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GLYPHOSATE (N-(PHOSPHONOMETHYL)GLYCINE) CONCENTRATIONS IN WATER COURSES – SYSTEMATIC REVIEW AND SCIENTOMETRIC ANALYSIS

CONCENTRAÇÕES DE GLIFOSATO (N-(FOSFONOMETIL)GLICINA) EM CURSOS DE ÁGUA – REVISÃO SISTEMÁTICA E ANÁLISE CIENTOMÉTRICA

CONCENTRACIONES DE GLIFOSATO (N-(FOSFONOMETIL)GLICINA) EN CURSOS DE AGUA – REVISIÓN SISTEMÁTICA Y ANÁLISIS CIENCIOMÉTRICO

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ABSTRACT
Glyphosate, which degrades into aminomethylphosphonic acid (AMPA), is the most widely used active ingredient in herbicides worldwide. Both compounds can enter aquatic systems through surface runoff, leaching, spray drift, and irrigation, leading to water contamination and subsequent incorporation into the food chain. This study aimed to perform a systematic review and scientometric analysis of research published between 2015 and 2025 on glyphosate and AMPA concentrations in surface and groundwater, and to compare geographically detected concentrations with national regulatory thresholds. A systematic review was conducted following the PRISMA protocol, complemented by scientometric analysis. Literature searches were performed in the Web of Science, PubMed, ScienceDirect, and SciELO databases. A total of 127 articles reporting glyphosate and AMPA concentrations in surface and groundwater were selected. The countries contributing the largest number of studies were Argentina, Brazil, Canada, the United States, Mexico, and Italy. Scientometric analysis revealed that these nations not only dominate research output but also constitute the most influential co-citation networks, with the most frequently cited study originating from the United States. The highest concentration reported was in Brazil (8,700 µg/L), which is 133 times above the Brazilian regulatory limit (65 µg/L). Statistical analyses further showed that glyphosate concentrations vary significantly by geographic region, with notable differences between Europe and North America. Glyphosate concentrations frequently exceed national maximum permissible limits, even in countries with stringent legislation such as those in Europe, where values surpassed the legal threshold of 0.1 µg/L at multiple sites. These findings underscore the widespread nature of glyphosate contamination and highlight the need for stronger monitoring and regulatory enforcement.

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Keywords: Surface Water. Groundwater. Glyphosate. Contamination. Systematic Review. Scientometrics.

RESUMO
O glifosato, que se degrada em ácido aminometilfosfônico (AMPA), é o ingrediente ativo mais amplamente utilizado em herbicidas em todo o mundo. Ambos os compostos podem entrar em sistemas aquáticos por meio de escoamento superficial, lixiviação, deriva de pulverização e irrigação, levando à contaminação da água e subsequente incorporação na cadeia alimentar. Este estudo teve como objetivo realizar uma revisão sistemática e análise cienciométrica de pesquisas publicadas entre 2015 e 2025 sobre concentrações de glifosato e AMPA em águas superficiais e subterrâneas, e comparar concentrações detectadas geograficamente com limites regulatórios nacionais. Uma revisão sistemática foi conduzida seguindo o protocolo PRISMA, complementada por análise cienciométrica. Buscas bibliográficas foram realizadas nas bases de dados Web of Science, PubMed, ScienceDirect e SciELO. Um total de 127 artigos relatando concentrações de glifosato e AMPA em águas superficiais e subterrâneas foram selecionados. Os países que contribuíram com o maior número de estudos foram Argentina, Brasil, Canadá, Estados Unidos, México e Itália. A análise cienciométrica revelou que essas nações não apenas dominam a produção científica, mas também constituem as redes de cocitação mais influentes, com o estudo mais frequentemente citado originário dos Estados Unidos. A maior concentração relatada foi no Brasil (8.700 µg/L), o que é 133 vezes acima do limite regulatório brasileiro (65 µg/L). As análises estatísticas mostraram ainda que as concentrações de glifosato variam significativamente por região geográfica, com diferenças notáveis entre a Europa e a América do Norte. As concentrações de glifosato frequentemente excedem os limites máximos permitidos nacionais, mesmo em países com legislação rigorosa como os da Europa, onde os valores ultrapassaram o limite legal de 0,1 µg/L em vários locais. Essas descobertas ressaltam a natureza generalizada da contaminação por glifosato e destacam a necessidade de monitoramento e fiscalização regulatória mais rigorosos.

Palavras-chave: Águas Superficiais. Águas Subterrâneas. Glifosato. Contaminação. Revisão Sistemática. Cienciometria.

RESUMEN
El glifosato, que se degrada en ácido aminometilfosfónico (AMPA), es el ingrediente activo más utilizado en herbicidas a nivel mundial. Ambos compuestos pueden ingresar a los sistemas acuáticos a través de la escorrentía superficial, la lixiviación, la deriva de pulverización y el riego, lo que lleva a la contaminación del agua y la posterior incorporación a la cadena alimentaria. Este estudio tuvo como objetivo realizar una revisión sistemática y un análisis cienciométrico de las investigaciones publicadas entre 2015 y 2025 sobre las concentraciones de glifosato y AMPA en aguas superficiales y subterráneas, y comparar las concentraciones detectadas geográficamente con los umbrales regulatorios nacionales. Se realizó una revisión sistemática siguiendo el protocolo PRISMA, complementada con un análisis cienciométrico. Se realizaron búsquedas bibliográficas en las bases de datos Web of Science, PubMed, ScienceDirect y SciELO. Se seleccionó un total de 127 artículos que informaban sobre las concentraciones de glifosato y AMPA en aguas superficiales y subterráneas. Los países que aportaron el mayor número de estudios fueron Argentina, Brasil, Canadá, Estados Unidos, México e Italia. El análisis cienciométrico reveló que estas naciones no solo dominan la producción de investigación, sino que también constituyen las redes de cocitación más influyentes, y el estudio más citado proviene de Estados Unidos. La

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concentración más alta reportada se registró en Brasil (8700 µg/L), 133 veces superior al límite regulatorio brasileño (65 µg/L). Los análisis estadísticos mostraron además que las concentraciones de glifosato varían significativamente según la región geográfica, con diferencias notables entre Europa y Norteamérica. Las concentraciones de glifosato frecuentemente exceden los límites máximos permisibles nacionales, incluso en países con una legislación estricta como los europeos, donde los valores superaron el umbral legal de 0,1 µg/L en múltiples sitios. Estos hallazgos subrayan la naturaleza generalizada de la contaminación por glifosato y resaltan la necesidad de un monitoreo y una aplicación regulatoria más rigurosos.

Palabras clave: Aguas Superficiales. Aguas Subterráneas. Glifosato. Contaminación. Revisión Sistemática. Cienciometría.

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1 INTRODUCTION

Glyphosate (N-(phosphonomethyl)glycine) is one of the most extensively used herbicides worldwide, particularly in agricultural systems where it is applied for weed control and pre-harvest grain desiccation (Bianco *et al.*, 2023; Connolly; Coggins; Koch, 2020). Applied mainly via spraying, glyphosate undergoes degradation largely through microbial activity and plant metabolism, generating aminomethylphosphonic acid (AMPA) as its primary metabolite (Delmonico *et al.*, 2014). Since their introduction to the market in the 1970s (Bianco *et al.*, 2023), glyphosate-based herbicides (GBHs) have become the most widely used class of herbicides globally. Their primary mechanism of action in plants and certain bacteria involves inhibition of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), a key enzyme in the shikimate pathway (Mesnage *et al.*, 2015). Because this pathway is absent in vertebrates, early assumptions suggested that glyphosate posed minimal risk to human health (Marino *et al.*, 2021; Mesnage *et al.*, 2015).

More recent evidence, however, has increasingly challenged this premise, pointing to potential indirect effects associated with long-term exposure. Although humans are not the intended targets, exposure can occur through ingestion of contaminated water (Ruiz-Toledo *et al.*, 2014), occupational contact (Bianco *et al.*, 2023), and dietary intake (Marino *et al.*, 2021). Multiple pathways of surface and groundwater contamination have also been documented, including heavy rainfall (Rodrigues *et al.*, 2019), spray drift (Aranha *et al.*, 2023), agricultural runoff (Aranha *et al.*, 2023), and leaching (Gunarathna *et al.*, 2018).

A broad spectrum of adverse health outcomes has been associated with human exposure to glyphosate and its metabolites, including endocrine disruption (Curwin *et al.*, 2006), oxidative stress, carcinogenicity (Bukowska *et al.*, 2022), chromosomal damage (De Souza *et al.*, 2020), type 2 diabetes mellitus (Pandey; Dabhade; Kumarasamy, 2019), inhibition of acetylcholinesterase (AChE) activity (Larsen *et al.*, 2016), as well as cardiometabolic and hepatic disorders (Bukowska *et al.*, 2022; Curwin *et al.*, 2006; De Souza *et al.*, 2020; Eskenazi *et al.*, 2023; Larsen *et al.*, 2016; Pandey; Dabhade; Kumarasamy, 2019). In 2015, the International Agency for Research on Cancer (IARC) classified glyphosate as a probable human carcinogen (Group 2A). However, in 2016, both the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) re-evaluated this designation and ultimately removed glyphosate from Group 2A, citing insufficient conclusive evidence (Mendonça *et al.*, 2020; Van Bruggen *et al.*, 2018).

Divergent perspectives regarding human health risks, combined with the continued growth in glyphosate usage, have led several countries — including Italy, Canada, Spain, and Portugal — to impose bans on this herbicide (Brovini *et al.*, 2021). Nevertheless, recent studies have reported elevated concentrations of glyphosate and its primary metabolite AMPA in water bodies even within countries enforcing restrictions, such as Italy (Feltracco *et al.*, 2022b; Gomarasca *et al.*, 2024) and Canada (Brown; Farenhorst, 2024; Edge *et al.*, 2023; Montiel-León *et al.*, 2019). These findings highlight both the environmental persistence of glyphosate and the limitations of regulatory measures in effectively mitigating aquatic contamination.

The contamination of water resources by glyphosate and AMPA has thus emerged as a globally relevant issue, requiring systematic assessment to elucidate its extent as well as research trends. In this context, scientometric and spatial analyses serve as strategic approaches for mapping the state of scientific production, identifying geographic and thematic gaps, and guiding future research agendas (de Castilhos Ghisi *et al.*, 2020). Accordingly, the present review pursues two main objectives: I. To analyze spatial patterns of glyphosate and AMPA contamination by: a) mapping the geographic distribution of concentrations through manual data extraction and compiling comparative tables of minimum and maximum values by country; and b) comparing detected concentrations with the prevailing national regulatory thresholds. II. To evaluate global scientific production on glyphosate and AMPA contamination in aquatic environments through scientometric analysis, focusing on: a) the evolution of publications and citations; b) the most frequently cited authors; and c) the most influential publications.

2 MATERIALS AND METHODS

a) Scope of Analysis:

The systematic review was conducted in accordance with the PRISMA protocol (Swartz, 2011), We assembled peer-reviewed articles reporting glyphosate and/or AMPA concentrations in groundwater (artesian and deep wells) and surface waters (rivers, lakes, and streams), published between 2015 and 2025 in English or Portuguese. Searches were performed in SciELO, ScienceDirect, Web of Science, and PubMed databases using predefined Boolean strings in both English and Portuguese. Examples of queries in English included Glyphosate OR AMPA AND surface water and Glyphosate OR AMPA AND

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groundwater. Equivalent terms were applied in Portuguese (e.g., Glifosato OR AMPA AND água subterrânea).

b) Eligibility Criteria:

Studies were included if they: (i) reported glyphosate and/or AMPA concentrations in groundwater or surface waters; (ii) described the study environment and analytical methods; (iii) were peer-reviewed journal articles published in English or Portuguese; and (iv) fell within the 2015–2025 timeframe. Exclusion criteria comprised: review/meta-analysis articles, retracted papers, methodological validation studies, experimental model studies (e.g., animals, microcosms), studies lacking concentration data (only frequency), or reporting concentrations solely in graphical format.

c) Data Extraction and Systematic Review:

After duplicate removal (RStudio, v.4.3.3), titles, abstracts, and full texts were screened against inclusion criteria. Eligible studies were catalogued in Microsoft Excel (2010, Office 14). Extracted information included: (i) authorship and year; (ii) country, region, or waterbody; (iii) analytical method used; (iv) evaluated compounds; and (v) minimum and maximum concentrations. Data extraction served two purposes: (a) mapping global distributions of reported concentrations, and (b) comparing observed levels with national regulatory thresholds.

d) Statistical Analysis

Statistical analyses were conducted in IBM SPSS Statistics (v.31.0.0.0). Data were stratified by major categories identified in the literature. According to distribution, parametric or non-parametric tests were applied. The Kruskal–Wallis test with Tukey post-hoc was used for group comparisons. Significance was set at $p < 0.05$. Outliers were screened using the boxplot method but retained in analyses.

e) Scientometric Analysis:

Selected bibliographic records (full text and cited references) were exported in plain text format (“download_XXX.txt”) and processed individually for each database. Scientometric analysis was performed using CiteSpace (v.6.3.R1), a Java-based platform for knowledge domain visualization (Zhou *et al.*, 2023). CiteSpace was employed to build:

Collaboration networks (authors, institutions, countries); Journal co-citation maps; Keyword co-occurrence networks; Temporal evolution of research hotspots. Node size represented frequency or citation count, while node color indicated temporal citation activity (Lin *et al.*, 2022). Time slicing was set from January 2015 to December 2025, selecting the top 20–50 most cited records per slice. The software shows the results in map form, the nodes indicate the search items and links between nodes describe quotes or mutual references between nodes. Rings are formed with different colors representing each node; the colors represent the chronological order of occurrence of links and items (de Castilhos Ghisi *et al.*, 2020). The blue color represents older articles, while the newer articles are orange, containing an outer purple ring that indicates good centrality (or yellow circles). Centrality is defined in the **(1).**

$$Centrality\ (node\ i) = \sum i \neq j \neq k \frac{Pjk(i)}{Pjk} \qquad \textbf{(1)}$$

In **(1)**, *pjk* represents the number of shortest paths between node *j* and node *k*, and *pjk (i)* is the number of these paths passing through node *i*. The analysis of bibliographic coupling was also used. The indicator used to evaluate the grouping is the coefficient of silhouette (Li et al., 2017), defined in the Eq. **(2).**

$$S(i)\begin{cases} 1 - a(i)/b(i),\ if\ a(i) < b(i), \\ 0, \quad if\ a(i) = b(i), \\ b(i)/a(i) - 1,\ if\ a(i) > b(i) \end{cases} \qquad \textbf{(2)}$$

In equation **(2)**, *DS*, *a(i)* corresponds to the average distance of *i* from all other data within the same cluster, *b(i*) s the smallest average distance of *i* from any other cluster of which *i* is not a member, and *s(i)* is the coefficient of silhouette and has interval [-1,1], given in Eq. **(3).**

$$-1 \leq s(i) \leq 1 \qquad \textbf{(3)}$$

Additionally, QGIS (v.3.34.3) was used to generate cartographic visualizations of the global distribution of studies, enabling the integration of scientometric and spatial perspectives.

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3 RESULTS AND DISCUSSION

The review revealed that the highest glyphosate concentrations were detected in South American and North American countries, with Brazil reporting the maximum concentration — 8,700 µg/L, equivalent to 133 times above the national regulatory limit (65 µg/L). This result underscores a marked discrepancy between environmental contamination levels and legal thresholds, suggesting shortcomings in both monitoring practices and regulatory enforcement of agricultural herbicide use.

The scientometric analysis demonstrated a progressive growth in publications addressing glyphosate and AMPA dissipation across environmental matrices, particularly in the last decade. A parallel trend was observed for studies examining toxicological risks to human health (Zhang *et al.*, 2022), including endocrine disruption, oxidative stress (Bukowska *et al.*, 2022), and chronic disease outcomes , reflecting the increasing societal and scientific concern surrounding these compounds.

The initial bibliographic search retrieved 87,036 records across the selected databases: 50,127 from Web of Science, 35,907 from ScienceDirect, 973 from PubMed, and 29 from SciELO **(Fig. 1)**. After duplicate removal, 16,210 unique entries remained. Non-relevant publications — such as studies focused solely on environmental risk assessments, toxicological experiments using animal models, or unrelated subject areas — were excluded. Ultimately, 127 articles met the inclusion criteria and formed the analytical dataset. This substantial reduction from initial retrieval to final inclusion highlights the fragmentation of the scientific literature, with a large portion addressing glyphosate-related themes without directly quantifying residues in aquatic environments. The final dataset, therefore, represents a highly specific but globally relevant corpus of research, suitable for comparative analysis of geographic contamination patterns and aligned evaluation with national regulatory standards.

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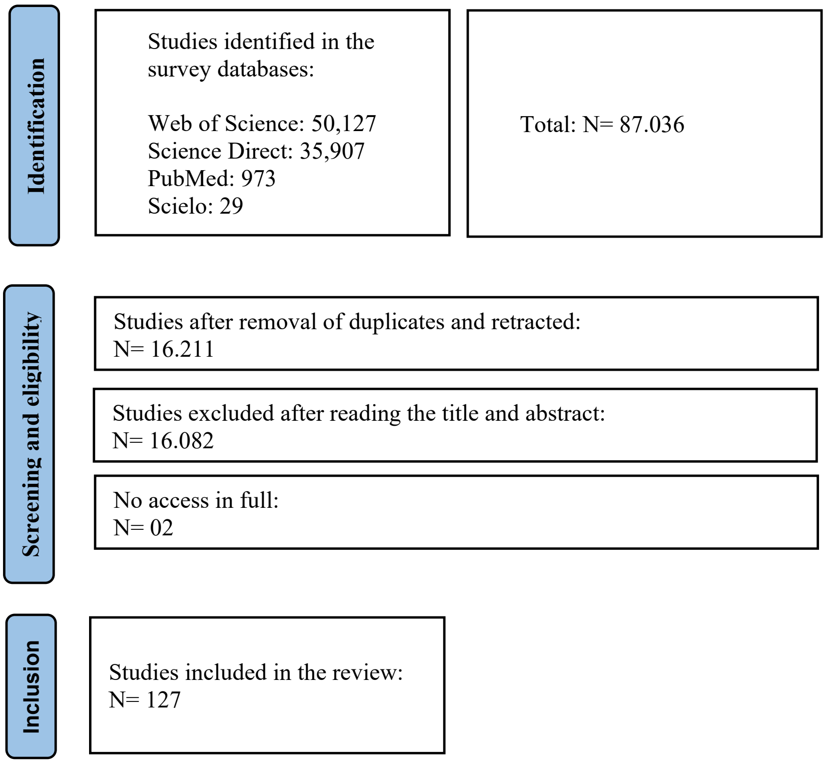
Figure 1

Systematic review diagram of glyphosate concentrations in waters worldwide. Figure adapted from the methodology PRISMA. (Swartz, 2011)



3.1 DESCRIPTIVE/SYSTEMATIC DATA ANALYSIS

3.1.1 Occurrence of Gly and AMPA in waters worldwide

The 127 studies included in this review were distributed across 35 countries, with the largest research outputs originating from Argentina (23 articles), Brazil (17), Canada (12), the United States (7), Mexico (6), and Italy (6) **(Fig 2; Table 1).** Argentina, Brazil, and the United States together account for 82% of global soybean production, a crop that relies heavily on glyphosate for weed management and pre-harvest desiccation. These countries are also characterized by comparatively less stringent regulatory frameworks, which, along with intensive agricultural practices, help explain both their extensive glyphosate usage and higher research activity in this area (Brovini *et al.*, 2021; Connolly; Coggins; Koch, 2020). Brazil represents a central case: in 2023, national records reported sales of 253,302 tons of glyphosate and its derivatives (IBAMA, 2023). This intensive use has been paralleled by a

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marked increase in studies evaluating glyphosate and AMPA concentrations in surface and groundwater, reflecting growing environmental and regulatory concerns within the country.

In the Asia-Pacific region, countries such as China and India are among the world's largest consumers of glyphosate (Richmond, 2018). Yet, our review identified only four studies in China, one in Malaysia, and two in Thailand **(Fig. 2)**, highlighting a clear mismatch between glyphosate consumption and environmental monitoring efforts.

In contrast, Europe emerged as the second-largest hub of scientific production on glyphosate contamination in waters, following the Americas **(Fig. 2; Fig 3).** Within the European Union, glyphosate usage has fluctuated considerably due to regulatory uncertainties and debates regarding its risk categorization (Richmond, 2018). These controversies have led several member states to adopt precautionary restrictions on glyphosate and glyphosate-based herbicides (Marino et al., 2021), which may partly account for the comparatively high number of monitoring studies conducted across Europe.

Table 1

Maximum and minimum concentrations found of glyphosate and the metabolite AMPA in surface and groundwater

Nº	Min-Max (AMPA)	Min-Max (Gly)	Country	Site	Guideline (µg/L)	References
1	N.M.	<LOD-0,42 µg/L	South África	Surface water	-	(Horn et al. 2019)
2	0,03-0,21 µg/L	0,03-0,90 µg/L	Germany	Surface water	0,1	(Tauchnitz *et al.*, 2020)
3	62,1-2633ng/L	11,2-106ng/L	Germany	Surface water	0,1	(Wirth et al. 2021)
4	0,2-6,5 µg/L	0,6-21,2 µg/L	Argentina	Suface water; Groundwater	240	(Demonte *et al.*, 2018)
5	0,75-42 µg/L	0,50-97 µg/L	Argentina	Surface water	240	(Alonso *et al.*, 2018)
6	0,44-69,90 µg/L	0,48-3,01 µg/L	Argentina	Groundwater	240	(Giacobone *et al.*, 2023)
7	0,7-49,4 µg/L	0,2-167,4 µg/L	Argentina	Surface water	240	(Lutri *et al.*, 2020)
8	0,77-0,90 µg/L	1,25-4,52 µg/L	Argentina	Surface water	240	(Berman *et al.*, 2018)
9	N.D.-0,5 µg/L	N.D.	Argentina	Surface water	240	(Lupi *et al.*, 2015)
10	0,100-2,600 µg/L	0,100-20,50 µg/L	Argentina	Groundwater	240	(Aparicio; Gerónimo, 2024)
11	2,3-233 µg/L	4,54-111 µg/L	Argentina	Suface water; Groundwater	240	(Vera-Candioti *et al.*, 2021b)
12	0,2-5,1 µg/L	0,1-35 µg/L	Argentina	Surface water	240	(Mas *et al.*, 2020)
13	0,32-2,00 µg/L	0,78-2,90 µg/L	Argentina	Surface water	240	(Pérez *et al.*, 2017)

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14	N.D.-5 µg/L	N.D.-19 µg/L	Argentina	Surface water	240	(Van Opstal *et al.*, 2023)
15	N.D. 4,8 µg/L	N.D.-125 µg/L	Argentina	Surface water	240	(Bonansea *et al.*, 2017)
16	N.D.	0,4-1,2 µg/L	Argentina	Surface water	240	(Ronco *et al.*, 2016)
17	0-0,10µg/L	0-1,7µg/L	Argentina	Surface water	240	(Jesabel Perez *et al.*, 2017)
18	0,2-4,5µg/L	0,2-17µg/L	Argentina	Surface water	240	(Mac Loughlin *et al.*, 2020)
19	N.D.-2,13µg/L	N.D.-7,62µg/L	Argentina	Surface water	240	(Peluso *et al.*, 2022)
20	0,53-1,90µg/L	0,73-1,80µg/L	Argentina	Suface water; Groundwater	240	(Primost *et al.*, 2017)
21	N.M.	Not available-1600µg/L	Argentina	Surface water	240	(Avigliano; Schenone, 2015a)
22	<0,6-4µg/L	<0,6-7µg/L	Argentina	Surface water	240	(Andrade *et al.*, 2021)
23	N.D.-4µg/L	7-12µg/L	Argentina	Surface water	240	(Peluso *et al.*, 2020)
24	N.D.-10,3µg/L	N.D.-22,4µg/L	Argentina	Surface water	240	(Peluso *et al.*, 2023)
25	0,1-3,7µg/L	0,1-8,5µg/L	Argentina	Suface water; Groundwater	240	(Okada *et al.*, 2018)
26	Not available-4µg/L	Not available-3µg/L	Argentina	Surface water	240	(Mayora *et al.*, 2024)
27	1,3-10 µg/L	1,1-14,2 µg/L	Australia	Surface water	1000	(Okada *et al.*, 2020)
28	0,55-2,42 µg/L	1,95-2,96 µg/L	Australia	Surface water	1000	(Okada *et al.*, 2019)
29	<0,50-32µg/L	<0,2-370µg/L	Australia	Surface water	1000	(Campbell *et al.*, 2025)
30	7,2-303µg/L	0,78-153µg/L	Belgium	Surface water	0,1	(Quaglia *et al.*, 2024)
31	0,23-5,8µg/L	0,64-6,1µg/L	Belgium	Surface water	0,1	(Tang *et al.*, 2015)
32	N.D.	N.D.-13,9 µg/L	Brazil	Surface water	65	(Dovidauskas *et al.*, 2022)
33	N.D.	0.6078-11.33 µg/L	Brazil	Surface water	65	(Correia; Carbonari; Velini, 2020)
34	0,65-1,9 µg/L	1,5-9,7 µg/L	Brazil	Suface water; Groundwater	65 e 500	(Pires *et al.*, 2020)
35	N.D.	0,5-8,7 mg/L	Brazil	Surface water	65	(Lima *et al.*, 2023)
36	N.D.	11,6-45,5 µg/L	Brazil	Surface water	65	(Damiani *et al.*, 2023)
37	N.M.	0,035-0,77 mg/L	Brazil	Surface water	65	(Feliciano *et al.*, 2025)
38	0,0026-0,2751µg/L	0,0062-1,5868µg/L	Brazil	Suface water; Groundwater	65 e 500	(Pires *et al.*, 2023b)

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39	N.M.	0,001-0,802µg/L	Brazil	Suface water; Groundwater	65 e 500	(Camiccia *et al.*, 2022)
40	N.M.	N.M.-0,72 µmol L	Brazil	Surface water	65	(Prezilius *et al.*, 2022)
41	23,46-41,25µg/L	51,88-117,07µg/L	Brazil	Surface water	65	(Gomes *et al.*, 2022)
42	0,50-1,40µg/L	0,31-1,65µg/L	Brazil	Surface water	65	(Mendonca *et al.*, 2020)
43	N.M.	12,58-65,11µg/L	Brazil	Groundwater	500	(Nunes *et al.*, 2024)
44	N.D.	N.D.	Brazil	Surface water		(Didone *et al.*, 2021)
45	N.M.	1.90 x 10^16-5.27 x 10^10 pmol/L	Brazil	Surface water	65	(Ohse *et al.*, 2024)
46	N.D.	N.D.	Brazil	Surface water	65	(Pimenta *et al.*, 2020)
47	26-234µg/L	27-371µg/L	Brazil	Suface water; Groundwater	65 e 500	(de Matos *et al.*, 2023)
48	Not available-0,85µg/L	Not available	Brazil and Paraguay	Surface water.	65	(Gabardo et al. 2024)
49	5-698 ng/L	15,6-663 ng/L	Canada	Groundwater	280	(Van Stempvoort *et al.*, 2016)
50	N.D.	N.D.-17 µg/L	Canada	Surface water	65	(Edge *et al.*, 2023)
51	17-3034 ng/L	25-3380 ng/L	Canada	Surface water	65	(Struger et al. 2015)
52	33-656 ng/L	2,8-3.000 ng/L	Canada	Surface water	65	(Montiel-León *et al.*, 2019)
53	1,75-14µg/L	N.M.-19µg/L	Canada	Surface water	65	(Raby *et al.*, 2022)
54	N.M.-2900ng/L	N.M.-17645ng/L	Canada	Surface water	65	(Donald et al. 2018)
55	N.D.	N.D.	Canada	Surface water	65	(Sanford; Prosser, 2020)
56	0,76-9,2ng/L	0,07-0,60ng/L	Canada	Surface water	65	(Picard *et al.*, 2021)
57	<LOD	<LOD	Canada	Surface water	65	(Ijzerman *et al.*, 2024)
58	153-5836ng/L	87-4095ng/L	Canada	Surface water	65	(Feng *et al.*, 2024)
59	0,11-3,1µg/L	0,057-0,53µg/L	Canada	Surface water	65	(Brown; Farenhorst, 2024)
60	Not available-55,7ng/L	Not available-483ng/L	Canada	Surface water	65	(Feng *et al.*, 2025)
61	N.M.	N.D.	China	Surface water	0,1	(Wang *et al.*, 2016)
62	<0,05-10,31µg/L	<0,05-32,49µg/L	China	Sup; subt.	0,1	(Geng *et al.*, 2021)
63	N.M.	N.D.	China	Groundwater	0,1	(Jing *et al.*, 2021)
64	2,5-37,1µg/L	0,41-37,1µg/L	China	Surface water	0,1	(Tan *et al.*, 2024)

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65	N.D.	N.D.	Colombia	Groundwater	-	(Bahamón-Pinzón *et al.*, 2024)
66	N.M.	204,5-441,5µg/L	Colombia	Surface water	-	(Alvarez Bayona *et al.*, 2022)
67	N.D.	0,12-6,24 µg/L	Spain	Surface water	0,1	(Melendez-Pastor *et al.*, 2021)
68	1505,6-4,8ng/L	10,2-3027,5ng/L	Spain	Suface water; Groundwater	0,1	(Lopez-Vazquez *et al.*, 2023)
69	0,055-0,184µg/L	0,03-0,228µg/L	Spain	Surface water	0,1	(Yusa *et al.*, 2021)
70	20-9500 ng/L	40-7900 ng/L	United States	Surface water	65	(Bradley *et al.*, 2017)
71	N.M.-34,100 ng/L	N.M.-91,700 ng/L	United States	Surface water	65	(Byers *et al.*, 2025)
72	N.M.-1700 ng/L	N.M.-420 ng/L	United States	Surface water	65	(Battaglin *et al.*, 2023)
73	0,50-2,5µg/L	1,6-13µg/L	United States	Surface water	65	(Ulrich; Ferguson, 2021)
74	N.M.-5,6µg/L	N.M.-8,1µg/L	United States	Surface water	65	(Medalie *et al.*, 2020)
75	N.M.	<2-27,8µg/L	United States	Surface water	65	(Mahler *et al.*, 2017)
76	N.M.	60-300ng/L	United States	Suface water; Groundwater	65 e 700	(Welch *et al.*, 2019)
77	2,94(Switzerland)-988 ng/L (Czech Republic)	8,40(Croatia) -3499 ng/L (Italy)	Europe*	Surface water	0,1	(Navarro *et al.*, 2024)
78	1,4-3µg/L	6,5-7,3µg/L	Europe*	Surface water	0,1	(Ginebreda *et al.*, 2018)
79	0,01-0,6 µg/L	0,1-1,7 µg/L	France	Surface water	0,1	(Le Cor *et al.*, 2021)
80	0,1-47µg/L	0,1-386,9µg/L	France	Surface water	0,1	(Lefrancq *et al.*, 2017)
81	367-1100ng/L	300-1500ng/L	France	Surface water	0,1	(Reoyo-Prats *et al.*, 2017)
82	3,66-12,9µg/L	0,40-1,19µg/L	France	Surface water	0,1	(Merdy *et al.*, 2025)
83	0,02-130µg/L	<0,02-12µg/L	Netherlands	Surface water	0,1	(Desmet *et al.*, 2016)
84	111-9900ng/L	14-340 ng/L	Netherlands	Surface water	0,1	(Geerdink *et al.*, 2020)
85	N.D.	N.D.	Netherlands	Groundwater	0,1	(Broers *et al.*, 2024)
86	0,05-3µg/L	0,2-2µg/L	Hungary	Surface water	0,1	(Toth *et al.*, 2022)
87	N.M.	125-455ng/L	Hungary	Suface water; Groundwater	0,1	(Szekacs; Moertl; Darvas, 2015)
88	N.D.	N.D.-1,32 µg/L	Iran	Surface water	-	(Pakzad *et al.*, 2023)
89	NI	NI-0,011ppb	Iran	Groundwater	-	(Samarghandi *et al.*, 2017)

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90	N.M.	0,05-10µg/L	Iran	Surface water	-	(Kalantary; Barzegar; Jorfi, 2022)
91	N.M.	0,01-0,04µg L	Ireland	Surface water	-	(Farrow *et al.*, 2025)
92	0,3-30,2µg/L	0,026-0,55µg/L	Italy	Surface water	0,1	(Campanale *et al.*, 2024)
93	N.D.	95-260ng/L	Italy	Surface water	0,1	(Feltracco *et al.*, 2022a)
94	<50-8500ng/L	<50-5500ng/L	Italy	Groundwater	0,1	(Suciu *et al.*, 2023)
95	0,05-1,4µg/L	0,06-2,1µg/L	Italy	Surface water	0,1	(Masiol; Giannì; Prete, 2018)
96	N.M.	0,17-0,42µg/L	Italy	Surface water	0,1	(Centanni *et al.*, 2024)
97	N.M.	2,33-200µg/L	Malaysia	Surface water	-	(Joni *et al.*, 2021)
98	N.D.	0,87-4,33µg/L	Mexico	Surface water	10	(Reynoso *et al.*, 2020)
99	1,74-7,4µg/L	N.D.-8,32 µg/L	Mexico	Groundwater	10	(Osten *et al.*, 2025)
100	N.D.	0,35-1,4µg/L	Mexico	Suface water; Groundwater	10	(Osten; Dzul-Caamal, 2017)
101	N.M.	0,44-1,42µg/L	Mexico	Groundwater	10	(Osten; Dzul-Caamal, 2017)
102	N.M.	56,96-510,6ppb	Mexico	Surface water	10	(Silva-Madera *et al.*, 2021)
103	0,413-0,472µg/L	<LOD	Mexico	Surface water	10	(de J. Bastidas-Bastidas *et al.*, 2024)
104	N.M.	N.M.-0,33µg/L	Nigeria	Surface water	-	(Nwinyimagu et al. 2023)
105	N.M.	N.D.-0,00002µg/L	Nigeria	Surface water	-	(Tongo *et al.*, 2022)
106	N.M.	1,02-22,54µg/L	Nigeria	Suface water; Groundwater	-	(Ayoola *et al.*, 2023)
107	N.M.	0,17-12µg/L	Norway	Surface water	0,1	(Stenrod, 2015)
108	N.M.	N.D.-0,4593ppm	Pakistan	Surface water	-	(Khan *et al.*, 2020)
109	0,131-0,2411µg/L	N.M.	Poland	Surface water	-	(Urbańska-Kozłowska et al.2025)
110	0,05-4,24 µg/L	0,03-4,69 µg/L	Portugal	Groundwater	0,1 µg/L	(Inês; Ana; Silva, 2024)
111	1,019-7,621µg/L	<LOD	Romania	Surface water	0,1	(Vlassa *et al.*, 2022)
112	0,029-2.006µg/L	0,005-0,503µg/L	Serbia	Surface water	0,1	(Agarski *et al.*, 2024)
113	2-11µg/L	1-45µg/L	Sri Lanka	Suface water; Groundwater	-	(Gunarathna *et al.*, 2018)
114	N.M.	0,05-3,5µg/L	Sri Lanka	Suface water; Groundwater	-	(Jayasumana *et al.*, 2015)

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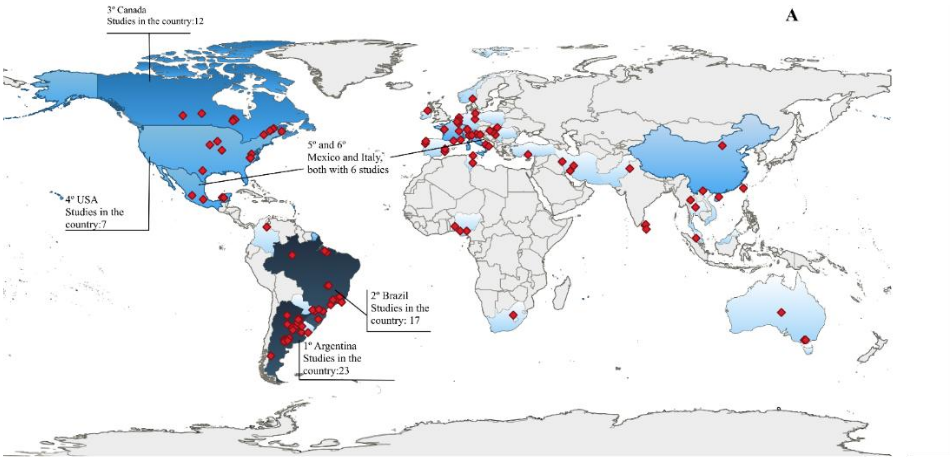
115	N.M.	0,36-7,31µg/L	Sri Lanka	Groundwater	-	(Ulrich *et al.*, 2023)
116	N.M.	N.D.	Sri Lanka	Surface water		(Jayasiri *et al.*, 2022)
117	N.M.	0,047-8,7µg/L	Switzerland	Surface water	0,1	(Poiger *et al.*, 2020)
118	N.D.-1,3µg/L	N.D.-0,38µg/L	Switzerland	Surface water	0,1	(Poiger *et al.*, 2017)
119	24-1680ng/L	<5-1430ng/L	Switzerland	Surface water	0,1	(Huntscha *et al.*, 2018)
120	0,04-4,34µg/L	0,04-0,1 µg/L	Thailand	Surface water	-	(Klaimala *et al.*, 2022)
121	Not available	Not available-0,47µg/L	Thailand	Surface water	-	(Patel *et al.*, 2024)
122	N.D.-1509 ng/L	N.D.-1354 ng/L	Taiwan	Surface water	-	(Lin; Chang; Sheen, 2022)
123	N.D.	0,1-1,73 µg/L	Tunisia	Surface water	-	(Dahmeni et al.2024)
124	0,610-76,70 µg/L	0,86-0,490 µg/L	Tunisia	Surface water	-	(Grünberger *et al.*, 2024)
125	N.M.	0,88-4,64ppm	Turkey	Surface water	-	(Aydin *et al.*, 2023)
126	580-890ng/L	227,5-1045ng/L	Uruguay	Surface water	-	(Rodríguez-Bolaña *et al.*, 2023)
127	6,9-1329ng/L	54,5-565ng/L	North Vietnam	Surface water	-	(Vu *et al.*, 2023)

(N.D): Not detected; (N.M): Not measured; Groudwater: well water and deep groundwater; Surface water: river water, lakes, wastewater, tap water, and streams; -: No corresponding value found; *Research conducted in various European countries. Source: Prepared by the authors.

Figure *2*

Distribution of publications by country from 2015 to 2025.



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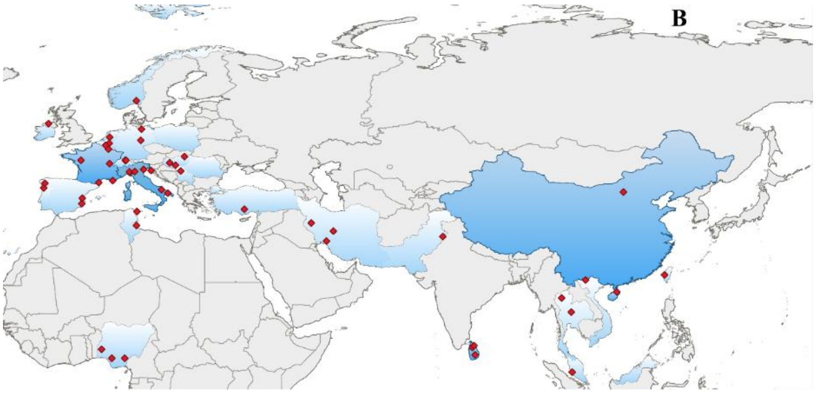

3.1.2 Detected concentrations of glyphosate and AMPA and their regulatory limits

Fig. 3 depicts the global distribution of maximum glyphosate concentrations reported. Statistical analysis (Kruskal–Wallis test) revealed a significant location effect on detected concentrations [$x^2(2) = 15.079$; $p < 0.001$], with post-hoc results indicating significant differences particularly between Europe and North America ($p = 0.736$). Overall, concentrations were consistently higher in South and North America, with Brazil, Argentina, Colombia, and Mexico recording the most critical values. To facilitate interpretation, concentrations were categorized relative to prevailing drinking water regulations: (a) ≤0.1 µg/L (European Union standard, most stringent), (b) 0.1–65 µg/L (range encompassing Brazilian and North American limits), and (c) >65 µg/L (above most national standards) **(Table 1).** The mapping analysis showed that the vast majority of records worldwide exceeded the EU limit (0.1 µg/L), including in European sites where lower concentrations would be expected under stricter regulation.

South America emerged as the most impacted region, with a high density of sites exceeding 65 µg/L (red markers in Fig. 3). Brazil presented the highest glyphosate concentration globally (8,700 µg/L;Lima *et al.*, 2023) — a value 133 times the national permissible limit (65 µg/L) and approximately 87,000 times higher than the EU guideline. Argentina recorded a maximum of 1,600 µg/L (Avigliano; Schenone, 2015b), while Mexico (510.6 µg/L Silva-Madera *et al.*, 2021) and Colombia (441,5 µg/L;Alvarez Bayona *et al.*, 2022) also reported values well above their national or international thresholds. By contrast, Canada

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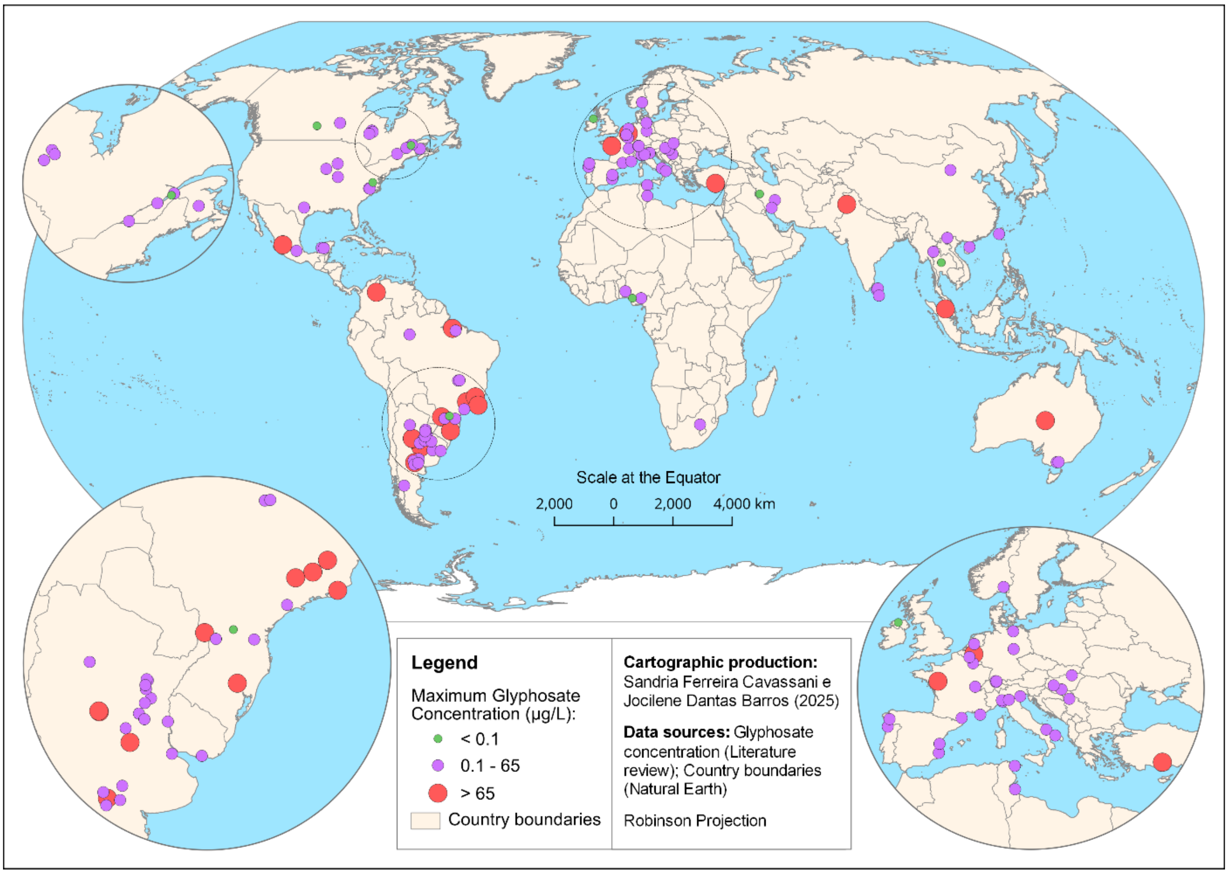
presented the two lowest concentrations globally (0.00007 µg/L and 0.0028 µg/L; Picard et al., 2021; Montiel-León et al., 2019), comparable to ultra-trace levels.

Figure *3*

World map of the maximum glyphosate concentrations found. The highest concentrations were found in South America, in Brazil (mean: 3,214 µg/L) and Argentina (1,600 µg/L) with a p-value of (.736).



Source: Cavassani; Barros, 2025 and research database.

For AMPA, the highest concentrations were likewise documented in Brazil and Argentina (de Matos *et al.*, 2023; Vera-Candioti *et al.*, 2021a) and in Belgium (Quaglia *et al.*, 2024). confirming a pattern of geographical overlap between glyphosate use intensity and metabolite accumulation **(Table 1)**. Conversely, the lowest AMPA values were reported in Switzerland, Canada, and Vietnam (Picard *et al.*, 2021;Vu *et al.*, 2023).

A comparison with existing global pesticide reviews (De Araújo *et al.,* 2022; Souza *et al.,* 2020) highlights a critical gap: these earlier studies did not include glyphosate or AMPA, despite glyphosate being the most widely used herbicide worldwide. This omission underscores the novel contribution of the present review, which integrates both systematic

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and scientometric approaches to demonstrate that glyphosate remains underrepresented in quantitative aquatic monitoring studies Pires *et al.* (2023). The mismatch between widespread application and limited monitoring points to significant environmental surveillance gaps.

Regarding legislation, most countries included in the 35-study dataset have established limits for glyphosate, including all EU nations, the US, Canada, Mexico, Brazil, Argentina, Paraguay, and Uruguay. However, many Asian countries (e.g., Malaysia, Sri Lanka, Thailand, Taiwan, Pakistan) and South Africa lack specific regulations, often defaulting to EU standards (as in China). Among countries with formal thresholds, the EU has the most restrictive value (0.1 µg/L), while Australia allows the highest (1,000 µg/L), followed by the United States (700 µg/L, groundwater), Brazil (500 µg/L, groundwater), Canada (280 µg/L), and Argentina (240 µg/L).

4 SCIENTOMETRIC DATA ANALYSIS

4.1 PUBLICATIONS AND CITATION NETWORK OVER THE YEARS

From 2020 onward, the number of publications addressing glyphosate concentrations in aquatic systems showed a marked increase, peaking in 2024 with 21 articles **(Fig. 4)**. This surge in research output is likely associated with the intensification of debates over environmental and public health risks and the growing international concern regarding water resource contamination. Moreover, the development and dissemination of sensitive and specific analytical methods in recent years appear to have facilitated the expansion of monitoring studies.

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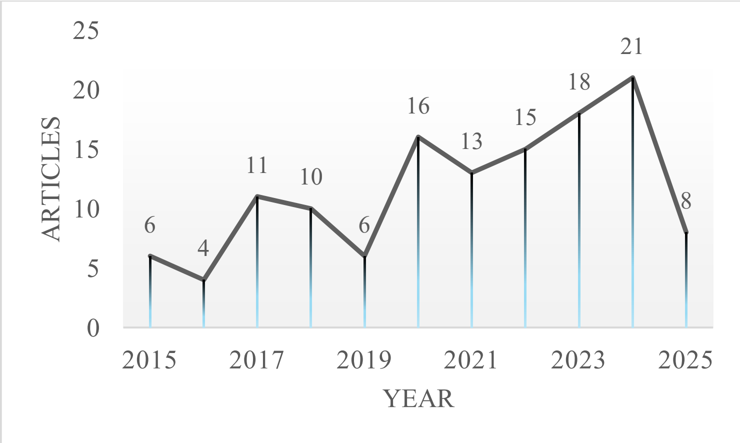
Figure 4

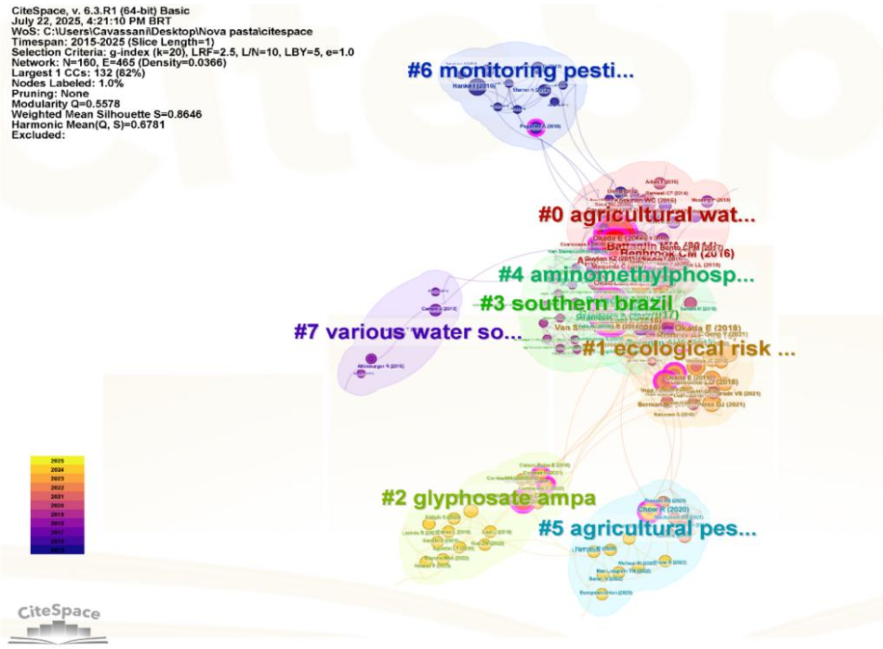
Number os article publications over the year. Source:Survey Data



To examine publication influence and author prominence, CiteSpace was employed to construct co-citation and collaboration networks. In **Fig. 5**, nodes highlighted in pink indicate citation bursts, where sudden increases in citation frequency reflect elevated visibility and influence of specific authors across the 127-article corpus. These bursts provide insight into researchers who have gained intellectual prominence within this field.

Figure 5

Author Citation network



Source: CiteSpace.

The network structure revealed eight distinct thematic clusters (#0–#7), with strong modularity (Q = 0.5578) and high silhouette values (S = 0.8646), confirming robust cluster separation and coherence. The largest cluster (#0 Agricultural Watershed) encompassed 30 studies, anchored by Okada *et al.* (2018), who investigated point-source glyphosate and AMPA pollution in Argentina. The second largest (#1 Ecological Risk Assessment) grouped 24 studies with a focus on ecotoxicological frameworks, led by Vera-Candioti *et al.* (2021a). Specialized research domains were identified in Clusters #2 (Glyphosate–AMPA) and #4 (Aminomethylphosphonic Acid), addressing degradation pathways and metabolite dynamics. Notable studies include Pires *et al.* (2023a), analyzing watershed contamination in Brazil, and Medalie *et al.* (2020), monitoring glyphosate residues in U.S. streams. The remaining smaller clusters (#5–#7) focused on pesticide monitoring across diverse aquatic matrices.

Citation analysis further identified the 10 most highly cited studies **(Table 2)** Bradley et al. (2017) emerged as the most influential, with 255 citations for the article Expanded Target-Chemical Analysis Reveals Extensive Mixed-Organic-Contaminant Exposure in U.S. Streams. Strikingly, half of the top ten most cited papers were published in 2017, highlighting this year as a pivotal milestone in glyphosate research. This temporal concentration coincides with the period following IARC's 2015 classification of glyphosate as a probable carcinogen and the subsequent FAO/WHO re-evaluation in 2016, events that intensified scientific and regulatory discourse globally. The dissemination of advanced analytical methodologies during this period further catalyzed research expansion, reinforcing the interplay between regulatory controversy, methodological innovation, and knowledge production.

In **Fig. 5**, small cluster density are observed, which indicate an increase in thematic publications concerning glyphosate and AMPA concentration in water courses. Network analysis in CiteSpace revealed 8 thematic clusters (ranging from #0 to #7) that represent the principal research foci on glyphosate and AMPA contamination in water courses. The high modularity represented by Q= 0.5578 and the silhouette value (S= 0.8646) indicate that the clusters are well-defined and coherent. The most dominant cluster (#0 agricultural watershed) possesses 30 members and has as its central article the study by Okada et al. (2018), published in Environmental Science and Pollution Research, on point pollution of glyphosate and AMPA in a rural watershed in Argentina. The second largest cluster (#1 ecological risk assessment) possesses thematic focus directed toward ecotoxicological approaches and contains 24 members. The central article is the study by Vera-Candioti et al. (2021a),

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published in Environmental Monitoring and Assessment, on environmental monitoring. Clusters #2 glyphosate AMPA and #4 aminomethylphosphonic acid are thematic areas focused on glyphosate degradation and its metabolite AMPA. Within these two thematic areas, notable authors include Pires et al. (2023a) with the study conducted in a watershed in Brazil (as well as #3 southern Brazil) and Medalie et al. (2020), a study conducted in streams in the United States. Clusters #5, #6, and #7 are formed by small members and are focused on the thematic area of pesticide monitoring in various water sources.

Regarding authors and publications, **Table 2** obtained from WoS delineated the 10 articles (within the 127 articles) most cited in studies on glyphosate and AMPA concentrations. The table also shows the values of total and annual citation counts for each article, in addition to information about the authors and the year in which the article was published. Through citation analysis of the articles, it can be perceived that the most influential author is Bradley et al. (2017), with a total of 255 citations in the article entitled "Expanded Target-Chemical Analysis Reveals Extensive Mixed-Organic-Contaminant Exposure in U.S. Streams." It is also possible to note that of the 10 most cited articles, 5 (five) were published in the year 2017, indicating that this period represented a relevant milestone for the advancement of research on the topic, and may be directly related to the international regulatory context subsequent to the classification of glyphosate by IARC in 2015 and the review by FAO and WHO in 2016, which intensified the global scientific debate regarding the effects of glyphosate exposure. Additionally, the dissemination of more sensitive analytical methodologies may have propelled advancement in research.

Table 2

10 most cited articles on glyphosate and AMPA concentrations in watercourses

Author, year	**Title**	**Total citations**	**Average per year**
Bradley *et al.*, 2017	Expanded Target-Chemical Analysis Reveals Extensive Mixed-Organic-Contaminant Exposure in U.S. Streams	255	28,33
Primost *et al.*, 2017	Glyphosate and AMPA, "pseudo-persistent" pollutants under real-world agricultural management practices in the Mesopotamic Pampas agroecosystem, Argentina	187	20,78

Jayasumana *et al.*, 2015	Drinking well water and occupational exposure to Herbicides is associated with chronic kidney disease, in Padavi-Sripura, Sri Lanka	155	14,09
Ronco *et al.*, 2016	Water quality of the main tributaries of the Paraná Basin: glyphosate and AMPA in surface water and bottom sediments	132	13,20
Poiger *et al.*, 2017	Occurrence of the herbicide glyphosate and its metabolite AMPA in surface waters in Switzerland determined with on-line solid phase extraction LC-MS/MS	126	14,00
Lefrancq *et al.*, 2017	High frequency monitoring of pesticides in runoff water to improve understanding of their transport and environmental impacts	116	12,89
Lupi *et al.*, 2015	Occurrence of glyphosate and AMPA in an agricultural watershed from the southeastern region of Argentina	114	10,36
(Alonso *et al.*, 2018)	Glyphosate and atrazine in rainfall and soils in agroproductive areas of the pampas region in Argentina	111	13,88
(Mahler *et al.*, 2017)	Similarities and differences in occurrence and temporal fluctuations in glyphosate and atrazine in small Midwestern streams (USA) during the 2013 growing season	97	10,78
(Demonte *et al.*, 2018)	Determination of glyphosate, AMPA and glufosinate in dairy farm water from Argentina using a simplified UHPLC-MS/MS method	90	11,25

Source: Research Data.

4.1.1 Most relevant keywords and cluster analysis

Keyword co-occurrence analysis was performed in CiteSpace, generating a structured network composed of 257 nodes and 1,022 links **(Fig. 6)**. The network presented acceptable modularity (Q = 0.3587) and satisfactory internal consistency (S = 0.5121), indicating that the identified clusters are thematically coherent and represent a well-organized knowledge domain.

The most frequent keyword was “surface water” (45 co-occurrences), highlighting the predominance of studies focused on rivers and lakes adjacent to agricultural areas. This was followed by “aminomethylphosphonic acid” (36), reflecting the growing research attention given to glyphosate’s primary metabolite (AMPA). The keyword “glyphosate” (26) indicated

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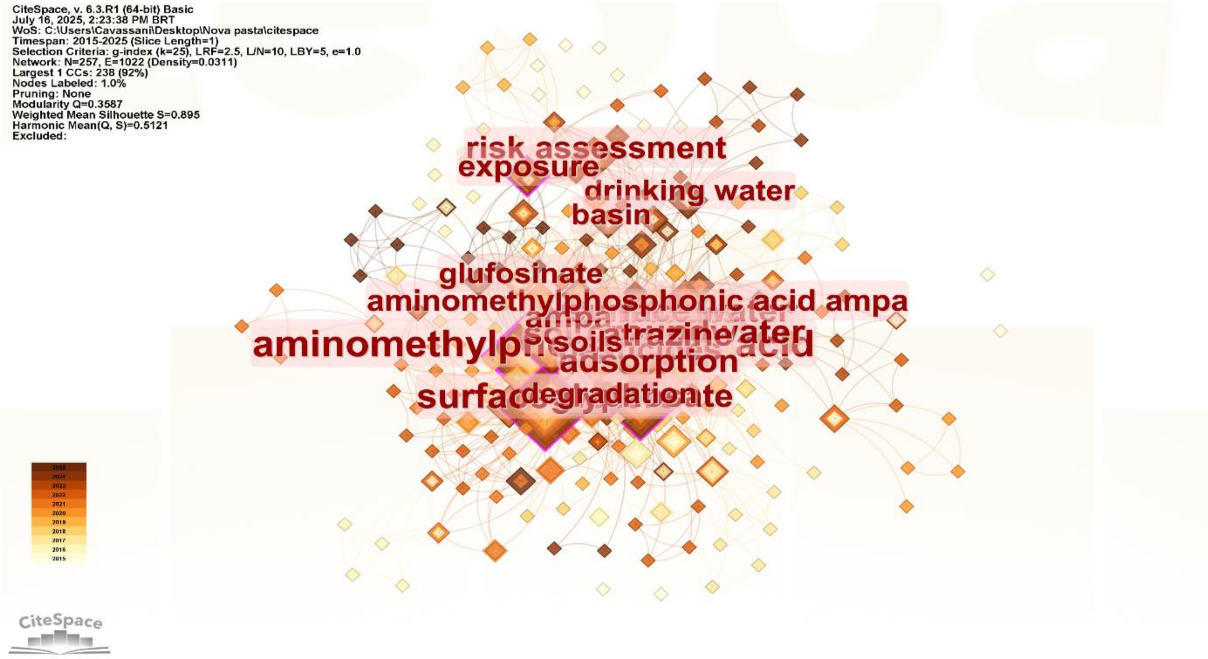
the parent compound as a central axis of investigation, while "soil" (23) suggested frequent consideration of soil-to-water leaching pathways. Together, these terms delineate the ecological interface between agricultural management, environmental transport, and freshwater contamination.

Figure 6

Most used Keywords and Citation bursts



Temporal burst analysis provided further insights into evolving research priorities **(Fig. 7)**. The keyword "streams" exhibited the strongest burst (intensity 3.81) between 2015–2017, corresponding to early investigations of contaminant transport in watershed systems. The methodological term "solid phase extraction" showed a burst strength of 3.68, with peak activity in 2021, reflecting advances in extraction and detection methods that have substantially increased monitoring sensitivity for glyphosate and AMPA. This technical evolution coincided with the surge in publication output observed after 2021 **(Fig. 2)**, suggesting a clear link between methodological innovation and research productivity.

In addition, the keyword "pesticides" (burst 3.41, peak in 2018) revealed a broadening of research scope toward comparative assessments across multiple agrochemicals, while "environmental fate" (burst 3.39) and "impact" (burst 3.25) indicate a growing emphasis on ecological persistence and human health risks. These terms collectively signal a transition from studies limited to chemical occurrence toward more integrated approaches addressing

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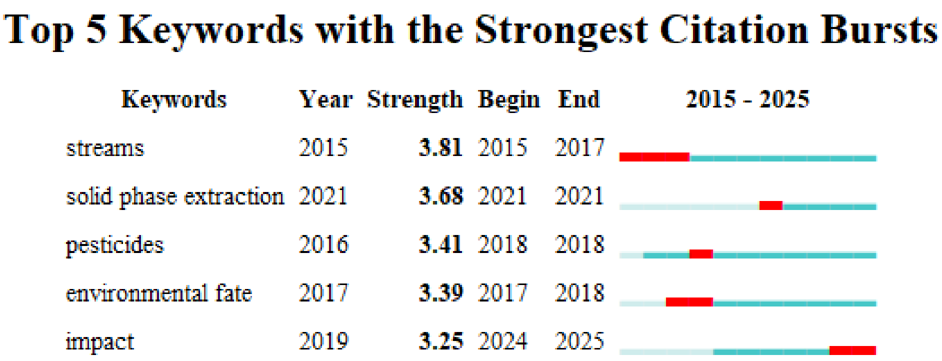
exposure pathways, toxicological outcomes, and regulatory implications. In summary, the keyword analysis highlights both the consolidation of glyphosate/AMPA research within traditional monitoring domains (surface waters, leaching) and the emergence of methodological and thematic innovations. The co-occurrence of environmental and toxicological terms illustrates a research field increasingly oriented toward understanding the ecological fate and health impacts of glyphosate, though notable geographic and thematic gaps remain.

Figure 7

Top 5 Keywords with the Strongest Ciation Bursts



Source:Cite Space.

4.1.2 Countries and cooperation analysis

Country-level analysis of research productivity, based on authors' institutional affiliations, provides critical insight into the geographic distribution of studies on glyphosate and AMPA concentrations in aquatic systems. As shown in **Fig. 8**, the cooperation network reveals both publication output and international collaboration clusters, with Argentina emerging as the most productive nation, leading with 26 publications, followed by Brazil (18), the United States (15), Canada (12), France (9), Italy (7), Switzerland (6), Spain (6), the Netherlands (5), and Mexico (5).

Beyond publication counts, betweenness centrality was employed to assess the influence each country exerts within the global research network (Chen, 2014). Argentina and the United States exhibited the highest centrality (0.29 each), followed by France (0.20), Italy (0.16), the Netherlands (0.09), Brazil and Mexico (0.06 each), Switzerland (0.05), and Spain (0.01). These results demonstrate that while Argentina and Brazil dominate in absolute

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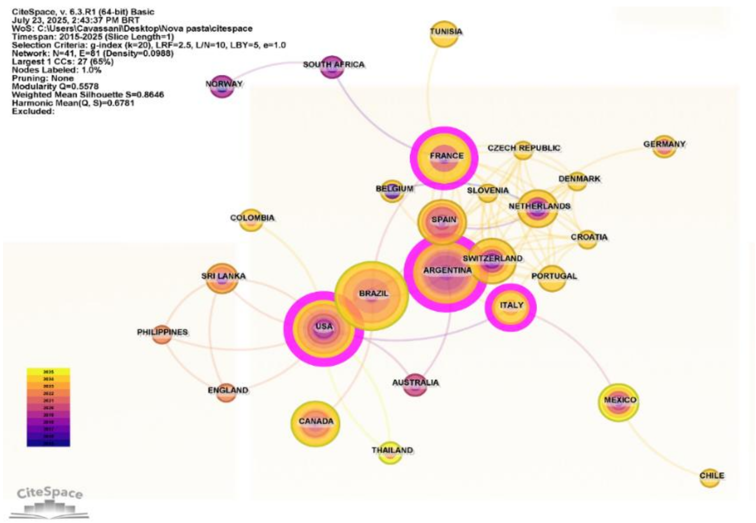
productivity, the network of international intellectual influence is more strongly anchored in the United States and several European countries.

This divergence highlights a structural asymmetry: in Argentina, high centrality appears linked to its dependence on transgenic soybean agribusiness, where intensive glyphosate use drives both environmental monitoring and international visibility of related studies (Fernandes *et al.*, 2019), In contrast, the United States' elevated centrality derives not only from research volume but also from its ability to mobilize large-scale collaborative networks supported by institutional funding, which positions it strategically in shaping international scientific and regulatory agendas. The impact of this position is exemplified by Bradley *et al.* (2017), the most highly cited study in this field. This contrast—between major producer countries in Latin America (Argentina and Brazil) and countries with stronger collaborative infrastructure (United States and Europe)—underscores a persistent imbalance between research productivity and global influence. Addressing this gap will require strengthening regional scientific cooperation in Latin America and reducing dependency on hegemonic research centers, thereby promoting more equitable participation in the generation of knowledge and in the formation of international environmental policies.

Figure 8

Collaboration network among the countries.



Source: CiteSpace.

5 CONCLUSION

This review demonstrates that the highest glyphosate concentrations occur predominantly in South and North America, with Brazil reporting extreme values that surpass the national regulatory threshold by more than two orders of magnitude. Scientometric analysis revealed a consistent upward trend in publications, reflecting heightened environmental concern and increasing toxicological evidence linking glyphosate and its metabolite AMPA to adverse human health outcomes. Despite this progress, important gaps remain: knowledge of the environmental pathways and long-term health impacts of these compounds is still fragmented, and even countries with stringent regulatory frameworks frequently report concentrations that exceed established limits. Such findings expose persistent weaknesses in monitoring and enforcement mechanisms. Taken together, the results highlight an urgent need to strengthen and harmonize global monitoring programs, foster greater international cooperation—particularly in underrepresented regions such as Asia and Africa—and integrate scientometric insights with environmental surveillance to identify emerging research fronts and inform more effective regulatory policies. By uniting evidence of widespread contamination with an evaluation of global research patterns, this study underscores glyphosate's dual role as an environmental pollutant and a matter of international scientific and political relevance, demanding coordinated action to protect both ecosystems and human health.

Future research should focus on expanding monitoring efforts in underrepresented regions, developing standardized analytical methods, and establishing long-term monitoring programs to better understand temporal trends and the effectiveness of regulatory interventions.

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DECLARATIONS

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