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Pesticide contamination and water quality in the Paraná 3 Basin Region: a systematic review of evidence and research gaps

Contaminação por pesticidas e qualidade da água na Região da Bacia do Paraná 3: uma revisão sistemática das evidências e lacunas de pesquisa

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ABSTRACT: This systematic review provides the first integrated assessment of pesticide contamination, water quality, and associated research gaps in the Paraná 3 Basin region. The basin is a transboundary agricultural watershed along the Brazil-Paraguay border that supplies the Itaipu hydroelectric reservoir. Through the ProKnow-C methodology, 26 studies were selected from 8,688 records. Only 3 studies (11.5%) directly addressed water contamination assessment within the Paraná 3 Basin, exposing a pronounced disparity between the region's strategic relevance and dedicated scientific output, which constitutes a structural research gap in itself. Thematic analysis showed glyphosate in 19.3% and AMPA in 21.8% of surface-water samples, with peak concentrations associated with rainfall-driven runoff. Atrazine and unregulated transformation products were also identified. However, while existing evidence relies heavily on spot-sample chromatographic monitoring, operational predictive models remain significantly underrepresented. The most frequently identified gaps include the lack of binational regulatory harmonization (38% of studies), insufficient hydrological and land-use data (31%), and the absence of continuous long-term monitoring (23%). Additional limitations associated with emerging contaminants and ecotoxicological complexity were identified in 4 studies (15%). This review supports basin-scale management and transboundary governance by recommending standardized bilateral monitoring protocols, open georeferenced environmental databases, and predictive modeling approaches for evidence-based decision-making.
Keywords: sustainability, water quality, pesticides, Itaipu reservoir, environmental monitoring.

RESUMO: Esta revisão sistemática apresenta a primeira avaliação integrada da contaminação por pesticidas, da qualidade da água e das lacunas de pesquisa associadas na região da Bacia do Paraná 3. A bacia é uma região hidrográfica agrícola transfronteiriça localizada na fronteira entre Brasil e Paraguai, e abastece o reservatório da Usina Hidrelétrica de Itaipu. Por meio da metodologia ProKnow-C, foram selecionados 26 estudos a partir de 8.688 registros. Apenas 3 estudos (11,5%) abordaram diretamente a avaliação da contaminação da água na Bacia do Paraná 3, revelando uma disparidade entre a relevância estratégica da região e sua produção científica, configurando uma lacuna estrutural de pesquisa. A análise temática identificou a presença de glifosato em 19,3% e AMPA em 21,8% das amostras de águas superficiais, com maiores concentrações associadas ao escoamento superficial decorrente de chuvas. Atrazina e produtos de transformação não regulamentados também foram identificados. No entanto, embora as evidências existentes se baseiem principalmente no monitoramento cromatográfico de amostras pontuais, os modelos preditivos operacionais continuam sub-representados na literatura. As lacunas mais frequentemente identificadas incluem a falta de harmonização regulatória binacional (38% dos estudos), a insuficiência de dados hidrológicos e de uso e cobertura da terra (31%) e a ausência de monitoramento contínuo de longo prazo (23%). Limitações adicionais associadas a contaminantes emergentes e à complexidade ecotoxicológica foram identificadas em 4 estudos (15%). Esta revisão pode subsidiar a gestão em escala de bacia e a governança transfronteiriça, evidenciando a necessidade de protocolos bilaterais padronizados de monitoramento, bancos de dados ambientais abertos e georreferenciados e modelagem preditiva para apoiar decisões baseadas em evidências.

Palavras-chave: sustentabilidade, qualidade da água, pesticidas, reservatório de Itaipu, monitoramento ambiental.

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1. Introduction

The management of water quality and the long-term sustainability of water resources represent a critical environmental challenge, particularly concerning ecosystem health and the sustainability of water resources (FAO, 2018). The Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) recognize this as a global risk to water governance, with approximately 70% of freshwater used for agriculture (Naganjali et al., 2024).

Persistent compounds such as atrazine and glyphosate are widely detected in surface and groundwater in more than 100 countries, posing risks to drinking water quality, aquatic biodiversity and food production systems (Battaglin et al., 2014; Álvarez Bayona et al., 2022). These concerns highlight the urgency of approaches that link agricultural practices, hydrological processes and environmental governance to promote sustainable water management (Foster & Chilton, 2003; Dodds et al., 2009; Carvalheiro, 2015).

Water contamination by pesticides is particularly critical in regions characterized by intensive agricultural practices and regulatory disparities, including border areas. In Brazil, pesticide consumption has increased significantly over recent decades, with a 78.3% rise between 2010 and 2020. This expansion partly reflects regulatory flexibility that permits the use of substances banned in other regions, including the European Union (Hess & Nodari, 2022). Such contamination affects aquatic ecosystems and may compromise water security and hydroelectric power generation (Steele & Aitkenhead-Peterson, 2011).

Rainfall patterns play an essential role in pesticide dispersion and persistence in aquatic systems. Intense precipitation increases surface runoff and contaminant transport, while dry periods reduce dilution capacity (Steele & Aitkenhead-Peterson, 2011). Beyond their effects on water bodies, pesticides also compromise soil quality and fertility (Gwynn, 2019), and their environmental behavior is increasingly shaped by climate-related shifts in rainfall regime (Ghini, 2008). Understanding these interactions is essential for evaluating environmental risks and guiding mitigation strategies.

The Paraná 3 Basin, shared by Brazil and Paraguay, is a prominent example of transboundary water governance in Latin America, where Itaipu reservoir is also located (Figure 1). This basin drains an extensive agricultural area dominated by soybean, corn and wheat cultivation, contributing to the recurrent detection of atrazine, glyphosate and AMPA (Battaglin et al., 2014; Álvarez Bayona et al., 2022). Its strategic relevance and the sensitivity of its contributing tributaries make this basin an important case for assessing how global patterns of pesticide contamination manifest under transboundary governance and intensive agricultural pressure (Tundisi, 2008; Souza et al., 2019). Additionally, special attention is needed for the water quality of the tributaries that supply the reservoir due to their influence on hydroelectric generation (Lima, 2022).

Figure 1 – Location of the Paraná Basin 3.
Source: authors. Adapted from (Google, 2025)

Although previous studies have addressed eutrophication (Ribeiro Filho et al., 2011; Soares et al., 2012), nutrient dynamics (Bini et al., 2010) and sediment contamination (Tundisi et al., 1993), no systematic review has focused specifically on pesticide contamination in the Paraná 3 Basin. This gap is particularly significant considering the rapid growth of pesticide use in Brazil (Hess & Nodari, 2022) and the associated environmental and public health risks (WHO, 2017; FAO, 2018). No existing studies integrate pesticide occurrence with rainfall variability, land-use dynamics and governance structures. There is also a lack of integrated frameworks incorporating advanced analytical tools and predictive modeling approaches to monitoring and support water management decision-making (Agarwal, 2013).

These limitations highlight the need to address the following research question: "*How does the existing scientific literature characterize the impacts of pesticide contamination on water quality management in the Paraná 3 Basin, and what are the essential requirements for an integrated transboundary monitoring and governance framework?*".

Thus, this review presents the first systematic review focused on pesticide contamination in the Paraná 3 Basin. The research aims to identify and critically analyze studies addressing water quality analysis in the Paraná 3 Basin, with emphasis on pesticide occurrence and its impacts on aquatic systems. Furthermore, the study synthesizes evidence across environmental and governance dimensions, identifies existing knowledge gaps, and evaluates the potential of predictive and data-driven approaches for water quality monitoring and forecasting. Ultimately, it provides evidence-based insights to support integrated basin-scale management, transboundary water governance, and sustainable agricultural practices.

The following section presents the theoretical background. The methods section describes the procedures for bibliographic portfolio selection, screening and analysis. The results and discussion section integrates bibliometric analysis, findings and implications. The final section offers concluding remarks and recommendations for future research.

2. Theoretical Background and Rationale for the Review

2.1. Governance and Regulatory Challenges in Transboundary Basins

Regulatory discrepancies in pesticide standards constitute a critical barrier to integrated water governance. The European Union adopts highly restrictive drinking-water limits, such as 0.1 µg/L for atrazine, while Brazil allows concentrations up to 2 µg/L. These divergences become especially problematic in transboundary river basins, where water flows disregard political borders. Regulatory asymmetries undermine monitoring and mitigation efforts across national boundaries (Araújo et al., 2022; Oliveira et al., 2023). Brazil's regulatory flexibility, which permits the use of pesticides banned in several other jurisdictions including the EU, contributes to increased environmental exposure and reinforces the need for harmonized standards (Hess & Nodari, 2022; Ramírez Hernandez et al., 2025). Understanding these asymmetries is fundamental for evaluating the risks and governance demands in the Paraná 3 Basin, which is jointly managed by Brazil and Paraguay.

Transboundary basins account for approximately 60% of the Earth's land surface and span 153 countries, illustrating the geopolitical, environmental, and institutional complexities of shared water resources. Basins such as the Mekong (Sahana et al., 2024), Danube (Bugarski et al., 2017), and Mississippi (Goolsby et al., 2000) demonstrate how agricultural intensification, hydrological alteration, and diffuse pollution generate challenges that exceed administrative boundaries. These cases illustrate the need for cooperative governance structures capable of addressing diffuse pesticide contamination, harmonizing regulatory frameworks, and promoting integrated basin-scale monitoring. This international evidence provides a conceptual foundation for understanding the complexities of transboundary governance in the Paraná 3 Basin.

2.2. Pesticide Contamination Processes and Global Evidence

Pesticides include herbicides, insecticides, and fungicides characterized by environmental persistence, mobility, and the potential to form toxic transformation products. Their presence in freshwater systems results from multiple pathways, including surface runoff, leaching, atmospheric deposition, and accidental application near riparian zones. Once in aquatic environments, pesticides can degrade into compounds such as aminomethylphosphonic acid (AMPA) from glyphosate and desethylatrazine (DEA) from atrazine, which often retain ecotoxicological relevance (Zhou et al., 2025). These processes result in acute and chronic toxicity in aquatic organisms, endocrine disruption, and cumulative impacts that threaten ecosystem functioning.

Studies across Asia, North America, and South America consistently demonstrate widespread pesticide contamination in reservoirs and river–reservoir systems. Concentrations have reached 102–821 ng/L in Chinese reservoirs (Chai et al., 2023), and more than 300 pesticide compounds have been detected in South Korea's Saemangeum Basin (Kim et al., 2023). Seasonal peaks associated with precipitation are frequently reported, as seen in the Yangtze Basin, where atrazine occurred in 100% of samples over a 20-year dataset (Xie et al., 2025). Spatial gradients generally show decreasing concentrations from agricultural areas toward reservoir bodies, reflecting dilution, deposition, and sedimentation processes (Chen et al., 2018). Furthermore, atrazine has been identified as one of the most widely monitored and detected herbicide compounds worldwide, often exceeding regulatory or ecotoxicological limits (Araújo et al., 2022).

This global literature reveals important patterns but also highlights the considerable role of local agricultural practices, hydrological conditions, cropping systems, and climatic variability. The heterogeneity of results reinforces the value of basin-specific assessments, as in the Paraná 3 Basin.

2.3. Monitoring Advances, Data-Driven Approaches, and Rationale for This Review

Traditional analytical methods such as HPLC, GC-MS, and LC-QTOF MS remain essential for precise quantification of pesticide residues, but their operational constraints limit large-scale or high-frequency monitoring (Dharmarathne et al., 2025). Recent advances in remote sensing have expanded monitoring capabilities through hyperspectral data collected by satellites, aircraft, and unmanned aerial vehicles, enabling high-resolution inference of water-quality indicators (Agrawal & Arafat, 2024; Hamzah et al., 2024; Feng et al., 2025; Pan et al., 2025).

Machine learning (ML) and artificial intelligence models, including Random Forest, XGBoost, and deep neural networks, have demonstrated superior performance in predicting pesticide concentrations, identifying contamination hotspots, and classifying water quality under variable environmental conditions (Sangwan & Bhardwaj, 2024; Lokman et al., 2025). These technological advances create new opportunities for predictive modeling and early warning systems in basins under intensive agricultural use, but they remain underexplored in the context of the Paraná 3 Basin.

In the Paraná 3 Basin region, Araújo et al. (2022) reported the presence of 43 pesticides, including atrazine metabolites, fipronil and difenoconazole, with clear associations to agricultural land use. Despite these findings, no study has integrated environmental, climatic, land-use and governance dimensions to assess pesticide contamination in the Paraná 3 Basin. This gap is particularly relevant because reservoirs function as both sinks and redistribution points for contaminants, while transboundary settings introduce regulatory asymmetries and coordination challenges that shape exposure and management responses.

3. Materials and Methods

This review employed the ProKnow-C methodology (Ensslin et al., 2010) for the systematic identification, selection and analysis of scientific publications (Figure 2). ProKnow-C is a consolidated methodology for bibliographic portfolio construction in the international literature and has been widely applied (Maciel et al., 2021; Rebello et al., 2023; Torres et al., 2024), compared with other review approaches (Carvalho et al., 2020), and combined with complementary methods (Fantozzi et al., 2024). The search strategy was structured around three thematic axes related to water quality, the Itaipu reservoir region and data mining or artificial intelligence. Keywords were combined to retrieve studies addressing water monitoring in the Paraná 3 Basin and analytical approaches based on data science.

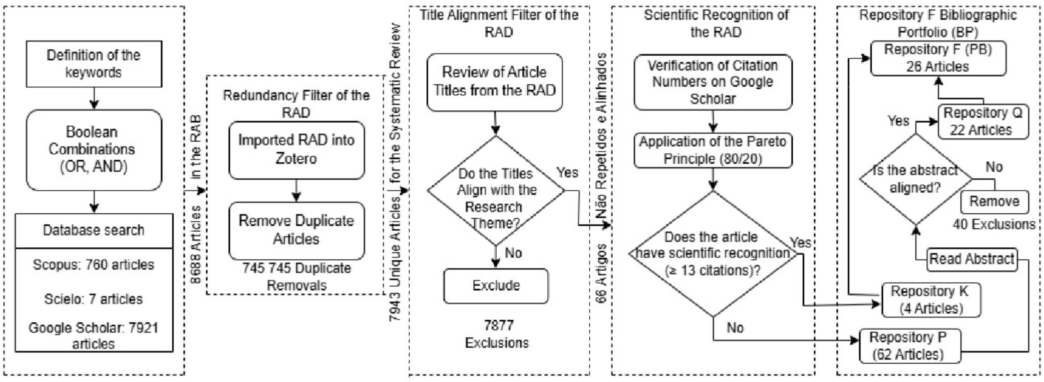

Figure 2 - Criteria and steps for the selection of scientific studies.
Source: authors.

Searches were performed in the Scopus, Scielo and Google Scholar databases on January 21, 2025, covering the period from 2014 to 2025 to encompass both foundational and recent contributions. These databases were selected to ensure coverage of international scientific output, Latin American regional publications and broadly indexed academic material. It should be clarified that the Web of Science database was not adopted as an independent source because Google Scholar performs indirect indexation of metadata from publications hosted in major scientific journals and conference proceedings (Martín-Martín et al., 2018). This includes publications indexed by Web of Science, Springer, Elsevier, and others major databases. Therefore, high-impact international studies were indirectly captured without redundant duplication of records, consistent with consolidated applications of the ProKnow-C methodology in recent systematic reviews.

The initial search retrieved 8,688 documents, which comprise the Raw Article Database (RAD). The distribution of results from keyword combinations and databases is presented in Table 1. The records were organized in the Zotero bibliographic management system (Zotero, 2025). Duplicate removal excluded 745 documents, leaving 7,943 records for title screening. This step assessed thematic adherence and resulted in the exclusion of 7,877 studies, primarily because many referred to a distinct region known as Itaipu Beach in Rio de Janeiro or focused exclusively on sediment analyses without assessing water quality. Sixty-six articles advanced to the Scientific Recognition stage.

Table 1 - Research results in scientific databases (2014 to 2025).

Combinations	*Scopus*	*Scielo*	*Google Scholar*
1. (“water quality” OR contamination) AND Itaipu)	615	7	6280
2. (pesticide OR contamination OR “water quality”) AND (policies OR regulations) AND Brazil AND Paraguay AND Itaipu)	72	0	612
3. ((“artificial intelligence” OR “machine learning” OR “data mining”) AND (“water quality” OR contamination) AND (Itaipu OR “Brazil-Paraguay”))	4	0	547
4. (“itaipu” AND (“climate change”) AND (“agrochemical contamination” OR pesticides) AND (“water quality” OR “hydrographic basin”) AND (“artificial intelligence”))	14	0	14
5. ((“artificial intelligence” OR “machine learning” OR “data mining”) AND (“water quality” OR “pesticide” OR “contamination”) AND Itaipu)	43	0	360
6. (“precipitation” OR “rainfall”) AND (“water contamination” OR “pesticide contamination”) AND (“Itaipu” OR “Brazil AND Paraguay”)	12	0	108
Total Items	**760**	**7**	**7,921**
Raw Articles Database (RAD)	**8.688**		

Source: authors.

Scientific recognition of the publications was assessed using citation counts retrieved from Google Scholar on February 4, followed by content adherence analysis according to the criteria established in the ProKnow-C methodology. Following the Pareto Principle (Delers, 2023), studies with at least 13 citations were classified as having high scientific relevance and were grouped into Repository F. The remaining documents were assigned to Repository P. Abstract screening of Repository P identified 22 studies with substantive alignment to the research scope, forming Repository Q. These 22 studies, combined with the four highly cited articles from Repository F, resulted in a final Bibliographic Portfolio (BP) of 26 publications. The BP and citation frequencies are summarized in Table 2.

Table 2 - Studies in the Bibliographic Portfolio (BP).

Title (Publication Year)	Reference	Citations 21/06/25
Comprehensive investigation of pesticides in Brazilian surface water by high resolution mass spectrometry screening and gas chromatography–mass spectrometry quantitative analysis	(Della-Flora et al., 2019)	45

Source: authors.

Table 2 - Continued...

Title (Publication Year)	Reference	Citations 21/06/25
Pesticides in surface water from Brazil and Paraguay cross-border region: screening using LC-QTOF MS and correlation with land use and occupation through multivariate analysis	(Becker et al., 2021)	27
Glyphosate and AMPA occurrence in agricultural watershed: the case of Paraná Basin 3, Brazil	(Mendonça et al., 2020)	19
Itaipu royalties: the role of the hydroelectric sector in water resource management	(Lorenzon et al., 2017)	18
Parasitological, microbiological, and antimicrobial resistance profiles of raw and drinking water in a tourist city in the tri-border region of South America	(Scherer et al., 2022)	9
Comprehensive assessment for the potential environmental impacts of the grand ethiopian renaissance dam on the downstream countries: Itaipu dam in the rearview mirror	(Morsy et al., 2021)	7
Brazilian vs. Paraguayan streams: differences in water quality in a cross-border subtropical region	(Ouchi-Melo et al., 2021)	5
Adapting watercourse agreements to developments in international law: the case of the Itaipu treaty	(Gwynn, 2019)	4
A new methodology for royalties distribution of the Itaipu hydroelectric plant: The hydrographic basin as the unit of analysis	(Lorenzon et al., 2018)	4
Bioindicadores de qualidade de água como ferramenta de impacto ambiental de uma bacia hidrográfica	(Schiller et al., 2017)	3
Evaluation of pseudo-total and labile metals (Cu^{2+}, Cr^{3+}, Ni^{2+}, Mn^{2+}, Pb^{2+} and Zn^{2+}) in surface sediments at the mouth of tributaries of the Itaipu Reservoir, Brazil	(Junior et al., 2018)	3
Trophic state index (tsi) of the reservoir of the Itaipu Binacional hydroelectric power plant, Brazil (2019)	(Souza et al., 2019)	2
Appraising services to the ecosystem: an analysis of Itaipu power plant's water supply in energy generation	(Mussi et al., 2020)	1
Caracterização limnológica e espectral de dois compartimentos aquáticos do reservatório Itaipu	(Buffon, 2016)	1
Preliminary study of the biodisponibility of magnesium and zinc in specimens of "armado" (pterodoras granulosus), captured in the reservoir of Itaipu	(Oliveira et al., 2014)	1
Quantification of metals in macrophytes in an aquaculture area of the Itaipu Binational reservoir	(Marengoni & Chambo, 2021)	1
Transboundary water relations of the Itaipu dam: unveiling Brazilian consensual hydro-hegemony	(Berkhout & Warner, 2023)	1
Análise espacial da turbidez no compartimento aquático São Francisco verdadeiro, reservatório de Itaipu, PR	(Dezordi, 2020)	0
Estruturas públicas voltadas ao desenvolvimento rural sustentável nos municípios lindeiros ao Lago da Usina Hidroelétrica de Itaipu	(Ferreira et al., 2018)	0
Extreme Precipitation Events During the Wet Season of the South America Monsoon: A Historical Analysis over Three Major Brazilian Watersheds	(Freitas et al., 2024)	0
IV-019-Índice de qualidade nas águas do rio Ocoí, tributário do reservatório de Itaipu-PR	(Costa et al., 2015)	0
Previous studies before and after impoundment on right bank of Itaipu dam reservoir	(Masulli & Taboada, 2023)	0
Prospecção de microcistina no paraná-contaminação, qualidade da água e degradação do meio ambiente	(Miguel et al., 2018)	0

Source: authors.

Table 2 - Continued...

Title (Publication Year)	Reference	Citations 21/06/25
Redes neurais na gestão das águas em reservatórios hidrelétricos: um estudo de caso na hidrelétrica Itaipu (Brasil)	(Silva et al., 2022)	0
Serviços ecossistêmicos e investimentos ambientais: um estudo de caso da usina hidrelétrica de Itaipu (2021)	(Mussi et al., 2021)	0
Dinâmica espaço-temporal da turbidez no reservatório de Itaipu, na região sul do Brasil, utilizando dados de sensoriamento remoto	(Facco, 2023)	0

Source: authors.

All studies included in the BP were examined in full for qualitative and thematic analysis.

4. Results and Discussion

This section presents an integrated analysis of the 26 studies comprising the Bibliographic Portfolio (BP), selected using the ProKnow-C methodology (Section 2). The results are organized into bibliometric findings, thematic evidence on water quality in the Paraná 3 Basin region, applications of data mining and machine learning, and a synthesis of research scope classification. Collectively, these analyses outline the evolution, contributions, and gaps in scientific production supporting integrated water resources management and transboundary water governance in the Paraná 3 Basin.

4.1. Bibliometric Analysis

The temporal distribution of publications (Figure 3, left) reveals a marked increase in scientific output between 2017 and 2021, a period that alone concentrates more than half of the BP's studies. This growth reflects rising interest in themes such as water quality degradation, pesticide contamination, and the adoption of remote sensing and advanced analytical methods in environmental monitoring. After 2021, a gradual decline occurs, partially due to ProKnow-C's citation-based filtering, which may exclude more recent studies not yet consolidated in the citation record (Ensslin et al., 2010). The cumulative curve reinforces this trend, demonstrating the consolidation of research inquiries on basin management, hydrological processes, and anthropogenic pressures in transboundary basins, including emerging applications of machine learning (Russell & Norvig, 2016).

Publication types within the BP (Figure 3, right) show a predominance of peer-reviewed journal articles (69.2%), followed by conference papers (15.4%), theses/dissertations (11.5%), and book chapters (3.8%). The dispersion across publication venues suggests that research on the Itaipu reservoir lacks a centralized outlet and is distributed across diverse environmental, hydrological, and interdisciplinary journals. This thematic dispersion is also reflected in the keywords and title-based textual analysis (Figure 4, left) , which identifies "Itaipu," "water," "basin," "hydroelectric," "reservoir," and "Brazil" as frequent terms. The coexistence of Portuguese and English descriptors, such as bacia/basin and reservatório/reservoir, underscores the regional relevance of national research institutions. It also highlights the importance of bilingual search strategies for comprehensive literature retrieval and regional monitoring analyses.

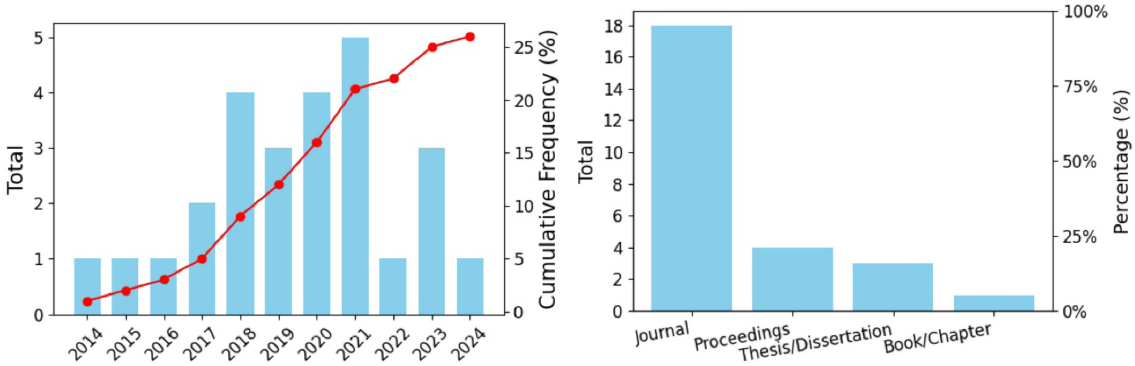

Figure 3 - Annual history publications and published media.
Source: authors.

Citation analysis (Figure 4, right) indicates a highly unequal distribution: four articles account for 72% of all citations. These influential works predominantly address pesticides and emerging contaminants, confirming the centrality of agricultural pollution and water quality risks in the scientific debate about the transboundary watershed.

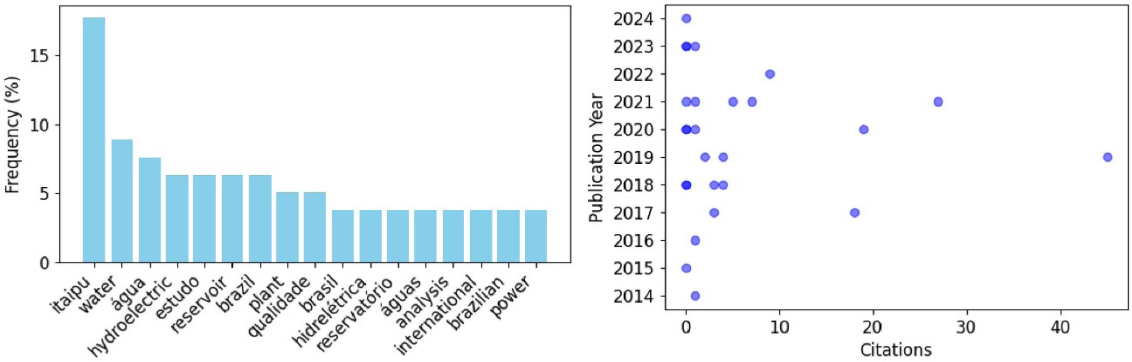

Figure 4 - Frequency of key terms and yearly citation counts.
Source: authors.

The co-authorship network (Figure 5) reveals two major collaborative clusters. The first, led by Simone Frederigi Benassi (Itaipu Binacional), is associated with environmental monitoring, limnology, and water resources management. The second, centered around Gilcélia Aparecida Cordeiro (UNILA), includes interdisciplinary collaborations addressing ecotoxicology, environmental impacts, and governance. Smaller, peripheral clusters include both older publications (blue nodes) and newer emerging groups (yellow nodes), reflecting the progressive diversification of research teams.

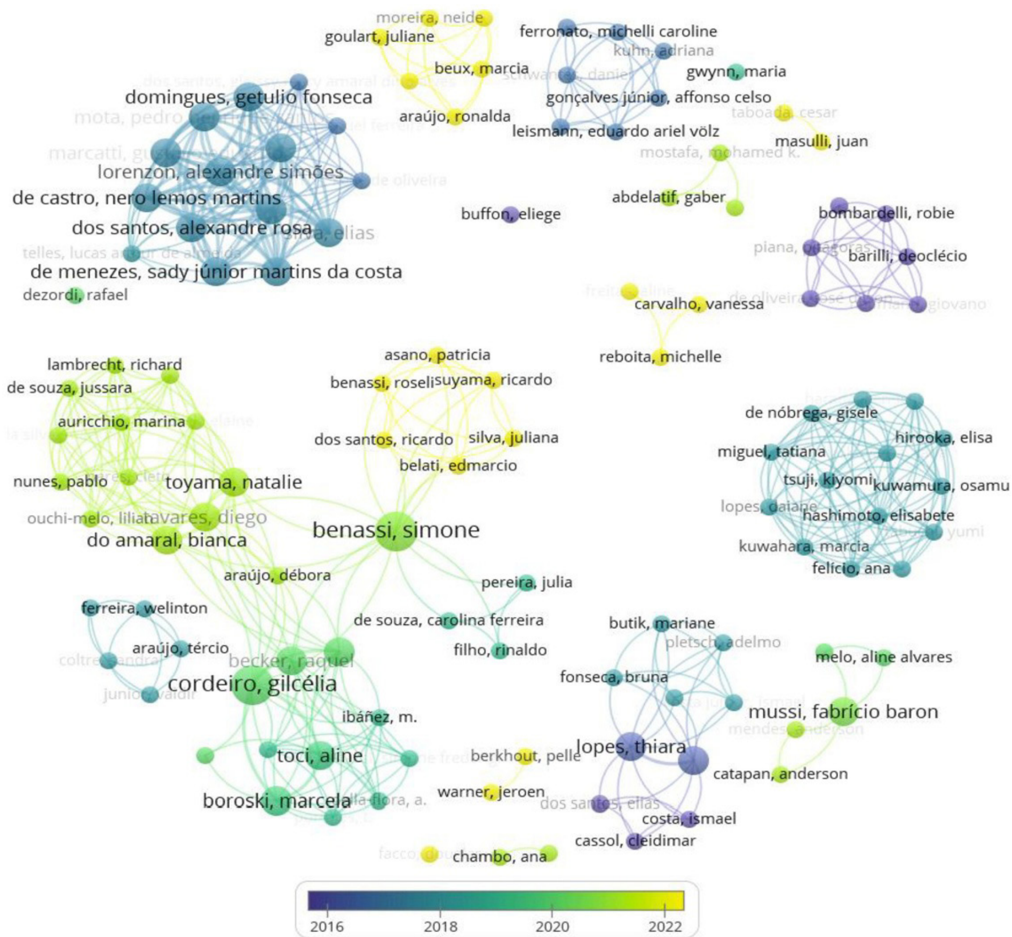

Figure 5 - Co-authorship network for papers in the Bibliographic Portfolio (BP).
Source: authors.

A similar pattern emerges in the conceptual network analysis (Figure 6), where clusters of water-quality-related terms dominate. Notably, no significant presence of machine learning terminology appears, even though several recent studies employ such methods. This suggests that the incorporation of data-driven approaches remains incipient and not yet reflected in the conceptual vocabulary of the field. Overall, the bibliometric analysis highlights a research landscape characterized by thematic dispersion, strong regional academic participation, and growing yet limited engagement with advanced computational tools.

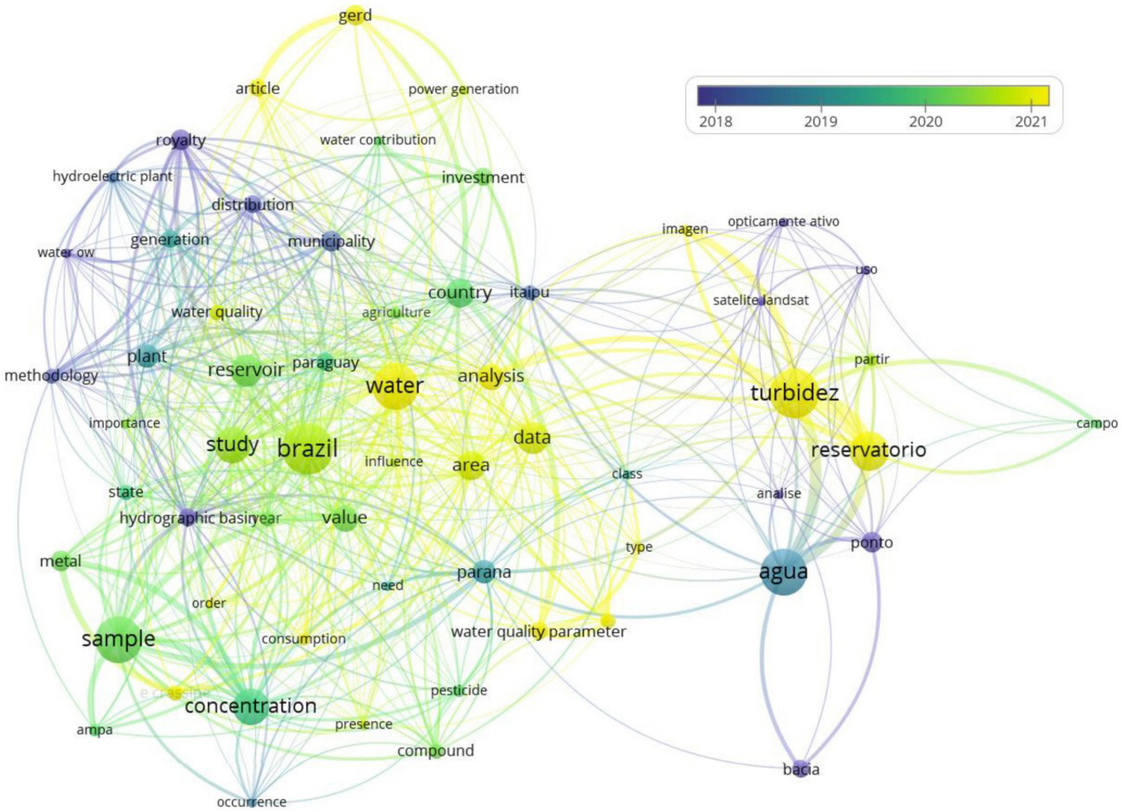

Figure 6 - Most frequent words in the paper's titles and abstracts.
Source: authors.

4.2. Water Quality Studies in the Paraná 3 Basin

Research in the BP encompasses three broad thematic axes: (i) pesticides and chemical contaminants, (ii) legal, institutional, and hydropolitical frameworks, and (iii) monitoring strategies examining microbiological, physicochemical, limnological, and ecological parameters, often complemented by remote sensing or advanced analytical techniques.

4.2.1. Legislative, Treaty-Based, and Policy-Oriented

Studies addressing governance and policy frameworks examine how hydropolitical arrangements shape environmental outcomes in the Itaipu reservoir region. Gwynn (2019) compares the 1973 Itaipu Treaty with contemporary international instruments, such as the 1997 UN Convention on Non-Navigational Watercourses, highlighting opportunities to integrate climate change considerations and environmental safeguards into binational agreements. Berkhout & Warner (2023) find that Brazil holds hegemonic control over water resource decision-making at Itaipu through a combination of normative, utilitarian, and discursive power. Complementing governance analyses, Lorenzon et al. (2017, 2018) propose a royalty-distribution model based on hydrological contributions such as watershed area, flow, and hydraulic head, offering a more equitable basis for financial compensation.

At the municipal scale, the study by (Ferreira et al., 2018) identified water and soil contamination as the most critical environmental issues across 12 municipalities bordering the reservoir, aggravated by insufficient financial and human resources for enforcing sustainability policies. Mussi et al. (2020)

report a stark imbalance in investment allocation: 94.6% of Itaipu's environmental resources are spent in areas supplying only 4% of reservoir inflow, whereas regions responsible for 96% of the water contribution receive just 5.4%. This asymmetry suggests opportunities to realign investment strategies according to hydrological relevance.

4.2.2. Water Quality Assessment

The water quality studies in the Bibliographic Portfolio address four interrelated dimensions: chemical contamination by pesticides and micropollutants, microbiological risks, ecological indicators, and limnological characterization. The following subsections synthesize the evidence along these dimensions and conclude with an assessment of the analytical methods employed across the portfolio.

- **Chemical contamination -** Pesticide occurrence constitutes the most prominent water quality concern documented in the basin. Della-Flora et al. (2019) identified atrazine and its transformation products across multiple sampling sites in the Paraná 3 watershed, including unregulated metabolites detected at low concentrations but with recognized ecological relevance. Mendonça et al. (2020) detected glyphosate in 19.3% and AMPA in 21.8% of 124 surface-water samples, with higher concentrations following rainfall events. These findings confirm surface runoff as the dominant contamination pathway. In addition to pesticides, microcystin concentrations represent an ongoing concern. Miguel et al. (2018) reported higher microcystin levels in the Paraná 3 Basin compared to the Tibagi Basin, linking contamination to fertilizer input, organic runoff, and hydropower-related environmental alterations. Although a declining trend was observed in 2014, the study underscores the need for continuous cyanotoxin monitoring.
- **Microbiological risks -** Scherer et al. (2022) analyzed 60 samples from raw, treated, and school-distribution water sources in Foz do Iguaçu, detecting Giardia, Cryptosporidium, and multidrug-resistant bacteria in samples classified as potable. These findings highlight persistent vulnerabilities in water treatment systems and the associated health risks, particularly for children.
- **Ecological indicators -** Bioindicator-based assessments reveal greater sensitivity to anthropogenic impacts than physicochemical metrics alone. Schiller et al. (2017) observed higher biodiversity in rural streams and a dominance of pollution-tolerant Chironomidae in urban watercourses. Macrophytes such as Eichhornia crassipes and Egeria densa demonstrate substantial metal-accumulation capacity (Marengoni & Chambo, 2021), while analyses of Pterodoras granulosus tissues indicated Mg and Zn concentrations below toxicity thresholds, suggesting adequate baseline environmental quality in reservoir fish (Oliveira et al., 2014). From an ecosystem-services perspective, Mussi et al. (2021) demonstrated that no-till farming reduces erosion to 1.7 tons per hectare per year and may avoid up to US$ 205.66 million annually in reservoir maintenance costs, reinforcing the cost-effectiveness of sustainable agricultural practices in the basin.
- **Limnological characterization and remote sensing -** Limnological assessments consistently classify the Itaipu Reservoir as ultra-oligotrophic (TSI = 39.41), with spatial gradients in chlorophyll-a, turbidity, and nutrient concentrations (Souza et al., 2019). Water Quality Index results for the Ocoí River range from "Good" to "Acceptable," with thermotolerant coliforms identified as the primary limiting factor (Costa et al., 2015). Spectral analyses by Buffon (2016) reveal marked differences between the Passo Cuê and São Francisco Verdadeiro compartments, with higher suspended solids and chlorophyll concentrations upstream. Remote sensing applications further extend monitoring capabilities: Dezordi (2020) demonstrated that turbidity dynamics in the São Francisco Verdadeiro River respond strongly to rainfall and reservoir level, and that Landsat 8 imagery provides reliable estimates of turbidity variation. A transboundary comparison by (Ouchi-Melo et al., 2021) indicated higher pH, conductivity, and nutrient concentrations in Brazilian streams, and higher turbidity and dissolved oxygen in Paraguayan streams, with urbanization exerting localized influence on water quality.
- **Analytical methods across the portfolio -** Figure 7 synthesizes the analytical approaches documented across the 26 studies. Multiparameter water quality indices were the most frequently employed method (8 studies, 31%), followed by colorimetric and spectrophotometric techniques including remote sensing-based approaches (6 studies, 23%), bioassay and bioindicator methods (5 studies, 19%), and metal-targeted techniques such as ICP-MS and atomic absorption spectrometry (4 studies, 15%). Notably, chromatographic and mass spectrometric platforms designed for organic micropollutant screening, including LC-QTOF MS, LC-MS/MS, GC-MS, and HPLC-UV/DAD, each appeared in no more than two studies

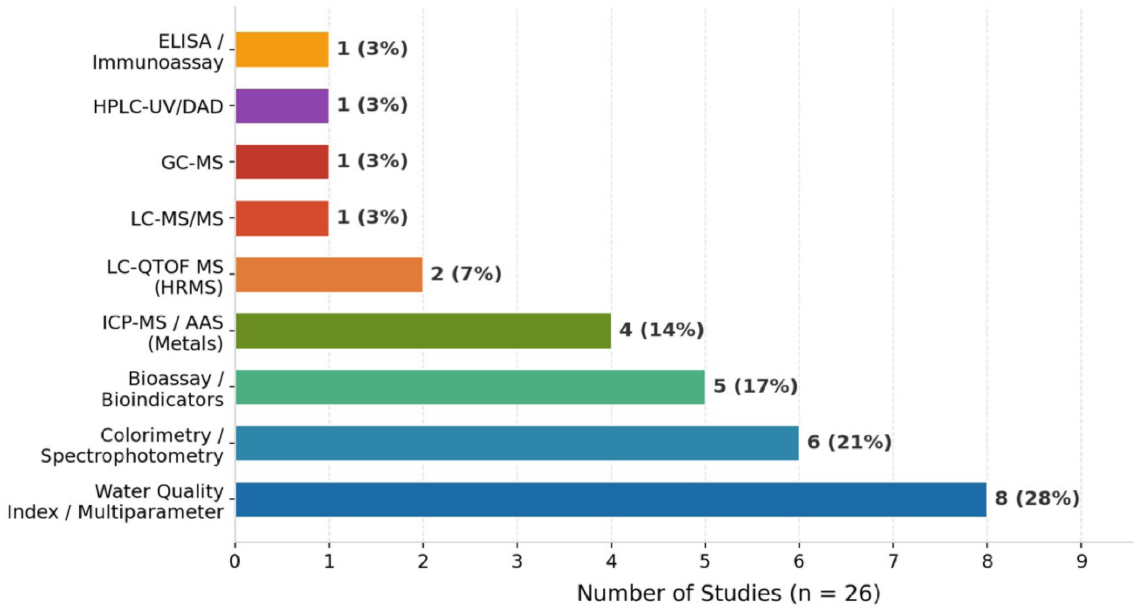

Figure 7 - Analytical methods reported across the 26 portfolio studies.
Source: authors.

This distribution reveals a significant analytical asymmetry: although pesticide contamination is the central concern of this review, targeted confirmatory methods for organic micropollutants remain underrepresented in the regional portfolio. The predominance of multiparameter indices and colorimetric monitoring, while valuable for broad-spectrum surveillance, is insufficient for robust water quality management and for adequately characterizing the temporal dynamics and mixture complexity of agrochemical residues. Strengthening the regional analytical infrastructure through the systematic adoption of validated LC-MS/MS or HRMS protocols constitutes a critical methodological priority for future monitoring programs.

Across all dimensions, recurrent contamination by pesticides, nutrients, microorganisms, trace metals, and cyanotoxins underscores the combined influence of agricultural intensity, rainfall seasonality, and land-use patterns on water quality in the Paraná 3 Basin. Advanced monitoring initiatives, including the Hidrosfera project (Itaipu Parquetec, 2025), the Itaipu–Parquetec–UNILA micropollutant monitoring program (Itaipu Binacional, 2024a), and ongoing institutional environmental monitoring efforts (Itaipu Binacional, 2024b), contribute essential datasets that complement academic research, as exemplified by Gabardo's (2023) geostatistical analysis of groundwater contamination patterns.

4.3. Machine Learning and Data Mining

Although conceptually underrepresented in titles and keywords (Figure 6), machine learning (ML) and data mining (DM) approaches (Russell & Norvig, 2016) appear in several studies and demonstrate substantial potential for environmental diagnosis and prediction.

In pesticide-related analyses, (Becker et al., 2021) screened 1,607 compounds, detected 43 pesticides, and confirmed 11 using LC-QTOF MS. PCA and hierarchical clustering revealed distinct contamination patterns associated with agricultural land use, while forested areas exhibited lower pesticide levels. Similar multivariate insights appear in (Junior et al., 2018), who a PCA to identify correlations between metal concentrations (Cu, Cr, Pb, Zn, Ni) and sediment parameters (pH, clay content, organic matter), linking contamination to agricultural and livestock activity.

Predictive models also emerge in ecological studies. (Silva et al., 2022) developed an ANN-GA model to estimate phytoplankton density based on physicochemical variables, showing that nitrate and ammoniacal nitrogen increase phytoplankton biomass, while COD exerts a nonlinear effect. The model achieves its best performance with two hidden layers (5 and 10 neurons), demonstrating the value of ML for forecasting ecological dynamics.

Remote sensing studies incorporate ML for classification and regression tasks. (Facco, 2023) applies Random Forest, CART, and Naive Bayes to Landsat, Sentinel-1/2, and Jason-3 datasets, finding that the GEOBIA + Random Forest approach provided the highest accuracy (R^2 = 0.91 for NDTI-based turbidity estimation). These methods reduce dependence on field sampling and improve the temporal resolution of water quality monitoring. ML approaches also support climate-related analyses. Freitas et al. (2024) employed ML tools with SPI-6 to detect extreme precipitation events from 1980 to 2022, identifying decreasing rainfall extremes and increasing drought frequency, with reliable detection of major events such as the 2014 floods and 2020–2021 droughts.

Overall, ML and DM studies reveal complex relationships between land use, contamination, and hydrological variability, while offering predictive capabilities to support data-driven decision-making and integrated basin management. Their limited representation in broader literature suggests substantial opportunities for future expansion. Despite these promising applications, a systematic synthesis of the maturity and diversity of data-driven approaches remains necessary.

Figure 8 provides a synthesis of machine learning (ML) and data science (DS) across the 26 studies included in the Bibliographic Portfolio. Panel A shows that only 5 studies (19.2%) explicitly applied ML or DS techniques within their analytical framework, whereas 21 studies (80.8%) relied exclusively on conventional statistical, physicochemical, or descriptive approaches. This limited adoption indicates that data-driven methos remain incipient in the regional literature and are not yet consolidated within the dominant conceptual framework of the field (Figure 7). Panel B details the analytical techniques employed among ML/DS-based studies. Principal Component Analysis (PCA) was the most frequently employed technique, appearing in three studies (60% of ML studies), mainly for identifying contamination gradients and correlating chemical or physical variables with land-use patterns. The remaining approaches, including Artificial Neural Networks (ANN), Random Forest, Hierarchical Clustering, and Geographic Object-Based Image Analysis (GEOBIA) combined with remote sensing, each appeared in 1 study (20% of ML/DS studies).

Figure 8 - Machine learning and data science applications in the Bibliographic Portfolio. (A) Proportion of studies with and without ML/DS approaches. (B) Distribution of ML/DS techniques among the selected studies.
Source: authors.

Notably, one study (Alegre/Facco) combined three methods simultaneously (Random Forest, Naive Bayes, and GEOBIA), achieving the highest model accuracy (R^2 = 0.91) for turbidity estimation from satellite imagery. The predominance of PCA, a dimensionality-reduction technique rather than a predictive model, suggests that the field has not yet advanced beyond exploratory multivariate analysis toward operational forecasting or risk prediction. The near-absence of deep learning, ensemble methods, or spatially explicit predictive models represents a significant methodological gap. Pesticide transport dynamics are governed by nonlinear interactions between precipitation, land use, and hydrological connectivity in the Paraná 3 Basin. These findings reinforce the urgent need to transition from exploratory statistical approaches to operational decision-support systems for water resources management.

4.4. Classification of Studies

Table 3 shows a classification of BP studies according to eight analytical scopes. The results show that 84.6% of publications address water quality, confirming the centrality of this theme. Climate and precipitation analyses (38.5%) and legislation or management studies (38.5%) appear moderately, while investment assessments represent 26.9%. Machine learning applications occur in only 19.2% of studies, and analyses focused on pesticides appear in 11.5%, despite their demonstrated environmental relevance. Comparisons between hydropower plants (15.4%) and studies on aquaculture or aquatic organisms (11.5%) remain limited.

Table 3 - Research papers scope in the 26 studies of Bibliographic Portfolio (BP).

Study	Water Quality Analysis	Precipitation or Climate Analysis	Legislation or Management Analysis	Investment Analysis	Machine Learning Analysis	Pesticide Analysis	Power Plant Comparisons	Aquaculture or Aquatic Life Analysis
(Becker et al., 2021)	☑	☑	☑		☑	☑		
(Lorenzon et al., 2017)	☑	☑	☑	☑				
(Freitas et al., 2024)	☑	☑			☑		☑	
(Miguel et al., 2018)	☑	☑					☑	
(Della-Flora et al., 2019)	☑	☑				☑		
(Mendonça et al., 2020)	☑	☑				☑		
(Morsy et al., 2021)	☑		☑	☑				
(Mussi et al., 2020)	☑		☑	☑				
(Marengoni & Chambo, 2021)	☑	☑						☑
(Ferreira et al., 2018)	☑		☑	☑				
(Masulli & Taboada, 2023)	☑	☑					☑	
(Mussi et al., 2021)	☑		☑	☑				
(Facco 2023)	☑	☑			☑			
(Ouchi-Melo et al., 2021)	☑		☑					
(Gwynn, 2019)			☑				☑	
(Lorenzon et al., 2017)			☑	☑				
(Schiller et al., 2017)	☑							☑
(Junior et al., 2018)	☑				☑			
(Berkhout & Warner 2023)			☑	☑				
(Costa et al., 2015)	☑	☑						
(Silva et al., 2022)	☑				☑			
(Souza et al., 2019)	☑							
(Scherer et al., 2022)	☑							
(Buffon, 2016)	☑							
(Dezordi, 2020)	☑							
(Oliveira et al., 2014)								☑
Percentage (%)	**84.6**	**38.5**	**38.5**	**26.9**	**19.2**	**11.5**	**15.4**	**11.5**

Source: authors.

No studies were found that directly examine the correlation between pesticide application, rainfall seasonality, and surface runoff. While existing literature addresses the presence of atrazine, glyphosate, and their metabolites, comprehensive analyses of their spatiotemporal dynamics remain limited, particularly concerning impacts on public health and ecosystems. Consequently, critical issues such as the mechanistic relationship between precipitation and contaminant transport, comparative evaluations between Brazil and Paraguay, ecotoxicological effects, and predictive modeling remain underexplored. Furthermore, the scarcity of structured, interoperable datasets constrains the adoption of advanced analytical approaches, limiting the capacity to anticipate environmental degradation and to support evidence-based public policies.

4.5. Research Gaps and Synthesis

The studies related to the Paraná 3 Basin reveal significant thematic diversity, with a predominance of studies focused on water quality assessment, transboundary governance, and environmental management. Investigations into legal frameworks and binational agreements, such as the Itaipu Treaty, show progress in integrating international law with environmental policies, suggesting improvements in royalty distribution and territorial planning. Despite these advancements, notable gaps were observed.

A quantitative synthesis of research gaps explicitly or implicitly identified across the 26 portfolio studies is presented in Figure 9. The most frequently cited limitation was the lack of effective binational integration and regulatory harmonization between Brazil and Paraguay, referenced in 10 studies (38%), underscoring the persistent institutional fragmentation that constrains transboundary water management and integrated basin governance. Insufficient hydrological data and inadequate representation of land-use dynamics each appeared in 8 studies (31%). The absence of structured, georeferenced, and temporally resolved datasets severely limits the capacity to model contamination pathways and attribute pollution sources. The lack of continuous long-term monitoring programs was identified in 6 studies (23%), highlighting the difficulty in generating longitudinal datasets capable of capturing seasonal variability, delayed contamination effects, and climate-driven hydrological changes. Additional limitations associated with emerging contaminants and ecotoxicological complexity were reported in 4 studies (15%). These gaps include pharmaceuticals and endocrine-disrupting compounds, sediment contamination assessment, and mixture toxicity or synergistic effects. Collectively, these limitations reveal limited incorporation of advanced ecotoxicological approaches in current basin-scale assessments.

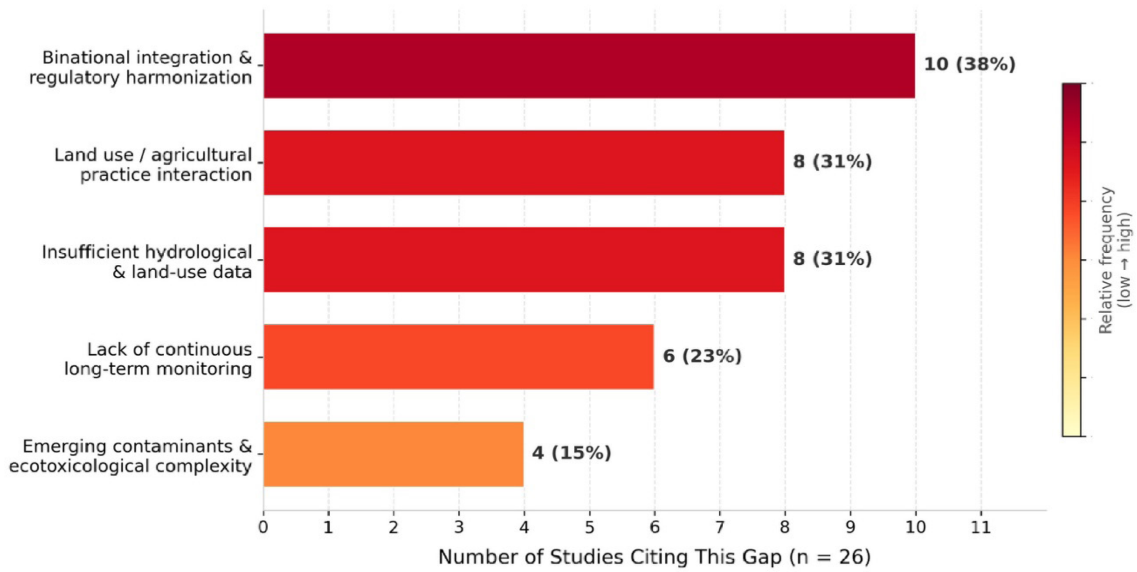

Figure 9 - Frequency of research gaps identified.
Source: authors.

Transboundary watersheds present substantial challenges for environmental management due to differences in legislation, monitoring strategies, and water quality standards adopted by neighboring countries. In the Paraná 3 Basin, these challenges are intensified by the strategic importance of the Itaipu reservoir and intensive agricultural activities occurring on both the Brazilian and Paraguayan sides of the watershed. In this context, regulatory asymmetries related to pesticide control and water quality thresholds may hinder integrated monitoring efforts and coordinated decision-making processes. To contextualize these differences, Table 4 compares the main water quality standards and pesticide-related parameters established by the Brazilian CONAMA 357/2005 (Brasil, 2005) and the Paraguayan SEAM Resolution 222/02 (SEAM, 2002).

Table 4 – Comparison of water quality standards established by CONAMA 357/2005 (Brazil) and SEAM Resolution 222/02 (Paraguay).

Parameter	Unit	Brazil – CONAMA Resolution 357/2005 Class 2	Paraguay – SEAM Resolution 222/02 Class 2	Observation
Atrazine (ATZ)	μg/L	< 2	< 3	Toxic to aquatic fauna and flora and characterized by environmental persistence
Chloride	μg/L	250	250	Indicates the presence of dissolved salts, which may originate from urban runoff
Fluoride	μg/L	1,4	Not specified	High concentrations may be toxic to aquatic organisms
Total phosphorus	mg/L	< 0.1	< 0.05	Elevated phosphorus levels increase the risk of algal blooms
Nitrate	μg/L	10	10	High levels indicate organic pollution
Nitrite	μg/L	1	1	Elevated levels indicate pollution
Dissolved oxygen (DO)	mg/L	≥ 6	≥ 6	Critically important for the survival of aerobic organisms. Low levels indicate organic pollution or eutrophication
pH	—	6 – 9	6 – 9	Ensures chemical and biological stability essential for aquatic life
Potassium	mg/L	< 12	Not specified	Excess concentrations may indicate agricultural pollution
Total dissolved solids (TDS)	g/L	0.5	0.5	Represents the amount of dissolved matter in water. High levels may indicate pollution or affect human health
Sulfate	μg/L	< 250,000	< 250,000	Elevated levels may be toxic and cause corrosion
Turbidity	NTU	< 100	< 100	Related to the presence of suspended particles. High turbidity may reduce light penetration, affecting photosynthesis and indicating pollution

The comparison presented in Table 4 reveals important regulatory inconsistencies between the two countries sharing the basin. Atrazine illustrates a significant asymmetry, as the Brazilian Class 2 threshold (< 2 μg/L) is more restrictive than the Paraguayan limit (< 3 μg/L), resulting in different compliance criteria within the same transboundary watershed. Additionally, neither regulatory framework establishes explicit Class 2 limits for glyphosate, AMPA, or atrazine transformation products, despite their recurrent detection in the reviewed studies and their recognized environmental relevance. Differences are also observed for parameters such as total phosphorus, fluoride, and potassium, which may compromise harmonized assessments of water quality conditions across the basin. These observations indicate that current regulatory frameworks remain insufficient to fully characterize the complexity of pesticide contamination in the Paraná 3 Basin. Consequently, the harmonization of monitoring protocols, contaminant thresholds, and reporting procedures emerges as a fundamental requirement for integrated and evidence-based transboundary water governance.

Sediment contamination assessment and mixture toxicity evaluation were each cited in a single study, despite their recognized relevance in agricultural watersheds exposed to multi-compound runoff. The convergence of these gaps, particularly the co-occurrence of binational governance deficits, data scarcity, and the absence of integrated ecotoxicological frameworks, indicates that the scientific community has repeatedly encountered the same structural barriers without achieving the inter-institutional coordination necessary to overcome them. This pattern reinforces the need for a systemic research agenda that simultaneously addresses analytical, hydrological, regulatory, and ecological dimensions of pesticide contamination in shared water resources. These findings indicate that the observed scientific gaps are not isolated limitations but persistent structural constraints recurrently acknowledged throughout the literature.

The scientific coverage of the Paraná 3 Basin relative to global and broader-context research is illustrated in Figure 10. Of the 26 studies selected through the ProKnow-C methodology, 23 (88.5%) address water quality, pesticide contamination, governance, or hydrological dynamics in broader national, regional, or international contexts, while only 3 studies (11.5%) are directly and specifically focused on pesticide water analysis in the Paraná 3 Basin itself. This disproportion, a 20-study gap between global evidence and locally grounded research, constitutes the most significant structural finding of this systematic review. It confirms that despite the basin's strategic relevance as a transboundary agricultural watershed supplying a major hydroelectric reservoir shared by two countries, targeted scientific inquiry remains critically scarce.

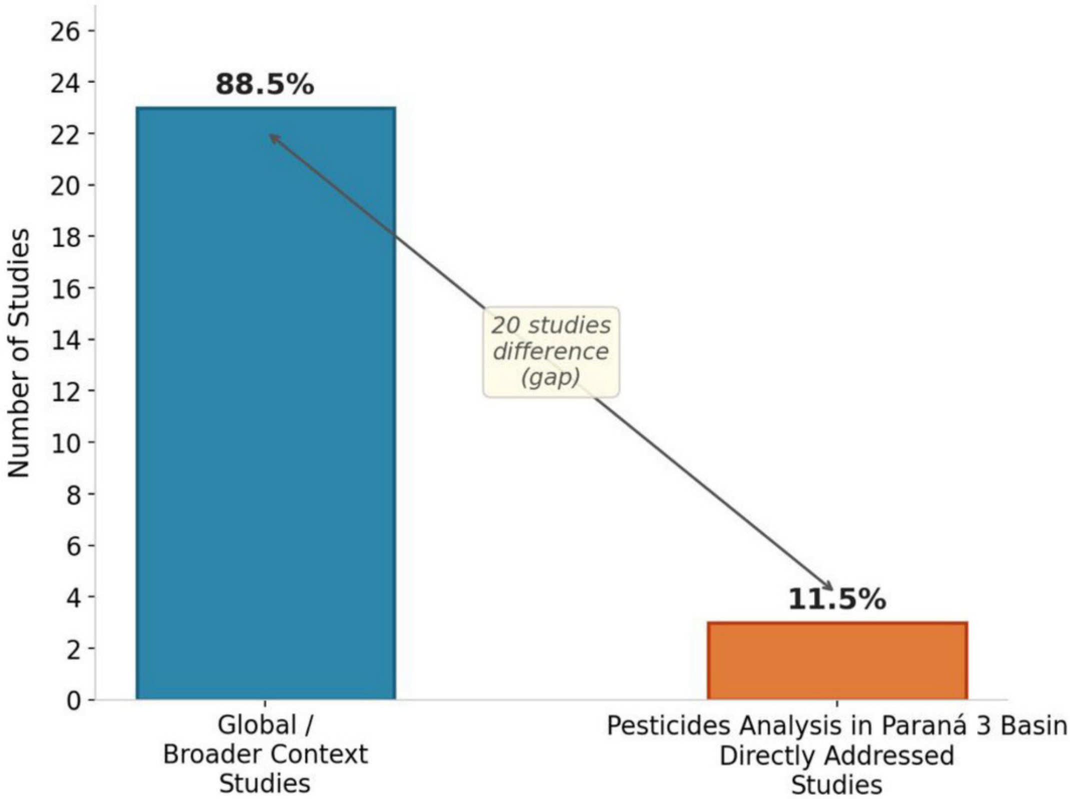

Figure 10 - Global studies vs. pesticides analysis studies in Paraná 3 Basin scientific coverage.
Source: authors.

The three specific studies addressing pesticide analysis and contamination in the Paraná 3 Basin, while substantive in scope, are insufficient to characterize the spatial heterogeneity of contamination, establish baseline conditions across tributary sub-basins, or support evidence-based decision-making and the development of empirically calibrated management tools. This gap also limits the transferability of global findings to local management decisions, as pesticide dynamics are highly sensitive to regional hydrological regimes, soil characteristics, land-use intensities, and climatic drivers. Closing this scientific deficit requires not only increased funding for basin-specific field campaigns but also coordinated bilateral research programs capable of generating the standardized, longitudinal datasets necessary for evidence-based water governance. This structural gap also contributes to the limited development of predictive models and integrated environmental management strategies.

The classification presented in Table 3, together with the gap analysis in Figure 9, confirms that the Bibliographic Portfolio encompasses an interdisciplinary yet fragmented body of research. Key issues, including the interplay between pesticide application and rainfall-driven transport, binational regulatory harmonization, ecotoxicological risk characterization, and operational predictive modeling, remain insufficiently addressed. The following section synthesizes these findings and outlines their implications for future research and environmental governance.

Table 5 consolidates the principal findings, bibliometric conclusions, and emergent research needs identified across the 26 studies comprising the Bibliographic Portfolio. The synthesis is organized along two complementary dimensions: thematic findings derived from the research question guiding this review, and bibliometric patterns observed in the portfolio's publication profile, authorship structure, and indexing coverage.

Table 5 – Synthesis of results, insights, contributions, and recommendations.

Research Question	Findings
How does the existing scientific literature characterize the impacts of pesticide contamination on water quality management in the Paraná 3 Basin, and what are the essential requirements for an integrated transboundary monitoring and governance framework?	➔ The topic is inherently interdisciplinary and has gained increased relevance over the past decade, predominantly addressed through physicochemical water quality assessments. However, studies that jointly integrate climatic variables, legal frameworks, and data-driven techniques remain scarce.
	➔ Four publications stand out for their scientific impact as measured by citation count: Della-Flora et al. (2019), Becker et al. (2021), Mendonça et al. (2020), and Lorenzon et al. (2017). Collectively, these studies advanced analytical methods for pesticide detection, established relationships between land use and contamination patterns, documented glyphosate and AMPA occurrence in the Paraná 3 Basin, and highlighted the role of hydroelectric royalties in water resource management
	➔ More than 80% of the portfolio studies exhibit an interdisciplinary investigative scope, as detailed in Table 3.
	➔ Only 3 (11.5%) of the portfolio studies directly addressed water contamination assessment within the Paraná 3 Basin, while additional limitations associated with emerging contaminants and ecotoxicological complexity were identified in 4 studies (15%).
	➔ Machine learning techniques were identified in 19.2% of the studies, indicating that data-driven approaches are still emerging in the region, likely constrained by the limited availability of publicly accessible and structured datasets for the Paraná 3 Basin.
	➔ Expanding predictive modeling efforts that incorporate precipitation and other environmental drivers would represent a significant methodological advancement, enabling deeper understanding of contamination dynamics and supporting integrated water resources management and transboundary water governance.
Bibliometric Dimension	**Conclusions**
Key studies for water quality management	➔ The four highest-impact studies address pesticide contamination and water resource governance in the Paraná 3 Basin region are (Della-Flora et al., 2019), (Becker et al., 2021), (Mendonça et al., 2020) and (Lorenzon et al., 2017).
Authorship	➔ The portfolio reveals a strong concentration of regional researchers and institutions, with notable interinstitutional collaboration and emphasis on local expertise.
Publication venues	➔ Peer-reviewed journal articles account for 69.2% of the portfolio, confirming journals as the primary dissemination channel for high-rigor research on this topic.
Keywords	➔ The absence of recurring keywords across the portfolio reflects broad thematic dispersion and diversity of research scopes.
Academic databases	➔ Google Scholar retrieved the highest number of relevant studies, outperforming Scopus and SciELO for this subject area.

Source: authors.

Three methodological limitations should be acknowledged. First, the search strategy combined Scopus, SciELO, and Google Scholar but did not include the Web of Science as an independent database. Because Google Scholar indexes a broad range of scientific metadata, including a substantial share of Web of Science-indexed publications, the practical impact on coverage is expected to be limited; nonetheless, the direct inclusion of the Web of Science in future updates of this portfolio could marginally extend coverage of high-impact international studies. Second, the ProKnow-C methodology applies citation counts as one indicator of scientific recognition, which may underrepresent recent studies that have not yet accumulated citations. To mitigate this risk, all candidate studies in Repository P were submitted to abstract-level relevance screening regardless of citation count, ensuring that recent and thematically aligned contributions were retained when relevant. Third, this review synthesizes the available primary literature on pesticide occurrence in the basin but does not generate new ecotoxicological evidence or quantitative ecological risk assessments. The lack of basin-specific water quality datasets, chronic toxicity evaluations, and integrated mixture-toxicity assessments represents one of the major gaps in the regional literature (Figure 9) and highlights the need for dedicated experimental and field-based studies beyond the scope of this review.

5. Conclusions and Future Perspectives

This systematic review constitutes the first integrated synthesis characterizing pesticide contamination, water quality evidence, and structural research gaps in the Paraná 3 Basin region and the Itaipu reservoir area. By applying the ProKnow-C methodology, a Bibliographic Portfolio of 26 studies was assembled, encompassing environmental, climatic, institutional, and technological dimensions that support water quality monitoring and define basin-scale management priorities.

Three principal findings emerge from the analysis and are directly anchored in the evidence presented in Sections 4.2–4.5. First, the recurrent detection of glyphosate and AMPA (Mendonça et al., 2020) and atrazine and its transformation products (Della-Flora et al., 2019), combined with the regulatory asymmetries documented in Table 4, underscores the urgency of dedicated management-oriented research; the fact that only 11.5% of the portfolio addresses pesticide contamination in the Paraná 3 Basin directly (Figure 10) reveals a structural research gap that itself constitutes one of the most relevant scientific findings of this review. Second, data-driven methods, including principal component analysis, artificial neural networks, and random forest classification, appear in five studies (19.2%), but remain confined to exploratory applications; no operationally oriented predictive model for pesticide dynamics in the basin has yet been developed. Third, the review evidences that binational regulatory coordination and the harmonization of monitoring protocols are essential requirements to overcome current structural barriers in transboundary governance.

Beyond the diagnosis, this review identifies clear investment priorities for environmental surveillance. Comparative water-quality assessments between the Brazilian and Paraguayan sides of the reservoir remain scarce, despite documented physicochemical and microbiological differences. Similarly, no study has jointly modeled pesticide occurrence, precipitation variability, and land-use change, an integrated approach considered essential for anticipating contamination events under dynamic agricultural and climatic conditions.

Advancing sustainable water governance in the Paraná 3 Basin will require a transition from fragmented diagnostic efforts. Future initiatives should prioritize spatially resolved, temporally continuous, and binationally coordinated research frameworks. Priority actions include the establishment of standardized bilateral monitoring protocols, the development of open and interoperable environmental databases, and the systematic incorporation of machine learning and remote sensing into contamination forecasting. The integrative framework proposed herein is not restricted to the Paraná 3 Basin. Rather, it provides a replicable methodological template for other transboundary agricultural watersheds confronting analogous pressures worldwide.

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