuticals	91% of locations with ≥1 drug; acetaminophen with highest median; influence of urban factors; One Health implications

Recent international literature has focused on reviewing existing knowledge on EC, with review articles assessing different techniques, multiple water matrices and EC, however there is a growing congroense towards LC -MS/MS as monitoring tool for determination of EC. The literature demonstrates a strong concentration on persistent and high-risk contaminants, particularly PFAS, pharmaceuticals, nitrates, heavy metals, and nutrient pollution associated with agricultural runoff. Studies conducted in the United States and Europe highlight the widespread occurrence of arsenic, nitrates, PFAS, and pharmaceutical residues in drinking water and surface waters, emphasizing both ecological and public health implications [24,33,34]. Urban monitoring campaigns reveal extensive pharmaceutical contamination, with compounds detected in up to 91% of sampling points and mixtures present in 79%, indicating complex exposure scenarios in densely populated regions [34]. At the same time, nutrient pollution remains a structural problem in Europe, where approximately 40% of water bodies fail to achieve "good ecological status," reflecting the persistent impact of nitrogen and phosphorus inputs despite decades of regulation [27].

A notable characteristic of international literature is the increasing integration of environmental monitoring with human exposure pathways and toxicological assessment. Several studies explicitly connect contaminant occurrence to vulnerable populations, chronic ingestion risks, endocrine disruption, antimicrobial resistance, and food-chain bioaccumulation [24,30,33]. This integration reflects a shift toward a One Health perspective, in which environmental contamination, ecosystem integrity, and public health are treated as interconnected dimensions of the same risk framework. In parallel, global assessments emphasize the need for holistic mitigation strategies that combine technological innovation with exposure reduction and regulatory reform [28,30].

Another prominent trend is the growing incorporation of risk modelling and predictive tools. Environmental modelling, ecological risk assessment, and human health risk frameworks are increasingly embedded within contaminant studies, strengthening the policy relevance of scientific findings [24,27]. Advanced detection and monitoring technologies, including multiplexed optical sensors, portable optical systems, and automated miniaturized platforms are being developed to support real-time surveillance and decentralized monitoring programs [25,30]. Simultaneously, technological mitigation research is expanding toward selective and high-efficiency removal systems, such as molecularly imprinted materials combined with advanced oxidation processes, although challenges related to scalability, stability, and environmental safety remain [25].

At the regulatory level, analyses of international legal frameworks reveal significant gaps in harmonization and enforcement, particularly regarding emerging contaminants and PFAS, underscoring the need for globally coordinated governance mechanisms [32].

Overall, the international research landscape appears to be advancing toward multidisciplinary integration, combining contaminant detection, exposure pathways, risk modelling, technological mitigation, and regulatory analysis, whereas the Portuguese context, although scientifically robust and expanding, still shows room for deeper integration between environmental monitoring, health risk modelling, and governance frameworks.

Table 2 below presents a comparative summary of the main methods used, the contaminants analyzed and the most relevant results, allowing gaps in knowledge to be identified and guiding future research on water resource contamination in Portugal.

Table 2. National articles on emerging contaminants (references [35–46]).

Nº	Reference	Analytical Technique	Sample Type	Emerging Contaminants	Results
1	Gomes *et al.* [35]	Review	Water streams	Pharmaceuticals, personal care products, micropollutants	Some ECs alter the microbiome, increase tolerance to antimicrobials and biofilms; effects depend on the type of contaminant and environmental context
2	Fernandes *et al.* [36]	LC-MS/MS	Surface water and sediments	Antibiotics, antidepressants	Identification of pharmaceutical compounds in rivers and sediments; ecological risk assessment
3	Magro *et al.* [37]	Electrochemistry / electrochemical reactor	Wastewaters	Triclosan and by-products	High degradation efficiencies with

					different anodes (Ti/MMO best)
4	Barbieri *et al.* [38]	LC-MS/MS	Surface water and groundwater	Polar pesticides	Development of an automated method for determining pesticides; application in agricultural areas
5	Viana *et al.* [39]	LC-MS/MS	Surface water and groundwater	Antibiotics	Antibiotic detection; ecological risk assessment
6	Cruz-Lopes *et al.* [40]	Biosorption	Aqueous solutions	Cr^{6+}, Ni^{2+}, Pb^{2+}	pH strongly influences adsorption; Pb^{2+} with greater removal; Ni^{2+} better at pH ~5; chestnut and walnut shells are better adsorbents
7	Montes *et al.* [41]	LC HRMS	Surface water, estuarine and wastewater	>3,500 priority compounds, including pharmaceuticals and industrial chemicals	343 substances identified; 153 PMTs; 23 vMvPs; reinforces need for monitoring and prioritization
8	Cruz-Lopes *et al.* [42]	BET adsorption; BJH; FTIR; SEM; XRD	Aqueous solution of Ni(II)	Nickel (II)	All biosorbents remove Ni; efficiency depends on pH and material; promising and sustainable natural materials
9	Gorito *et al.* [43]	LC-MS/MS	Surface waters, estuaries and coastline	34 micropollutants (herbicides, PFAS, pharmaceuticals)	Isoproturon, PFOS and several common pharmaceuticals; persistent presence; need for mitigation
10	Afonso *et al.* [44]	LC-MS/MS	Waste water	19 pharmaceuticals + Diuron	Removal of 40 to 83%; almost total elimination for Fluoxetine, Venlafaxine, Atenolol and Diuron
11	Macena *et al.* [45]	Adsorption; SEM; BET; PXRD	Walnut and chestnut shells; wood and burnt wood	Pb^{2+}	High efficiency; dominant chemisorption; sustainable potential as bioadsorbents
12	Cruz-Lopes *et al.* [46]	Adsorption; UV-Vis photocatalysis	Aqueous solutions with antibiotics	Ceftriaxone	Biochar with high adsorption; TiO_2 with moderate removal; combination with synergistic effect

The twelve national studies summarized in Table 2 reveal substantial methodological diversity, yet they converge around three main analytical dimensions: dominant contaminant typologies, degree of risk assessment integration, and monitoring continuity with LC-MS/MS, being the most reported technology for the determination of EC, so as in international studies.

Regarding contaminant typologies, pharmaceuticals, antibiotics, pesticides, herbicides, and other organic micropollutants clearly dominate the Portuguese research landscape. LC-MS/MS emerges as the predominant analytical technique due to its high sensitivity and capacity for multi-residue detection across complex matrices [38,39]. Large-scale screening efforts identified extensive contaminant diversity, including 343 substances detected through suspect screening using LC-HRMS in northern Portugal-Galicia, and approximately 90% of monitored compounds in WWTPs and river basins meeting PMT criteria, with 18 classified as posing significant environmental risk [41]. Estuarine monitoring campaigns further confirmed the frequent occurrence of compounds such as isoproturon, PFOS, trimethoprim, and diclofenac, even at low concentrations, highlighting persistence as a key concern [43].

Pharmaceutical contamination is particularly widespread, as shown in both national and European-scale assessments. Urban stream monitoring detected pharmaceuticals in 91% of sampling sites, with contamination patterns influenced by population density and landscape structure [34]. In parallel, microbial-level impacts have been documented, with evidence that antibiotics and non-antibiotic pharmaceuticals such as carbamazepine and diclofenac can alter microbial behavior and exert selective pressure for antimicrobial resistance, although effects on biofilms remain methodologically inconsistent [35].

Heavy metals also remain a significant research focus, particularly in the development of biosorption-based mitigation strategies. Lignocellulosic residues such as walnut and chestnut shells achieved removals above 90% for Pb^{2+}, Ni^{2+}, and Cr^{6+}, with adsorption strongly influenced by pH [40,42]. Under optimized conditions, removals of 97–99% for Pb^{2+} were reported, following pseudo-second-order kinetics [45]. Advanced hybrid materials, such as pine bark biochar combined with TiO_2, achieved nearly 96% removal of ceftriaxone through synergistic adsorption and photodegradation mechanisms [46]. Additionally, microalgal consortia cultivated in treated wastewater removed between 40% and 83% of pharmaceuticals and one herbicide, achieving almost complete removal of fluoxetine, venlafaxine, atenolol, and diuron, while maintaining robust biomass production [44]. Electrochemical degradation approaches also demonstrated technological potential, with Ti/MMO anodes identified as the most efficient for triclosan removal [37].

Concerning the degree of risk assessment integration, a small portion of Portuguese studies combine chemical quantification with ecological or human health risk evaluation. Antibiotic monitoring coupled with ecological risk assessment frameworks demonstrates the importance of complementary toxicity and persistence data for meaningful interpretation [36,39]. Broader risk-oriented analyses highlight the environmental persistence, bioaccumulation potential, and classification of compounds as PMT or vMvP, reinforcing concerns about long-term ecological exposure [41]. However, risk modelling isn't systematically present. Studies such as Gomes *et al.* [35] emphasize the need for standardized methodologies and stronger integration within a One Health framework, particularly regarding microbial resistance dynamics.

With respect to monitoring continuity, differences emerge between punctual and longitudinal approaches. Automated methodologies capable of processing large volumes of samples provide high-accuracy but time-limited datasets [38], whereas passive sampling strategies integrated with LC-MS/MS enable more continuous detection of low-concentration compounds [39]. Year-long monitoring in estuarine environments [43] represents a more systematic approach, while suspect screening campaigns and WWTP assessments provide extensive but often cross-sectional contamination snapshots [41]. Overall, although analytical capacity is technically advanced, sustained long-term monitoring frameworks remain less consolidated.

Collectively, the Portuguese research landscape demonstrates strong analytical sophistication and growing integration of mitigation technologies, including electrochemical systems, biosorption using forest residues, and microalgal treatment. Nevertheless, compared to broader international discussions that increasingly combine predictive modelling, regulatory analysis, and systemic exposure frameworks [1,34], national studies remain more focused on detection, characterization, and localized risk assessment than on integrated governance-oriented modelling.

Thus, while Portugal exhibits a robust scientific foundation in contaminant identification and technological experimentation, further consolidation of long-term monitoring programs and predictive risk integration would strengthen the translation of scientific evidence into strategic environmental management.

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Table 3 was developed using primary experimental and observational studies, deliberately excluding review papers, since they do not provide original concentration values but instead compile secondary data from multiple sources. This methodological choice ensures that the information presented is consistent, precise, and directly derived from measured values, avoiding duplication or misattribution of data. For each included study, the contaminants investigated, the concentration ranges measured or detected, the analytical or experimental context (laboratory removal tests, environmental monitoring, advanced sensor detection), and the corresponding reference were systematically extracted.

Table 3. Emerging Contaminants, Concentrations and References [26,39,42,46].

Emerging Contaminant	Concentration (in water)	Notes / Context	Reference
Ni^{2+} (nickel)	5–200 mg/L for isotherms; 25 mg/L for kinetics	Adsorption studies using lignocellulosic biosorbents (walnut shell, chestnut shell, pine wood, burned wood)	[42]
Ceftriaxone (antibiotic)	5–50 mg/L (isotherms); 15 mg/L (kinetics)	Removal using functionalized pine bark biochar + TiO_2 photocatalysis	[46]
PFAS	Up to **1 ppb** detected	Detection via advanced 4D microcavity optical sensor (whispering-gallery mode)	[26]
Antibiotics	ng/L range (some up to ~150 ng/L)	Environmental monitoring using POCIS passive samplers in surface and groundwater	[39]

The concentration ranges presented in Table 3 reveal a critical scale discrepancy between laboratory-based removal experiments (mg/L) and environmentally detected levels (ng/L–µg/L), highlighting the challenge of translating experimental efficiency into real-world relevance. This difference can reach 10^4 to 10^6 times, raising critical questions regarding the direct extrapolation of laboratory-observed efficiency to real-world scenarios. At high concentrations, adsorption mechanisms tend to promote rapid saturation of active sites and the achievement of high removal percentages. However, at trace levels, processes may be governed by distinct phenomena, such as more pronounced diffusional limitations, competition with natural organic matter, matrix effects, and changes in solid–liquid partition dynamics. Therefore, a high removal efficiency expressed in mg/L does not necessarily guarantee equivalent performance at ng/L, particularly when complex and multicomponent environmental systems are considered.

From a technological perspective, this discrepancy may lead to an overestimation of the performance of certain adsorbent materials or advanced treatment processes if evaluation is restricted to idealized conditions. From an environmental standpoint, ecological relevance is associated with chronic exposure to low concentrations, where even trace levels may exert cumulative ecotoxicological effects. Consequently, the validation of treatment technologies should incorporate testing at environmentally representative concentrations, as well as real matrices, to ensure that the demonstrated efficiency is effectively transferable to practical applications.

The highlighted data reveal significant variability across contaminant types and the scales at which they occur in aquatic environments. Metallic contaminants such as Ni^{2+} appear in high mg/L ranges typical of controlled adsorption experiments, while pharmaceutical pollutants like ceftriaxone are also studied in mg/L concentrations during removal tests. In contrast, environmentally detected antibiotics occur at ng/L levels, reflecting their trace presence in natural waters and the need for sensitive analytical methods. PFAS are detected at extremely low concentrations (around 1 ppb) using advanced optical technologies, and antibiotic resistance genes (ARGs) represent biological contaminants measured not by mass but through genetic markers. Together, these distinctions illustrate the complexity of emerging contaminant assessment and the breadth of analytical strategies required to address water pollution challenges.

3.2. Treatment Technologies and Technological Maturity (TRL)

To provide a clearer overview of the technological approaches discussed, Table 4 presents a summary of the treatment technologies evaluated in the studies, highlighting the contaminants addressed, the operational scale, and the respective Technology Readiness Level (TRL) based on the scale proposed by the European Commission [47]. The operational scale (or Technology Readiness Scale) and the respective TRL are an assessment system used to measure the degree of maturity of a technology, from the initial stages of research to its commercial use. The European Commission adopted a 9-level scale (TRL 1–9), aligned with the scale originally developed by NASA, but adapted to the European context of innovation, funding, and public policies.

Table 4. Comparison of treatment technologies evaluated in each study on emerging contaminants [26,29,37,40,42,44–46].

Nº	Reference	Analytical Technique	Sample Type	Emerging Contaminants	Results
1	Saetchnikov *et al.* [26]	Optical sensor (treatment: detection system)	Aqueous solutions	PFAS	Lab scale; sensitive detection; early TRL 3–4
2	Subirats *et al.* [29]	Microalgae–biofilter system	Groundwater	Nitrates, pesticides, antibiotics	Pilot scale; good nitrate removal; TRL 5–6
3	Magro *et al.* [37]	Electrochemical reactor	Wastewater	Triclosan	Lab scale; high degradation; TRL 4–5
4	Cruz-Lopes *et al.* [40]	Biosorption	Aqueous solutions	Cr^{6+}, Ni^{2+}, Pb^{2+}	Lab scale; efficient metal removal; TRL 3–4
5	Cruz-Lopes *et al.* [42]	Adsorption (BET, FTIR, SEM, XRD)	Aqueous solution	Ni^{2+}	Lab scale; good adsorption; TRL 3–4
6	Afonso *et al.* [44]	Full-scale WWTP processes	Wastewater	Pharmaceuticals, Diuron	Industrial scale; moderate–high removal; TRL 8–9
7	Macena *et al.* [45]	Adsorption (SEM, BET)	Aqueous solutions	Pb^{2+}	Lab scale; high removal; TRL 3–4
8	Cruz-Lopes *et al.* [46]	Adsorption + UV–Vis photocatalysis	Aqueous solutions	Ceftriaxone	Lab scale; synergistic removal; TRL 4–5

A critical analysis of Table 4 reveals that most technologies remain at laboratory scale (TRL 3–5), with only one study reaching industrial implementation (TRL 8–9). This predominance of experimental-scale research indicates that, although removal efficiencies are frequently high under controlled conditions, the transition to full-scale application remains limited. Furthermore, many studies rely on synthetic aqueous matrices and tightly controlled operational parameters (as pH, temperature, contaminant concentration), which may not fully reflect the variability of real environmental systems. These findings suggest that the current technological landscape

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demonstrates strong theoretical and experimental potential but still faces significant barriers in achieving operational maturity and large-scale deployment.

As previously discussed, the heatmap (Figure 2) highlighted a strong national emphasis on historically regulated contaminants, such as heavy metals, while international studies showed greater homogeneity in the EC considered and risk assessment approaches. This thematic asymmetry is mirrored in the technological landscape: research efforts are concentrated on conventional pollutants, and the transition toward scalable solutions for emerging contaminants remains limited.

Moreover, the heatmap revealed a lower incidence of risk assessment integration in national studies, which may partially explain the slower progression toward higher TRLs. Technologies developed primarily under controlled laboratory conditions, often using synthetic aqueous matrices and tightly regulated parameters such as pH, temperature, and contaminant concentration, tend to remain confined to experimental validation stages. While removal efficiencies are frequently high under these idealized conditions, the absence of broader environmental variability and risk-based performance evaluation constrains their operational advancement. Thus, the technological immaturity identified in Table 4 can be interpreted not merely as a technical limitation, but as a reflection of the research priorities and methodological patterns evidenced in the bibliometric heatmap analysis.

Research on adsorption technologies based on lignocellulosic materials has demonstrated significant potential for contaminant removal. When considering Figure 2, it is even possible to make a bridge between national studies focusing on heavy metals removal through adsorption. Studies conducted by Cruz-Lopes *et al.* [40,42] demonstrate the high efficiency of lignocellulosic biosorbents in the adsorption of heavy metals such as Ni^{2+}, Cr^{6+} and Pb^{2+}, with performance strongly dependent on pH and the physicochemical characteristics of the materials. Macena *et al.* [45], when exploring lignocellulosic by-products for lead removal, reinforced the potential of these materials as low-cost and highly effective alternatives. Similarly, Cruz-Lopes *et al.* [46] showed that pine bark biochar combined with TiO_2 can remove cephalosporins from aqueous matrices, highlighting a promising technological route for mitigating persistent pharmaceuticals. Collectively, these studies broaden the debate on viable technological solutions for Portugal by demonstrating that innovation capacity is not restricted to conventional or highly specialized systems but also encompasses renewable materials with high applicability potential.

In the field of biotechnological solutions, Subirats *et al.* [29] describe a pilot-scale system combining microalgae with a cork/wood biofilter for the treatment of contaminated groundwater. The system achieved removal efficiencies of up to 98% for nitrates and over 90% for pesticides and antibiotics throughout all seasons. Additionally, the biofilter significantly reduced bacterial load and resistance genes, while the microalgal biomass remained free of contaminant accumulation, suggesting potential agricultural reuse. The authors conclude that this approach constitutes a green, sustainable, and economically viable alternative for drinking water production in rural areas. However large-scale cultivation of microalgae faces significant hurdles across economic and operational domain, the scale-up process is complex requiring critical optimization of process [48,49]. Gurreri et al., [49] conducted a Life-Cycle Assessment reporting the need of a large consumption of chemicals (8 kg/kg dry weight), a high electrical energy consumption (around 267 kWh/ kg DW) and concluding that the sustainability of the process of microalgae cultivation was very hard to achieve

Beyond individual technologies, the transition of these innovative approaches to operational scale faces significant challenges, particularly regarding implementation costs, energy requirements, and adaptation to variable environmental conditions. In contrast, countries such as Germany and the United States have advanced in the adoption of hybrid systems that combine physical-chemical and biological processes with digital technologies for continuous monitoring, enabling real-time water quality management and improved operational control.

Within this broader technological landscape, although Portugal has developed a solid and expanding scientific base, strengthening the interface between knowledge production and public policy formulation remains essential. The effective integration of emerging technologies into treatment and monitoring systems, together with updated regulatory standards and formal recognition of sustainable biosorbents, represents a decisive step toward building a more comprehensive and effective national strategy for monitoring and mitigation.

It is important to note that nitrates (NO_3^-) are not traditionally classified as emerging contaminants (ECs) in the same way as pharmaceuticals, biosurfactants, or personal care products. Nevertheless, increasing scientific attention suggests that nitrates may warrant reconsideration within the emerging contaminant discourse. Selvarangam *et al.* [50] and Aju et al. [51] argue that there are scientific grounds to frame nitrates as an emerging environmental risk, despite their historical classification as conventional pollutants. In a recent publication emphasized the growing global awareness of nitrate contamination as a major environmental problem [52]. Furthermore, research conducted in Bangladesh characterizes nitrate pollution in groundwater as an emerging threat to public health due to its persistence and the chronic risks associated with long-term ingestion.

3.3. Governance, Monitoring and Implementation Gaps

Despite the scientific progress described in the previous sections, advances in detection and treatment have not yet been translated into a fully consolidated transition towards sustainable wastewater management. In Portugal, monitoring of emerging contaminants is still predominantly associated with short-term academic projects, rather than integrated into permanent national surveillance frameworks. This fragmentation compromises temporal continuity and weakens the ability to generate consistent datasets capable of informing evidence-based regulatory decisions.

A similar imbalance can be observed at the regulatory level. Although Directive (EU) 2020/2184 and the subsequent watch list mechanism established by Commission Implementing Decision (EU) 2022/679 represent important advances in the European framework, the effective incorporation of emerging contaminants into binding national monitoring parameters remains partial. As discussed by Silva [16] and Sampaio [12], several compounds frequently detected in Portuguese water bodies are not yet systematically included in mandatory control programs. Furthermore, risk assessment approaches still tend to focus on individual substances, despite growing scientific recognition of mixture effects and cumulative exposure patterns [1,5]. This regulatory delay reinforces a predominantly reactive model of governance, where scientific evidence often precedes formal policy adaptation.

From an implementation perspective, the technological transition also faces structural constraints. While advanced treatment options—such as adsorption systems, electrochemical processes and microalgae-based solutions—have demonstrated promising removal efficiencies [29,37,42], most remain at laboratory or pilot scale when assessed under the Technology Readiness Level framework proposed by the European Commission. As highlighted by Novoveská *et al.* [48] and Gurreri *et al.* [49], large-scale deployment is frequently limited by energy demand, operational complexity and economic viability. In the absence of regulatory incentives or dedicated funding instruments, wastewater treatment utilities tend to prioritize compliance with existing standards rather than the proactive adoption of innovative solutions targeting contaminants that are not yet legally required.

Taken together, these monitoring, regulatory and implementation constraints illustrate the persistence of a structural gap between scientific progress and institutional practice. Although analytical capabilities in Portugal have significantly advanced—particularly through the application of LC-MS/MS and HRMS techniques [36,41]—the integration of these capacities into permanent surveillance networks remains limited. Strengthening coordination between scientific research, environmental agencies such as APA, and wastewater management authorities therefore becomes essential to ensure that knowledge production effectively supports sustainable and resilient water governance in line with European and global sustainability commitments.

4. Conclusions

In Portugal, existing studies consistently report the presence of contaminants such as nitrates, pesticides and antibiotics, especially in areas subject to agricultural, urban and industrial pressures. As discussed throughout this review, these findings not only confirm localized contamination patterns but also reflect broader structural challenges in water quality management. The persistence of these compounds across different aquatic matrices compromises ecosystem integrity and raises concerns regarding long-term human exposure. In this context, the issue intersects directly with several Sustainable Development Goals (SDGs), notably, SDG 6 (clean water and sanitation); SDG 3 (good health and well-being); and SDGs 14 and 15 (life below water and life on land), highlighting the need for more integrated and preventive approaches to water governance.

Despite these constraints, Portugal benefits from a solid scientific base and advanced analytical capabilities, as evidenced by the widespread application of LC-MS/MS and HRMS techniques in recent studies. The occurrence of pesticides, pharmaceuticals, antibiotics and nutrients across different water bodies has been widely documented, reflecting active research engagement and technical competence. However, the integration of this knowledge into continuous national monitoring frameworks remains limited. Several compounds are still absent from mandatory control parameters, and coordination between research institutions, wastewater treatment plants and regulatory authorities is not yet fully consolidated, constraining the translation of scientific evidence into systematic management practices.

Strengthening sustainable wastewater governance therefore requires a shift from fragmented initiatives to more integrated approaches. This involves expansion of continuous monitoring systems supported by sensitive analytical methods, incorporating multidisciplinary risk assessments that combine environmental chemistry, ecotoxicology and modelling, and progressive validation of innovative treatment technologies under real operating conditions. Rather than isolated technological upgrades, a coordinated framework linking science, regulation and infrastructure planning appears essential to reduce long-term contamination pressures and enhance water system resilience.

The future of water management in Portugal depends on strengthening the alignment between scientific knowledge, technological innovation and regulatory frameworks. As demonstrated throughout this review, advances in analytical detection and treatment technologies have not yet been fully matched by institutional integration and long-term monitoring strategies. Bridging this gap requires not only the expansion of continuous surveillance programs but also clearer regulatory signals and mechanisms that facilitate the gradual adoption of innovative solutions, particularly within small and decentralized wastewater systems.

Overall, this study highlights that the challenge of emerging contaminants is not solely technological, but structural. While Portugal has developed significant scientific expertise and analytical capacity, the transition towards integrated and sustainable wastewater management remains constrained by fragmented monitoring, partial regulatory incorporation and limited technological scale-up. By comparatively examining occurrence patterns, treatment maturity and governance gaps, this review contributes to a more coherent understanding of how science, policy and infrastructure must converge to ensure long-term water resilience in line with European sustainability commitments.

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Abbreviations

The following abbreviations are used in this manuscript:

AOPs	Advanced oxidation processes
APA	Portuguese Environment Agency
CCL	Contaminant Candidate List
ECs	Emerging contaminants
EPA	United States Environmental Protection Agency
EU	European Union
LC – HRMS	Liquid Chromatography – High Resolution mass spectrometry
LC -MS/MS	Liquid Chomatography coupled to mass spectrometry
MDPI	Multidisciplinary Digital Publishing Insitute
MIPs	Molecularly imprinted materials
NASA	National Aeronautics and Space Administration
PFAS	Polyfluoroalkyl substances
PFOS	Perfluorooctane Sulfonate
PMT	Persistent, moving and toxic substances
SDG	Sustainable Development Goals
TRL	Technology Readiness Level
UNEP	United Nations Environmental Program
USA	United States of America

UV	Ultra-violet
vMVPs	Very persistent and very mobile substances
WWTP	Wastewater treatment plants

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