

Global research trends in male fertility and environmental factors (2016-2025) a multi-database bibliometric analysis and cross-validation study

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Abstract

Objective

To systematically clarify the knowledge structure, developmental trajectory, research hotspots and emerging frontiers of global research on environmental factors and male fertility from 2016 to 2025, and to predict future research directions for this field.

Methods

Literatures were retrieved from the Web of Science Core Collection (WoSCC). Bibliometric and visual analysis was conducted using CiteSpace, VOSviewer, SCImago Graphica and Pajek, focusing on publication dynamics, global collaboration networks, disciplinary distribution, citation characteristics, research hotspots and frontier evolution of the field. In addition, to evaluate the robustness of results and explore feature differences between databases, we conducted multi database validation and comparative analysis using data from Scopus and PubMed.

Results

A total of 4,958 relevant literatures were retrieved from WoSCC, the annual publications and citations of this field increased significantly from 2016 to 2025. China ($n = 989$) and the United States ($n = 985$) formed the dual core of global research. The research presented distinct interdisciplinary characteristics, with Environmental Sciences and Toxicology as the core disciplines. These results have been validated by the Scopus database. Oxidative stress, endocrine disruptors, environmental exposure and reproduction were the dominant research themes. The above results were validated by conducting clinical and mechanistic research searches on the Pubmed database. Co-citation and cluster analysis identified male rat model, spermatogonial stem cell, semen quality and sperm DNA damage as the key research foundations, and epigenetic transgenerational inheritance, emerging pollutant exposure and early warning biomarker development as the important emerging frontiers.

Conclusion

Research on this field has developed rapidly in the past decade, with a sound global collaboration network and clear interdisciplinary research characteristics. Oxidative stress is the core mechanism connecting various research subfields. Future research should focus on in-depth exploration of epigenetic and transgenerational mechanisms, research on effects of emerging pollutants, and development of sensitive early warning biomarkers and translational intervention strategies.

1. Introduction

In recent years, the global incidence of infertility has been on a steady upward trajectory, with approximately 17% of reproductive-age couples worldwide currently experiencing or having previously struggled with infertility—an issue that has emerged as a pressing global public health concern(1–3). Notably, about 50% of infertility cases can be partially or fully attributed to male-related factors(4, 5), and a growing body of research has documented a consistent decline in male fertility over the past decades(6–8), thus garnering widespread attention from the global academic community. Male fertility is jointly modulated by multiple factors, including genetics(9), environmental exposures(10), disease status(11), and lifestyle choices(12). Furthermore, against the backdrop of the universal prevalence of various pollutants and climate change, environmental factors have become a focal point of research as a key driver of reduced male fertility. Semen quality serves as the primary indicator of male fertility, and mounting evidence has confirmed that environmental factors adversely affect spermatogenesis, steroidogenesis and sperm function, thereby impairing semen quality and compromising male fertility potential(13, 14). More importantly, recent findings suggest that environmental factors can exert transgenerational effects on offspring health via epigenetic mechanisms(15–18). Despite the substantial volume of relevant studies published in this domain, systematic analyses addressing its current research status, knowledge structure, cooperation network and future development trends remain relatively lacking.

Bibliometrics is an interdisciplinary field integrating mathematics, statistics, and documentation science, which centers on quantifying bibliographic data to reveal patterns of academic literature and the evolutionary characteristics of disciplinary development(19). Currently, by virtue of professional software such as CiteSpace(20) and VOSviewer(21), researchers can conduct integrated quantitative and qualitative analyses of database literature, systematically synthesize the research contributions of different countries, academic institutions, and scholars, and accurately identify research hotspots and evolving trends within a specific field. This analytical approach has now been applied to various disciplines including surgery(22), internal medicine(23), obstetrics and gynecology(24), nursing(25), and environmental science(26). In light of this, the present study employs bibliometric methods to systematically analyze the literature focusing on the effects of environmental factors on male fertility, based on the multi-database from 2016 to 2025. The aim of this study is to clarify the knowledge structure and developmental trajectory, predict its future research directions, and provide theoretical insights and practical guidance for further in-depth investigations.

2. Material and methods

2.1 Data source and search from WoSCC

The literature reviewed in this study was retrieved from the Web of Science Core Collection (WoSCC) database on February 24, 2026. The literature was searched using the following criteria: TS=((male OR men OR masculin*) AND (reproduct* OR fertili* OR spermat* OR sperm OR testicular OR testis OR gonad*) AND ("environment* factor*" OR "environment* exposure*" OR "environment* toxicant*" OR pollut* OR "air pollut*" OR "chemical exposure*" OR "heavy metal*" OR "endocrine disruptor*" OR

"temperature effect*" OR "climate change" OR "particulate matter" OR "PM2.5" OR "BPA" OR "electronic waste"))). The search criteria were limited as follows:

- (1) Document type: articles;
- (2) No species restriction;
- (3) Language: English;
- (4) Publication date: From January 1, 2016 to December 31, 2025.

All records of the eligible articles, including titles, authors, abstracts, keywords, and references, were exported in Plain Text format and saved as a file named "download_txt". Subsequently, this exported file was imported into CiteSpace 5.7.R5 software for subsequent bibliometric analysis.

2.2 Data analysis and visualization of literatures from WoSSC

The specific parameter settings for CiteSpace 5.7.R5 are as follows: Time range: January 2016 to December 2025, with one year per time slice; Term sources: Titles, Abstracts, Author Keywords, and Keyword Plus; Node types: Authors, Institutions, Countries, Keywords, References, Cited Authors, and Cited Journals; Link strength measurement: Cosine similarity; Selection criteria: g-index with $k = 25$; Visualization mode: Cluster View-Statics with Merged Network displayed. Bibliometric analysis and visualization were performed with the use of CiteSpace 5.7.R5(20). This software enables data visualization by means of functions like co-citation networks and citation burst, which serve to illustrate the structure and distribution of scientific knowledge within a specific field. SCImago Graphica Beta 1.0.53 (27) was employed to construct geographic collaboration maps, for the intuitive visualization of the spatial distribution and collaborative intensity across different countries and regions.

In addition, VOSviewer 1.6.19(21) and Pajek 6.01(28) were used for analysis of keyword, such as clustering analysis, temporal visualization, and research density analysis. Within the clustering analysis, the category of each node is indicated by its color, and the size of a node represents its frequency of occurrence. Co-occurrence network of keywords was used to examine the research hotspots, whereas the timeline of keyword appearance and research density were applied to depict the field's development path and anticipate upcoming research tendencies.

2.3 Cross-database validation of results

To address the limitation of single-database bias and leverage the strengths of different databases, We validated the results using Scopus and Pubmed databases. Firstly, based on the same search criteria, relevant literature searches were conducted in the Scopus database to verify the publication volume, countries and core fields. Pearson correlation analysis is used to analyze the similarity of annual publication volumes in different databases, with $P < 0.05$ indicating statistical significance. Secondly, we

utilized the Pubmed database to search for clinical studies, epidemiological investigations, and in vitro and in vivo experiments to validate the clinical relevance and mechanistic basis of key research topics

3. Results

3.1 Annual Publications

A total of 4,958 documents were retrieved from the WoSCC. Annual publication output increased from 367 in 2016 to 630 in 2025, with the total number of citations surging from 297 to 19,185 over the same period. As illustrated in Figure 1A, both publication and citation numbers witnessed rapid growth from 2016 to 2021, followed by a plateau phase from 2022 to 2024 and a second explosive surge starting in 2025.

Statistical analysis identified Renshan Ge as the most productive author, with 27 publications in this field. China (n = 989) and the United States (n = 985) emerged as the leading countries/regions in terms of publication output, while the Chinese Academy of Sciences was the most prolific research institution, accounting for 93 publications. The top 5 most productive countries/regions, institutions and authors are summarized in Table 1. As shown in the country/regional research collaboration network map (Figure 1B), global research collaboration in this field forms a well-structured network, with China and the United States serving as dual cores, Europe as a key hub, and collaborative ties radiating to research entities worldwide.

Table 1 Top 5 Authors, Institutions and Countries/Regions, by Number of Publications (2016-2025)

Ranking	Author	Number of Publications	Year
1	RENSHAN GE	27	2018
2	JIA CAO	26	2016
3	JINYI LIU	21	2016
4	RUSS HAUSER	17	2018
5	LUIGI MONTANO	17	2022
Ranking	Institution	Number of Publications	Year
1	Chinese Acad Sci	93	2016
2	Huazhong Univ Sci & Technol	68	2016
3	Wenzhou Med Univ	50	2017
4	Univ Copenhagen	47	2016
5	Univ Chinese Acad Sci	44	2017
Ranking	Country/Region	Number of Publications	Year
1	China	989	2016
2	USA	985	2016
3	FRANCE	210	2016
4	ITALY	200	2016
5	BRAZIL	197	2016

3.2 Research Field Analysis

Statistical analysis of the disciplinary distribution of research in this field revealed prominent interdisciplinary characteristics, with core focus areas including Environmental Sciences (n = 1438), Toxicology (n = 950), Biochemistry & Molecular Biology (n = 313), and Reproductive Biology (n = 310) (Figure 2A).

The dual-map overlay of journals reveals the position of the research topic relative to major research disciplines. Each point denotes a journal, with the map split into a left citing map and a right cited map. Citation links (curves) demonstrate the origin and development of citations. Curves between the two maps reflect interdisciplinary relationships, while the z-Scores function highlights stronger trajectories, with higher scores shown by thicker lines.

As can be seen from Figure 2B, publications in the Ecology/Earth/Marine field (blue trajectory) are obviously influenced by those in the Plant/Ecology/Zoology, Molecular/Biology/Genetics, and

Environmental/Toxicology/Nutrition fields. In addition, publications in the Molecular/Biology/Immunology field (orange trajectory) are influenced by those in the Molecular/Biology/Genetics, Environmental/Toxicology/Nutrition, and Plant/Ecology/Zoology fields; publications in the Veterinary/Animal/Science field (yellow trajectory) are influenced by those in the Molecular/Biology/Genetics and Plant/Ecology/Zoology fields.

Figure 2C presents the top 15 journals with the highest Citation Burst intensity during 2016–2025. Most of these journals have a burst period from 2023 to 2025, indicating that they are the core publication venues in the current field. *THESIS* has an earlier burst period (2017–2020), reflecting the important role of early dissertations in the foundation stage of the field. Journals such as *INT J MOL SCI* (Strength = 68.84) and *ANTIOXIDANTS-BASEL* (Strength = 47.64) have the highest burst intensity, suggesting that directions such as oxidative stress and molecular science are the current research hotspots.

Among the top 10 journals, Environmental Sciences (e.g., *ENVIRON HEALTH PERSP*, *SCI TOTAL ENVIRON*, *CHEMOSPHERE*, *ENVIRON POLLUT*) and Toxicology/Reproductive Biology (e.g., *REPROD TOXICOL*) dominate, which is completely consistent with the disciplinary distribution we analyzed earlier (Figure 2A), confirming that this field is centered on environmental toxicology and reproductive health (Table 2). Although *SCIENCE* and *NATURE* rank relatively low, they have extremely high Impact Factors (IFs) of 45.8 and 48.5, respectively, indicating that major breakthrough achievements in this field are often published in these top journals.

Table 2 The top 10 co-cited journals ranked by number of citations

Ranking	Co-cited journals	Citations	Country	Most Recent IF	Most Recent JCR partition
1	<i>PLOS ONE</i>	2237	USA	2.6	Q2
2	<i>P NATL ACAD SCI USA</i>	1665	USA	9.1	Q1
3	<i>ENVIRON HEALTH PERSP</i>	1652	USA	9.8	Q1
4	<i>SCI TOTAL ENVIRON</i>	1583	NETHERLANDS	8.0	Q1
5	<i>SCI REP-UK</i>	1522	UK	3.9	Q1
6	<i>CHEMOSPHERE</i>	1514	UK	8.1	Q1
7	<i>REPROD TOXICOL</i>	1422	USA	2.8	Q2
8	<i>SCIENCE</i>	1381	USA	45.8	Q1
9	<i>ENVIRON POLLUT</i>	1375	UK	7.3	Q1
10	<i>NATURE</i>	1292	UK	48.5	Q1

3.3 Analysis of co-cited references

To investigate the specific content of research on environmental factors and male fertility, we performed a co-citation analysis of references using CiteSpace 5.7.R5. The results are presented in Figure 3A, where each node represents a cited reference. The size of the node corresponds to the number of citations, the color-coded rings indicate the time periods of citation, and the width of each ring represents the number of citations within that period. Node annotations display the authors and publication years of the cited articles. The most frequently cited article was "Temporal trends in sperm count: a systematic review and meta-regression analysis" by Levine H et al.(8), published in *Human Reproduction Update*. This comprehensive meta-regression analysis reported a significant decline in sperm count between 1973 and 2011, and it was cited 63 times. The top 10 most frequently cited references are listed in Table 3.

We then performed a cluster analysis on references cited more than 5 times, which revealed that all references were primarily grouped into 12 distinct clusters. The clustering metrics, Modularity $Q = 0.7244$ and Weighted Mean Silhouette $= 0.912$, indicated significant modularity and a high degree of cluster consistency, confirming the reliability of the clustering results. The main themes of each cluster included "male rat", "spermatogonial stem cell", "semen quality", and "sperm DNA damage," with detailed cluster results and representative citations shown in Figure 3B. A fisheye view (Figure 3C) was used to intuitively display the temporal emergence of citations within each cluster. Citation burst detection also revealed that references with high burst strength were predominantly published in 2016 and after 2020, as detailed in Figure 3D.

Table 3 Top 10 co-cited references in the research of environmental factors and male fertility

Ranking	Year	First Author	Title	Journal	Citations
1	2017	Levine H(8)	Temporal trends in sperm count: a systematic review and meta-regression analysis	<i>HUM REPROD UPDATE</i>	63
2	2016	Skakkebaek NE(29)	Male Reproductive Disorders and Fertility Trends: Influences of Environment and Genetic Susceptibility	<i>PHYSIOL REV</i>	52
3	2019	Walsh BS(30)	The Impact of Climate Change on Fertility	<i>TRENDS ECOL EVOL</i>	44
4	2015	Wisniewski P(31)	Adult exposure to bisphenol A (BPA) in Wistar rats reduces sperm quality with disruption of the hypothalamic–pituitary–testicular axis	<i>TOXICOLOGY</i>	42
5	2014	Peretz J(32)	Bisphenol a and reproductive health: update of experimental and human evidence, 2007-2013	<i>ENVIRON HEALTH PERSP</i>	38
6	2020	Xie XM(33)	Exposure to polystyrene microplastics causes reproductive toxicity through oxidative stress and activation of the p38 MAPK signaling pathway	<i>ECOTOX ENVIRON SAFE</i>	35
7	2015	Gore AC(34)	EDC-2: The Endocrine Society's Second Scientific Statement on Endocrine-Disrupting Chemicals	<i>ENDOCR REV</i>	34
8	2013	Rochester JR(35)	Bisphenol A and human health: A review of the literature	<i>REPROD TOXICOL</i>	33
9	2014	Lassen TH(36)	Urinary bisphenol A levels in young men: association with reproductive hormones and semen quality	<i>ENVIRON HEALTH PERSP</i>	30
10	2018	Sales K(37)	Experimental heatwaves compromise sperm function and cause transgenerational damage in a model insect	<i>NAT COMMUN</i>	29

3.4 Hotspots and Frontiers analysis

In this study, co-occurrence and cluster analysis of keywords was performed using VOSviewer, and all keywords were categorized into five distinct clusters. Specifically, Cluster 1 (purple) covered "accumulation", "expression", "genes", "persistent organic pollutants" and "mechanisms", representing studies on the accumulation of persistent organic pollutants and the regulatory mechanisms of gene expression. Cluster 2 (yellow) included "fertility", "health", "infertility", "semen quality" and "sperm

motility", corresponding to research on fertility, infertility and semen quality evaluation. Cluster 3 (blue), the core cluster of the field, contained key terms including "exposure", "oxidative stress", "reproductive toxicity", "spermatogenesis" and "toxicity", which reflected the fundamental research on environmental exposure, oxidative stress, reproductive toxicity and spermatogenic mechanisms. Cluster 4 (green) comprised "climate change", "reproduction", "temperature" and "stress", focusing on the associations between climate change, ambient temperature and reproductive function. Cluster 5 (red) included terms such as "endocrine disruptors", "bisphenol a", "gene expression" and "testosterone", representing research on the effects of endocrine-disrupting chemicals on hormonal expression and testosterone levels. Detailed cluster results are presented in Figure 4A.

Temporal analysis of keyword occurrence revealed the structural characteristics and developmental trends of this research field. As shown in Figure 4B, the high-frequency co-occurrence period of core keywords was concentrated from 2020.5 to 2021.5, indicating a concentrated and explosive development of research in this field over the past five years. Density analysis of the research content represented by each keyword (Figure 4C) demonstrated that "exposure", "oxidative stress", "reproduction" and "endocrine disruptors" were located at the core of the research network, serving as the dominant themes with the highest research attention in this field.

3.5 Cross-database validation of results

We retrieved a total of 6,124 documents from the Scopus database. The publication trend was similar to that of the WoSCC, increasing from 532 documents in 2016 to 774 documents in 2025, with a plateau occurring around 2022 (Figure 5A). The Pearson correlation coefficient for the annual publication trend was 0.902 ($P < 0.05$). China (1,728) and the United States (1,142) remained the two most productive countries, but the gap in publication output between them widened, which may be attributed to the broader disciplinary coverage of the Scopus database. In terms of research areas, Environmental Sciences remained a core field (Figure 5B). The annual publication trends of the top five most prolific journals are shown in Figure 5C.

To validate the clinical relevance and mechanistic basis of key research topics, we performed a supplementary search in the PubMed database using the following search strategy:((male infertility) OR (semen quality) OR (sperm DNA damage)) AND ((environmental exposure) OR (endocrine disruptors) OR (oxidative stress) OR (bisphenol A) OR (PM2.5) OR (microplastics)) AND (clinical trial[pt] OR human study[pt] OR in vitro OR in vivo) AND 2016/01/01[dp] : 2025/12/31[dp]. A total of 1,983 documents were retrieved. The annual publication trend closely mirrored the results from the WoSCC and Scopus databases (Figure 5A). The Pearson correlation coefficients were 0.798 (WoSCC vs. PubMed) and 0.900 (Scopus vs. PubMed), both statistically significant ($P < 0.05$). Keyword clustering analysis revealed that "Oxidative Stress" is the core mechanism in this field, consistent with the results from the WoSCC analysis.

4. Discussion

Against the global backdrop of continuous decline in male reproductive health, this field has evolved into a critical interdisciplinary frontier bridging environmental health, reproductive biology and toxicology(38). This study presents the first comprehensive bibliometric and visual analysis of the entire field based on multi-database, spanning publication dynamics, global collaborative networks, disciplinary integration, citation landscapes, and research hotspots/frontiers. The findings provide a rigorous empirical foundation for understanding the current state of research and identifying future directions, offering actionable insights for interdisciplinary researchers and public health policymakers alike.

4.1 Publication Dynamics, Global Collaborative Patterns and Core Publication Venues

The sustained growth in annual publications and the explosive rise in total citations over the study period reflect the escalating academic and public health attention to environmental determinants of male fertility. The emergence of China and the United States as dual global research cores is a defining feature of the field's collaborative landscape, reflecting the alignment of scientific research investment with regional environmental and public health priorities. Additionally, the majority of authors and institutions with the highest number of publications are from China, while most of the highly cited references and core journals are from the United States. The European acts as a critical bridge in global collaboration. The well-structured global collaboration network (Fig. 1B) further underscores that interdisciplinary and international collaboration is a prerequisite for advancing research in this field, as environmental factors and male fertility represent a global challenge that transcends national boundaries.

Research in this domain is characterized by distinct interdisciplinary features, with its core focus anchored in Environmental Sciences, Toxicology, Biochemistry & Molecular Biology, and Reproductive Biology. The dual-map overlay analysis of academic journals further delineates the knowledge flow and interdisciplinary citation networks that underpin the evolutionary trajectory of this field. The predominance of journals specializing in environmental science and reproductive toxicology (e.g., *ENVIRON HEALTH PERSP*, *SCI TOTAL ENVIRON*, *REPROD TOXICOL*) within the top 10 co-cited journals corroborates that environmental toxicology and reproductive health serve as the disciplinary cornerstone of this research area. Journals exhibiting the highest citation burst intensity during the period 2023–2025, including *INT J MOL SCI* and *ANTIOXIDANTS-BASEL*, explicitly mirror the current research frontiers centered on oxidative stress and molecular toxicology, thereby confirming that mechanistic explorations into the molecular pathways underlying environmental reproductive impairment represent the predominant focus of contemporary research in this field. The earlier citation burst of *THESIS* (2017–2020) highlights the pivotal role of graduate dissertations in establishing the foundational research framework, as they provide preliminary datasets, innovative hypotheses, and talent pipelines that facilitate subsequent in-depth inquiries.

4.2 Research Hotspots and Emerging Frontiers

Co-citation and keyword analyses reveal that alongside rising global infertility prevalence, current research predominantly concentrates on adverse reproductive impacts induced by ambient air pollutants(39, 40), heavy metals(41, 42), endocrine disrupting chemicals (EDCs) (43, 44) and microplastics.

4.2.1 Endocrine Disrupting Chemicals

EDCs is an exogenous substance or a mixture that alters function(s) of the endocrine system and consequently causes adverse health effects in an intact organism, or its progeny, or (sub)populations. The overrepresentation of BPA research(31, 32, 35, 36) in the top 10 underscores BPA as the model environmental EDCs for male fertility research, with studies spanning animal experimental validation and human epidemiological investigation. Widely applied in polycarbonate and epoxy resin manufacture, BPA mainly enters human bodies via dietary intake (45). Cumulative epidemiological and animal evidence confirms that urinary or seminal BPA concentrations are negatively correlated with sperm count and motility; BPA exposure reduces sperm quantity, impairs sperm motility, elevates sperm DNA fragmentation and compromises fertilization capacity(46, 47) Mechanistically, the phenolic chemical structure of BPA mimics endogenous estrogen to disturb the negative feedback loop of the hypothalamic-pituitary-gonadal (HPG) axis, suppress pituitary gonadotropin secretion, hinder spermatogenesis and inhibit steroidogenesis in Leydig cells(48). As an androgen receptor (AR) antagonist, BPA downregulates testicular AR expression, disrupts mitochondrial homeostasis and stimulates excessive reactive oxygen species (ROS) generation, ultimately triggering Sertoli cell apoptosis. In recent years, increasing studies shift focus toward paternal transgenerational toxicity of BPA: paternal BPA exposure suppressed the expression of the key carnitine transporter *OCTN2* in fetal testis, disrupts testicular carnitine homeostasis and aggravates oxidative stress and germ cell apoptosis in progeny(49) Apart from BPA and its structural alternatives (BPS, BPF), parabens, triclosan, phthalates (DEHP, DINP) and per- and polyfluoroalkyl substances (PFAS) are well-recognized EDC candidates. Accumulating evidence validates their detrimental effects on semen quality and offspring health, with oxidative stress identified as the shared core toxic mechanism(50)

4.2.2 Air Pollution

Ambient air pollution remains a persistent public health threat to male reproductive function(51). Existing evidence verifies air pollutants restrain spermatogenesis and increase sperm DNA damage, among which fine particulate matter PM_{2.5} is the predominant hazardous constituent. Acting as a composite particulate carrier, PM_{2.5} adsorbs massive EDCs including polycyclic aromatic hydrocarbons and phthalates, which cross the blood-testis barrier to disrupt testosterone synthesis and provoke testicular oxidative injury. A spatial cross-sectional study based on American cohorts demonstrates non-linear positive correlations between PM_{2.5} exposure and sperm DNA fragmentation index (DFI); moreover, significant interaction exists between particulate exposure and socioeconomic status (SES), implying men from low-SES regions suffer more severe sperm DNA impairment induced by air pollution(52). Multiple domestic epidemiological researches from China further confirm PM_{2.5}, PM₁₀,

CO, SO₂ and O₃ deteriorate routine semen parameters to varying degrees, and sperm DNA methylation alteration mediates the causal link between paternal PM_{2.5} exposure and adverse birth outcomes of offspring(18, 53–55). Additional seminal plasma metabolomics evidence indicates PM_{2.5} disturbs D-aspartic acid metabolism, which potentially mediates the decline of semen quality (56).

4.2.3 Heavy Metals

Human activities such as mining, alloy production, cement manufacture and fossil fuel combustion continuously release nickel, cadmium and other heavy metals into the living environment, leading to ubiquitous chronic low-dose human exposure (57). Testicular tissue is exceptionally susceptible to cadmium toxicity: cadmium destroys the blood-testis barrier, seminiferous tubule integrity as well as physiological function of Sertoli and Leydig cells, and triggers massive germ cell loss through diverse pathways including oxidative stress-mediated germ cell death, testicular edema, impaired androgen synthesis, disturbed gene transcription, unbalanced ionic homeostasis and damaged vascular endothelium (58). As an emerging nano-sized heavy metal contaminant, nickel nanoparticles (Ni NPs) impair spermatogenesis by facilitating *DRP1*-dependent excessive mitochondrial fission and *PINK1*/Parkin-mediated aberrant mitophagy, subsequently inducing oxidative stress and mitochondria-triggered germ cell apoptosis (59). Given oxidative stress is the central driver of heavy metal-related reproductive toxicity, abundant animal studies in recent years explore the protective effects of various antioxidant supplements against metal-induced testicular damage (60, 61).

4.2.4 Microplastics

Plastic products are ubiquitous in daily life, and plastic debris smaller than 5 mm is defined as microplastics (MPs)(62). Accumulating evidence has verified widespread MP contamination in soil, ambient air and marine environments. Human exposure mainly occurs via ingestion of contaminated food and drinking water or inhalation. After systemic absorption, MPs are distributed to multiple organs across the body and capable of penetrating the blood–brain barrier and blood–testis barrier, triggering adverse impairments to the nervous and male reproductive systems(63). Existing research has documented that MP exposure reduces sperm concentration and deteriorates semen quality(64), and meta-analyses have identified excessive ROS overproduction as the pivotal initiating molecular event underlying MP-induced male reproductive toxicity(65). Mechanistically, MPs compromise male reproductive function through multiple cascades, including mitochondrial dysfunction, elevated germ cell apoptosis, suppressed testosterone biosynthesis, disruption of the blood–testis barrier (BTB), and intestinal microbiota dysbiosis.

Recent advances further confirm that biodegradable polylactic acid (PLA) decomposes into nanoplastics (NPs) (< 100 nm). Benefiting from their ultrafine particle size, nanoplastics penetrate biological tissues and organs more efficiently and thereby exert more potent reproductive toxicity than conventional microplastics(66). Multi-omics profiling reveals age-dependent toxic patterns of polystyrene nanoplastics (PS-NPs): PS-NPs predominantly perturb RNA metabolism in juvenile mice, whereas they severely disrupt DNA catabolism as well as collagen and extracellular matrix metabolism in aged

animals. Meanwhile, PS-NPs downregulate the expression of scavenger receptor class B type I (*SR-BI*), which blocks testosterone synthesis and accelerates premature testicular senescence in young rodents(67). Another multi-omics investigation elaborates that PS-NP exposure activates the *NF-κB/IL-17/HIF-1* axis while inhibiting *PPAR-γ* signaling, consequently exacerbating DNA damage and germ cell apoptosis, suppressing autophagy and disturbing lipid energy metabolism. In parallel, PS-NPs disrupt intestinal flora homeostasis and initiate the *TLR4/MyD88/NF-κB*-mediated inflammatory cascade; systemic inflammation subsequently circulates toward testicular tissue and ultimately drives reproductive toxicity(68)¶

4.3 Cluster analysis and Future Prospects

Cluster analysis of co-cited references and keywords yielded highly robust and consistent results, with themes spanning animal models (male rat), key cellular targets (spermatogonial stem cells, SSCs), core outcome measures (semen quality), core mechanism (oxidative stress) and molecular damage endpoints (sperm DNA damage). Given the remarkable consistency in reproductive physiology with humans, short sexual maturation time, high reproductive efficiency, and pronounced sensitivity to environmental exposures, male rats represent an optimal animal model for investigating underlying mechanisms and developing intervention strategies in this research area(69, 70). As the basis for spermatogenesis, SSCs represent one of the most widely utilized cell models for investigating the mechanisms by which environmental exposures influence male fertility(71, 72). Semen quality is a central endpoint for assessing male reproductive injury caused by environmental exposures(73), among which sperm DNA damage is one of the crucial mechanisms(52). The results revealed two peak periods of high-impact reference publication (2016 and post-2020), which align with the field's developmental trajectory: the 2016 burst corresponds to the initiation of the study's time window and the foundational research that drove the 2016–2021 rapid growth phase(32, 35, 36, 74–76), while the post-2020 burst reflects the concentrated production of high-impact mechanistic research that defined the field's current focus(30, 33, 37, 53, 77, 78).

Based on the comprehensive bibliometric analysis of the field's current state, hotspots, and emerging frontiers, three evidence-based future research directions are proposed: (1) In-depth exploration of epigenetic and transgenerational mechanisms: Building on the current focus on oxidative stress and gene expression, future research should prioritize the epigenetic regulatory mechanisms (DNA methylation, histone modification, non-coding RNA)(79) of environmental factors on male fertility, particularly the transgenerational inheritance effects of low-dose chronic environmental exposure. (2) Research on emerging environmental pollutants and combined exposure effects: Most existing research focuses on single environmental stressors (e.g., BPA, cadmium), but humans are exposed to complex mixtures of pollutants in real-world settings. Future research should strengthen investigations into the reproductive toxicity of emerging pollutants (e.g., microplastics, PFAS, electronic waste pollutants)(80, 81). (3) Development of sensitive early warning biomarkers and translational intervention strategies: Building on the field's applied core (semen quality, fertility), future research should focus on developing novel, sensitive, and non-invasive biomarkers of environmentally induced male reproductive damage to

enable early detection and risk stratification in at-risk populations. Concurrently, translational research should explore evidence-based intervention strategies (e.g., antioxidant supplementation, nutritional intervention, lifestyle modification) to mitigate the reproductive toxicity of environmental exposure, bridging the gap between basic research and clinical/public health practice.

4.4 Limitations

This study presents a comprehensive macro-level analysis of research on environmental factors and male fertility (2016–2025), though several limitations should be acknowledged when interpreting the findings. First, while multi-database data were incorporated, the analysis remains primarily WoSCC-centered; Scopus and PubMed were only used for supplementary validation, without thorough integration of multi-database literature. Second, the keyword-based search strategy may have omitted relevant studies using non-standard terminology (e.g., inconsistent use of oxidative stress vs. reactive oxygen species), potentially introducing minor inaccuracies in keyword clustering and hotspot identification. Third, no subgroup analysis was performed by research type (basic experiments, human epidemiology, or clinical studies), limiting insights into divergent trends and synergies across research paradigms.

5. Conclusion

This comprehensive bibliometric and visual analysis (2016–2025) systematically maps the global research landscape of environmental factors and male fertility, revealing a field that has grown rapidly in volume, impact, and interdisciplinary integration, with China and the United States as dual global cores and Europe as a critical collaborative hub. The field is defined by four core research themes (exposure, oxidative stress, reproduction, endocrine disruptors). EDCs, BPA in particular, have been the definitive research hotspots in this field over the past decade, while in recent years, emerging environmental exposure factors such as microplastics/nanoplastics and per- and polyfluoroalkyl substances (PFAS) have come to the fore. The findings of this study confirm that, with the advent of omics and other research technologies, investigations in this field have evolved from exploratory association studies to in-depth mechanistic elucidation, and the impacts of paternal environmental exposure on offspring health have attracted growing attention. This study provides a rigorous empirical foundation for understanding the current state of the field and identifying future research priorities, emphasizing the need for in-depth exploration of epigenetic and transgenerational mechanisms, research on the toxic effects of emerging pollutants and their combined exposure, the expansion of research on climate change and reproductive health, and the development of translational biomarkers and intervention strategies.

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Availability of data and material (data transparency)

All datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Code availability (software application or custom code)

Not applicable

Authors' contributions

Du Chao: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing-Original Draft, Writing - Review & Editing **Lisha Chen:** Data curation, Formal analysis, Methodology, Visualization, Writing-Original Draft, Writing – review & editing **Fan Xinyue:** Methodology, Visualization, Writing–original draft **Ao Li:** Methodology, Visualization **Yu Yuexin:** Formal analysis, Project administration, Funding acquisition, Supervision, Writing – review & editing.

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Figures

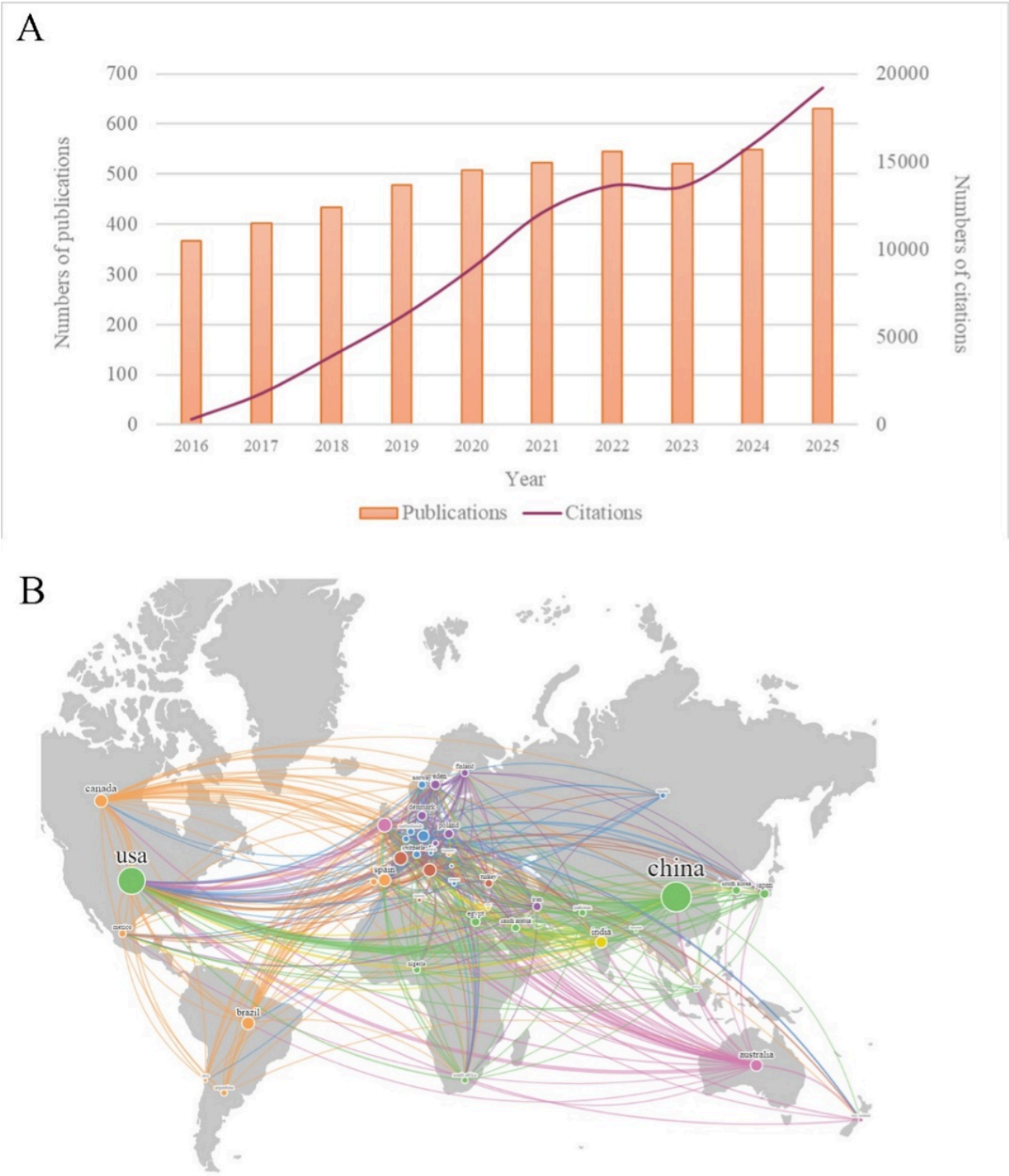


Figure 1

Analysis of research fields related to environmental factors and male fertility. (A) Publication output of each discipline in the field of environmental factors and male fertility. (B) Journal dual-map overlay for research on environmental factors and male fertility. (C) Top 15 journals with the strongest citation bursts in this research field.

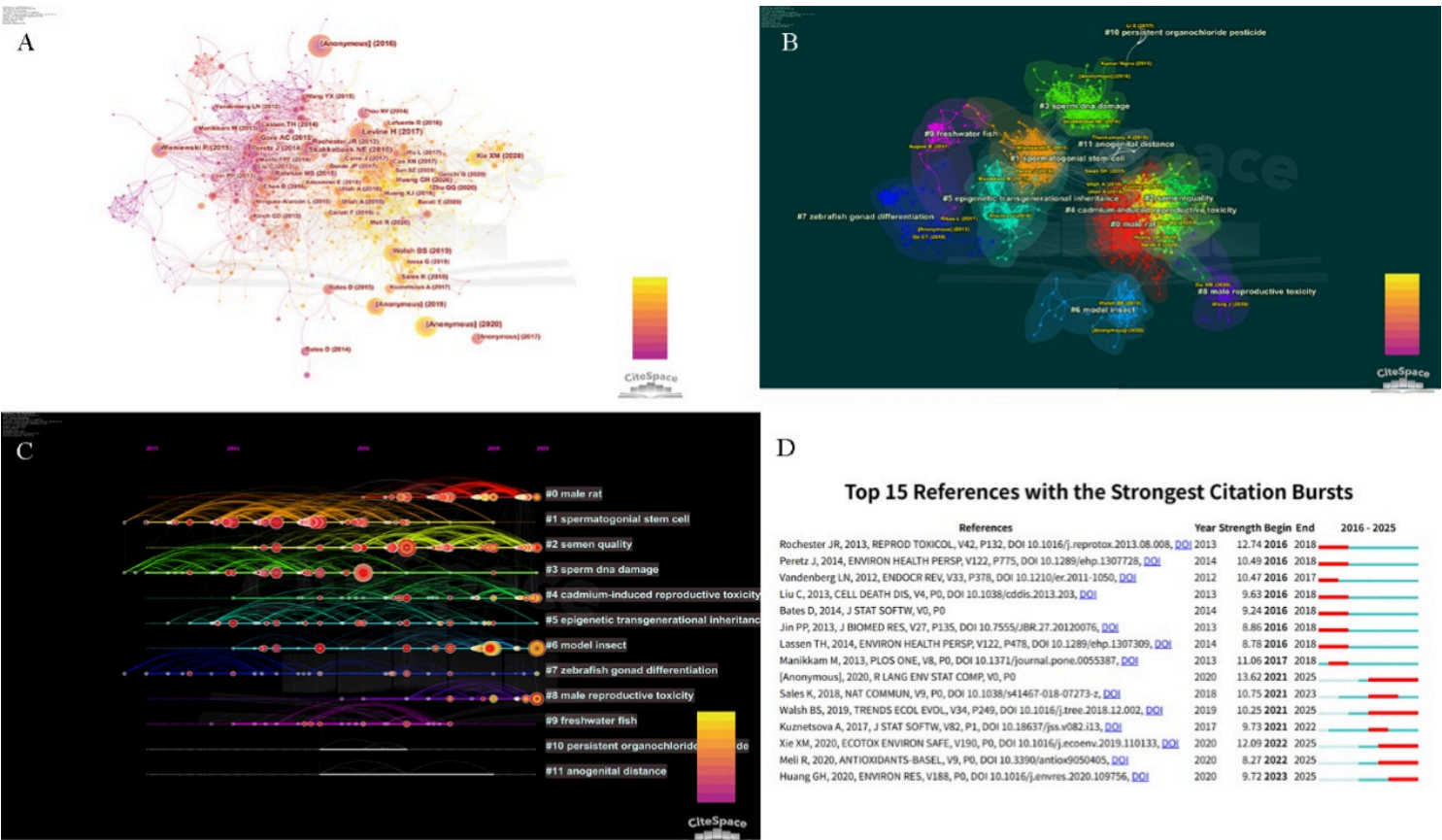


Figure 3

Citation analysis of environmental factor and male fertility. A: Co-citation Network Diagram of references related to environmental factor and male fertility; B: Citation cluster analysis results related to environmental factor and male fertility; C: Citation clustering fisheye diagram; D: Top 15 references with the strongest citation burst.

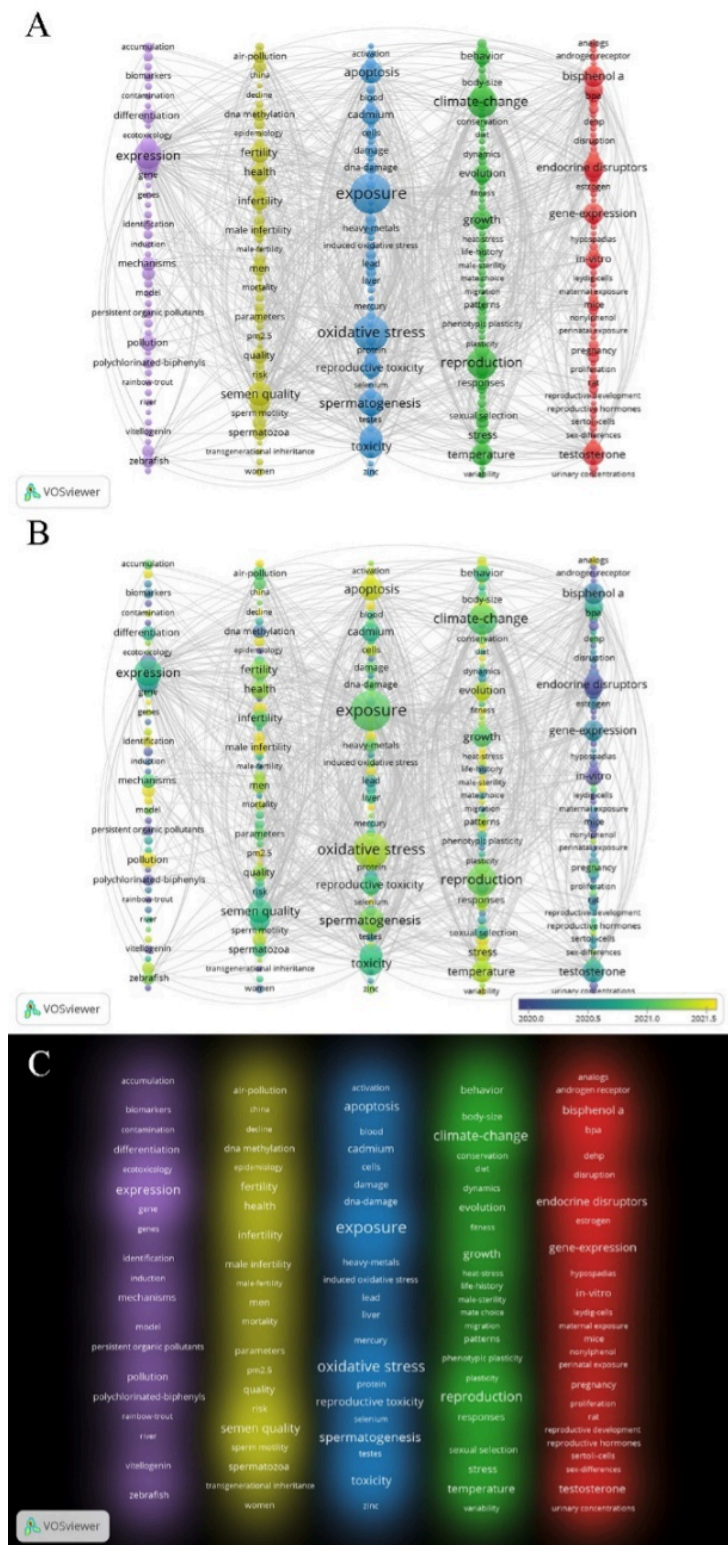


Figure 4

Co-occurrence Network Diagram of key words related to environment factors and male fertility. A: The cluster analysis of keywords. B: Overlay visualization of keywords. C: Density visualization of keywords.

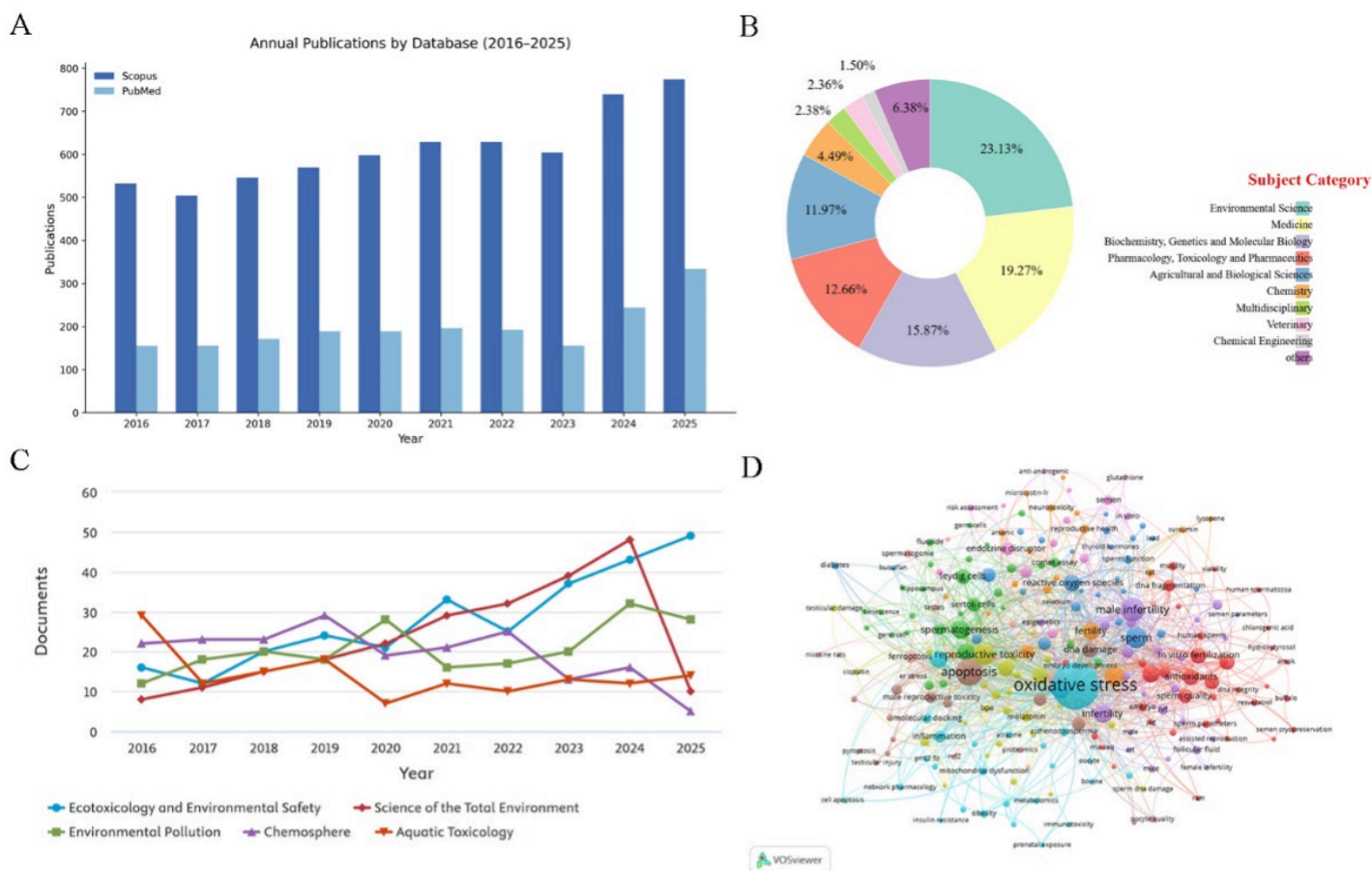


Figure 5

Cross-database validation and bibliometric analysis. (A) Annual publication output from Scopus (dark blue) and PubMed (light blue) between 2016 and 2025. (B) Distribution of subject categories among Scopus-indexed publications. (C) Temporal trends of annual publications in the five most productive journals. (D) Keyword co-occurrence network from PubMed-indexed studies