

Pharmaceutical Footprint in the Environment: A Research Landscape and Bibliometric Analysis (1997-2024)

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ABSTRACT

Pharmaceutical footprints refer to the environmental impacts of pharmaceutical production, including greenhouse gas emissions from raw material processing to disposal. Despite extensive research, the impact of pharmaceuticals on ecosystems remains a significant concern due to the lack of comprehensive literature on this topic. This study presents a critical analysis of the research landscape of Pharmaceuticals in the Environment (PHEN) using Bibliometric Analysis (BA). The Scopus database was utilised to analyse publications on PHEN from 1997 to 2024 by examining publication trends, key stakeholders, social networks, and thematic areas. The findings revealed 314 publications (comprising 198 articles, 97 reviews, and 19 conference papers) after identifying and screening publications from Scopus. The publication's output and citation trends suggest that stakeholders' interest in PHEN increased over the study period. The top researchers are D. À. Barceló and A. B. A. Boxall (with 7 publications each), whereas the *Uniwersytet Gdański* and the University of York are the top affiliations. The European Union and the United States are the top funders and countries. The PHEN research landscape is characterised by academic and industry collaborations, particularly in the United Kingdom. The keywords co-occurrence analysis revealed that PHEN research is currently focused on 3 main areas: "pharmaceutical environmental risk", "aquatic pollution impact", and "pharmaceutical drug research". Future research should focus on developing integrated assessment models, innovative technologies, life cycle assessments, and cost-effective monitoring systems to enhance policy development and public awareness of human-environment pharmaceuticals.

Keywords: Aquatic Pollution, Bibliometric Analysis, Ecotoxicology, Pharmaceutical Footprints, Research Landscape.

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INTRODUCTION

The increasing presence of pharmaceuticals and their derivatives in ecological systems is a significant concern (Nikolaou *et al.*, 2007), particularly considering the constantly changing environment. The complex interrelationship between pharmaceuticals and the environment has been exacerbated by the widespread manufacturing and consumption of these products around the globe (Valavanidis *et al.*, 2014; Velagaleti and Gill, 2001). Pharmaceuticals, chemical residues, and their derivatives are commonly found globally in terrestrial, aquatic, and atmospheric zones (Adjei *et al.*, 2022; Carter *et al.*, 2014; Li *et al.*, 2019). Although pharmaceuticals are fundamental to human and animal health, their residues frequently enter the environment via excretion, improper disposal of unused medicines, and industrial effluents, where they persist as contaminants in water,

soil, and biota. In this article, pharmaceuticals refer to Active Pharmaceutical Ingredients (APIs) and their metabolites used in human and veterinary medicine, including prescription and over-the-counter drugs that can enter environmental compartments through manufacturing, use, and disposal.

There is a growing demand for comprehensive investigations on the nature, fate, occurrence, and impact of pharmaceuticals on human, wildlife, and ecosystem health. Due to pharmaceuticals' short- and long-term impacts, the last two decades have witnessed an increased discourse surrounding their environmental impact (Chauhan *et al.*, 2022; Sumpter *et al.*, 2022). This dynamic has created a critical research niche to identify, examine, and highlight the complex interplay between human health, industrial practices, and ecological systems.

Numerous studies have been published covering a wide range of topics related to pharmaceuticals in the environment. Studies have highlighted the occurrence, consequences, and impacts of pharmaceuticals and related chemical substances on human health and the environment (Desbiolles *et al.*, 2018; Gworek *et al.*, 2020; Halling-Sørensen *et al.*, 1998; Ibáñez *et al.*, 2021; Ngqwala and Muchesa, 2020). Particular areas of interest include the analysis of pharmaceuticals as endocrine-modifying materials



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(Arcand-Hoy *et al.*, 1998; Bayen *et al.*, 2013; Biswas *et al.*, 2021), as well as risk assessment and management (Cooper *et al.*, 2008; dos Santos *et al.*, 2021; Godoy *et al.*, 2015; Schulman *et al.*, 2002; Walter and Mitkidis, 2018) relating to human health and safety. Other studies have sought to address pharmaceuticals' threats to wildlife and ecosystems, highlighting the necessity of preventive measures and public awareness.

Furthermore, techniques for identifying and removing pharmaceuticals, residues, metabolites, and active chemical compounds from various aquatic and terrestrial environments have been examined in detail (Cuong *et al.*, 2011; Heberer, 2002; Kermia *et al.*, 2016; Neha *et al.*, 2021; Pal *et al.*, 2022). For example, various research teams have proposed using practical innovations such as mass spectrometry to promptly and efficiently identify pharmaceuticals and their metabolites (Borman *et al.*, 2008; Chen *et al.*, 2005; Evans and Kasprzyk-Hordern, 2014; Kosjek *et al.*, 2007; Mohamed *et al.*, 2012). Other analytical methodologies include mid-infrared spectroscopy and fast liquid chromatography to address issues related to the occurrence, fate, and removal of pharmaceuticals (Druy, 2004). Recent advancements have demonstrated the potential of nano-adsorbents (Neha *et al.*, 2021) and biomaterials (Bayoumy *et al.*, 2020) to eliminate hazardous pharmaceutical compounds.

Given its importance, numerous studies in the Scopus database have published critical reviews on the topic's scientific growth and technological developments. These include diverse topics, including the occurrence and fate of pharmaceuticals (Ruan *et al.*, 2019), health and environmental concerns (Khan *et al.*, 2020; Nguyen *et al.*, 2023; Tahiri *et al.*, 2023), safety climate and performance (Otitolaiye *et al.*, 2026), removal techniques (Eniola *et al.*, 2022; Fraiha *et al.*, 2024; Ghazal *et al.*, 2022), bioaccumulation (Sokołowski *et al.*, 2024), and prospective tactics for reducing the environmental impact (Helwig *et al.*, 2024). Further analysis revealed that despite numerous articles and review papers on pharmaceuticals in the environment, no study has examined the research landscape.

Therefore, this study aims to critically analyse the pharmaceuticals' environmental research landscape using publication trends and bibliometric analysis and to help fill parts of this research gap by mapping key stakeholders, collaboration patterns, and thematic hotspots in PHEN research. Bibliometric analysis is a powerful approach for quantitatively evaluating patterns, trends, and scientific output in a particular topic (Donthu *et al.*, 2021; Otitolaiye and Abd Aziz, 2023). This study analyses a large amount of material published in the last 25 years using bibliometrics. This analysis will provide insights into the global distribution of research efforts and collaborative networks and identify the most significant articles and prolific authors. The manuscript also identifies research gaps and prospects for the field because the dynamic nature of pharmaceutical production,

consumption patterns, and emerging toxins requires constant scientific investigation and adaptation.

METHODOLOGY

The study aims to map and analyse the research landscape of the sources, fate, occurrence, effects, and removal of Pharmaceuticals from the Environment (PHEN) using Bibliometric Analysis (BA). To accomplish this task, a search query was devised based on the primary keywords on the topic to identify related publications in the selected scientific database. On 2 January 2025, a structured search was conducted in the Elsevier Scopus database to identify publications on Pharmaceuticals in the Environment (PHEN). The search used the query 'TITLE-ABS-KEY (pharmaceutical* AND NOT "personal care product*" AND environment)' and was limited to English-language documents classified as articles, reviews, or conference papers.

The publication year filter was set to include records from 1997 to 2024. Scopus was selected because it provides broad international coverage of peer-reviewed journals, conference proceedings, and review articles in environmental science, pharmacology, and public health, which are central to PHEN research. The initial search retrieved a total of 1,256 documents. The recovered documents were then screened to remove unconventional document types (e.g., editorials, notes, trade publications, and short news items), non-peer-reviewed records, and non-English publications using the LIMIT-TO and EXCLUDE functions in the Scopus database. Only documents classified as English-language were retained to ensure consistent interpretation of titles, abstracts, and keywords. The screening process was based on the "front page" filtering method described in the literature (Ho, 2013; Ho and Fu, 2016; Nyakuma *et al.*, 2023). This approach ensures that only documents with the primary keywords are found in the title and abstract of the selected publication. After this screening process, 314 publications on the PHEN research landscape (198 articles, 97 reviews, and 19 conference papers) were retained and analysed further. Figure 1 presents a flowchart of the methodology adopted in this study.

The recovered documents were subsequently subjected to bibliometric analyses, including: (i) publication trends, (ii) social network, (iii) stakeholder, and (iv) keyword co-occurrence analyses in PHEN research. These four dimensions were selected to capture complementary aspects of the PHEN research landscape: temporal growth (publication trends), collaboration structures (social network), leading actors (stakeholder analysis), and thematic hotspots (keyword co-occurrence). In this study, we prioritised mapping the structure and thematic evolution of the field, so citation-based indicators (e.g., citation counts, field-weighted citation impact) were not used as primary measures, given their sensitivity to publication age and disciplinary citation norms.

Bibliometric analysis was chosen because it enables researchers to quantitatively evaluate large datasets, uncover collaboration networks, identify influential contributors, and highlight thematic hotspots (Nyakuma *et al.*, 2021; Otitolaiye *et al.*, 2022). This approach is particularly suitable for PHEN research due to its interdisciplinary nature, spanning environmental science, pharmaceutical studies, and public health.

RESULTS AND DISCUSSION

General publication trends

The temporal variations in the total annual publications on PHEN research are depicted in Figure 2. As observed, the number of publications between 1997 and 2024 ranged from 1 to 26 (or an average of 11.21), culminating in a total of 314. The data shows that there has been a steady rise in publications on the topic, which could be ascribed to the growing concerns about the discharge of pharmaceuticals into the environment, posing human health and occupational safety risks. As such, there has been increased scientific interest within the scientific community with concerted efforts to explore the nature, extent, and impacts of pharmaceuticals on humanity and the environment.

The attention given to PHEN by researchers and other major stakeholders in the scientific community has also soared over the years, owing to social impact, increased collaboration, funding, and policy decisions, which can cumulatively impact any field of research. Based on the findings shown in Figure , the number of publications and scientific interest in this topic will continue to increase. Therefore, the number of stakeholders (researchers, affiliations, countries, and funding bodies) is expected to increase.

Stakeholder analysis

In this study, stakeholders are defined as the main actors contributing to the PHEN research landscape, namely authors, their institutional affiliations, countries, and funding organisations involved in producing the indexed publications. The composition of stakeholders in research typically includes authors/researchers, affiliations, funding organisations, and countries actively involved in the research landscape (Ajibade *et al.*, 2023a; Wong *et al.*, 2020b). Typically, stakeholders are directly or indirectly engaged in activities related to scientific growth and technological development (Nyakuma *et al.*, 2021; Otitolaiye *et al.*, 2026). The top stakeholders in the area were deduced from publication data recovered from the Elsevier Scopus database. Although Scopus does not capture the entire universe of scientific publications, it is widely used in bibliometric studies and provides extensive international coverage of peer-reviewed sources in environmental and pharmaceutical sciences, making it suitable for mapping PHEN research. Figures 3 (a-d) show the top 5 researchers, organisations, nations, and funders. The data is based on the publication output of PHEN research among stakeholders across the globe.

As Figure 3(a) shows, the top researchers in the field are *D.À. Barceló* and *A.B.A. Boxall*, each with 7 publications. High publication rates are typically ascribed to research affiliation, country of residence, and funding availability. The impact of researchers' affiliations can be examined by analysing their outputs within the research landscape, as shown in Figure (b). The most productive affiliations are the *Uniwersytet Gdański* and the *University of York*, each with 8 publications. The productivity of the *University of York* (United Kingdom, UK) is mainly due to the research efforts of *A.B.A. Boxall* and peers, whereas that of *Uniwersytet Gdański* is due to *P. Stepnowski*. Another notable affiliation is *AstraZeneca*, an international pharmaceutical company based in the UK. The company's presence in the top five most productive affiliations shows that the PHEN research landscape is characterised by strong collaborations between academia and industry, particularly in the UK. The presence of *AstraZeneca* among the most productive affiliations suggests that parts of the pharmaceutical industry are actively engaged in PHEN research. Such involvement may reflect strategic interests in improving environmental performance, anticipating regulatory requirements, and exploring competitive advantages associated with greener products and processes. At the same time, industry-funded research may prioritise topics aligned with business continuity, underscoring the importance of transparency and balanced participation of public and academic stakeholders in this field. According to various commentaries, these collaborations can significantly transform the research environment by encouraging innovation, information transfer, and an emphasis on applied research (Bozeman *et al.*, 2013). Collaborations can also hasten the transition from academic discoveries to real-world applications, which propel the creation of ground-breaking technologies, goods, and services (Klarin, 2019). Partnerships between industry and academia also help commercialisation efforts, technology transfer, and policy creation (Chai and Shih, 2016). Such collaborations can also pave the way for interdisciplinary methods, resource sharing, and workforce development, all of which contribute to knowledge creation, scientific progress, and advanced economic development.

Further analysis revealed that three out of the top five affiliations in PHEN research are based in the UK. Despite being a global concern, PHEN research on pharmaceuticals' nature, fate, sources, and impacts has been prioritised in the UK because of its potential effects on human health, safety, and ecosystems (Wong *et al.*, 2003). When discharged into the environment without proper treatment, pharmaceuticals can cause long-term disruption and harm to terrestrial and aquatic species, resulting in resistance to medicines such as antibiotics (Bilal *et al.*, 2019; Pal *et al.*, 2022; Valavanidis *et al.*, 2014). Increasing public awareness and stricter rules can motivate further studies to determine the scope of the problem and create plans to adhere to environmental standards. Finally, the PHEN research landscape is closely related to Sustainable Development Goals on clean water and

sanitation (SDG 6), life below water (SDG 14), and life on land (SDG 15), because many of the analysed publications address pharmaceutical contamination of freshwater systems, aquatic ecosystems, and terrestrial environments and the measures needed to protect them (UN, 2015, 2024).

Despite significant efforts and research progress in the UK, the nation with the most publications on the topic is the United States of America, with 58, which is followed by the United Kingdom (40) and China (26), as shown in Figure (c). In our dataset, publications with at least one US-based affiliation account for a substantial share of PHEN output, indicating that US institutions play a central role in the global collaboration network on this topic. However, given that Scopus does not index the entire universe of scientific publications, these figures should be interpreted as indicative rather than exhaustive. Germany and India are tied in 4th place, each with 24 publications. The dominance of the US in the PHEN research landscape could be attributed to the nation's comprehensive guidelines that mandate the strict regulation and monitoring of pollutants, such as pharmaceutical residues, in the environment. Examples of such policies include the Safe Drinking Water Act, the Resource Conservation and Recovery Act, and the Clean Water Act. Examples of such policies include the Safe Drinking Water, Resource Conservation and Recovery, and Clean Water Acts (USEPA, 2026a, 2026b). All of which seek to curb or mitigate pollutant release or impact on human health and the environment. Likewise, the existence of

government agencies at the federal, municipal, and local levels, such as the Environmental Protection Agency (EPA) and the National Institutes of Health (NIH), is mandated to provide oversight of monitoring, regulation, and research funding in such areas. The US is also aptly positioned to lead in PHEN due to its state-of-the-art research infrastructure, widespread regulatory systems, and multidisciplinary know-how, promoting innovative researchers in the landscape. Lastly, possible drivers of the United States' leadership in this research landscape include strong collaborations between academia and industry, extensive research infrastructure, and long-standing investment in applied environmental and public health research. However, this study does not quantify the proportion of the global PHEN publication universe that involves US institutions, so this interpretation should be viewed as indicative rather than a definitive comparative ratio.

Figure (d) shows that the top funder of PHEN research is the European Commission, with 18 sponsored research studies, which is followed by the National Natural Science Foundation of China (11 publications) and the European Regional Development Fund (9 publications). In contrast, PHEN research involving US institutions in this dataset appears to be supported by a diverse mix of national agencies (for example, environmental and health research funders) and international programmes, many of which are grouped into broader "other" categories in Scopus funding data. As a result, US-specific funding sources cannot be fully disaggregated from the available records and should

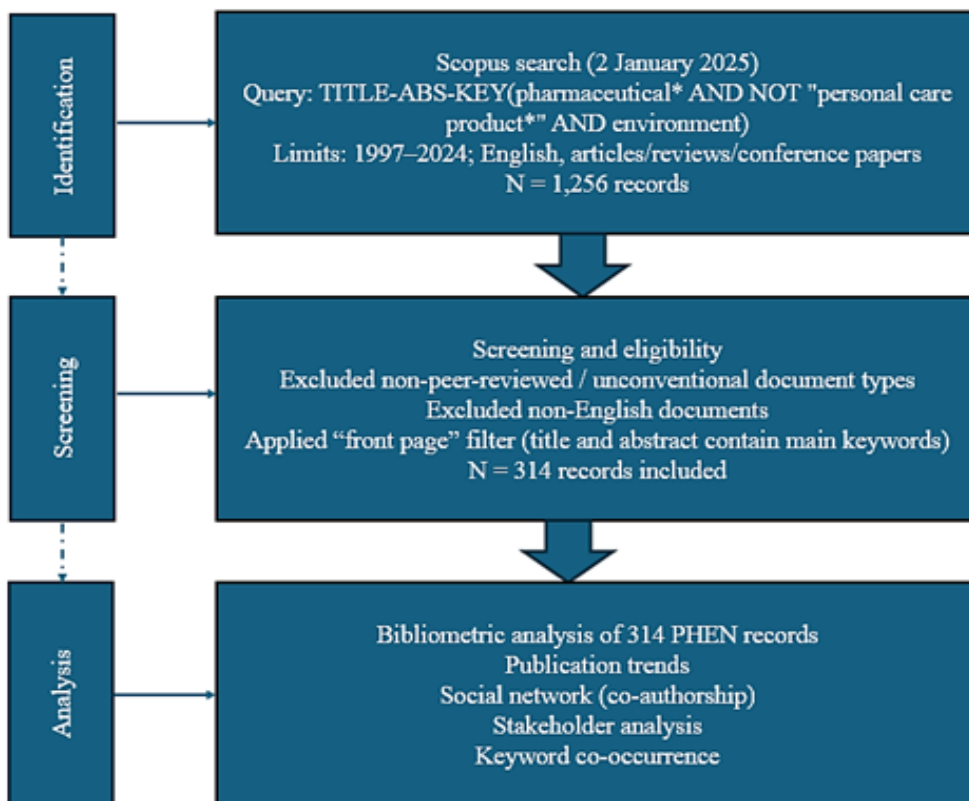


Figure 1: Flowchart of the study methodology.

be interpreted with caution. The analysis of the PHEN research landscape, therefore, shows that no single nation or international agency dominates the funding climate in the area. This indicates that the research landscape is characterised by a distributed and distinct funding framework, with support from various private, public/government-based, and international sources. This funding diversity reveals the globalised nature of the PHEN research landscape and has necessitated the adoption of tailored processes to address region-specific challenges in the field.

Over the years, the significant impact of PHEN research has impacted humanity, health, and ecosystems and resulted in numerous publications, many of which are highly cited. The top ten most-cited publications on the PHEN research landscape are shown in Table 1.

As observed in Table , the top 10 most-cited publications have been cited between 456 and 2795 times (i.e., an average of 1186.5) over the years. Further analysis shows that 6 of the top 10 were reviews, whereas 4 were articles. The most highly cited publication is “Occurrence, fate, and effects of pharmaceutical substances in the environment- A review” by Halling-Sørensen *et al.* (1998), cited 2795 times. The authors demonstrated that the widespread use of antibiotic-based feed additives and growth promoters as micropollutants has potential adverse biological effects. As such, the paper highlighted the various routes of exposure, policy guidelines, and existing information on the nature, occurrence, and impacts of such pollutants, which hitherto have been reported in the literature. Other notably highly cited publications are “Occurrence, fate, and Removal of Pharmaceutical Residues in the Aquatic Environment: A Review of Recent Research Data” by Heberer (2002) and “Pharmaceuticals in STP Effluents and their solar photodegradation in aquatic environment” by Andreozzi *et al.* (2003), which gained 2441 and 1121 citations, respectively.

Overall, the top 10 most highly cited publications focused on ways to address PHEN. The emphasis has been on aquatic ecosystems to characterise their occurrence, fate, effects, and removal methods critically. Reviews have drawn attention to the widespread presence of pharmaceutical chemicals in many environmental spheres, such as rivers, soils, and wastewater from sewage treatment plants worldwide (Li, 2014). Potential mitigation measures, including solar photodegradation, advanced oxidation processes, membrane filtration, and adsorption on activated carbon or Nano adsorbents, have also been presented in these studies (Andreozzi *et al.*, 2003). Studies have also explored the environmental problems caused by pharmaceuticals and stressed the importance of using green chemistry techniques (Khetan and Collins, 2007). Furthermore, some studies have examined the prevalence and fate of pharmaceutically active chemicals by concentrating on specific case studies, such as the Hölje River in Sweden (Bendz *et al.*, 2005). Further investigations are required into the effects of pharmaceuticals on the environment, along with long-term, practical, and sustainable solutions.

Social network analysis

The stakeholders' high citation and publication rates, particularly for researchers and countries, indicate that numerous factors play crucial roles. One such factor is collaboration among stakeholders in the global PHEN research landscape. Therefore, the extent of stakeholder collaboration was examined using co-authorship analysis in VOSviewer, following established social network and bibliometric approaches (Arruda *et al.*, 2022; Wasserman and Faust, 1994). Figures 4 and 5 present Network Visualisation Maps (NVMs) of collaborations among stakeholders in the PHEN research landscape.

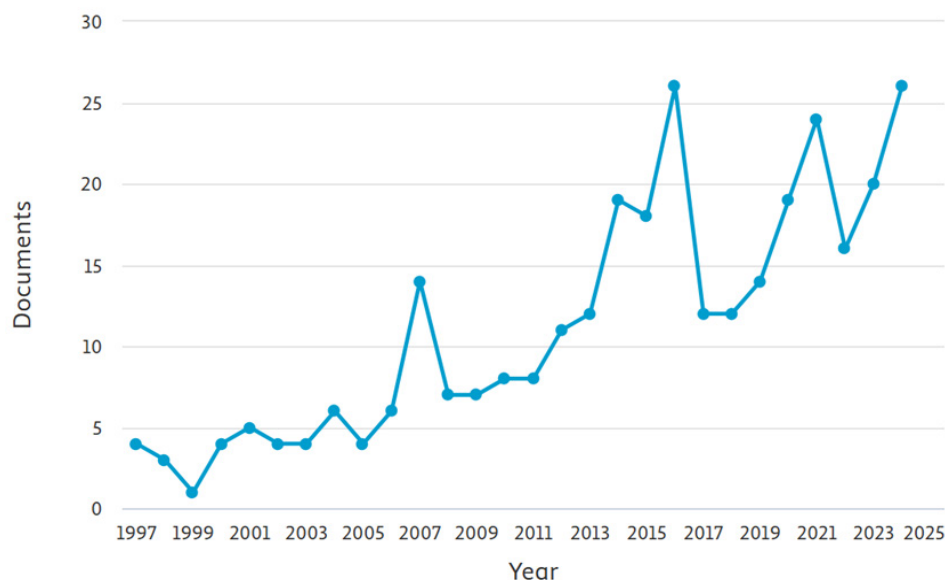


Figure 2: Temporal variation in publications output on PHEN (1997-2024).

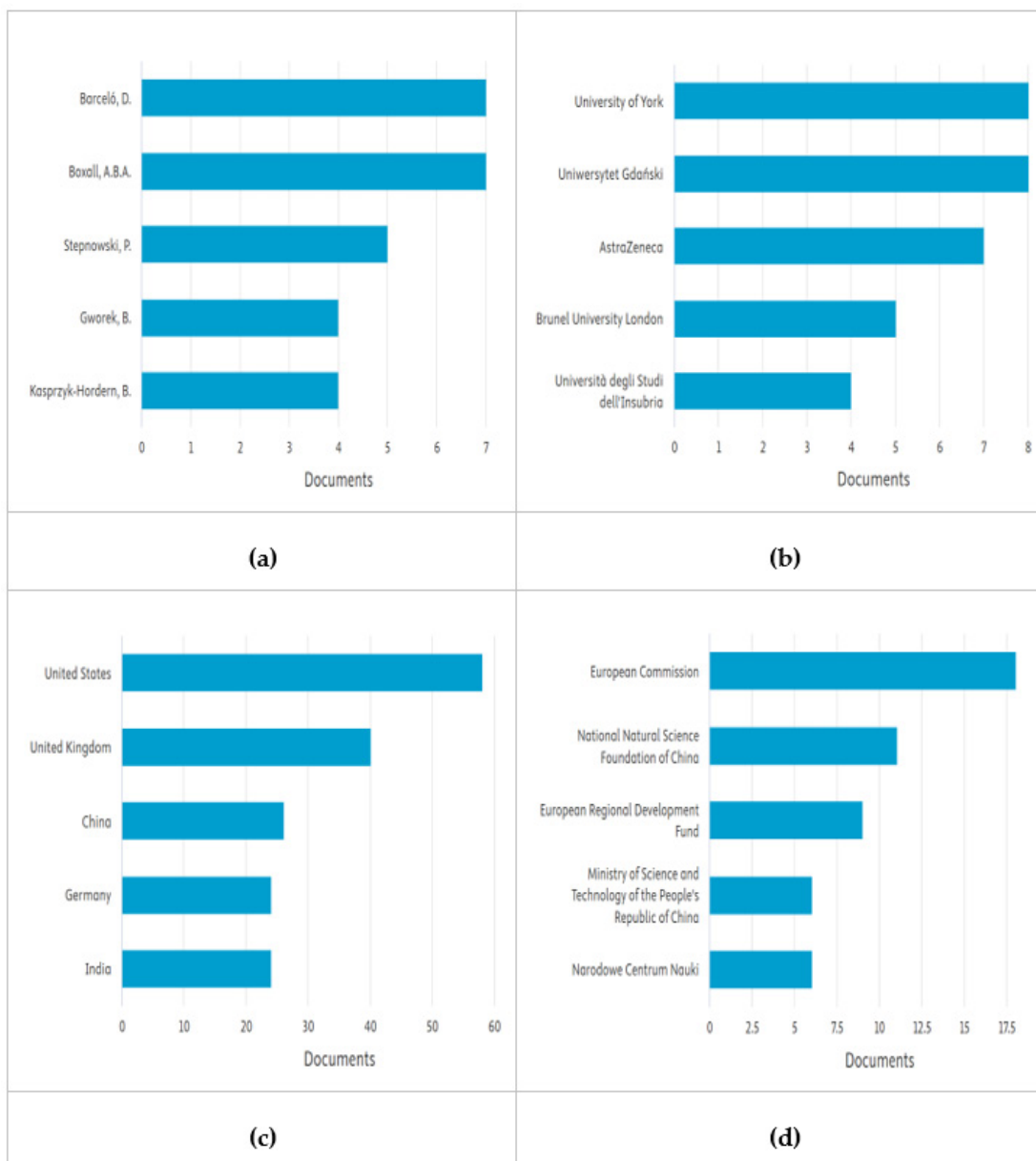


Figure 3: Top stakeholders in the PHEN research landscape.

Figure 4 shows the NVM for co-authorship among researchers in PHEN Research. The NVM depicts the network of co-authors and the collaborative patterns among the top authors in the field. The nodes and sizes denote authors and their productivity levels, whereas the links between nodes indicate co-authorships. The lines and thickness between the nodes denote the strength of the collaborations between the authors. The NVM shows 10 items, 3 clusters, links of 21, and Total Link Strength (TLS) of 24. In these maps, each link represents a co-authorship relationship, and the Total Link Strength (TLS) quantifies the overall strength of an item's connections to others in the network.

As observed, there are three significant clusters of researchers with extensive co-authorship in the research landscape, as shown by the various links and nodes. The largest cluster (red) comprised

authors such as Arnold KE, Boxall A.B.A., Brown AR, and Madden JC, whereas the smallest cluster (blue) comprised Gaw S, Hutchinson TH, and Thomas KV. Further analysis shows that only 10 of the 33 researchers with two or more publications have engaged in various co-authored publications. This indicates that the rate of co-authorship and collaboration among researchers was low at 30.30%. Hence, it could be reasonably inferred that collaboration and co-authorships are not the primary factors responsible for the high rate of publications among researchers in the PHEN research landscape.

Figure 5 shows the network visualisation map for co-authorship among countries actively involved in the PHEN research landscape. The map also shows four significant clusters of nations that have actively co-authored publications on this topic.

The largest (red) cluster includes Canada, Germany, Italy, and Sweden, while the smallest has France and Spain. Further analysis shows that 12 of the 68 nations have co-authored 10 or more publications, which indicates a collaboration rate of 17.64% in the research landscape. The highest TLS was observed for the United Kingdom 14, the United States 13, and Spain 10, which indicates these are the dominant nations in the PHEN landscape over the years examined in this study.

Hotspot and thematic area analyses

Analysing research hotspots or thematic areas in any field provides critical insights into current and emergent areas (Ajibade *et al.*, 2023b). Typically, this analysis is conducted using the author and indexed keywords that occur frequently in searches for a topic (Wong *et al.*, 2022). This study used the keyword co-occurrence analysis feature in VOSviewer to examine the research hotspots and thematic areas, as also deployed in the literature (Wong *et al.*, 2020a). Figures 6 (a, b) show the network and overlay visualisation maps of the significant keywords occurring in PHEN research. The Network Visualisation Maps (NVM) and Overlay Visualisation Maps (OVM) show that out of the 3948 keywords on PHEN research, 16 occurred 50 times or more during the search and analysis, which resulted in 3 major clusters (comprising 4 to 8 keywords), 120 links, and TLS of 4,111. The highest occurring keywords (occurrences) are drug (130), pharmaceutical preparations (108), and human (92), whereas

the highest TLS (frequency) are drug (818), pharmaceutical preparations (733), and water pollutants/chem (656).

Furthermore, the Keyword Co-Occurrence (KCO) showed that, based on occurrences and TLS of primary keywords, drugs, pharmaceutical preparations, humans, and water pollutants/chem are the most intricately linked keywords on the research landscape on PHEN based on the occurrences and TLS. Despite being fundamental to the health of humans, “pharmaceuticals” typically wind up in the environment as pollutants in water due to misplaced methods of disposal of human waste and industrial emissions. Such chemical-based pollutants (such as active medicine residues) could also end up in water sources, potentially harming water ecosystems and jeopardising the health of people and animals alike. On the other hand, the keywords “pharmaceutical preparations” emphasise the importance of responsible waste management in their formulation and production processes to prevent environmental contamination. Lastly, the keyword “Human” highlights humanity's critical role in creating various techniques for sustainable waste management, influencing policy, and comprehending the impact of pharmaceutical footprint, pollution sources and stakeholders.

Cluster analysis was subsequently employed to identify and examine the current and emerging research themes in the PHEN research landscape. The clusters resulting from KCO analysis represent research themes or hotspots in the literature on the topic (Yang *et al.*, 2023; Yang *et al.*, 2022). To facilitate interpretation

Table 1: Top 10 most highly cited publications on PHEN.

References	Title of Study	Publication Year	Cited by	Document Type
Halling-Sørensen <i>et al.</i> (1998)	Occurrence, fate, and effects of pharmaceutical substances in the environment-A review	1998	2795	Review
Heberer (2002)	Occurrence, fate, and removal of pharmaceutical residues in the aquatic environment: A review of recent research data	2002	2441	Review
Andreozzi <i>et al.</i> (2003)	Pharmaceuticals in STP effluents and their solar photodegradation in the aquatic environment	2003	1121	Article
Kümmerer (2009)	The presence of pharmaceuticals in the environment due to human use - present knowledge and future challenges	2009	1026	Review
Beek <i>et al.</i> (2016)	Pharmaceuticals in environmental occurrences and perspectives	2016	1019	Article
Khetan and Collins (2007)	Human pharmaceuticals in the aquatic environment: A challenge to green chemistry	2007	935	Review
Nikolaou <i>et al.</i> (2007)	Occurrence patterns of pharmaceuticals in water and wastewater environments	2007	813	Review
Bendz <i>et al.</i> (2005)	Occurrence and fate of pharmaceutically active compounds in the environment, a case study: Høje River in Sweden	2005	688	Article
Li (2014)	Occurrence, sources, and fate of pharmaceuticals in the aquatic environment and soil	2014	571	Review
Corcoran <i>et al.</i> (2010)	Pharmaceuticals in the aquatic environment: A critical review of the evidence for health effects in fish	2010	456	Review

Note: Older publications have had more time to accumulate citations, which partially explains the higher citation counts observed for early foundational reviews.

of the keyword clusters, this study introduces three descriptive labels for the main thematic groupings identified: Pharmaceutical Environmental Risk (PER), Aquatic Pollution Impact (API), and Pharmaceutical Drug Research (PDR). In Figure 6(a), the largest cluster (Cluster 1) consists of 8 keywords: drug, environmental monitoring, human, humans, pharmaceutical preparations, risk assessment, water pollutants, and water pollutants/chemicals. The second largest cluster (Cluster 2) consisted of 4 keywords: aquatic environment, nonhuman, review, and wastewater. Lastly, the third and smallest cluster (Cluster 3) includes the keywords article, drug products, pharmaceuticals, and priority journal.

Cluster 1 keywords describe what this study terms Pharmaceutical Environmental Risk (PER). PER reflects the prospective damage that may be triggered by the entry of pharmaceuticals into the environment via improper disposal, industrial discharges, and human- or veterinary-related waste streams. These dangers influence wildlife, aquatic life, and human health, underscoring the need for sustainable management approaches to alleviate the environmental footprint of pharmaceutical products.

On the other hand, Cluster 2 refers to what we term Aquatic Pollution Impact (API), capturing studies that examine the effects of pharmaceutical residues on aquatic ecosystems. Water pollution by this class of pollutants has become a significant area in scientific research, as pharmaceutical residues can interrupt growth, reproduction, and behaviour of aquatic organisms, potentially imbalancing ecosystems and exacerbating antimicrobial resistance. Lastly, findings in this cluster and our synthesis of the broader literature suggest the necessity for

groundbreaking resolutions, regulatory frameworks, and efficient wastewater treatment to decrease the pharmaceutical footprint.

Cluster 3 keywords best describe what this study terms Pharmaceutical Drug Research (PDR). PDR explores the influence of drugs on the environment by investigating drug design, life cycle, formulation, and delivery in relation to their environmental impact. Recent studies increasingly focus on eco-friendly and biodegradable pharmaceuticals and environmental contamination, underscoring the need for sustainable methods and environmental considerations in drug development practices.

Research gap and future directions

Despite significant progress in understanding the environmental impacts of pharmaceuticals, several critical gaps remain in the research landscape. One major issue is the lack of holistic integration across the three thematic clusters identified in this study: Pharmaceutical Environmental Risk (PER), Aquatic Pollution Impact (API), and Pharmaceutical Drug Research (PDR). Current studies often focus on isolated aspects of pharmaceutical environmental impacts without considering their interconnected ecological, aquatic, and industrial dimensions. For example, PER studies emphasise toxicity and disposal risks but rarely incorporate findings from API research on aquatic contamination or PDR investigations into sustainable drug design. This fragmentation limits the development of cohesive strategies to address the complex interplay between human health, industrial practices, and ecosystems (Beek *et al.*, 1998).

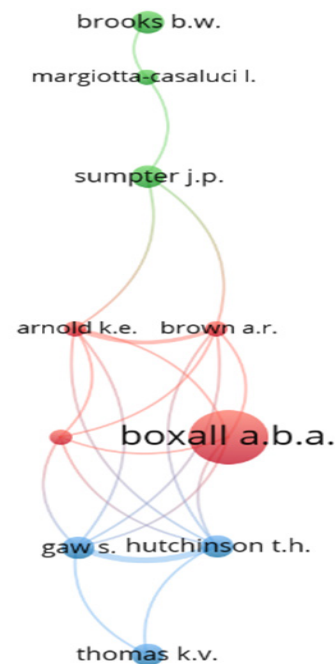


Figure 4: NVM for co-authorship among PHEN researchers.

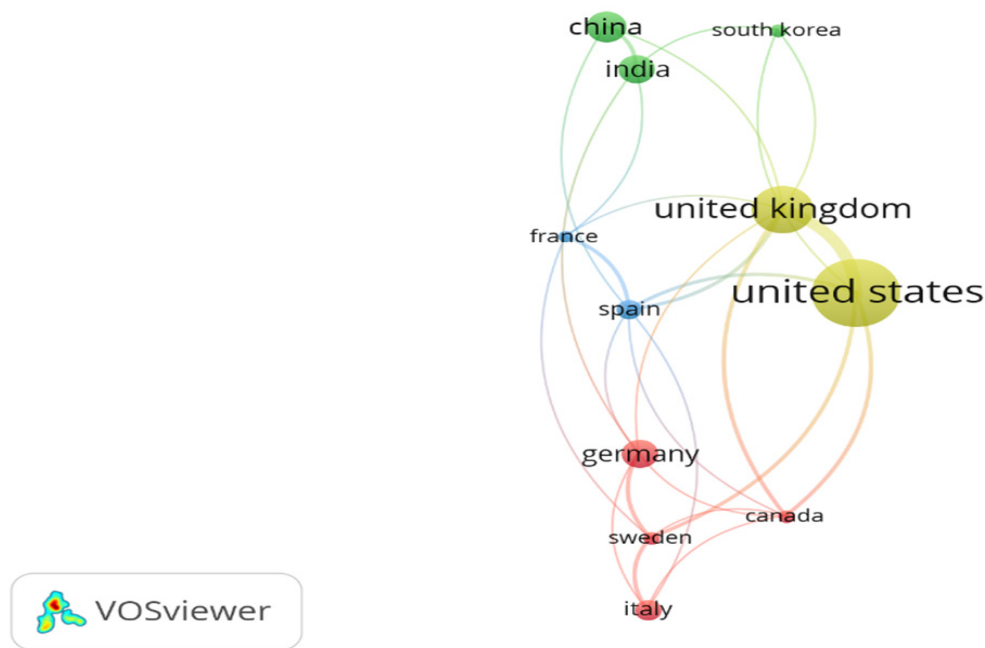


Figure 5: Network visualisation of co-authorship of countries in PHEN.

Another significant gap is the inadequate focus on the long-term impacts of pharmaceutical residues. While existing research prioritises short-term risks such as acute toxicity or immediate ecological disruptions, there is insufficient investigation into cumulative effects like antimicrobial resistance, bioaccumulation in food chains, and endocrine disruption over extended periods (Halling-Sørensen *et al.*, 1998; Heberer, 2002). For instance, the non-steroidal anti-inflammatory drug diclofenac's role in the collapse of vulture populations highlights the catastrophic consequences of unaddressed long-term ecological impacts (Swan *et al.*, 2006). Addressing these long-term effects is crucial for developing sustainable mitigation strategies.

Regional disparities in research focus also pose a challenge. The majority of PHEN studies originate from developed nations such as the United States, the United Kingdom, and European Union countries. Despite being significant contributors to global pharmaceutical production, developing regions remain underrepresented in the literature (USEPA, 2026a, 2026b; Vieira *et al.*, 2023). This imbalance limits the applicability of findings to global contexts and overlooks unique challenges faced by regions with weaker regulatory frameworks or limited access to advanced wastewater treatment technologies.

Furthermore, there is a notable lack of research exploring the socioeconomic dimensions of pharmaceutical pollution. Few studies have examined how pharmaceutical residues affect societal costs or evaluated the effectiveness of policies. Regulatory barriers often hinder the adoption of eco-friendly drug formulations, while inadequate wastewater infrastructure exacerbates contamination in low-income countries (Walter

and Mitkidis, 2018; Kümmerer, 2009). Additionally, healthcare systems rarely integrate environmental considerations into prescribing practices or public awareness campaigns.

Lastly, data gaps persist in understanding and quantifying environmental emissions across the broader pharmaceutical life cycle from production through use to disposal. While some studies have documented impacts associated with specific pharmaceutical products (e.g., inhalers), comprehensive and transparent lifecycle assessments remain limited. This lack of systematic lifecycle information undermines efforts to operationalise sustainability ambitions in the sector, because incomplete emissions data make it difficult for policymakers and industry to set robust baselines, track progress, and design effective mitigation strategies (Khetan and Collins, 2007).

To address these gaps, future research should prioritise developing integrated assessment models that combine ecological risk assessments with industrial life-cycle analyses to evaluate pharmaceutical footprints holistically. Such models could link PER's risk frameworks with PDR's green chemistry innovations while incorporating API's aquatic contamination data. These frameworks should also focus on underrepresented regions where pharmaceutical production is high but regulatory oversight is weak (Beek *et al.*, 2016).

Another area of future examination is promoting green pharmaceutical design. Emphasis should be placed on developing "benign-by-design" drugs that degrade rapidly in the environment without compromising therapeutic efficacy. This study suggests that regulatory reforms are needed to incentivize eco-friendly formulations by offering subsidies or tax benefits to

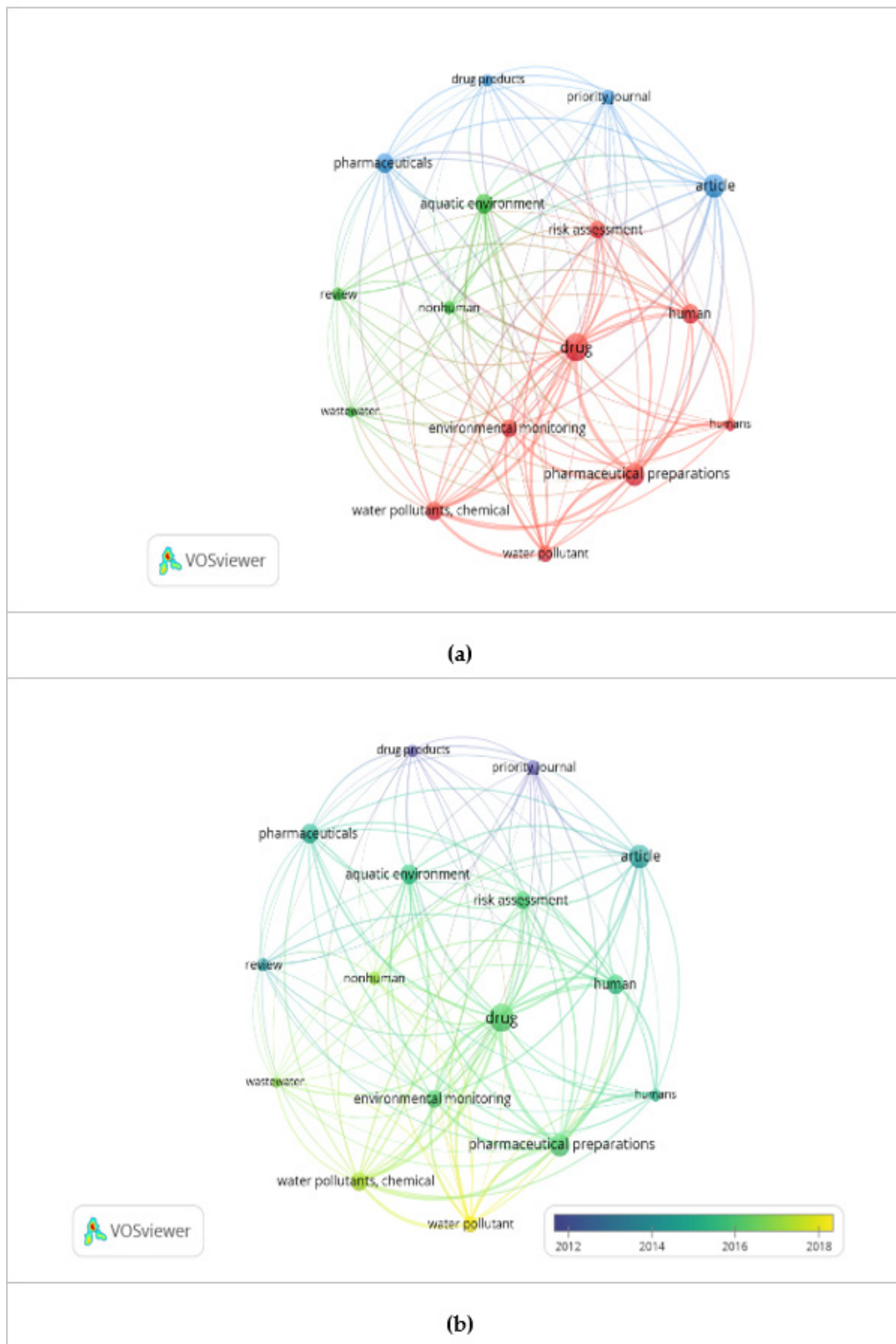


Figure 6: Keywords co-occurrence maps for PHEN research landscape. (a) Network visualisation without temporal overlay; (b) Overlay visualisation with a colour gradient indicating the average publication year of keywords.

pharmaceutical companies adopting sustainable practices (Leder, Rastogi, and Kümmerer, 2015).

Innovative monitoring technologies should also be developed to detect pharmaceuticals at trace levels in water, soil, and air.

Nanotechnology-based sensors could enable real-time detection and support harmonized global regulations on pharmaceutical emissions (Ramesh *et al.*, 2022), complementing broader policy instruments such as environmental taxes or emission pricing schemes.

Interdisciplinary collaboration between environmental scientists, pharmacologists, policymakers, and industry stakeholders is essential for addressing multifaceted challenges at the human-environment-pharmaceutical nexus. Such partnerships can facilitate knowledge transfer between academia and industry while promoting policy development informed by scientific evidence (Sindhu *et al.*, 2025).

Expanding research efforts in developing regions should be a priority. Case studies examining pharmaceutical pollution hotspots in Southeast Asia and Africa can inform targeted interventions and capacity-building initiatives (Beek *et al.*, 2010). Public awareness campaigns targeting consumers and industries must also be implemented to promote responsible disposal practices for unused medications and encourage sustainable production methods (Wilkinson *et al.*, 2022).

Finally, adopting green chemistry principles in pharmaceutical manufacturing processes can minimise environmental impacts during production. Renewable energy sources should be integrated into manufacturing facilities to further reduce carbon footprints, while scaling up advanced wastewater treatment methods, such as membrane bioreactors and nano adsorbents, to efficiently remove pharmaceutical residues (Khalid, 2025).

By addressing these gaps through interdisciplinary approaches and innovative solutions, PHEN research can transition from descriptive analyses to actionable strategies that align with global sustainability goals such as the United Nations Sustainable Development Goals (SDGs) and biodiversity conservation frameworks.

CONCLUSION

This research landscape on pharmaceutical footprints in the environment was examined through bibliometric analysis of related publications on the topic indexed in the Scopus database from 1997 to 2024. The findings reveal a steadily growing number of publications and citations on this topic during this period, which suggests that scientific interest and the social impact of PHEN research have soared over the years. Social network analysis showed that the PHEN research landscape comprises numerous prolific researchers, affiliations, and countries whose research output is primarily influenced by the availability of financial support from major funding sponsors. In addition, collaborations through co-authorships also played a role in productivity.

The KCO analysis identified the highest occurring keywords (occurrences) as drug (130), pharmaceutical preparations (108), human (92), and water pollutants/chem (656) as the highest occurring keywords. Cluster analysis revealed three thematic areas: “Pharmaceutical Environmental Risk”, “Aquatic Pollution Impact”, and “Pharmaceutical Drug Research”, which are the current focus areas for PHEN research. PER is the potential

harm caused by improper disposal, industrial discharges, and human-related waste streams. API examines the impact of pharmaceuticals on aquatic ecosystems, highlighting their potential to disrupt growth and behaviour. PDR investigates drug design, life-cycle, formulation, and delivery, focusing on eco-friendly and biodegradable pharmaceuticals. Overall, it could be surmised that sustainable management approaches and environmental concerns are crucial in drug advancement practices to reduce the pharmaceutical footprint and protect wildlife, aquatic life, and human health.

Despite progress in this area, PHEN research faces numerous gaps, including the need for a holistic approach across the three clusters. By “holistic,” this study refers to integrative frameworks that combine environmental risk assessment, aquatic impact studies, and sustainable drug design rather than treating each thematic area in isolation. There is also a need for a comprehensive understanding of the long-term socio-economic impacts of PHEN and its consequences, as this is crucial for developing balanced future policies. Hence, future research should develop integrated assessment models, innovative technologies, life-cycle assessments, and cost-effective monitoring systems. Interdisciplinary studies on the human-environment-pharmaceutical nexus can contribute significantly to policy development and public awareness. This study demonstrated that PHEN research has significant potential for future studies.

LIMITATIONS OF THE STUDY

Some limitations of this study must be acknowledged, which are unique to several Bibliometric Analyses (BA). First, while this study provides valuable insights into PHEN research trends, it is limited by its reliance on a single database (Scopus) and exclusion of non-English publications. Future studies may benefit from integrating multiple databases (e.g., the Web of Science) to achieve broader coverage. Secondly, although this study performed an analysis of highly cited publications in PHEN research. This presents another limitation, as citation does not provide a true picture of influential work in an area because citation trends are dynamic and may reflect self-citation rather than true impact. Numerous citations may indicate high impact, but standard procedures, tools, methods, definitions, and designs may lead researchers to believe that papers with many citations are of good quality or weight. Citations may not always accurately represent the study’s content, as they may be attributed to the methodology rather than to the study’s overall significance. This is a significant limitation in bibliometric analysis. Lastly, this study provides a quantitative analysis of PHEN research using bibliometric analysis, focusing on publication trends, citations, and thematic areas. However, it does not offer a comprehensive qualitative understanding of the contextual, cultural, and organisational factors affecting these trends. Future studies may use qualitative methods, such as systematic reviews or case studies, to investigate

these aspects and provide deeper insight into PHEN across various regions. Despite these limitations, this study provides valuable insights for researchers to address limitations and propose future research.

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ABBREVIATIONS

PHEN: Pharmaceuticals in the Environment; **PER:** Pharmaceutical Environmental Risk; **API:** Aquatic Pollution Impact; **PDR:** Pharmaceutical Drug Research; **BA:** Bibliometric Analysis; **NVM:** Network Visualisation Maps; **OVM:** Overlay Visualisation Maps; **EPA:** Environmental Protection Agency; **NIH:** National Institutes of Health; **UK:** United Kingdom; **US:** United States of America; **KCO:** Keyword Co-occurrence; **TLS:** Total Link Strength.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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