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Review

A Bibliometric Analysis of Mechanisms and Regulation of Hydrochemistry-Driven Soil Erosion in China

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Abstract

Soil erosion is a critical environmental issue restricting ecological security and agricultural sustainable development in China. Traditional studies have predominantly focused on physical driving factors such as hydraulic and wind erosion, while the regulatory effects of hydrochemistry on soil erosion have long been neglected. To clarify the mechanisms and regulatory processes of hydrochemistry-driven soil erosion in China, this study collected 795 relevant publications from the Web of Science Core Collection spanning from 2000 to 2025. Based on bibliometric methods, visualization software including VOSviewer 1.6.20 and CiteSpace 6.4.R1 were adopted to analyze publication trends, author distributions, research institutions, and keyword co-occurrence characteristics. The results indicated that the number of publications concerning hydrochemistry-driven soil erosion in China has increased year by year since 2000. China ranks first in total publication output, showing a dominant research position in this field. The Chinese Academy of Sciences contributed the largest number of publications among all research institutions. Keyword co-occurrence analysis over the past 25 years demonstrated that soil erosion, runoff, and water erosion serve as the core research hotspots. Further analysis revealed the regulatory mechanisms of key hydrochemical parameters (e.g., pH value, ionic strength, and dissolved organic carbon) throughout erosion processes. In-depth keyword analysis confirmed that current research on hydrochemistry-driven soil erosion in China remains at the preliminary stage, lacking comprehensive exploration of microcosmic mechanisms and systematic regulation strategies. Therefore, intensified research efforts and optimized regulatory frameworks are urgently required in future studies. This study can provide theoretical foundations and technical references for improving the understanding of erosion driving mechanisms and enhancing soil erosion management efficiency across diverse regions of China.

Keywords: water chemistry; soil erosion; ecological security; knowledge map

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1. Introduction

Soil erosion is one of the core manifestations of global land degradation. According to the 2025 report of the United Nations Office for Disaster Risk Reduction, approximately 30% of the global land area is threatened by soil erosion, causing an annual economic loss of 300 billion US dollars and a grain yield reduction of 33.7 million tons. Climate

change and land use change are the dominant driving factors, among which the interaction between slope gradient and rainfall erosivity presents the most significant effect. Against this background, China is among the countries most severely affected by soil erosion, and relevant research in China provides valuable references for global soil conservation. It is evident that soil erosion is the primary factor driving global soil degradation and associated ecological problems. These issues pose a substantial threat to agricultural productivity and ecosystem stability. Here, the term soil erosion refers to the erosion of soil caused by natural factors (such as precipitation and wind) and human activities (such as agricultural farming and mining). This process leads to the loss of soil particles, which directly results in the loss of organic matter and nutrients in the plow layer and reduces soil fertility [1–3]. The long-term effects of erosion are twofold: firstly, effects from the erosion process itself, and secondly, the consequent irreversible land degradation. In China, the issue of soil erosion is especially pronounced, and it has emerged as a critical impediment to the sustainable advancement of agriculture [4]. For example, the red soil region in Southern China is particularly susceptible to erosion (red soil is an acidic ferralsol rich in iron oxides that is widely distributed in southern China, featuring poor structure and weak erosion resistance). The issue of soil erosion is rendered more complex and severe by the unique geographical and climatic conditions of the region. The climatic characteristics of high temperature and rainy weather in this area lead to strong surface runoff during the rainy season, which further exacerbates the loss of soil particles [5]. Research has demonstrated that escalation in extreme precipitation events can also exert a profoundly deleterious effect on society, manifesting in forms such as floods, soil erosion, and a decline in agricultural productivity [6]. These phenomena invariably have an inevitable impact on the pursuit of sustainable socio-economic development and the preservation of the ecological environment. Precipitation is the most significant factor affecting regional water erosion, determining the spatial and temporal pattern of regional soil erosion to a certain extent [7,8]. In light of the observed increase in global extreme precipitation events in recent decades, there has also been an increase in the incidence of soil water erosion events [9]. There is an increasing correlation between extreme precipitation and water erosion events.

In China, black soil regions, as typical eroded areas, are located in high-latitude cold zones with a relatively unique erosion environment (black soil is a fertile humus-rich soil, while red soil is an acidic iron-rich soil; both are susceptible to water erosion in China). Multiple erosion agents, including water, wind, and freeze–thaw action, coexist within the region. Among these, water erosion is distributed extensively, is of high intensity, and exerts a significant influence, constituting the predominant erosion type in the black soil area [10]. Strong water erosion can lead to damage to farmland and infrastructure, changes in transport corridors, reduced surface water quality, and deterioration of the ecological environment [11]. According to statistical data [12], the black soil region in Northeast China covers an area of approximately 1.1 million square kilometers, accounting for 19.7% of the national total soil erosion area. The black soil layer is being eroded and degraded at a rate of 2–3 mm per year.

The soil environmental degradation is becoming increasingly prominent. Heavy metal pollution, acid rain deposition and pesticide residues are particularly problematic, as they pose a serious threat to agricultural production and ecosystem health. In this regard, the national government has promulgated a series of laws, regulations and policy documents, elucidating the direction and focus of soil pollution prevention and control. The “Soil Pollution Prevention and Control Action Plan” (Soil Ten) (State Council, 2016) was the first document to propose the concept of “classified governance” and clarify the implementation of key remediation measures in high-risk areas. The “Soil Pollution Prevention and Control Law” (National People’s Congress, 2018) established “soil pollution prevention and control”

as a matter of national legal status, emphasizing the principle of "who pollutes, who governs". It is evident that the policy documents in question have been instrumental in promoting soil quality and safety at the national strategic level. Furthermore, they have facilitated a more profound examination of the mechanisms of soil erosion and migration, with a particular emphasis on the hydrochemical driving mechanisms. This has in turn enabled the development of advanced technologies for remediation and prevention.

Soil erosion is a multi-dimensional coupling process, in which hydrochemistry is not only an important driving factor, but also a key bridge connecting the hydrological cycle, geochemical weathering and biogeochemical feedback. Conventional single-disciplinary research, which concentrates on a single factor such as rainfall erosion, has proven challenging in elucidating the variations in erosion observed across different regions. The introduction of multidisciplinary methods has been demonstrated to facilitate a comprehensive understanding that encompasses molecular mechanisms and extends to watershed scales.

In the context of global water relations, water fulfills a dual role as both a physical porter and a chemical activator. Human activities have been demonstrated to exert an influence on the chemical composition of precipitation and runoff [13]. The resultant chemical erosion of soil has been identified as a factor that has been neglected and which accelerates global soil erosion.

Soil erosion driven by hydrochemical processes is essentially different from physical erosion caused by hydraulic and wind forces. It is a complex coupling process dominated by chemical actions and synergized by physical transportation. Its hazards present stronger concealment, sustainability and cumulative superposition effects, exerting profound impacts on the evolution of soil resources, the stability of ecosystems, and human production and daily life.

The core microscopic mechanisms of hydrochemical erosion mainly include ion exchange, particle dispersion and flocculation. Ion exchange refers to the replacement of exchangeable ions on the surface of clay minerals by various cations in water, which changes the electric double-layer structure on particle surfaces and the interparticle interaction force. Particle dispersion occurs when variations in the hydrochemical environment destroy the bonding of soil aggregates, leading to the disintegration of aggregate structures and the separation of fine particles. Flocculation is induced when high-valence ions compress the electric double layer and promote fine particles to aggregate, thereby remodeling the soil microstructure. These three processes jointly determine soil structural stability and the development of soil erosion [14].

On the one hand, hydrochemical processes destroy soil aggregate structures and the organic cementation bonds between particles through ion exchange, acid–base dissolution and other approaches. This deteriorates soil pore structure and reduces porosity, further inducing soil compaction and secondary desertification. It completely disturbs the original soil profile, worsens soil physical and chemical properties, declines soil fertility, and ultimately results in continuous degradation or even complete loss of land productivity.

On the other hand, damaged soil structure and reduced soil fertility directly weaken the anchoring capacity and nutrient absorption efficiency of vegetation roots and inhibit normal vegetation growth, leading to a gradual decline in regional vegetation coverage. This further triggers cascading ecological effects such as intensified soil and water loss and expanded land desertification, damages the original habitats of animals and plants, reduces regional biodiversity, and accelerates the degradation and imbalance of watershed ecosystems. Its impacts are no longer limited to local land degradation but can extend to downstream water bodies via runoff migration, inducing a series of water environmental problems such as water eutrophication, estuarine acidification and abnormal carbon chemical conditions in coastal waters.

This indicates that current soil erosion prevention and control can no longer rely merely on traditional slope engineering measures. It is necessary to adopt coordinated strategies integrating water quality regulation and hydrochemical environment management. Therefore, systematically clarifying and revealing the internal mechanism of hydrochemically driven soil erosion has important theoretical value and practical significance for improving regional soil and water conservation management systems, optimizing erosion prevention schemes, controlling engineering geological disasters, and maintaining watershed ecological security [15–17].

Although some hydrochemical processes can disperse soil colloids, they do not necessarily lead to soil erosion. For instance, saline–alkali soils are mostly distributed in low-lying areas of arid environments, where annual evapotranspiration exceeds precipitation or the soils are affected by high-salinity groundwater. Soil salinization is caused by the capillary rise of high-salinity groundwater and subsequent water evaporation. Although salinization and alkalization can disperse soil colloids, such processes cannot be defined as soil erosion. Only when the dispersed soil particles are transported by slope runoff and deposited at the lower slope position can the process be defined as soil erosion.

To comprehensively clarify the research status and developmental trends of soil erosion in China, numerous studies have systematically explored erosion issues from diverse perspectives. Existing relevant research can be generally categorized into macroscopic review, internal mechanism analysis, technical method application, and external influencing factor exploration. In terms of macroscopic research overview, Zhu et al. [18] summarized the progress of soil and water conservation and erosion control in China. From the perspective of erosion mechanisms, Wang et al. [19] revealed the underlying processes of soil and water loss. With respect to technical means, Zhang et al. [20] adopted geographic information systems (GIS) to conduct quantitative erosion research, demonstrating that multidisciplinary methods including geographic information science and mathematical statistics can provide reliable technical support for soil erosion prediction. In addition, scholars have also focused on changing environmental factors and soil property variations. Zhou et al. [21] reported that increased spring snowmelt runoff and prolonged autumn rainfall duration could aggravate soil erosion in high-latitude regions of China. Regarding soil organic carbon variation, Zhu et al. [22] explored the response of soil organic carbon to slope erosion through aggregate grading and carbon isotope analysis, providing molecular geochemical evidence for erosion research. Globally, Borrelli et al. [23] adopted the RUSLE model to simulate global water erosion dynamics from 2015 to 2070. Furthermore, Tiwari [24] verified that saline solution could chemically weaken soil shear strength, indicating the non-negligible chemical effect on soil mechanical properties. Although the above studies have enriched the theoretical understanding of soil erosion, most existing studies primarily focus on conventional erosion processes and soil organic carbon variation. Macroscopic regulation mechanisms driven by water chemistry have rarely been systematically summarized in China's erosion research. Globally, the internal linkage between hydrochemical variation, soil mechanical properties, and erosion evolution remains insufficiently recognized. The neglect of hydrochemical constraints may lead to uncertainties when utilizing pre-industrial soil data for erosion prediction.

In view of this, the present study conducted a bibliometric analysis of the literature on hydrochemical-driven soil erosion in China included in the Web of Science core database from 2000 to 2025, with an aim to clarify the research status and development trend in this field. This study employed bibliometric methods and associated data mining and visualization tools, including VOSviewer 1.6.20 and CiteSpace 6.4.R1, to systematically analyze the number of literature publications, author distribution, research institutions and keywords. The relationship between hydrochemistry and soil erosion processes was systematically

analyzed, revealing the core mechanism of hydrochemical-driven soil erosion. The study also proposed differentiated regulation strategies to provide a reference for the research direction of water chemistry driving soil erosion and soil and water conservation in China.

1.1. Research Purpose and Objectives

1.1.1. Research Purpose

Soil erosion is a global environmental problem and a critical issue concerning national ecological and food security in China. Due to its vast territory and complex topographic and climatic conditions, soil erosion exhibits obvious regional heterogeneity across the country, among which water erosion is the dominant erosion type. There is an essential intrinsic correlation between hydrochemical processes and soil erosion. On the one hand, hydrochemical processes, including ion dissolution, element migration and chemical weathering, serve as vital driving forces for the separation and transport of soil particles. On the other hand, soil erosion causes massive losses of nutrients (e.g., carbon, nitrogen, and phosphorus) and heavy metal pollutants, thereby threatening watershed ecological security. The distinct regional disparities in hydrochemistry–erosion interactions in China provide a natural laboratory for theoretical exploration. The black soil region in Northeast China suffers from coupled degradation of soil acidification and erosion; the Loess Plateau is confronted with sediment management and watershed ecological conservation; the karst areas in Southwest China are dominated by the coupling mechanism between hydrogeochemical cycles and rocky desertification; the red soil regions in Southern China are severely affected by geochemical erosion induced by acid rain. However, existing studies mainly concentrate on physical erosion processes and predictive models, while insufficient attention is being paid to hydrochemical driving mechanisms, and a systematic theoretical framework has not yet been established.

Based on bibliometric analysis, this study systematically summarizes the global research progress of hydrochemistry-driven soil erosion. Combined with regional characteristics and national strategic demands, this work aims to improve the theoretical system of soil erosion and provide scientific support for the formulation of differentiated soil management policies in China.

1.1.2. Research Objectives

1. Conduct performance analysis of the most productive authors, institutions and countries in this field.
2. Reveal the intellectual foundation and landmark literature that shape this field through co-citation analysis.
3. Identify current research hotspots and future directions via keyword burst detection analysis.
4. Explore the mechanisms and control strategies of hydrochemically driven soil erosion through in-depth analysis.

2. Materials and Methods

2.1. Data Collection

The data of this study are derived from the Web of Science core collection database. The search strategy uses the keyword combination 'topic' = ((“water chemistry” OR “chemical properties of water” OR “ionic composition” OR “solute chemistry” OR “salinity” OR “SAR” OR “sodium adsorption ratio” OR “Na/Ca ratio” OR “EC” OR “electrical conductivity” OR “TDS” OR “total dissolved solid” OR “pH” OR “alkalinity” OR “bicarbonate” OR “divalent cation” OR “Ca^{2+}” OR “Mg^{2+}” OR “chloride” OR “sulfate” OR “anion composition”) AND (“soil erosion” OR “water erosion” OR “sediment yield” OR “soil detachment” OR “runoff”)) AND (China). The search scope is limited to the core

sub-database of the database. The time span is from 1 January 2000 to 1 December 2025. After manual screening to eliminate the non-research literature and remove duplicates, 795 valid international publications were finally obtained as analysis samples, the detailed screening procedure is illustrated in Figure 1.

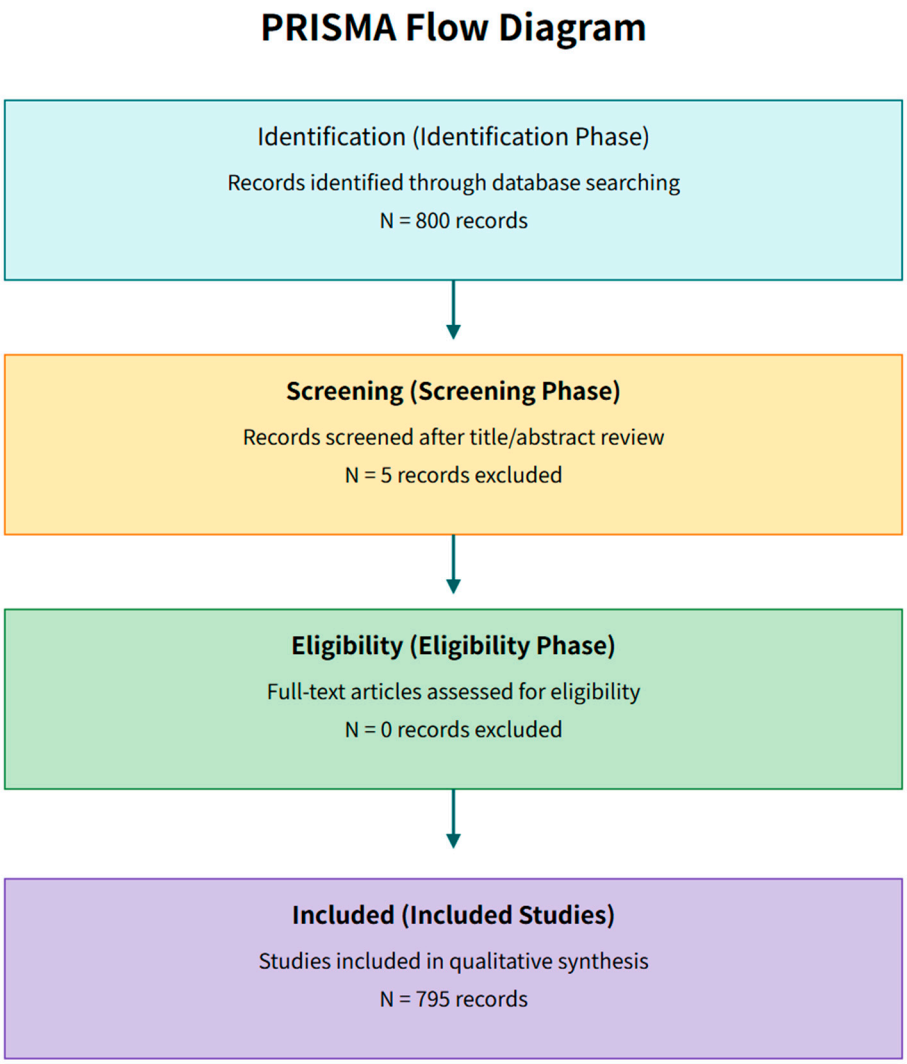


Figure 1. PRISMA flow diagram.

2.2. Exclusion Criteria for "Irrelevant" Literature

In this study, the literature was screened based on two dimensions of relevance. Any of the literature that failed to meet the criteria in either dimension was deemed irrelevant and excluded.

2.2.1. Driving Factor Dimension

Relevant Literature: Studies that focus on hydrochemical properties, specifically:

Water pH: The effects of acidic or alkaline water on soil particle bonding.

Ion Concentration and Type: Particularly the roles of H^+, Ca^{2+}, Mg^{2+}, K^+, heavy metal ions, etc.

Chemical Scaling and Dissolution: The impacts of carbonate precipitation, acid dissolution, and other chemical reactions on soil structure.

Regulation Measures: Studies employing limestone powder, gypsum, lime water, chemical stabilizers, etc., to control soil erosion.

Irrelevant Literature: Studies where the core driving factors are hydraulic (e.g., rainfall intensity, flow velocity, discharge, slope gradient), biological (e.g., vegetation coverage), or soil mechanical properties (e.g., clay content, porosity), with no involvement of hydrochemical properties.

2.2.2. Research Content Dimension

Relevant Literature: Studies that focus on either:

Mechanistic Analysis: For example, how acidic water disrupts soil colloidal structure, or how Ca^{2+} and Mg^{2+} promote soil aggregate formation.

Experimental or Model Validation: Laboratory simulations of pH effects on erosion rates, or the development of coupled hydrochemical–erosion models.

Irrelevant Literature: Studies that only address macro hydrological characteristics, climate change impacts on erosion, or solely soil physical properties (e.g., bulk density, pore structure) without mentioning hydrochemical effects.

After excluding all the irrelevant literature that focused solely on hydraulic or biological factors based on the above criteria, a total of 795 eligible publications were retained as the basis for data analysis, providing reliable data support for this study.

The Web of Science Core Collection was selected as the primary data source for literature retrieval in this study for the following reasons. First, journals included in the WoS database are strictly screened based on indicators such as the Journal Citation Reports (JCR) impact factor, ensuring the quality of the retrieved literature. Second, WoS possesses long-term archival records dating back to 1900 in the fields of environmental science, geoscience, and soil science, which facilitates the analysis of long-term research trends. Finally, its embedded citation analysis function enables the tracking of research hotspots evolution and knowledge foundations, thereby supporting in-depth systematic review.

Nevertheless, the Web of Science still has inherent limitations despite its high academic influence. Firstly, the database is dominated by English publications, potentially causing inclusion bias against valuable research achievements from non-English-speaking countries such as China and Brazil. Secondly, it fails to fully cover regional journals and the literature of emerging interdisciplinary subjects. In addition, the inclusion of open-access journals and conference papers is inconsistent, which may impair the comprehensiveness of literature acquisition. These limitations should be carefully considered when interpreting the research results.

Common databases in the field of soil erosion also include the China National Knowledge Infrastructure (CNKI), Scopus, and Google Scholar. CNKI contains a large number of Chinese publications, regional monitoring data, and academic dissertations. Scopus covers more regional non-SCI journals and the interdisciplinary literature, while Google Scholar has the broadest coverage including gray literature and conference papers. If these databases were incorporated in this study, the proportion of localized engineering cases and applied research would increase. Nevertheless, multiple data sources may disperse keyword clustering and complicate the evolution mapping. In comparison, the Web of Science Core Collection provides highly standardized and well-balanced literature, which is more suitable for revealing macroscopic research trends and dominant theoretical frameworks in this field.

2.3. Research Methods

This study adopts the bibliometric method and applies two visualization software, VOSviewer 1.6.20 and CiteSpace 6.4.R1, to conduct knowledge graph analysis. Developed by Chen Chaomei's research team [25], these tools are widely used for knowledge graph construction and disciplinary trend assessment. As a typical bibliometric research rather

than a systematic review that must strictly comply with PRISMA 2020 guidelines, this study mainly focuses on quantitative literature sorting and exploration of academic development trends. By analyzing publication volume, research institutions and keywords, it systematically summarizes research hotspots, mainstream directions and temporal evolution laws in this field, which can provide scientific references and theoretical support for further in-depth research on the mechanism and regulation strategies of hydrochemistry-driven soil erosion in China.

In this study, two mainstream bibliometric software, VOSviewer 1.6.20 and CiteSpace 6.4.R1, were adopted for complementary analysis to ensure result reliability. In CiteSpace, the time slice was set to one year with a Top N threshold of 50. The g-index algorithm (k = 25) and the Pathfinder pruning method were applied. This software supports burst term detection and betweenness centrality analysis, making it suitable for identifying dynamic evolutionary processes and research frontiers. VOSviewer 1.6.20 was used for association strength normalization. The screening thresholds were set to no less than three publications per author and no less than five keyword occurrences, with a clustering resolution of 1.00. It is capable of visualizing massive bibliometric datasets. The consistent outputs of the two tools mutually verified the robustness of the research conclusions [26,27].

3. Results

3.1. Number of Publications and Regions

3.1.1. Number of Publications

From 2000 to 2025, the Web of Science database published 800 related papers. After sorting out and eliminating the duplicate and unrelated literature, a trend analysis of the number of publications was carried out on the 795 included papers. It can be seen from Figure 2 that the annual number of documents and the cumulative number of documents in this research field are on the rise as a whole, indicating that the research interest in this field has been growing steadily. Specifically, from 2000 to 2007, the number of related papers was relatively low, with an average of about six articles per year, indicating that the research on the field of soil erosion driven by water chemistry in China was in its infancy. Since 2008, the annual number of papers has been on the rise as a whole, from 24 in 2008 to 72 in 2025, with an average annual number of 41 papers, reaching a peak in 2025. This shows that researchers have been increasingly interested in the study of hydrochemical-driven soil erosion in China since 2008. The high degree of attention may be the concentrated manifestation of the driving effect of relevant policies such as soil erosion control, for example the No. 8 document issued by the Soil and Water Conservation Commission in 2008 on the issuance of 'Technical Review Points for Soil and Water Conservation Programs for Development and Construction Projects [28].

3.1.2. Analysis of National/Regional Publications

Based on the WOS database, the countries of publication were analyzed through Citespace. Figure 3 is the national distribution map of the top 20 countries with the largest number of publications. It can be seen that among the main countries and regions that studied the hydrochemical-driven soil erosion in China from 2000 to 2025, the five countries with the largest number of publications are China (535), the United States (100), Spain (40), Australia (22), Germany (18). Using VOSviewer 1.6.20 to analyze the cooperation relationship between these countries, as shown in Figure 4, it can be seen that the United States and Australia cooperated most with other countries around 2014, and international cooperation in this field gradually increased after 2016, especially in 2018–2020. The cooperation network is more intensive. The nodes of China and the United States are significantly larger than those of other countries, and they are the core output subjects in this field. Although

the nodes of Germany, the Netherlands and India are small, they are in the key connection position of the cooperation network and are important participants in the region. Multi-country cooperation has jointly promoted the research progress of hydrochemical-driven soil erosion in China.

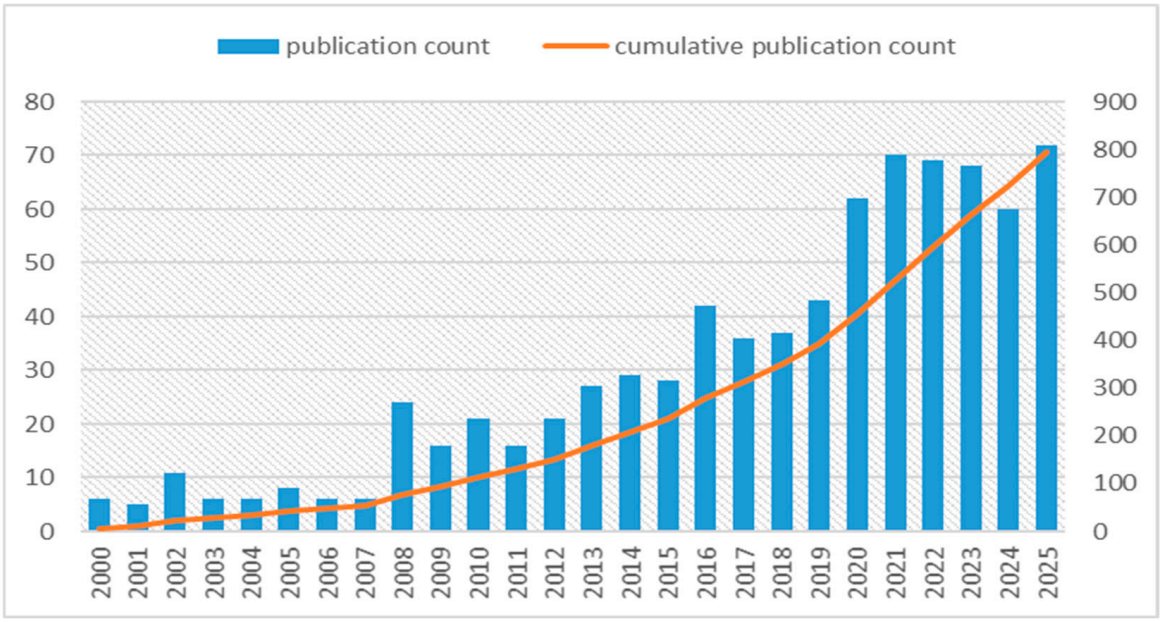


Figure 2. Number of publications and cumulative publications (2000–2025). Note: The figure shows number of publications and cumulative publications (2000–2025). Blue bars represent the number of publications per year (left y-axis, unit: count), and the orange line shows the cumulative number of publications (right y-axis, unit: count). The figure shows a gradual increase in annual publications, with a rapid growth phase starting around 2016.

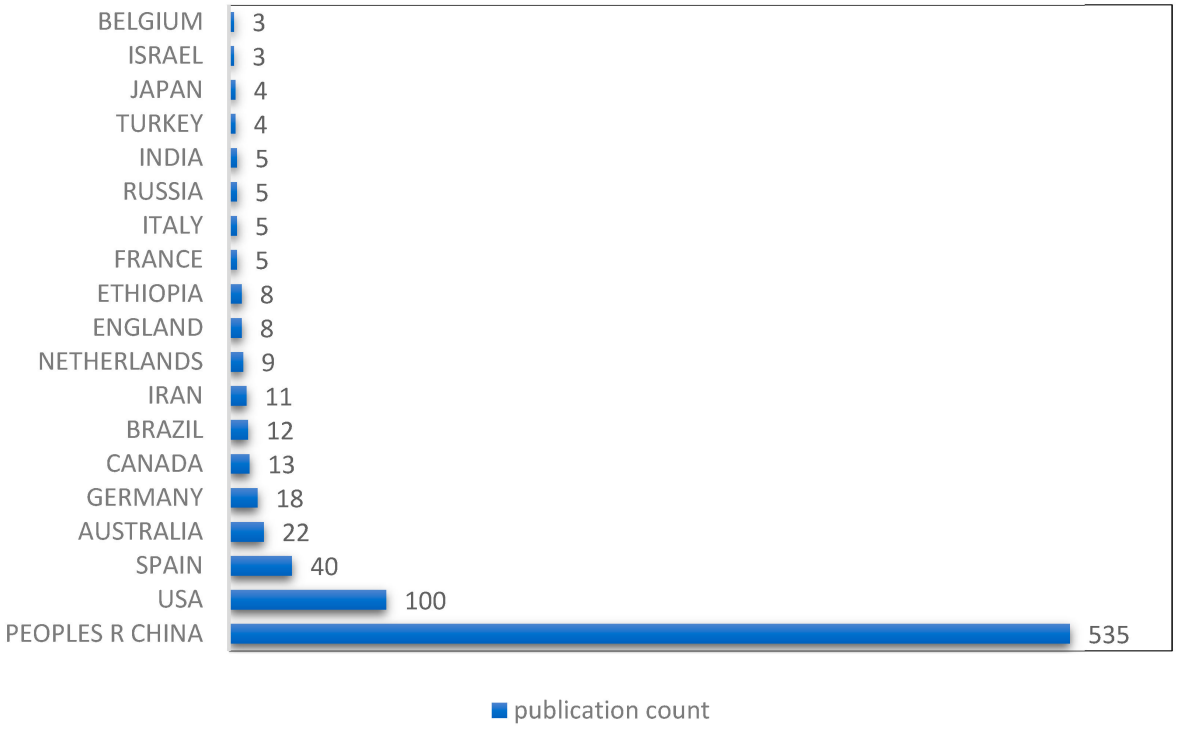


Figure 3. The number of research publications by country. Note: The figure shows the number of research publications contributed by different countries/regions, ranked in ascending order of publication count.

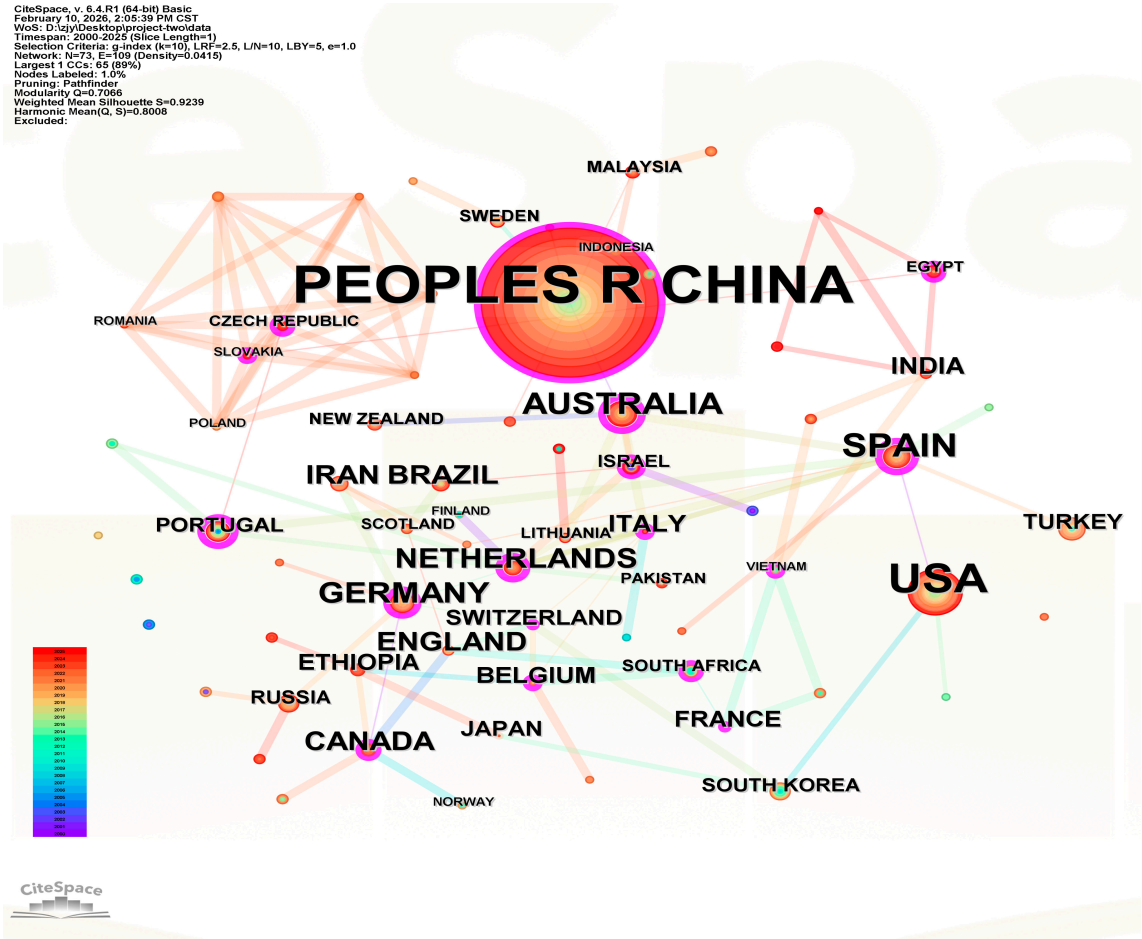


Figure 4. National cooperation map. Note: The figure shows the national collaboration map (CiteSpace visualization). Node size = Publication output; Line width = Cooperation strength. The map was generated using CiteSpace 6.4.R1 with association strength normalization. The keyword occurrence threshold was set to ≥5 times, and the clustering resolution was 1.00. Node size represents occurrence frequency, and lines indicate co-occurrence relationships.

3.2. Study on the Distribution Characteristics of Authors

The authors of the 795 papers on hydrochemical-driven soil erosion in China from 2000 to 2025 in the WOS database were analyzed, and the author map and cooperation relationship were obtained. From Figure 5, it can be seen that since 2010, there are more and more researchers in the field of hydrochemical-driven soil erosion in China. Li Peng, Li Zhanbin, Li Zhongwu, J. Rodrigo-comino and other high-yield authors are at the core of the cooperation network and play a key role; some authors, such as Li Dingqiang, have formed a close cooperative relationship with other authors, which is helpful to promote the in-depth development of research. It is worth noting that foreign authors have appeared in the network, indicating that there is some international cooperation in this field. It can be seen from Table 1 that nine of the top 10 authors are Li Peng, who ranks first (twelve articles), followed by Li Zhanbin (eight articles), and Li Zhongwu and Rodrigo-comino (seven articles each), indicating that they are the core research forces in this field in China. Although some emerging researchers have published fewer papers around 2024, they have become an important new force to promote the development of this field.

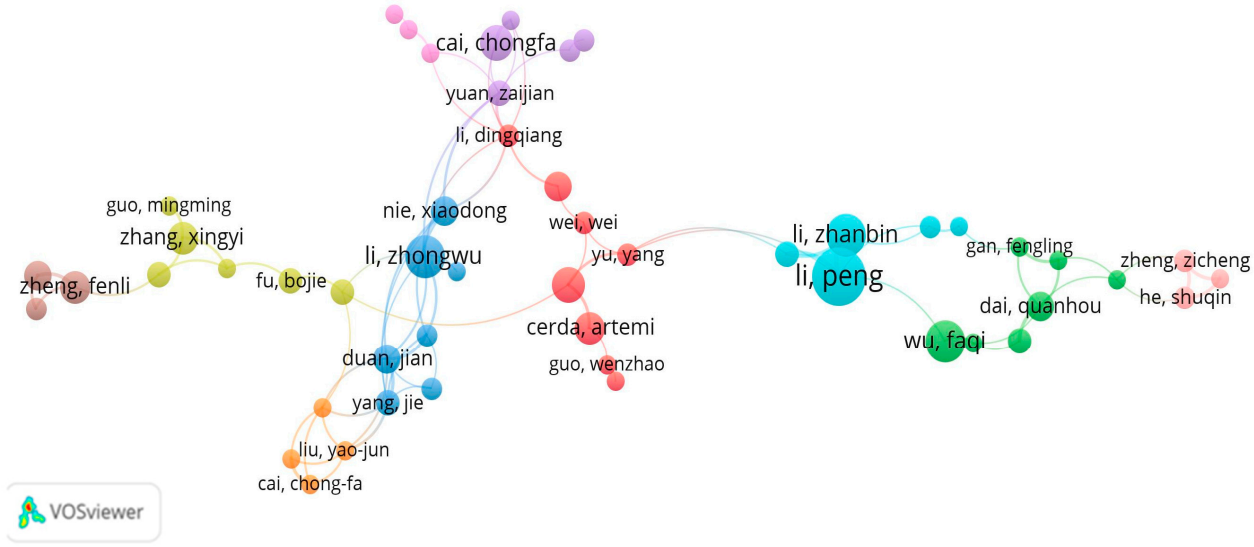


Figure 5. Author cooperation map. Note: The author collaboration network was generated by VOSviewer 1.6.20 with association strength normalization. The minimum publication threshold for authors was set to 3. Nodes represent authors, and node size indicates publication frequency. Links represent cooperative relationships between authors, and line thickness denotes collaboration intensity.

Table 1. Top 10 authors by the number of publications.

Order	Author	Earliest Year of Occurrence	Publications	Proportion of Publications
1	Li Peng	2019	12	1.51%
2	Li Zhanbin	2022	8	1.00%
3	Li Zhongwu	2013	7	0.88%
4	J. Rodrigo-comino	2018	7	0.88%
5	Li Dingqiang	2010	6	0.75%
6	Duan Jian	2022	5	0.63%
7	Cai Qiangguo	2007	5	0.63%
8	Wu Faqi	2017	5	0.63%
9	He Shuqin	2018	4	0.50%
10	Liu Yaojun	2025	4	0.50%

Note: Literature proportions were calculated from a total of 795 included publications.

3.3. Distribution Characteristics of Research Institutions

It can be seen from Table 2 that the top 15 research institutions published a total of 648 papers in the field of hydrochemical-driven soil erosion from 2000 to 2025, accounting for about 81.5% of the total number of publications, which indicates that the research concentration is high, and the scientific research output is mainly concentrated in these institutions. The number of papers published by the Chinese Academy of Sciences ranks first, with 85 more papers than Northwest A & F University (the second-ranked institution) and 111 more papers than the University of Chinese Academy of Sciences (the third-ranked institution). The number of publications by research institutions ranked 4–7 is also not significantly different, ranging from 20 to 23. Combined with the analysis of the cooperation network diagram of the research institutions in Figure 6, it can be seen that there is a clear cooperative relationship between the core institutions in China (Chinese Academy of Sciences, Northwest A & F University) and the representative research institutions in Spain (University of Valencia), the United States (USDA's Agricultural Research Bureau) and other countries. Based on the node density of the cooperation network, the cooperation between domestic institutions shows higher tightness. Although international cooperation was initially carried out, its proportion in the overall cooperation network and the closeness of

cooperation are significantly lower than those between domestic institutions. In general, the domestic research field has formed a multi-subject structure with universities, government agencies and research institutes as the core; at the same time, domestic institutions and overseas institutions have built a preliminary bridge of international cooperation, laying the foundation for the international expansion of the research field.

Table 2. Statistical table of literature output and citation of main research institutions.

Order	Research Institutions	Publications	Citations	Total Link Strength
1	Chinese Academy of Sciences	174	6626	336
2	Northwest A&F University	89	3964	182
3	University of Chinese Academy of Sciences	63	2415	149
4	Ministry of Water Resources	45	2027	97
5	Chinese Academy of Sciences & Ministry of Water Resources	30	924	73
6	Beijing Normal University	53	2724	61
7	Ministry of Education	17	226	59
8	Xi'an Technological University	36	981	57
9	Beijing Forestry University	32	513	55
10	Huazhong Agricultural University	32	1333	49
11	China Institute of Water Resources and Hydropower Research	22	460	46
12	University of Valencia	15	620	38
13	United States Department of Agriculture, Agricultural Research Service	21	1512	34
14	China Three Gorges University	11	175	28
15	Ministry of Water Resources	8	461	28

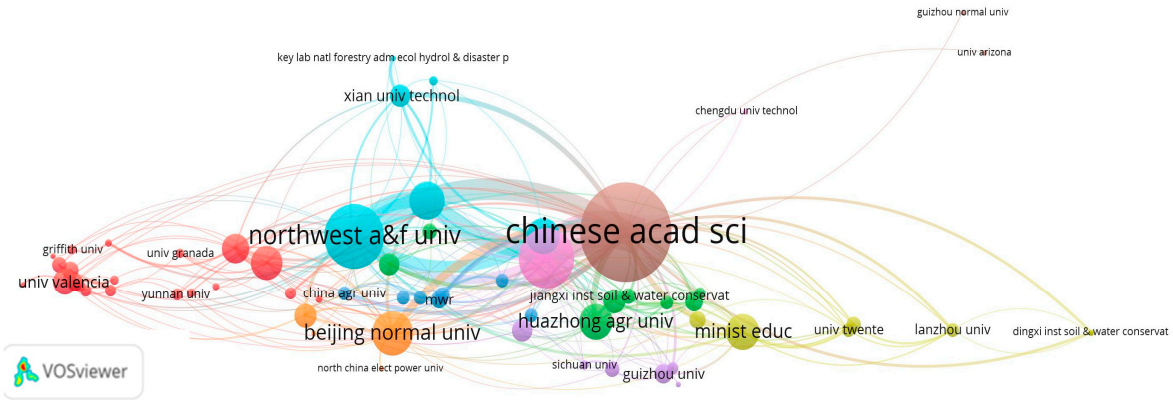


Figure 6. Research institutional cooperation map. Note: The institutional collaboration network was generated by VOSviewer 1.6.20 with association strength normalization. The minimum publication threshold for institutions was set to 3. Nodes represent research institutions, and node size indicates publication output. Links represent collaborative relationships between institutions, and line thickness denotes collaboration intensity.

3.4. Keyword Co-Occurrence Analysis

The utilization of keywords is paramount in reflecting the core theory of the article. In order to further explore the core of the field of hydrochemical-driven soil erosion in China, based on the WOS database, this study used the VOSviewer 1.6.20 visualization tool to analyze the keywords co-occurrence of the literature in the field of hydrochemical-driven soil erosion in China. As shown in Figure 7, it can be seen that the largest nodes in the figure: "soil erosion", "runoff", and "water erosion" are the core research objects in this field, with the highest frequency of occurrence, and the Centrality is more than 0.1, which constitutes the "triangular core " of the research field. This dominant position is not accidental, but is determined by the internal relations of natural geographical processes and the evolution of research methods; other nodes (such as "sediment", "land use", "conservation") are related research directions around the core theme. Different color node groups correspond to different themes (e.g., green clusters focus on "soil erosion mechanism", red clusters associate with "relationship between runoff and water erosion"); the connections between the nodes (such as the rough connection between "soil erosion" and "runoff") indicate that the research correlation between the two is very strong. It can be seen that keywords are widely distributed and related. The frequency and centrality of keywords reflect the core and focus of research in this field. The keywords that are top 20 in frequency are listed in Table 3. It can be seen from the table that "soil erosion" ranks first with the frequency of 359 occurrences. Combined with keywords such as "runoff", "water", and "sediment", this shows that soil erosion and hydrological processes are the core research directions in this field; at the same time, 'loess plateau' appeared 145 times as a regional keyword, which clarified that the research area focused on the Loess Plateau. From the perspective of "Centrality" index, the centrality values of high-frequency keywords such as "soil erosion" and "runoff" are higher (e.g., "soil erosion" reaches 0.43), which means that these words are the core nodes in the research network of this field and connect most related research; the centrality of keywords such as "region" and "transported" in the later period is zero, and most of them are supplementary topics in the subdivision direction. In terms of time, from 2001 to 2025, the early period (2001–2004) was dominated by basic themes such as "soil erosion" and "runoff"; after 2010, the research on micro-processes such as "detachment" and "aggregate stability" gradually extended; after 2020, technical method keywords such as "simulated rainfall" appeared, reflecting the expansion trend of research from macro-themed to subdivision process and technical means.

Table 3. High-frequency keywords.

Order	Keywords	Count	Centrality	Earliest Year of Occurrence
1	Soil erosion	359	0.43	2001
2	Runoff	277	0.36	2008
3	Sediment yield	176	0.14	2003
4	Water erosion	158	0.11	2002
5	Loess plateau	145	0.11	2015
6	Land use	106	0.03	2004
7	Impact	68	0.06	2006
8	Water	62	0.02	2013
9	Overland flow	55	0.07	2010
10	Detachment	52	0.06	2018
11	Erosion	46	0.01	2002
12	Rainfall	43	0.01	2006
13	Catchment	41	0.01	2013
14	Aggregate stability	25	0.02	2019
15	Infiltration	21	0.11	2000

Table 3. *Cont.*

Order	Keywords	Count	Centrality	Earliest Year of Occurrence
16	Rainfall intensity	21	0.01	2019
17	Surface runoff	16	0.00	2020
18	Model	15	0.01	2017
19	Interrill erosion	15	0.00	2011
20	Flow	15	0.01	2015

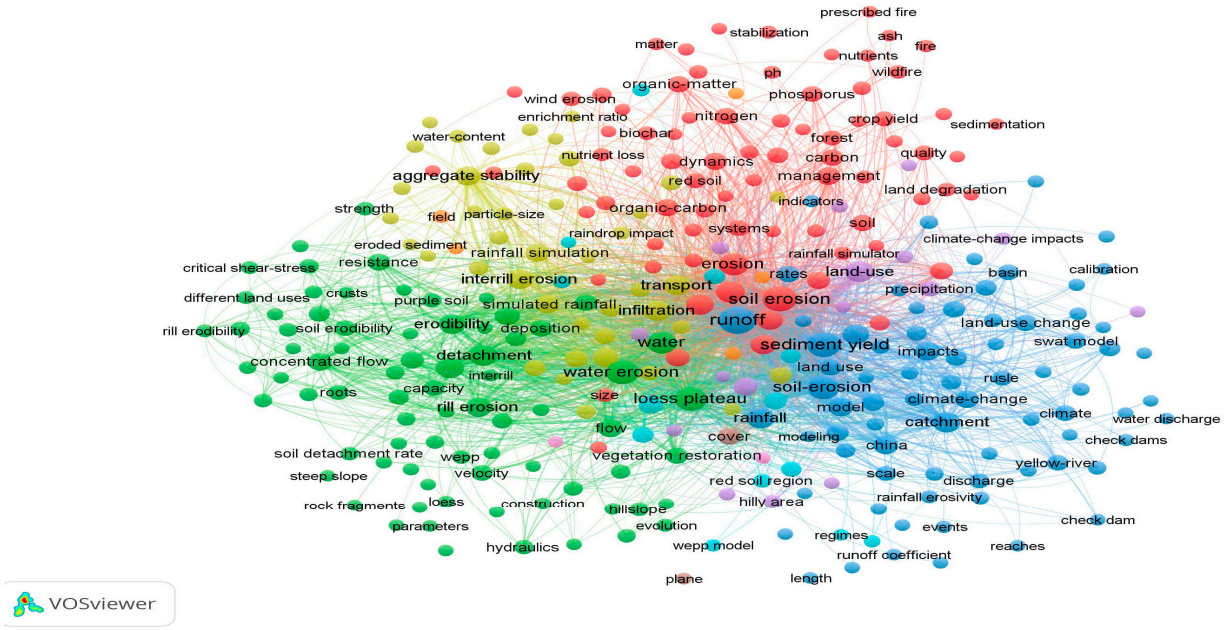


Figure 7. Keyword co-occurrence map. Note: The keyword co-occurrence map was generated by VOSviewer 1.6.20. The association strength normalization was adopted, the minimum keyword occurrence threshold was 5, and the clustering resolution was 1.00. Node size represents occurrence frequency, and line thickness indicates the association strength between keywords.

3.5. Hot Frontier Research Analysis

Through keyword co-occurrence and cluster analysis of 795 publications in the field of hydrochemical-driven soil erosion in China from 2000 to 2025, the results are shown in Figures 8 and 9. According to Figure 8, the nodes: "erosion", "runoff", and "water erosion" are in the center of the map and the brightest color. They are the absolute core topics in this field and have the highest research attention. The surrounding related words: "sediment", "catchment", and "catchment detachment" are the high-frequency related research directions around the core theme. In general, the research takes "soil erosion–runoff–water erosion" as the core, and extends the subdivision directions of "sediment transport, catchment process, erosion separation mechanism", which reflects the research framework in this field.

It can be seen from Figure 9 that the keyword clustering timeline map can clearly show the research hotspots at each time point on the timeline. The map takes "soil erosion" as the core node, and connects the basic themes of "sediment yield", "runoff", "loess plateau" and so on by connecting lines. It reflects that "soil erosion" is the core of research in this field, and other themes are centered on it. There are thirteen key subdivision directions (#0–#12), including soil detachment, loess plateau, interrill erosion, xiliugou basin, rainfall erosivity, temperate environment, soil detachment rate, rill development, etc. These subdivision directions are connected to the core theme through nodes, reflecting the extension of research from "soil erosion" to specific processes, regulatory measures, and influencing

factors. The color of the line (from blue to red) corresponds to the correlation strength (the deeper the color, the stronger the correlation). It is evident that the color of the line demarcating "soil erosion", "sediment yield" and "runoff" is more saturated, suggesting that research in these areas exhibit the strongest correlation. The nodes in the subdivision direction are mostly orange/red, indicating that they are a more focused research branch. It can be seen that the current core research focuses on the coupling relationship of "soil erosion–runoff–sediment yield" as the core of the basic process, and at the same time, it is refined to micro-erosion processes such as "soil separation" and "temporary gully erosion". Focusing on natural factors such as "rainfall intensity" and "soil anti-erodibility", and the role of human regulation measures such as "vegetation restoration", all studies have anchored the specific region of the "Loess Plateau", reflecting the regional focus of this research.

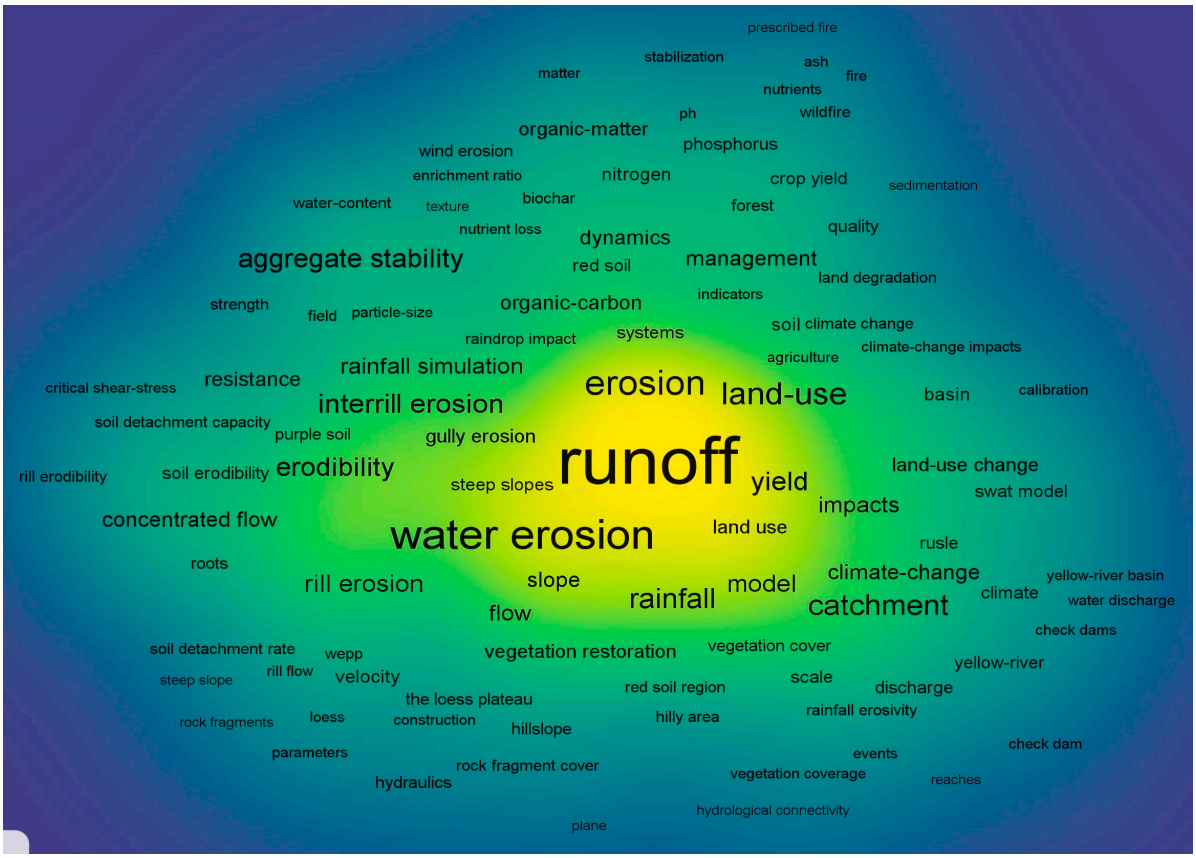


Figure 8. Keyword density map. Note: The keyword density map was generated by VOSviewer 1.6.20 with association strength normalization. The minimum keyword occurrence threshold was set to 5. Color gradients represent keyword density, where brighter colors indicate higher aggregation intensity and research hotspots.

In addition to the intuitive visualization characteristics, the internal research logic behind the keyword clusters was further summarized in this study. The highly correlated coupling of "soil erosion–runoff–sediment yield" indicates that current research still relies on traditional hydrological erosion frameworks. The concentrated research on the Loess Plateau demonstrates an obvious regional preference, whereas hydrochemical erosion mechanisms in southern acidic soil areas remain insufficiently emphasized. Furthermore, most clustered topics focus on macroscopic hydraulic processes, while microcosmic chemical interactions (e.g., ion exchange, colloidal dispersion, and electrolyte effects) are rarely integrated into erosion frameworks. This finding confirms that existing studies generally ignore hydrochemical constraints and lack systematic exploration of chemical-driven erosion

mechanisms. Therefore, future research should strengthen the combination of hydrochemical parameters and soil physical erosion processes to fill the current research gap.

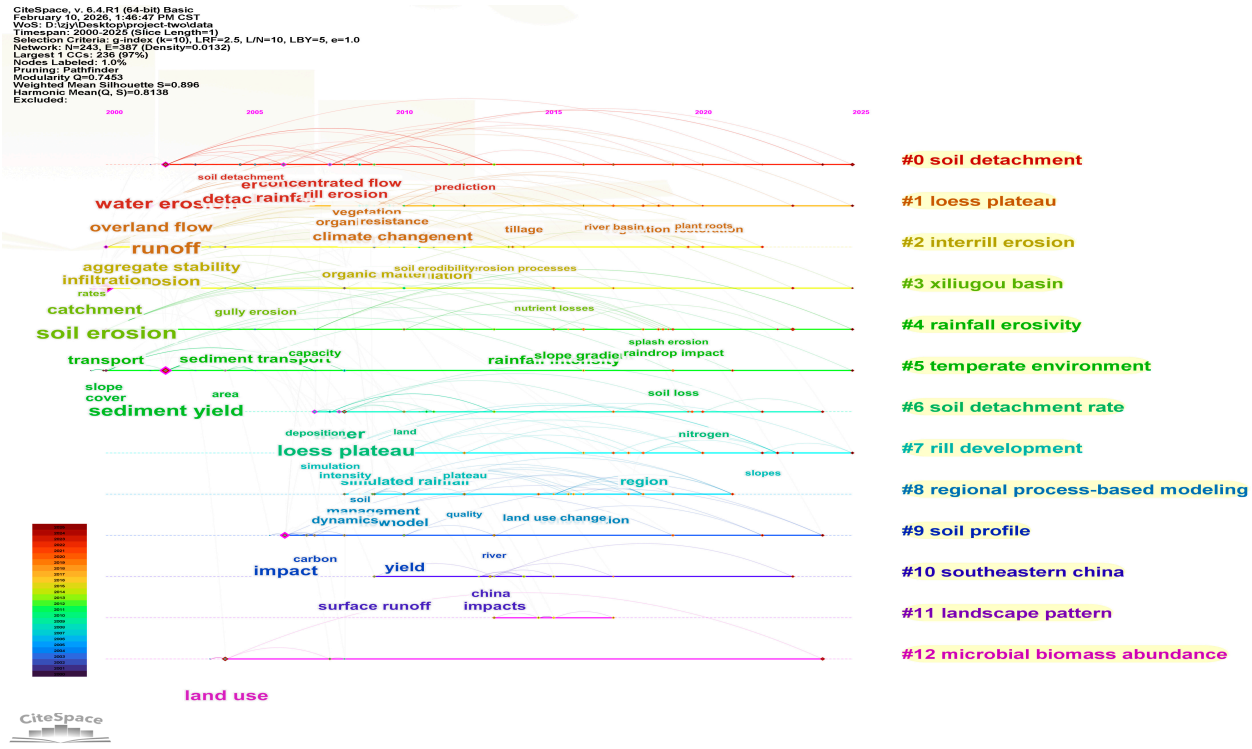


Figure 9. Keyword clustering timeline map. Note: The keyword timeline clustering map was generated by CiteSpace 6.4.R1. The parameter settings included a time slice of 1 year, Top N of 50, g-index (k = 25), and Pathfinder pruning. Nodes denote keywords, and links reflect their co-occurrence relationships over time.

3.6. Spatio-Temporal Evolution Mechanism of Dominant Theme

The keyword co-occurrence analysis (Figure 6) revealed that soil erosion, runoff, and water erosion form a tightly coupled triad, occupying the central position in the network. This observed dominance is not merely a fortuitous occurrence; rather, it is indicative of a fundamental physical linkage among the aforementioned processes. Runoff is the primary hydraulic driver that mobilizes soil particles, while water erosion represents the dominant form of soil loss in most Chinese catchments, especially in the Loess Plateau and the black soil regions of Northeast China (Wang et al. [12]; Li & Zhou [29]). Consequently, these three terms frequently co-occur in the literature, forming the core of the water–soil conservation research paradigm (Zhang et al. [30]).

Moreover, the sustained prominence of these themes over the past decade is closely tied to technological advancements and policy imperatives. The rapid development of remote sensing (e.g., Sentinel-1 SAR) and GIS tools has dramatically lowered the cost of monitoring runoff and erosion processes, leading to a surge in publications focused on hydrological erosion coupling and large-scale sediment transport modeling (Yang et al., [31]). Concurrently, the escalating frequency of extreme precipitation events in the context of climate change has augmented the societal pertinence of runoff-induced erosion, thereby further reinforcing the research focus on these subjects (Xue & Zhang [32]).

This phenomenon is corroborated by the extant literature. For instance, Gao et al. [33] demonstrated the application of InSAR technology for high-resolution monitoring of soil erosion, highlighting a methodological shift towards space-based observation. In a similar vein, Xue and Zhang [33] emphasized the integration of runoff dynamics with sediment

transport models to assess flood-induced erosion risk in the upper Yangtze River basin. The extant research demonstrates that the triad of soil erosion, runoff, and water erosion remains pivotal, and is undergoing a transition towards multiscale, interdisciplinary approaches, reflecting the latest scientific knowledge.

3.7. Analysis of High Frequency Citations

Citation frequency is a key indicator of the impact and dissemination of academic achievements. Highly cited papers, representing cutting-edge findings and research foundations in the field, provide critical references for clarifying disciplinary development and the positioning of this study.

Based on the Web of Science Core Collection database, this study visualized the citations of literature on water chemistry-driven soil erosion in China (2000–2025) using the VOSviewer 1.6.20 software (Figure 10). The results indicate close citation relationships among the literature, which can be roughly divided into three core research themes.

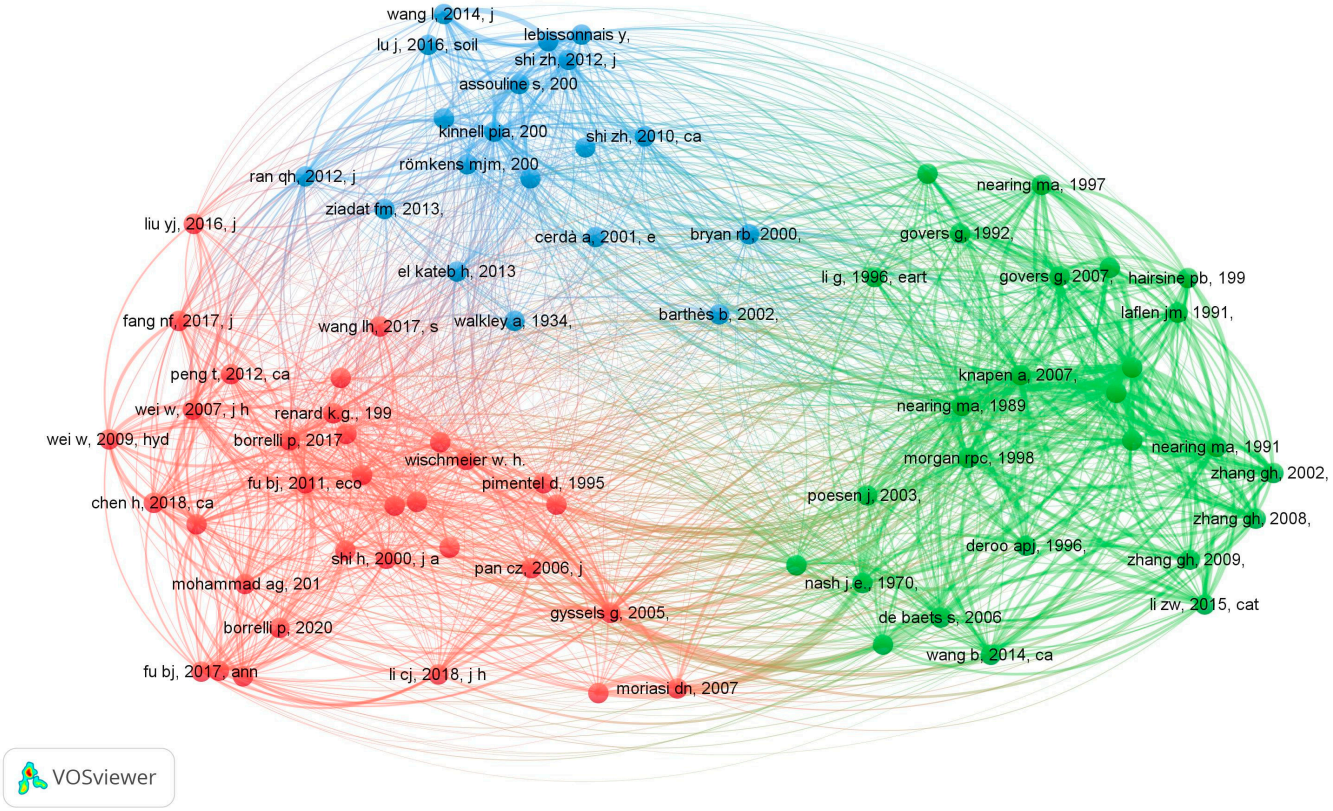


Figure 10. Citations co-occurrence map. Note: The citation co-occurrence map was generated by VOSviewer 1.6.20 with association strength normalization. The minimum citation threshold was set to 5. Nodes represent cited papers, and node size indicates citation frequency. Links represent co-citation relationships, and line thickness denotes association strength.

Table 4 presents the top 10 most cited papers, including six by Chinese authors, three by Italian authors, and one by a Moroccan author, focusing on soil erosion, water erosion, soil loss, and their environmental effects. The most cited paper, Hydrogeomorphic Ecosystem Responses to Natural and Anthropogenic Changes in the Loess Plateau of China (862 citations), systematically discussed hydrogeomorphic ecosystem responses to natural and anthropogenic changes on the Chinese Loess Plateau, establishing a regional hydrological erosion coupling framework. However, it focused primarily on physical processes (e.g., runoff and sediment) and insufficiently addressed the coupling mechanism between hydrochemical migration and erosion.

Table 4. Top 10 citations.

Order	Author	Title	Year of Publication	Total Citations/Times
1	Fu Bj	Hydrogeomorphic Ecosystem Responses to Natural and Anthropogenic Changes in the Loess Plateau of China	2017	862
2	P. Borrelli	Global Phosphorus Shortage will be Aggravated by Soil Erosion	2020	557
3	Chen H	Global Negative Effects of Nitrogen Deposition on Soil Microbes	2018	546
4	P. Borrelli	Soil Erosion Modelling: A Global Review and Statistical Analysis	2021	491
5	Shen Ho	Impacts of Rainfall Intensity and Slope Gradient on Rill Erosion Processes at Loessial Hillslope	2016	247
6	Liu By	The Assessment of Soil Loss by Water Erosion in China	2020	225
7	Li Cj	Impact of Biochar Addition on Soil Properties and Water-fertilizer Productivity of Tomato in Semi-arid Region of Inner Mongolia, China	2018	133
8	P. Borrelli	Assessment of the Impacts of Clear-cutting on Soil Loss by Water Erosion in Italian Forests: First Comprehensive Monitoring and Modelling Approach	2017	66
9	Fang Nf	Runoff and Soil Erosion of Field Plots in a Subtropical Mountainous Region of China	2017	65
10	Bahddou	Changes in Soil Surface Properties under Simulated Rainfall and the Effect of Surface Roughness on Runoff, Infiltration and Soil Loss	2023	52

The second-ranked paper, Global Phosphorus Shortage Will Be Aggravated by Soil Erosion (557 citations), first quantified soil erosion's impact on global phosphorus loss, revealing erosion's environmental chemical effects. However, it relied on global model estimations, lacking regional in situ observations and hydrochemical mechanism verification. The third-ranked paper, Global Negative Effects of Nitrogen Deposition on Soil Microbes (546 citations), clarified nitrogen deposition's impacts on soil ecosystems but did not couple nitrogen deposition with the direct driving mechanisms of soil erosion.

Scholar Borrelli, P. contributed three top-10 papers (2017, 2020, 2021), with an average of 371 citations, focusing on global-scale soil erosion assessment and element loss effects—reflecting international attention to erosion's environmental chemical effects. Overall, highly cited literature in this field is characterized by "emphasizing physical processes over chemical mechanisms": most focus on macro hydrological erosion coupling or element loss effects, with a lack of research on the micro-mechanisms of water chemistry-driven soil erosion and regional in situ observations. This highlights the necessity and innovation of this study, which focuses on water chemistry-driven soil erosion mechanisms.

4. Discussion

This study systematically reveals the development trends, knowledge structure, and evolutionary paths in the field of hydrochemical-driven mechanisms and regulation of soil erosion in China from 2000 to 2025 based on bibliometric methods. Through a comprehensive analysis of 795 relevant literature records from the Web of Science Core Collection, this paper comprehensively outlines the dynamic development and full-cycle evolution of this interdisciplinary field over the past two decades from multiple dimensions, including annual publication trends, national and institutional collaboration networks, keyword frequency and clustering, and the evolution of research frontiers. The results fully reflect the profound changes in the field in terms of research directions, methodologies, technical means, and application scenarios, providing solid literature support and theoretical references for accurately grasping research hotspots and breaking through core bottlenecks in subsequent studies.

Combined with the keyword clustering map and burst detection analysis (as shown in Figures 8 and 9), the research focus has exhibited distinct staged evolutionary characteristics throughout the 20-year development of the field:

In the initial stage (2000–2022), the field centered on the introduction and feasibility verification of emerging technologies such as machine learning, focusing on basic monitoring of soil erosion, response laws of hydrochemical factors, and preliminary quantitative prediction, which laid a solid methodological and theoretical foundation for the discipline [16].

In the developmental stage (2023–2024), research topics rapidly diversified and research dimensions continued to expand in depth, gradually shifting to subdivided directions including specific algorithm optimization, multi-source monitoring data fusion, and targeted applications in typical eroded areas, with significantly improved relevance and practicality [18].

In the recent deepening stage (2024–2025), the field has further focused on core challenges such as quantification of model uncertainty, vertical expansion of research scales, and coupled analysis of hydrochemical processes and soil erosion mechanisms. The overall research has undergone a major transformation from "technology-driven" to "problem-oriented" and "system integration", marking that the field has entered a new stage of high-quality and in-depth development [31–33].

Notably, the hydrochemical-driven mechanisms and regulation of soil erosion should be regarded as the breakthrough point in this field, providing theoretical support for soil and water conservation practices.

4.1. Mechanism of Hydrochemical-Driven Soil Erosion

The driving mechanism of soil erosion can be categorized into two distinct categories: physical driving (such as rainfall splash erosion, mechanical force of runoff erosion) and chemical driving (which encompasses hydrochemical action). A bibliometric analysis was conducted to ascertain the trends in research focus related to the phenomenon of soil erosion. The analysis revealed a gradual shift in research focus, from early themes such as soil erosion prevention and control, to more in-depth investigations into the mechanisms of soil erosion and hydrochemical migration processes. This change is closely related to the national policy orientation. The "Soil Pollution Prevention Law" explicitly stipulates that "soil quality monitoring and risk assessment should be carried out in areas where soil pollution has occurred". Consequently, the academic community has begun to direct increased attention towards the dissolution, migration and enrichment processes of heavy metals and salinized substances in the soil within the hydrological cycle, otherwise referred to as the "hydrochemical drive". In addition, soil pollution and

degradation are closely affected by multiple driving factors and typically concentrated in sensitive vulnerable regions, which are strongly associated with industrial emissions around industrial zones, groundwater table rise in areas with high-salt parent materials, and long-term excessive application of agricultural chemical fertilizers. Typical sensitive areas susceptible to soil pollution mainly include the peripheral zones of industrial and mining enterprises, farmland irrigation areas and salinized watersheds, where the hydrochemical processes dominate the evolution of soil quality and structural degradation. On the one hand, hydrochemical-driven soil erosion has been shown to destroy soil structure, weaken soil physical protection, release organic matter and nutrients originally encapsulated by aggregates, and accelerate its decomposition and loss. Conversely, the selective nature of erosion leads to the preferential removal of soil fine particles or micro-aggregates, resulting in the loss of organic matter and nutrients. This, in turn, contributes to a decline in soil organic matter, total nitrogen, and total phosphorus, thereby exacerbating erosion [34–38].

Hydrochemical-driven soil erosion has been demonstrated to adversely affect soil structural stability. In addition, it has been demonstrated that this phenomenon can indirectly promote the detachment and migration of soil particles. This is achieved by altering the chemical properties of the soil or the interaction between the particles. The following chemical factors have been identified as the primary drivers of hydrochemical-driven soil erosion.

4.1.1. Ionic Strength and Cation Composition

The flocculation/dispersion tendency of soil clay colloids is determined by their ionic strength and cation composition. The surface of soil colloids characteristically adsorbs cations (e.g., Ca^{2+}, Mg^{2+}) to form a flocculation state (i.e., a stable, non-releasing state). It has been demonstrated that an increase in ionic strength results in an increase in the stability of the colloidal flocculation structure, due to an increase in the amount of divalent cations (Ca^{2+}, Mg^{2+}). This increase in stability makes the structure resistant to erosion. Conversely, it has been demonstrated that a decrease in ionic strength, concomitant with an increase in the concentration of monovalent cations (Na^{+}), results in an exponential increase in the colloid release rate [39,40]. It has been demonstrated that a low ionic strength will result in the thickening of the double-layer film on the colloid surface. This, in turn, leads to the dispersion of the colloid, the disintegration of its structure, and the ease of its erosion. In the aqueous phase, under stable flow conditions and when certain chemical conditions are met, colloids may be observed to undergo a gradual release from the solid phase and migration with the water flow, provided that the kinetic energy of the colloid exceeds the adhesion interaction energy [41]. Conversely, in the course of transient change, that is, in the presence of instantaneous hydrochemical or hydrophysical disturbances [42], the surface charge of the colloid will be impacted, thereby influencing their interaction and dispersion between particles, leading to the expeditious release of a substantial number of colloids. It is evident that colloids are subject to electrostatic repulsion and van der Waals attraction. A decrease in electrolyte concentration (e.g., as a result of rainfall leaching or freshwater infiltration) leads to the opening of the electric double layer. This, in turn, leads to a greater repulsive force between colloids than gravitational attraction, triggering colloid release. This further results in the disintegration of soil aggregates, thereby increasing sediment concentration in runoff. Although partial hydrochemical processes can disperse soil colloids, such processes do not necessarily trigger soil erosion. For instance, saline–alkali soils are mostly distributed in low-lying arid areas with evaporation exceeding precipitation, or are affected by high-salinity groundwater. Soil salinization is primarily caused by the capillary rise of saline groundwater and subsequent water evaporation. Although salinization and alkalization can disperse soil colloids, these processes cannot be defined as soil erosion. Soil erosion

occurs only when dispersed soil particles are transported by overland flow and eventually deposited at downslope positions.

4.1.2. pH Level

In the tropical climate of Southeast Asia, soil water erosion is frequently documented as a significant soil problem. The alteration of pH value has been demonstrated to influence the occurrence and progression of erosion. The rise and fall of pH directly affects the surface charge, solubility and colloidal stability of soil colloids (e.g., colloidal clay minerals, iron and aluminium oxides) [43]. Acidic conditions (low pH) have been shown to enhance mineral dissolution, destroy cementation phases (e.g., oxide–colloid binding), release soluble ions and reduce agglomeration stability. Conversely, alkaline conditions (high pH) have been demonstrated to continuously increase the negative charge density on the surface of soil particles, thereby enhancing repulsion between them. The repulsion exerted by the clay causes it to be displaced, the soil is dispersed, the plasticity index is reduced, and the runoff is more readily peeled off. At the point of zero charge (PZC), the dispersed colloids are more likely to aggregate or condense. Conversely, a pH value below and above PZC will promote the release of colloids [44]. Furthermore, in the presence of strong alkaline conditions, the presence of Na^+ has been shown to impede the release of bentonite colloids [45]. The elevated pH value will augment the negative charge of the colloid, thereby potentiating electrostatic repulsion between the negative charges of the colloid [46]. This leads to the release of colloidal particles, the breakdown of soil aggregates, the dispersion of particles, the destruction of surface cover, and the ready formation of runoff transport pathways.

4.1.3. Dissolved Organic Matter (DOM)

Dissolved organic matter (DOM) has been demonstrated to play a dual role in the process of soil erosion, functioning as both a “lubricant” and a “binder”. It is evident that, in the context of diminished rainfall or irrigation, the colloidal organic matter present within the surface layer of soil undergoes dissolution into the water phase. This phenomenon directly results in the degradation of soil microstructure. The process under investigation involves the adsorption of cations (e.g., Ca^{2+} and Mg^{2+}) by dissolved organic matter (DOM) on the surface of soil particles. These cations are subsequently eluted by rainfall or irrigation, resulting in the weakening of charge shielding between soil particles. This, in turn, leads to the redispersion of colloidal particles that were originally tightly bound, due to repulsion, forming larger “debris” particles. Following the destruction, the soil particles lost their original structure and were more easily separated by external forces such as raindrop impact, thus entering the erosion cycle. Conversely, dissolved organic matter (DOM) has the capacity to modify the physical and chemical characteristics of water. It has been demonstrated that, owing to its natural “lubricating” properties, it has the capacity to markedly reduce both the viscosity and surface tension of water. When the water flow carries a high concentration of DOM, the fluidity of the water is enhanced, and the hydrodynamic viscosity is reduced, resulting in an increase in the scouring force of the water flow on the soil particles, and the particles are more easily taken away [47–51].

Dissolved organic matter has been shown to significantly affect soil erosion resistance by disrupting colloidal structure and reducing water viscosity. This bridging effect is pivotal, linking soil chemical alterations to physical erosion processes.

4.1.4. Salinity Concentration

Salinity concentration is a significant chemical driving factor affecting soil erosion, which has the capacity to substantially alter the stability and erodibility of soil aggregates by regulating the dispersion and flocculation state of soil colloids. It has been demonstrated that high salt concentrations (i.e., high ionic strengths) are capable of effectively

compressing the electric double layer of soil colloids. This process has been shown to reduce electrostatic repulsion between colloidal particles, thereby enhancing interparticle attraction, promoting the flocculation of soil particles, and improving aggregate stability. Furthermore, it has been observed that this can improve soil infiltration performance and inhibit the formation of surface crusts, thus enhancing soil erosion resistance. Conversely, a reduction in salt concentration (low ionic strength, such as that caused by salt dilution resulting from rainfall leaching) leads to an expansion of the colloidal double layer. The electrostatic repulsion thus becomes greater than gravity, resulting in a significant number of soil colloids being released and dispersed. These colloids then block soil pores, thereby aggravating surface crust formation and increasing surface runoff. This, in turn, leads to a substantial improvement in soil erodibility, thus promoting soil erosion [52,53].

Furthermore, the composition of salt exerts a superimposed effect on this phenomenon. The presence of salt dominated by divalent cations, such as Ca^{2+} and Mg^{2+}, has been shown to have a positive effect on soil flocculation and erosion resistance. In contrast, salt dominated by monovalent cations, such as Na^{+}, has been observed to have a detrimental effect on colloid dispersion and further promotes soil erosion [54,55].

In essence, the chemistry of water is the driving force behind soil erosion, whereby chemical reactions initially compromise the stability of soil structure, subsequently facilitating the physical transport of water and resulting in the loss of soil particles. Hydrochemical processes exhibit a tight closed-loop interaction with soil structure and hydrological processes. Ion dissolution and colloid migration weaken soil cementation capacity, disrupt aggregate structure, and alter soil pore characteristics. The variations in soil structure further regulate infiltration, runoff generation, and confluence processes, thereby modifying runoff erosion dynamics. In turn, hydrological processes drive solute leaching and ion redistribution and intensify the chemical weathering of soil and rock. The coupled interactions jointly regulate soil erodibility and water-sediment transport, serving as a critical intrinsic mechanism controlling regional water erosion evolution.

4.2. Effects of Geomorphic Location and Climatic Conditions on Hydrochemistry-Driven Soil Erosion

The hydrochemical processes of soil erosion are spatially heterogeneous and significantly constrained by geomorphic and climatic conditions. China possesses complex and diverse landforms. Considerable differences in hydrogeological conditions across various geomorphic units, ranging from eastern plains and western plateaus to southern hilly lands and northern gullies, lead to distinct regional characteristics of hydrochemical driving mechanisms.

In terms of geomorphic conditions, mountainous and hilly regions feature steep terrain and rapid surface runoff, resulting in stronger leaching intensity of hydrochemical elements compared with plain areas. The gully region of the Loess Plateau is characterized by loose loess parent material and dense gully networks, serving as the primary sediment source of the Yellow River. Its hydrochemical signatures are predominantly controlled by carbonate weathering. The southwest karst region develops well-established underground river systems, forming dual surface–subsurface hydrochemical circulation pathways with complicated coupling mechanisms between rocky desertification and soil erosion. The black soil region of the Northeast Plain is dominated by freeze–thaw cycles with distinct seasonal hydrochemical variations.

Climatic conditions constitute another critical factor regulating hydrochemistry-driven soil erosion. Annual precipitation decreases gradually from the southeast coast to the northwest inland, and the 800 mm precipitation isoline acts as a crucial boundary for hydrochemical erosion processes. Humid southern regions receive annual precipitation above 1000 mm, where high temperature and abundant rainfall accelerate intense chemical

weathering and element leaching. By contrast, semi-humid and semi-arid northern regions have limited and concentrated precipitation, exhibiting prominent seasonal hydrochemical characteristics. Rainfall intensity serves as a vital trigger for severe erosion, and rainstorm events induce the rapid release of hydrochemical elements within a short period. Temperature indirectly modulates hydrochemical processes by regulating microbial activity and chemical reaction rates.

The coupling interaction between landform and climate further shapes the spatiotemporal patterns of hydrochemistry-driven soil erosion. For instance, humid climates combined with hilly terrain in southern China create an environment characterized by intensive leaching and high erosion modulus. The semi-humid climate and gully landforms of the Loess Plateau contribute to intense sediment discharge into the Yellow River. An in-depth understanding of such coupling mechanisms is essential for formulating differentiated soil and water conservation strategies [56–59].

4.3. Regulation of Soil Erosion Driven by Water Chemistry

In order to address the issue of soil erosion in China, the government has implemented a series of restoration measures, with a resultant decrease in the intensity of soil erosion for 34.04% of the land. For instance, in the Loess Plateau, which experiences the most severe soil erosion in China, the project to return farmland to forest and grass was initiated in 1999, resulting in a marked improvement in the situation [60]. Furthermore, various soil amendments are employed to enhance soil structural stability and erosion resistance. The application of natural amendments has been demonstrated to exert a substantial influence on the cation exchange capacity (CEC) of soil, concomitantly enhancing its aggregate stability. This effect is attributed to the augmentation of soil organic matter content, which in turn leads to an improvement in soil moisture and nutrient retention. For instance, the application of biochar has been demonstrated to enhance the stability of soil carbon pools by adsorbing and stabilizing iron oxides and aromatic compounds in soil, thereby reducing the loss of soil nutrients caused by runoff and erosion [58].

Bio-amendments have been shown to significantly enhance soil water stability and erosion resistance by regulating soil microbial communities and secreting organic matter. For instance, polysaccharides and organic acids secreted by AMF (Arbuscular Mycorrhizal Fungi) have been shown to promote the formation of soil microaggregates, enhance soil water retention, and improve soil anti-scourability [61]. New materials, including W-OH colloidal materials, have also been developed as a means of reducing rainfall-induced hydrodynamic erosion. These materials are capable of filling pores and enhancing the stability of the surface structure [62].

It is evident that microorganisms play a key role in enhancing soil surface structural stability and erosion resistance. Microbial communities can improve soil physicochemical properties via diverse mechanisms, including physical and biochemical processes. These effects primarily result in alterations in aggregate particle size distribution and enhanced soil structure stability [63]. In a study by Chamizo et al., it was observed that the introduction of cyanobacteria into diverse soil textures led to a substantial increase in the total nitrogen and organic carbon content of the soil. This increase in nutrient content subsequently promoted the formation of soil aggregates, thereby enhancing soil structure stability [64]. The findings of Jia et al. demonstrated that microorganisms are the primary agents responsible for regulating soil enzyme activities. It has been demonstrated that the process of decomposition of organic matter in soil is accelerated by them through cell metabolism and the secretion of extracellular enzymes. In addition, the stability of the soil surface structure is increased, and soil erosion resistance is enhanced [65].

Secondly, it is proposed that farmlands should adopt conservation tillage systems (including rotation, no-tillage and reduced tillage, etc.) with scientific rotation systems. The hypothesis is that this will effectively increase the organic carbon storage in the tillage layer and enhance the carbon sink function of farmland [66–68].

Moreover, the "Guiding Opinions on Promoting Soil Pollution Risk Control and Green Low-Carbon Remediation" (No. 2023) set out new requirements for "green low-carbon remediation", thereby encouraging researchers to direct their attention to the use of hydrochemical methods (e.g., bioleaching, acid leaching) to achieve low-cost, low-environmental-load soil remediation.

4.4. Regional Differences and Differentiated Regulation Strategies

From the perspective of geomorphological and climatic zoning, differentiated strategies should be adopted to regulate the hydrochemical driving mechanisms of soil erosion across China:

Southern red soil hilly region: Priority should be given to mitigating the impacts of acid rain. Lime amelioration can be applied to alleviate soil acidification, while slope management measures can be implemented to reduce runoff scouring.

Loess Plateau gully region: Engineering measures such as grain-for-green programs and check dams should be primarily adopted, combined with vegetation restoration to enhance soil erosion resistance.

Northeast black soil region: Conservation tillage should be strengthened to reduce surface runoff, increase soil organic matter content, and mitigate the degradation of the black soil layer.

Southwest karst region: Systematic ecological management of mountains, rivers, forests, farmlands, lakes, and grasslands should be implemented to restrict rocky desertification expansion and protect groundwater resources [69–75].

This study only focuses on relevant literature within mainland China, and its conclusions are applicable to the field of hydrochemical-driven soil erosion mechanisms and regulation in China. To extend the findings to a global context, further cross-regional comparative studies are required, incorporating differences in physical geography, climate, soil properties and other conditions across regions, so as to ensure the rigor of research statements.

5. Conclusions

Based on the relevant literature from 2000 to 2025 in the field of hydrochemical-driven soil erosion mechanisms and regulation in China, this study conducted systematic bibliometric analysis and mechanism review, clarifying the global evolution and development trends of research in this domain. The results show that since 2000, both the annual and cumulative number of publications on hydrochemical-driven soil erosion in China have maintained a steady upward trend. Since 2010, research attention in this field has continued to rise, the research team has expanded continuously, and core research directions have focused on key issues such as soil erosion mechanisms, hydraulic erosion processes, and soil loss prevention and control.

In-depth mechanism analysis indicates that the core pathway of hydrochemical-driven soil erosion is as follows: chemical components first destroy the cementing structure of soil particles and weaken soil stability, which, combined with the physical transport effect of water flow, ultimately leads to the detachment and loss of soil particles. At present, a diversified system has been formed for mainstream control measures against such erosion, mainly including ecological restoration such as returning farmland to forests and grasslands, application of soil conditioners to strengthen soil structure, use of biochar to

adsorb and stabilize iron oxides and aromatic compounds for soil carbon pool stabilization, and application of biological amendments to regulate microbial communities and secrete organic matter to improve soil water stability and erosion resistance.

In summary, hydrochemical-driven soil erosion is a complex process involving the coupling of chemical degradation and physical transport. Its core mechanism lies in the regulation of microscopic hydrochemical indicators such as soil pH, salinity, and ionic composition, which alter the cementation state and aggregate stability of soil, thereby affecting the macroscopic erosion resistance of soil. Existing studies have confirmed that soil acid–base imbalance and salt accumulation directly degrade inter-particle cohesion and aggravate soil disintegration and loss. However, unreasonable control measures often focus only on physical protection while ignoring the root cause of hydrochemical imbalance. Therefore, soil erosion control should not rely solely on physical and ecological measures such as returning farmland to forests and slope protection; it must also be combined with targeted hydrochemical regulation strategies, such as applying alkaline amendments to adjust soil acidity, implementing special treatments for salinization to restore chemical equilibrium, and optimizing water and fertilizer management to maintain soil structural stability. Multiple measures should be taken simultaneously to restore soil chemical equilibrium and structural integrity.

Although considerable progress has been made in relevant research, weaknesses still exist in areas such as accurate prediction of erosion under extreme hydrochemical environments and the development of long-term ecological control technologies. Further improvement of the erosion prevention and control system is needed to provide scientific support for regional soil and water conservation as well as ecological protection and restoration.

Compared with previous studies, this paper still has certain limitations, particularly with regard to the precise management of regional soil erosion via region-specific adaptive models. Therefore, in order to break through the current technical bottleneck and promote the efficient and sustainable development of hydrochemical-driven soil erosion control, future research should go deeper in the following directions: First, closely combine the mandatory remediation standards of the “Soil Pollution Prevention Law”, and develop hydrochemical-driven remediation technologies suitable for different land use types (such as agricultural land, construction land). Secondly, in response to the principle of “who pollutes, who governs” in the “Soil Pollution Prevention and Control Action Plan”, use knowledge of acid leaching and bioleaching technology of heavy metal contaminated sites (such as mining areas, metallurgical plants) to achieve effective removal of pollutants. The third is to follow the “guidance on promoting soil pollution risk management and green low-carbon remediation”, and develop green hydrochemical treatment methods using biodegradable additives to reduce secondary pollution and carbon emissions. Fourth, strengthen technological innovation, develop low-cost and easy-to-operate IoT platforms, and promote efficient and large-scale application of technology. These studies can provide more robust theoretical and technical support for soil erosion control in China, and promote ecological security and the sustainable development of agriculture. In anticipation of the impending challenges posed by China’s intricate natural and geographical circumstances, compounded by the escalating concerns surrounding soil erosion, the following policy recommendations are put forward to provide a framework for subsequent scientific and technological research endeavors, with their practical implementation in mind.

Firstly, it is proposed that the issue of hydrochemical-driven soil erosion should be incorporated within the “ecological civilisation construction plan in the field of natural resources” and the global soil protection framework. Furthermore, the importance of this issue in the evaluation of ecosystem service function should be elucidated. The second is to

strengthen cross-sectoral collaborative supervision. Hydrochemical pollution is frequently the consequence of multiple sources, including agriculture (e.g., chemical fertilizers and pesticides), industry (e.g., wastewater discharge) and urbanization (e.g., rain and sewage diversion). It is recommended that a "soil–water" joint prevention and control mechanism be established, involving multiple departments. The third is to increase financial investment and innovation in science and technology. The establishment of a dedicated fund to support the application of "green degradation materials" in the context of soil erosion control is recommended. The utilization of financial subsidies has been identified as a key strategy to encourage farmers to employ green degradation materials, such as biochar and lime modifiers, with the aim of enhancing soil buffering and water retention capacity. This approach is intended to mitigate the deleterious effects of salt and acid–base on soil structure.

In summary, to promote the transformation of hydrochemical-driven soil erosion control research into policy, it is necessary to build a systematic and efficient cultivated land ecological protection system by improving laws and regulations, building multi-sectoral joint prevention and control, and increasing the application of green technology.

Overall, based on long-term bibliometric methods, this study systematically sorts out the research evolution, coupling mechanisms, and prevention–control regulation systems of hydrochemistry-driven soil erosion in China. Compared with single mechanism experiments or localized observation studies, this paper clarifies the research hotspots, evolutionary context and technical application status of this field from a macro perspective. It summarizes the internal coupling logic that hydrochemical processes weaken soil structure while hydrological processes amplify erosion effects, and clarifies the current governance idea of combining physical-ecological measures with chemical regulation. This study not only concludes the existing technical deficiencies and poor regional adaptability of current research, but also proposes multi-dimensional optimization paths in combination with national soil management policies. It can provide a bibliometric reference for subsequent similar reviews on hydrochemical soil erosion, and offer a macro background basis and research guidance for microscopic erosion mechanism experiments, regional differentiated governance and green amendment technology development. Additionally, this research provides theoretical references and decision support for soil and water conservation, land ecological restoration, and sustainable utilization of soil resources.

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