NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Bulletin of Geography. Physical Geography Series, No. 30 (2026): 93–110
http://doi.org/10.12775/bgeo-2026-0006

Mapping the research landscape on landfills and groundwater: a Scopus-based bibliometric review 2000–2024

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Abstract. This Scopus-based bibliometric review maps research on landfill–groundwater interactions (2000–2024) to identify dominant themes, underexplored topics and methodological gaps that limit evidence-based groundwater protection near landfills. Using the query "landfill" AND "groundwater", we extracted 601 records and analysed trends with Biblioshiny, MapChart and Excel. The analysis highlights the countries, institutions and keywords on which the literature concentrates. It shows a shift from standalone laboratory approaches toward integrated frameworks that combine hydrogeological monitoring, laboratory chemistry and GIS/remote-sensing support. These results provide a roadmap for future studies and for decision-makers by prioritising interdisciplinary research needs, including leachate–aquifer pathways, medium-sized cities and long-term monitoring strategies.

Key words:
Landfill,
groundwater,
groundwater pollution,
GIS,
leachate

Introduction

Globally, the steady increase in municipal solid waste generation is attributed to rising population and swift urbanisation (Chen et al. 2020). The World Bank's statistical data indicate that, on average, individuals worldwide contribute ~0.74 kilograms of waste daily (Kaza et al. 2018). Alarmingly, high-income nations, despite accounting for only 16% of the global population, are responsible for over 34% of total waste generated, amounting to ~683 million tons (Chadha et al. 2023). Looking ahead, forecasts project global waste generation to increase to 3.40 billion tons by 2050, directly correlating with urbanisation and economic development (Omotayo 2024). Rapid population growth, expansion of cities, and industrialisation processes are causing a sharp increase in waste volumes (Fayshal 2024). As a result, waste-related problems are becoming more complex, making effective waste management an increasingly urgent issue. Waste not only causes aesthetic and sanitary harm but can also disrupt urban ecological balance through soil, water and air pollution (Wilson et al. 2022). This situation directly impacts public health, leading to various diseases, allergies and other environmental hazards.

Many urban centres worldwide are facing increasing waste accumulation and the need for effective waste management strategies (Laureti et al. 2024). This situation creates local environmental challenges and may also contribute to broader ecological concerns (Eriksen et al. 2021). Therefore, organised waste management has become an important component of urban environmental planning (Hossain et al. 2024). To support a sustainable and healthy urban environment, waste reduction, collection, recycling and safe disposal should be implemented in a systematic and consistent manner (Wilson et al. 2022). These processes can help reduce environmental impacts and improve resource utilisation (Benson et al. 2024). The escalating volume of waste considerably increases the requirement for specialised landfill sites for its storage and disposal (Zhang et al. 2024). Consequently, the proliferation of these landfills underscores the critical need to mitigate adverse environmental impacts. It is also essential to implement effective waste management systems to ensure ecological safety (Lakhouit 2024).

Waste management is recognised as one of the most important processes in contemporary society (Hajam et al. 2023). It comprehensively addresses the collection, transportation, utilisation and recycling of waste, enabling its transformation into valuable resources. This process helps mitigate environmental damage and fosters economically viable solutions (Alaghemandi 2024).

Notwithstanding, the disposal of municipal solid waste in numerous nations predominantly relies on landfilling (Mor and Ravindra 2023). This method's cost-effectiveness and operational expediency render it a preferred option in diverse geographical areas (Hung et al. 2014). However, landfill placement must strictly adhere to ecological and regulatory standards to safeguard environmental integrity. Specifically, these sites must not adversely affect soil, water or air quality (Sumathi et al. 2008). The adverse impacts of landfill operations on groundwater quality constitute a significant concern. Thus, to preserve the health of proximate populations and the ecological integrity of the natural environment, it is imperative to implement systematic monitoring of groundwater contamination levels in the vicinity of landfills. Additionally, it is essential to assess potential health hazards and guarantee the potability of drinking water sources (Wang et al. 2021). Recent studies also show that relying on a single technique may be insufficient for accurately delineating landfill-related groundwater contamination, and recommend integrated workflows that combine geophysical surveys with spectroscopy and hydrogeochemical analyses to improve pollution identification and assessment (Wang et al. 2025).

Landfills are widely considered a primary source of groundwater contamination. This presents significant complexities for agencies charged with the stewardship of water resources. These entities are mandated to maintain the quality and ensure the safety of subterranean water reserves (Aharoni et al. 2022). Groundwater constitutes an indispensable resource for human sustenance and plays a pivotal role in economic development. It serves as a fundamental supply for potable water and finds broad application across industrial sectors, commercial activities and agricultural practices (Grönwall and Danert 2020). Therefore, minimising the adverse impact of landfills on groundwater is paramount. At the same time, effectively safeguarding this vital resource requires strict adherence to environmental regulations, meticulous landfill design, continuous pollution monitoring and routine health risk assessments (Njewa et al. 2025). Recent reviews also emphasise that groundwater contamination is typically multi-source and requires an integrated management approach that combines prevention, mitigation and remediation alongside improved monitoring and analytical assessment (Sridhar and Parimalarenganayaki 2025). Although groundwater typically migrates slowly through fractured rock and permeable soil strata and is naturally protected by barriers like surface soil or unsaturated zones, these natural safeguards frequently prove insufficient at landfill sites (Zeng et al. 2023). Recent evidence further shows that groundwater pollution around landfill sites is strongly controlled by both landfill age and local hydrogeological conditions, which influence the composition of pollutants and the likelihood of their permissible levels being exceeded in surrounding aquifers (Wen et al. 2025). These hydrogeological conditions significantly elevate the risk of pollutants infiltrating groundwater, necessitating that contaminants undergo neutralisation and treatment before they enter water layers (Nishmitha et al. 2025). Unfortunately, many existing landfills lack adequate hydro-isolation layers or feature substandard liners, a deficiency that significantly heightens the risk of groundwater pollution from leachate, the liquid generated by waste decomposition (Gupta et al. 2024).

Leachate poses the most significant of the health risks associated with landfills (Gunarathne et al. 2024). It is generated through the biological degradation of waste materials in conjunction with the ingress of water into landfill cells. This deleterious liquid then infiltrates subsurface strata and, due to its substantial content of heavy metals and myriad contaminants, perturbs soil pH, oxidation–reduction potentials, microbiological dynamics and dissolved oxygen levels (L. Wang et al. 2024). Leachate exposure can also alter the geotechnical behaviour of soils (e.g., changing their strength and permeability), which may further facilitate contaminant migration and increase groundwater vulnerability near landfill sites (Harun et al. 2025). The percolation of leachate into groundwater poses significant health and environmental hazards, as it can contaminate drinking water supplies (Parvin and

Tareq 2021). A particularly alarming factor is that leachate production continues even after landfill closure, leading to lasting ecological threats that necessitate ongoing surveillance and efficient treatment strategies (Ghosh et al. 2023). The contamination of groundwater by landfill operations constitutes an extended process. This protracted impact is partly attributable to the composition of municipal solid waste, of which ~70% is biodegradable. Consequently, an estimated 10% of this waste eventually manifests as leachate, which is subsequently discharged from the landfill facility (Zhang et al. 2021). For effective ecological protection, it is vital to choose the most appropriate and safe locations for landfills. This selection process crucially necessitates a comprehensive assessment that integrates environmental, economic, social and political considerations, as these are fundamental to sound waste management and environmental safeguarding (Kuhaneswaran et al. 2025).

Ensuring environmental protection and preventing pollution necessitate the effective treatment and disposal of landfill leachate. Consequently, this has increasingly emerged as a central area of scientific inquiry (Wang et al. 2024). The rapid expansion of scientific literature has posed significant challenges for researchers seeking to effectively analyse large datasets. Therefore, bibliometric analysis has gained increasing relevance for enhancing current knowledge, identifying critical challenges and delineating potential research avenues (Büyükkidik 2022). Numerous bibliometric studies have focused on critical aspects of land- and water-management-related issues (Khasanov et al. 2021; Jumaniyazov et al. 2023; Juliev et al. 2024; Kannazarova et al. 2024a; Kannazarova et al. 2024b; Berdyyev et al. 2025). Specifically, research has explored the impact of climate change on land resources (Berdyyev et al. 2025), soil erosion in Central Asian countries (Juliev et al. 2024) and the utilisation of degraded lands with limited agricultural or economic suitability (Jumaniyazov et al. 2023). Furthermore, investigations have extended to groundwater resources within Commonwealth of Independent States (CIS) countries, including the monitoring of groundwater levels in irrigated lands (Kannazarova et al. 2024). The causes and consequences of landslides in Central Asia (Khasanov et al. 2021) and the cultivation of agricultural products (Kannazarova et al. 2024) have also been thoroughly examined. Moreover, these methodologies provide a statistical framework for the evaluation of scholarly publications, facilitating the precise discernment of central research themes, areas requiring further investigation, and emergent research trajectories with significant potential (Wang et al. 2024).

The primary objective of this research is to methodically and accurately assess the influence of landfills on groundwater. This is achieved through a comprehensive analysis of scientific literature, empirical studies and practical applications, aiming to delineate effective strategies for pollution minimisation and management at landfill sites. The anticipated findings will facilitate the evaluation of groundwater quality near landfills, contribute to ecological preservation and provide actionable recommendations for sustainable water resource governance. Moreover, this study will significantly refine the formulation of evidence-based methodologies for monitoring and mitigating the environmental repercussions of landfills, with a specific focus on subterranean water systems. Despite the growing number of studies, there remains the need for a consolidated overview of which authors are driving this field, which themes dominate, and which research directions remain weakly developed; this study addresses these gaps through a transparent, Scopus-based bibliometric mapping and synthesis.

Methodology

This study employed a bibliometric approach to systematically map and evaluate the scientific literature addressing the relationship between landfills and groundwater. The bibliographic data were retrieved from the Scopus database, which was selected due to its broad coverage of peer-reviewed journals and standardised export formats suitable for bibliometric analyses. The search scope covered the period 2000–2024, and only English-language publications were included to ensure consistency across records and improve comparability. A structured search query was developed and executed in Scopus. The query targeted article titles to capture studies explicitly focused on landfill–groundwater interactions and related terminology. The search string applied was: TITLE (landfill AND groundwater OR groundwater pollution OR ground water OR groundwater resources OR groundwater contamination OR hydrogeology OR aquifer) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBYEAR, 2000) OR LIMIT-TO (PUBYEAR, 2024)). All records returned by the query were exported from Scopus in a bibliometric-compatible format, including core metadata fields such as publication year, document title, authors, author affiliations, source title, abstracts, author keywords, indexed keywords, cited references, and citation information. The exported dataset was cleaned and standardised prior to analysis. Bibliometric indicators and scientific mapping were generated using Biblioshiny, which supports performance analysis and science mapping techniques. To enhance the presentation of bibliometric patterns, Microsoft Excel was used for descriptive summaries and the preparation of basic charts and tables, while MapChart was applied to produce geographic visualisations. Results were ultimately presented through tables, graphs and maps to provide a clear, multi-dimensional overview of the literature. A summary of the key data sources and extracted variables is provided in Table 1.

Results

Table 2 shows the number of relevant articles on landfill–groundwater research published each year from 2000 to 2024, their ordinary citation rate and ampleness. Overall, the publication trajectory indicates a clear shift from an early phase dominated by fewer but highly influential papers toward a later phase characterised by rapidly increasing output with lower average citations due to citation-time lag. For ease of understanding, it is confined into three periods. Early period (2000–2006): During this period, the number of publications was relatively low, but several articles showed high citation rates. For example, in 2001, ten articles were published, and the citation rate was 57.2%. Similarly, in 2006, 17 articles were published, with a citation rate of 58%. These high citation rates suggest that early studies played an important role in shaping later research directions. Middle period (2007–2015): During this period, the number of publications gradually increased, while the citation rate generally decreased. For example, in 2011, 19 articles were published, with a citation rate of 15.3%. This pattern may reflect the expansion of the field, as citations became distributed across a larger number of publications. Recent period (2016–2024): During this period, the number of publications increased substantially. In 2019, a record number of 50 articles was published. The highest publication output was observed in 2024, with 53 articles. However, recent publications have lower citation rates because they have had less time to accumulate citations. For example, articles published in 2024 had a citation rate of 0.87%. Importantly, the lower averages of more recent articles should be interpreted cautiously, as the many papers published in 2022–24 have had limited time to accumulate citations; therefore, the key result here is the sustained growth in research attention rather than immediate citation impact.

Table 1. Main information about data source

Description	Results
Timespan	2000–2024
Sources (Journals, Books, etc.)	280
Documents	601
Annual Growth Rate %	6.03
Document Average Age	9.64
Average citations per doc	22.11
References	20,466
KeyWords Plus (ID)	4,025
Author's Keywords (DE)	1,182
Authors	1,867
Authors of single-authored docs	34
Single-authored docs	44
Co-Authors per Doc	4.11
International co-authorships %‰	15.31

Visual representations play a crucial role in understanding complex relationships in scientific research. Among them, the three-field plot is an effective tool that illustrates the interconnections between different elements such as countries (represented by "AU_CO"), sources (represented by "SO"), and keywords plus (represented by "ID"). In the context of research on landfills and groundwater, this type of visualisation provides a comprehensive overview of publication trends, leading contributors and frequently explored topics. Figure 1 presents such a plot, offering insights into the global distribution of research, the most active sources, and the most commonly used KeyWords Plus in the field. The first column on the left represents the countries. It shows 20 countries that have published articles on the impact of landfills on groundwater. Among them, China is the leading contributor, indicated by a red rectangle, and is connected to several

Table 2. Main information about data source

Year	MeanTCperArt	N	MeanTCperYear	CitableYears
2000	30.92	13	1.19	26
2001	57.20	10	2.29	25
2002	7.50	10	0.31	24
2003	32.55	11	1.42	23
2004	24.62	13	1.12	22
2005	13.00	22	0.62	21
2006	58.00	17	2.90	20
2007	19.83	12	1.04	19
2008	46.76	21	2.60	18
2009	27.87	15	1.64	17
2010	33.13	15	2.07	16
2011	15.26	19	1.02	15
2012	30.44	18	2.17	14
2013	10.58	19	0.81	13
2014	33.26	19	2.77	12
2015	36.45	20	3.31	11
2016	34.17	24	3.42	10
2017	29.73	22	3.30	9
2018	16.65	34	2.08	8
2019	25.00	50	3.57	7
2020	18.53	34	3.09	6
2021	22.44	43	4.49	5
2022	11.75	44	2.94	4
2023	6.07	43	2.02	3
2024	1.74	53	0.87	2

*MeanTCperArt – -Mean Total Citations per Article, N- – number of articles, MeanTCperYear- – Mean Total Citations per Year, CitableYear – Number of Citable Years

journals including Environmental Monitoring and Assessment, Science of the Total Environment, Waste Management, Chemosphere, and Environmental Science and Pollution Research. The second column, located in the centre of the plot, represents the sources. The countries are connected to the sources where they have published their articles. The journal with the highest number of publications is Environmental Monitoring and Assessment, shown with an orange rectangle, which is the largest among all. It is clear from the plot that nearly all the sources have published articles on the impact of landfills on groundwater, indicating a high level of research interest in this topic. The third column on the right displays the additional KeyWords Plus. The 20 most frequently used KeyWords Plus in the articles are presented here. Each is directly linked to the countries and sources in which it was most often used. The most commonly used KeyWords Plus – "landfills" and "groundwater" – are shown with green rectangles and appear to be used in roughly the same number of articles. The visualisation clearly shows that these two keywords plus are the most dominant in the research field. Taken together, the plot indicates that the field is organised around a small set of core environmental themes (landfills and groundwater) that appear across multiple high-output journals, with China acting as a major hub connecting both publication venues and dominant keyword usage.

Table 3 highlights the most active authors in the landfill–groundwater literature and shows how many papers each has contributed. Xi B stands out as the leading contributor with 11 publications. Wang Y and Yang Y follow with nine papers each, reflecting consistent research output over the study period. Van Breukelen Bm and Zhao Y have also played a prominent role, each having published eight articles. The remaining authors listed – Braster M, Dąbrowska D,

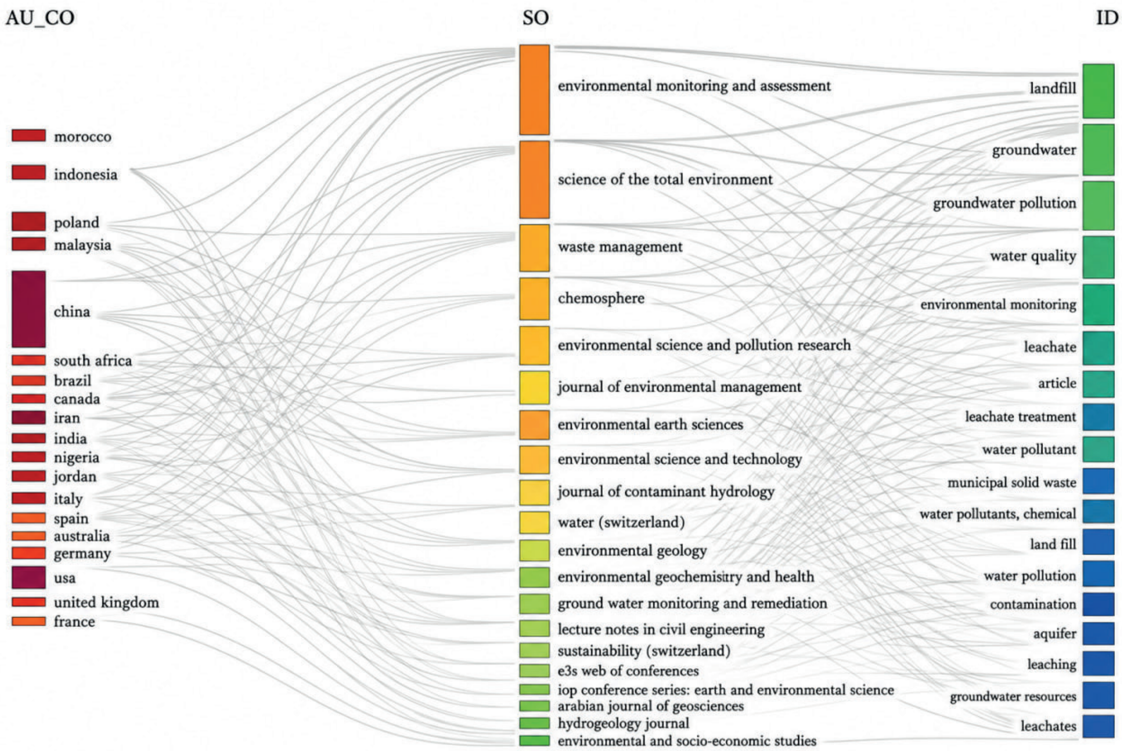

Fig. 1. Three-fold analysis of missing data imputation

Jiang Y, Liu Z and Röling Wfm – have each authored seven papers, placing them among the core group of recurring contributors in this research area. This concentration suggests that a relatively small group of authors provides steady continuity in the topic, which is useful for identifying key research hubs and tracking methodological development across time.

Figure 2 shows, in a simple way, how the ten most productive authors in Table 3 contributed to the "Landfills and Groundwater" literature between 2000 and 2024. Years are shown on the x-axis and authors on the y-axis; each author's line represents their active period, while the circles mark years with publications. Larger circles indicate higher citation impact in that year, and darker circles indicate more publications. Overall, the figure suggests that contributions are not evenly spread over time: some authors were more active in the early years of the field, whereas others became more visible later, especially after the mid-2010s. It also shows that productivity and impact do not always move together – some authors gain strong citations from a limited number of papers, whereas others publish more steadily with moderate citation growth. In short, Figure 3 helps identify both when leading authors were most active and how their publication and impact patterns differ across the field's development.

Table 3. Most relevant authors

Authors	Articles
Xi B	11
Wang Y	9
Yang Y	9
Van Breukelen Bm	8
Zhao Y	8
Braster M	7
Dąbrowska D	7
Jiang Y	7
Liu Z	7
Röling Wfm	7

Figure 3 presents not only the number of publications but also the level of international collaboration, represented by Single Country Publications (SCP) and Multiple Country Publications (MCP). China leads in this field with a total of 95 articles, of which 85 are SCP and ten are MCP. Similarly, India has published 48 articles, comprising 45 SCP and only three MCP; this indicates that, despite a high number of publications, international collaboration remains relatively low. Poland and the United States have each

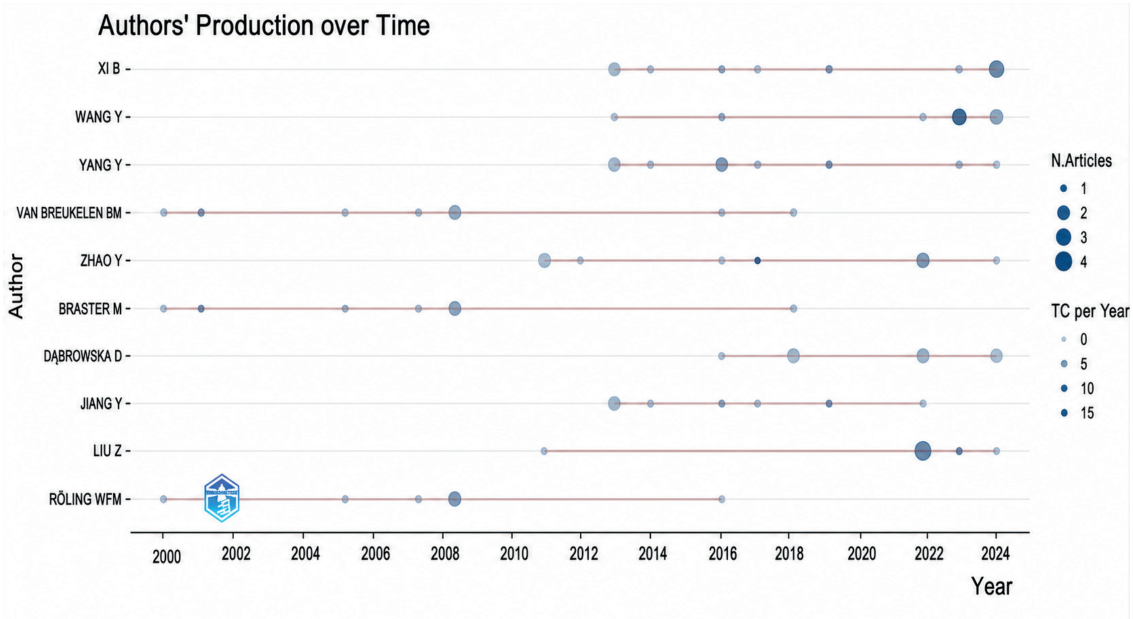

Fig. 2. Authors' production over time

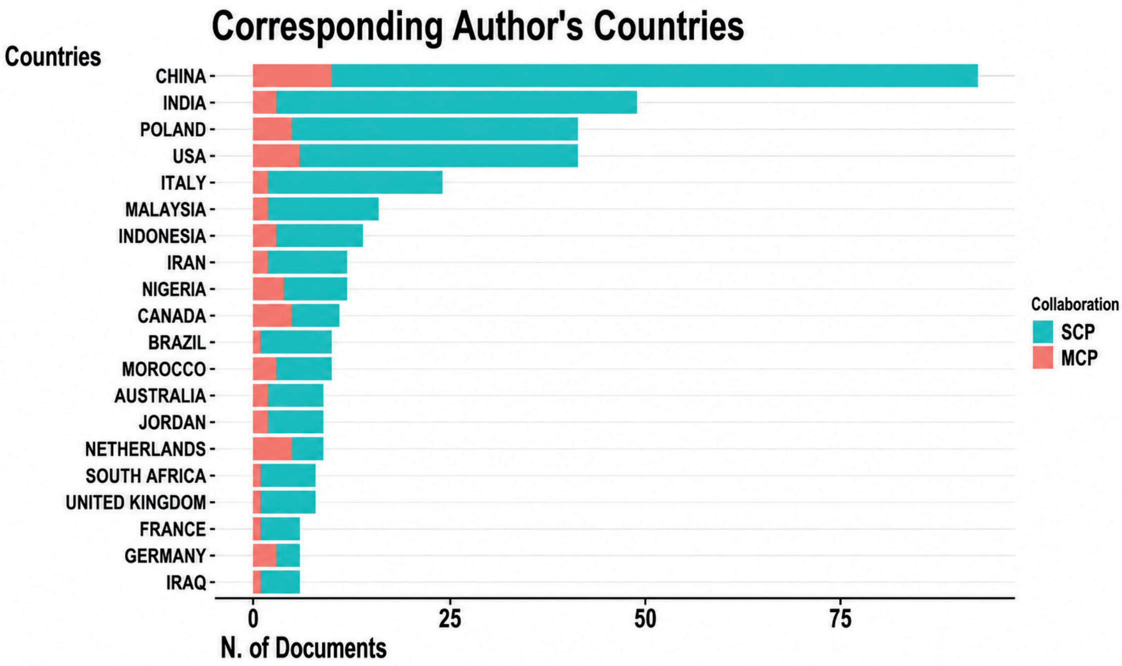

Fig. 3. Corresponding author countries
*\SCP: Single Country Publications, MCP: Multiple Country Publications

produced 41 articles. For Poland, 36 are SCP and five are MCP, while for the US, 35 are SCP and six are MCP. These figures suggest that both countries tend, like India and China, to focus more on domestic research efforts rather than international partnerships. Overall, the SCP–MCP split implies that research output is high but collaboration is comparatively modest, which may limit cross-regional transfer of monitoring practices and standardised assessment frameworks – an important gap for a globally relevant environmental topic.

Table 4 presents the most globally cited documents on groundwater quality near municipal solid waste landfill sites. The most cited article was published in 2006 in Environmental Monitoring and Assessment and has received 567 citations, indicating its strong influence in this research field. Several highly cited studies focus on landfill-related groundwater contamination in countries such as China, India and Egypt, where landfill-related groundwater pollution has been widely studied. The table also shows that many influential articles were published in well-established journals, including Science of the Total Environment, Environmental Monitoring and Assessment, Environmental Science & Technology, and Environmental Pollution. Some of these studies examine emerging contaminants, such as PFAS, pharmaceuticals and personal care products, which are important because they can persist in groundwater and may pose long-term risks to the environment and human health.

Figures 4 and 5 capture the main thematic focuses of the reviewed literature by presenting the 50 most frequently used author keywords drawn from 601 Scopus-indexed papers published between 2000 and 2024 on landfills and groundwater. Figure 4 (the word cloud) offers a quick visual snapshot of the field: keywords are arranged in a dense layout, and their size increases with how often they appear, so the most common terms immediately stand out. The strongest emphasis is clearly on groundwater impacts, with "groundwater pollution" appearing as the most dominant keyword (428 occurrences), followed closely by "groundwater" (401) and "landfill" (400). Several other highly visible terms-such as "water quality", "leachate", "leachate treatment", "environmental monitoring", "contamination", "aquifer/aquifers", "leaching" and "water pollutants" show that the literature repeatedly addresses not only the existence of pollution, but also its main source movement pathways and practical responses. While the word cloud emphasises prominence visually, Figure 5 (the treemap) presents the same keyword set in a more structured and quantitative way. Here, each block represents a keyword, and its area reflects its share of total occurrences, making it easier to compare relative importance. The treemap confirms the same leading themes: "groundwater pollution" accounts for 8% of all keyword occurrences, with "groundwater" (7%) and "landfill" (7%) close behind. A second group of frequently used terms – including "water quality" (5%), "leachate treatment" (4%), "leachate" (4%), "ground water" (4%), and "environmental monitoring" (3%) – suggests that many studies go beyond describing the problem and move toward discussions related to assessment, control and management. The presence of additional recurring terms such as "contamination", "aquifer", "leaching", "leachates", "water pollution", "water pollutant", "chemical water pollutants", "waste disposal", "refuse

Table 4. Most globally cited documents

№	Title	Journal	Total Citations	Year of publication	TC Per Year
1	Leachate Characterisation and Assessment of Groundwater Pollution Near Municipal Solid Waste Landfill Site	*Environmental Monitoring and Assessment*	567	2006	28.35
2	A review of groundwater contamination near municipal solid waste landfill sites in China	*Science of The Total Environment*	320	2016	32.00
3	Impact of landfill leachate on the groundwater quality: A case study in Egypt	*Journal of Advanced Research*	261	2015	23.73
4	Occurrence and ecological potential of pharmaceuticals and personal care products in groundwater and reservoirs in the vicinity of municipal landfills in China	*Science of The Total Environment*	257	2014	21.42
5	Sonochemical Degradation of Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoate (PFOA) in Landfill Groundwater: Environmental Matrix Effects	*Environmental Science & Technology*	251	2008	13.94
6	Relationships between Microbial Community Structure and Hydrochemistry in a Landfill Leachate-Polluted Aquifer	*Applied and Environmental Microbiology*	239	2001	9.56
7	Geochemical assessment of groundwater quality in vicinity of Bhalswa landfill, Delhi, India, using graphical and multivariate statistical methods	*Environmental Geology*	187	2007	10.39
8	Perfluoroalkyl acids in municipal landfill leachates from China: Occurrence, fate during leachate treatment and potential impact on groundwater	*Science of The Total Environment*	185	2015	16.82
9	Contamination of groundwater with per- and polyfluoroalkyl substances (PFAS) from legacy landfills in an urban re-development precinct	*Environmental Pollution*	179	2019	25.57

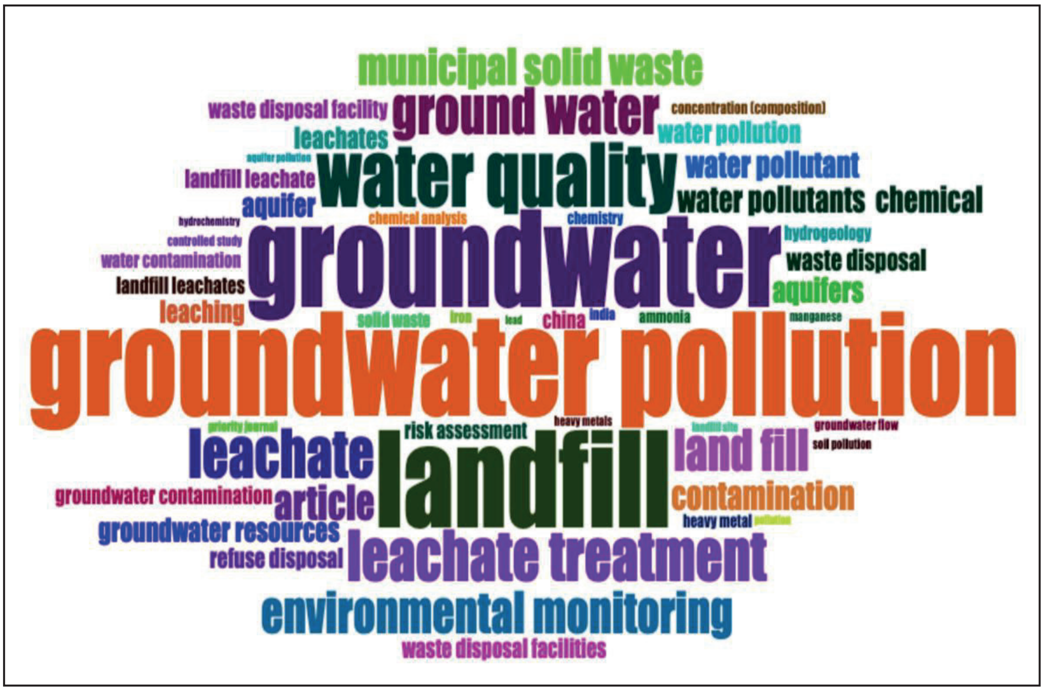

Fig. 4. Word cloud of most frequent keywords

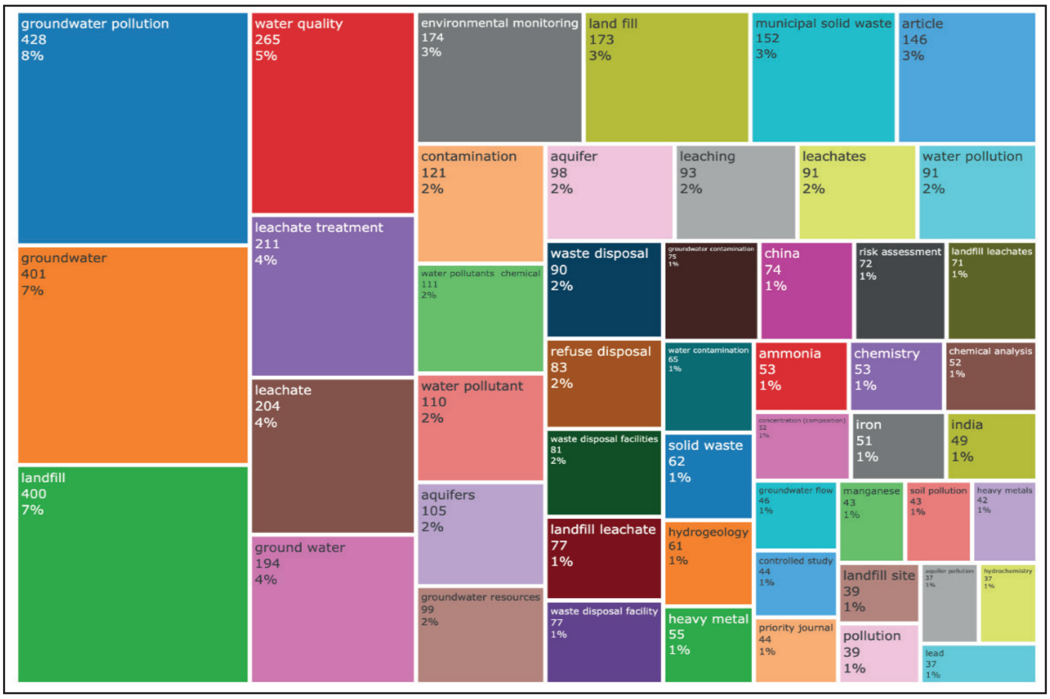

Fig. 5. Tree map visualisation of data

disposal" and "hydrogeology" further highlights the interdisciplinary nature of the field, where hydrochemical analysis, pollutant transport, and waste-management practices are closely connected. Overall, these two figures portray a highly consistent research landscape. Most studies concentrate on groundwater contamination linked to landfills, with strong attention to leachate generation and migration, water-quality and pollutant assessment, and practical themes such as monitoring and treatment. Based on keyword prominence, "groundwater pollution/groundwater/landfill" and the management-oriented terms ("water quality", "leachate", "monitoring", "treatment") represent well-established themes that define the core of the field. In contrast, smaller treemap blocks point to more fragmented or emerging subtopics, which provides a concrete basis for identifying underdeveloped directions that merit deeper investigation in future studies.

Figure 6 demonstrates how the themes discussed in articles about the effects of landfills on groundwater pollution have changed over time. The circular shapes in the graph clearly highlight the times when particular topics became popular. The timeframe from 2020 to 2023 is especially noteworthy for its activity. During this period, terms such as "aquifer pollution", "water contamination", "waste disposal", "landfill", "landfill leachate", "groundwater pollution", "groundwater" and "municipal solid waste" were commonly referenced. The data indicates that "groundwater pollution" was the most frequently mentioned keyword and stayed a key issue from 2008 to 2021. Similarly, the term "groundwater" was extensively researched between 2014 and 2021. The topic of "landfill" was also a significant area of study from 2011 to 2021. In more recent years, phrases like "municipal solid waste landfill" have started to emerge as popular subjects, reflecting an increasing incorporation of contemporary methods and technologies in this field. Overall, the timeline suggests thematic consolidation around long-standing core topics (groundwater pollution/groundwater/landfill), followed by a recent broadening toward more specific operational contexts (e.g., municipal solid waste landfill), indicating a shift from general impact framing toward more applied and system-level problem definitions.

This section evaluates the thematic expansion and significance of research subjects based on academic publications. Figure 7 illustrates a thematic map that organises topics into four segments. Each segment features circles of varying colours and sizes, indicating centrality (i.e., the significance of a topic within the larger research landscape) and density (i.e., the internal maturity and cohesiveness of a topic). Furthermore, the dataset comprises keywords within each cluster, detailing their frequency, centrality and impact values. A total of 14 clusters have been recognised and classified as follows:

The thematic map is divided into four quadrants. The upper-right quadrant represents motor themes, which have both high centrality and high density. These themes are important and well developed within the research field. In this study, water quality, groundwater and aquifer pollution belong to this group, showing that they are central topics in

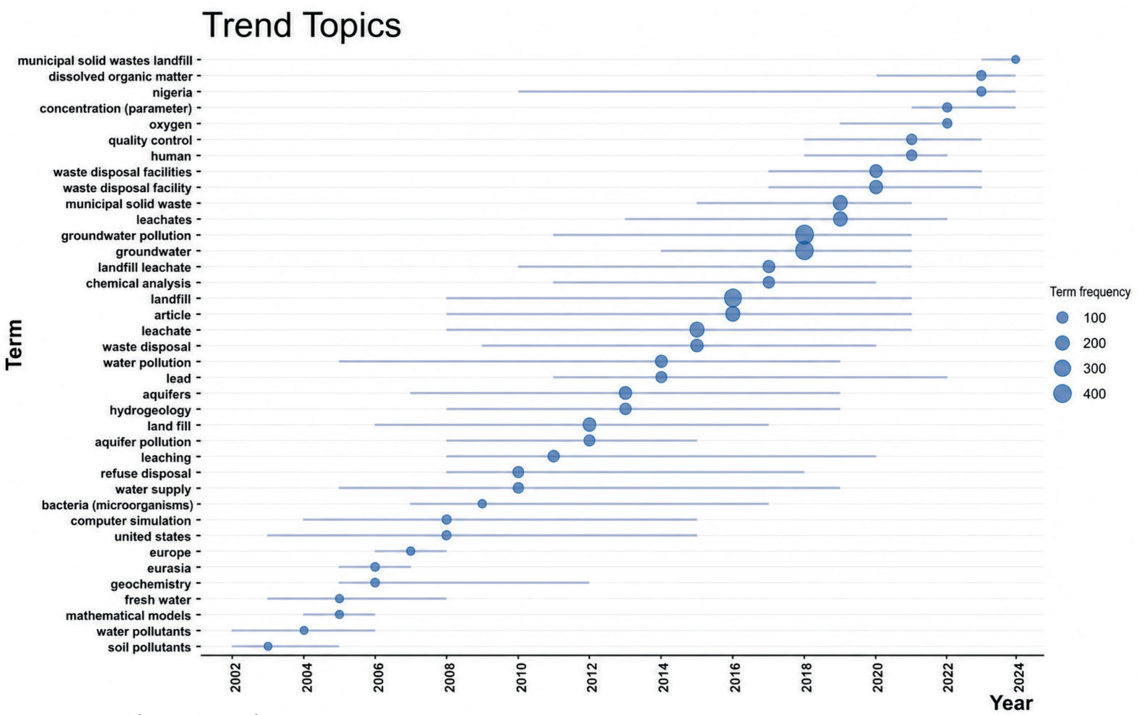

Fig. 6. Trends in research topics

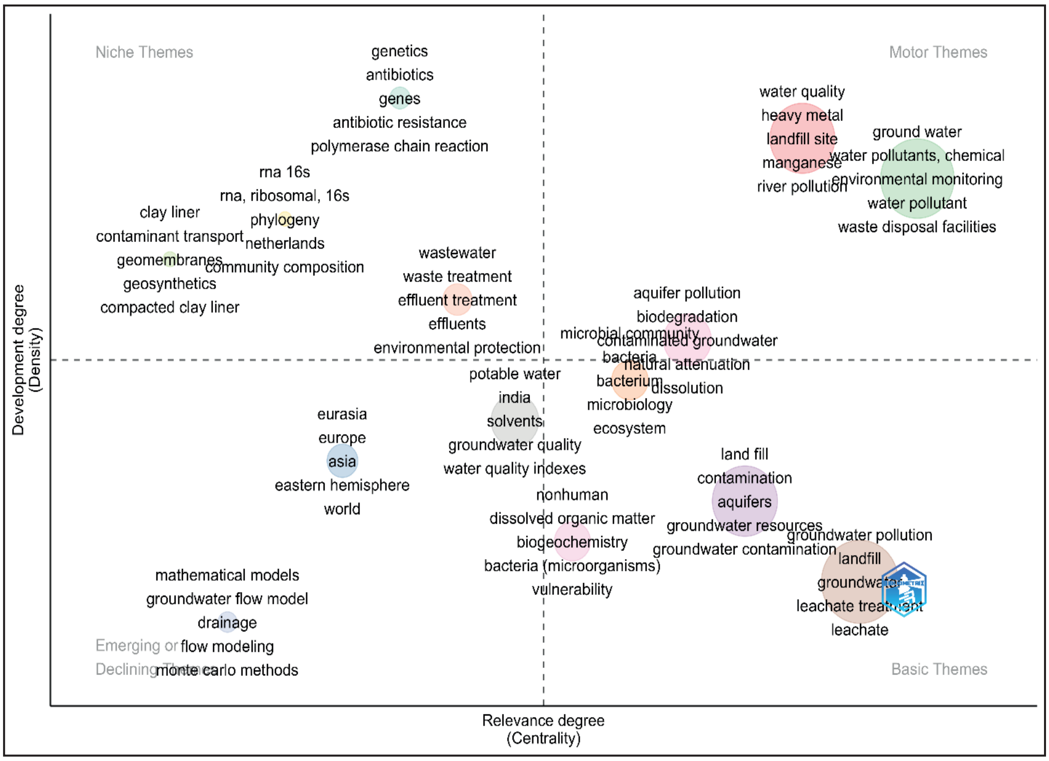

Fig. 7. Thematic map of the impact of landfills on groundwater

landfill–groundwater research. The upper-left quadrant includes niche themes. These themes have high density but low centrality, meaning that they are well developed but less connected to the broader research field. Genetics, wastewater, clay liner and 16S rRNA are included in this group. The lower-left quadrant represents emerging or declining themes, which have both low centrality and low density. Topics such as Eurasia, potable water and mathematical models are located in this quadrant, suggesting that they are either newly developing or receive limited attention. The lower-right quadrant includes basic but underdeveloped themes. These themes have high centrality but low density, meaning that they are important for the field but require further investigation. Landfill, microbial community and groundwater pollution belong to this group. Overall, the thematic map shows that the main research focus is on water quality, groundwater pollution and aquifer contamination. However, some specialised and methodological topics remain less developed and may provide directions for future research.

Discussion

Research on the siting of modern landfills and the protection of groundwater from contamination heavily relies on laboratory analyses and GIS (Mohammadi Seif Abad et al. 2021a). However, this formulation may unintentionally understate the critical role of field-based investigations, which are foundational in groundwater and landfill-related research. Field studies such as groundwater sampling, hydrogeological surveys, in-situ measurements, monitoring well networks and geophysical investigations provide the primary empirical data upon which both laboratory analyses and GIS-based models are built. Therefore, laboratory analyses, GIS tools and field investigations should be acknowledged as complementary and interdependent components within a unified methodological framework rather than treated as isolated approaches. To facilitate a comprehensive bibliometric analysis of the selected articles, we systematically divided them into three distinct methodological categories for in-depth examination. These categories correspond to the primary research approaches identified in the literature: studies centred on laboratory methods, research using GIS, and an integrated approach that combines both. Importantly, this classification is used here to interpret bibliometric patterns and should be more clearly distinguished from technical conclusions about "best" methods in practice. Strengthening this distinction helps the discussion move beyond reiterating the results and instead connects the findings to research gaps and methodological needs. Laboratory analyses are essential for quantifying pollutants and their concentrations, while GIS technologies provide the spatial context for modelling pollution pathways and assessing risk (Safarov et al. 2024). The synergy between these two methodologies is particularly effective for delivering precise and actionable results. Therefore, our analytical framework was designed to evaluate the contribution of each of these approaches to the field (Reed et al. 2021).

Laboratory: Of the 601 articles analysed, 70.5% were based on laboratory studies, which are considered crucial for assessing the environmental impact of landfills. These investigations are particularly important for quantifying oxygen consumption and heavy-metal concentrations (Ye et al. 2019a). The reviewed literature employed a diverse range of methods, including physical, biological, chemical (Hepburn et al. 2019), physico-chemical (Han et al. 2016) and biochemical (Kale et al. 2010) techniques. The chemical laboratory method was the most widely used approach for the accurate measurement of key water and soil pollutants. Furthermore, hydrochemical and factor analyses are frequently applied to pinpoint sources of nitrogen pollution in the shallow groundwater beneath landfills (Han et al. 2020). The resulting data are foundational for evaluating the extent of groundwater contamination and for developing appropriate ecological safety measures (Ye et al. 2019b). From a broader implications perspective, the dominance of laboratory-focused publications suggests that much of the field prioritises pollutant identification and process understanding at local scales. However, a key research gap is the limited scaling of these localised findings into regional vulnerability assessment and decision-making, which typically requires explicit linkage with field monitoring and spatial modelling. However, a significant limitation is that laboratory analyses are typically localised and may therefore be inadequate for assessing broader regional risks.

GIS: Of the articles analysed, 37 (6.15% of the total) used GIS. GIS is a critical tool for analysing landfill location, hydrogeological conditions, and surface structure, all of which are essential for environmentally responsible site selection (Mohammadi Seif Abad et al. 2021b). However, the high cost of conventional monitoring, which relies on regular water sampling and chemical analysis, presents a significant challenge for environmental management around landfills (Korshunov and Nevzorov 2020). For this reason, GIS is particularly useful for predicting pollution and identifying the direction of water flow. Nevertheless, GIS-based outputs are ultimately dependent on the availability and quality of field and laboratory data, and therefore the use of GIS as a standalone approach is most appropriate for screening and preliminary assessments rather than for confirming contamination. Nevertheless, a key limitation is that GIS-based analysis, relying on modelling, can only provide risk assessments and not measure actual contamination levels. Consequently, using GIS as a standalone tool is generally limited to preliminary analyses. The reviewed literature often achieved more effective results by integrating various models such as Modular Finite-Difference Groundwater Flow Model, Modular Three-Dimensional Multi-Species Transport Model, POLLUTE (Contaminant Migration and Transport Model) version 7, Groundwater Modelling System, Artificial Neural Network, Radial Basis Function Artificial Neural Network, Multilayer Perceptron Artificial Neural Network, and (DRASTIC) Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, hydraulic Conductivity within GIS environments (El-Zein and Rowe 2008; Bagheri et al. 2017; Rad and Fazlali 2020). Here, the bibliometric insight is the relatively small share of GIS-centred studies, whereas the technical implication is that GIS becomes substantially more actionable when coupled with empirical field monitoring and laboratory verification and supported by physically based flow/transport or vulnerability models. This integrated approach enhances the predictive capabilities of GIS while acknowledging its limitations in direct measurement. The combination of GIS with other models allows for a more comprehensive and robust assessment of environmental risk.

Combination: This category, which combines laboratory analyses with GIS, comprises 32 articles, or 5.3% of the total. The integration of these two approaches facilitates a more thorough assessment of landfill environmental impacts. Although limited in proportion, this category is forward-looking because it directly addresses an important research gap: translating localised measurements into spatially explicit tools suitable for siting decisions, monitoring prioritisation, and developing groundwater protection strategies. A key challenge in assessing groundwater pollution is that high contamination levels are typically attributed to anthropogenic sources, while natural contamination is often overlooked (Preziosi et al. 2019a). To ensure accurate evaluation, it is essential to establish the natural baseline conditions of a site before landfill operations begin. This allows for a clear distinction between natural fluctuations and pollution resulting from the landfill (Preziosi et al. 2019b). For this reason, the combined use of laboratory analyses and GIS technologies yields more precise data. Within the reviewed literature, models such as the DRASTIC model and the Environmental Risk Index, mathematical index (El Naqa 2004; Christenson et al. 2012; Najafi Saleh et al. 2020), were frequently used in conjunction with laboratory analyses. This process involved applying spatial interpolation and creating thematic maps, an approach that proved to be both scientifically sound and practically effective.

Of the articles analysed, 108 did not fall into the three primary categories. These studies employed different methodologies that were not the focus of our bibliometric analysis, which concentrated on laboratory, GIS, and integrated approaches. Rather than being treated only as "other", these studies may signal methodological diversification and the need for stronger interdisciplinary integration (hydrogeology, geochemistry, spatial analysis, monitoring design, and governance) so that bibliometric insights can better inform practical landfill management and groundwater protection. Based on the preceding analysis, the integrated use of laboratory and GIS technologies represents the most effective and reliable method for assessing environmental risks associated with landfills (Eghtesadifard et al. 2020). This approach is superior because it combines the precise modelling of risk zones with the confirmation of actual pollutant presence (Chadalavada et al. 2025). Although such integrated analyses are not yet widespread, their scientific and practical significance is considerable. The effectiveness of this combined methodology has been corroborated by international studies (Kurtaliqi et al. 2024). For instance, in a groundwater study in India, (Mishra et al. (2018) highlighted that the joint application of laboratory and GIS methods provides an effective monitoring tool for controlling contamination risks around landfill sites. This approach is highly valuable for policymakers and the public, as it offers a robust framework for informed decision-making. A similar application was reported in a study from Iran by (Najafi Saleh et al. 2020). These examples underscore the practical value of integrating laboratory analyses with GIS, demonstrating that this third, integrated approach is not only scientifically sound but also delivers actionable results. Therefore, future research and landfill management strategies should prioritise the development and application of this comprehensive methodology to achieve more accurate and effective environmental risk assessments.

Conclusion

This bibliometric study, based on the analysis of 601 articles, reveals a two-stage trend in publication volume over the examined period. Initially, the number of publications showed a decline, followed by an increase. The most prolific authors and research hubs are concentrated in China, the United States, India and Poland. The research was systematically categorised into three main methodological directions. The most prevalent approach was laboratory-based studies, which are widely applied for assessing the impact of landfills on groundwater. The second most common direction involved GIS, primarily used for spatial interpolation and map generation. The third, and most effective, direction consisted of studies that integrated both laboratory analysis and GIS. These combined approaches consistently proved to be the most reliable and accurate in yielding results. These bibliometric outcomes can be translated into several practical use cases. First, they provide a clear rationale for method selection in environmental impact assessments and routine groundwater monitoring near landfill sites: where possible, teams can combine laboratory hydrochemistry with GIS-based spatial analysis rather than relying on a single approach. In practice, GIS can be used to delineate priority monitoring zones, support the choice of sampling locations and visualise hotspots, while laboratory results verify contaminant profiles and trends over time. This combination helps practitioners make concrete decisions on monitoring-well placement, the parameters to test, and the sampling frequency, especially in hydrogeologically sensitive areas. Second, the concentration of research hubs in China, the United States, India and Poland offers guidance for capacity-building and collaboration. Institutions in regions with limited representation in the literature can use this evidence to identify potential partners and training directions, focusing on the technical skills most commonly applied in the field (leachate characterisation, groundwater quality assessment, and GIS-supported spatial evaluation). This can also inform funding and equipment priorities, such asfor example investing in laboratory analytical capability alongside basic geospatial infrastructure for mapping and decision support. However, a key limitation of this study is its reliance on a single bibliometric database. Future research should therefore incorporate data from a wider range of international databases to achieve a more comprehensive and global perspective. To further strengthen practical relevance, future bibliometric work could explicitly link dominant research themes to specific management actions – such as improving leachate control measures, tightening groundwater monitoring requirements, or evaluating remediation performance across different landfill types and sizes. To further advance this field, future studies should not only focus on large-scale areas but also investigate the specific challenges of small- and medium-sized landfills. It is also recommended that future research adopt an integrated approach, incorporating economic, social and political factors alongside environmental assessments. This holistic framework would provide a more effective foundation for developing sustainable solutions to the complex challenges associated with landfill management.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: ST, MJ; data collection: ST, ZK; statistical analysis: ST, MJ, ZK, ZD, MK; manuscript preparation: ST, MJ, ZD, MK; literature review: ST, ZK, MK.

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Received 2 September 2025
Accepted 5 March 2026