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Visualization Network Analysis of Studies on Agricultural Drainage Water Treatment

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Abstract: Excessive chemical substances in agricultural drainage water have serious adverse effects on the ecological environment of the watershed into which they are discharged. Therefore, it has attracted widespread attention from scholars worldwide. In this paper, 282 scientific articles related to agricultural drainage water treatment are selected from the Web of Science Core Collection database, and CiteSpace was used to visualize and analyze the knowledge map of this field. The most productive authors, institutions, and countries in agricultural drainage water research are graphically presented in this paper. Developing countries are becoming the core force in this realm of inquiry. In addition, this paper explains the changes in research topics in this field over time and reveals current research hotspots, including "desalination", "denitrification", and "phosphorus removal". Future research endeavors in using bioreactors and agricultural drainage water ditches for treating agricultural drainage water are implied to become a research focus in this field. This paper also emphasizes that future environmental protection research should increase case studies in developing countries and develop corresponding solutions based on the actual situation of agriculture in rural areas of developing countries.

Keywords: agricultural drainage water; visual analysis; CiteSpace

1. Introduction

Agricultural production inevitably results in the production of a certain amount of agricultural drainage water. The excessive use of fertilizers and pesticides in agricultural production has led to numerous water quality issues in watersheds affected by agricultural drainage water. For example, the excessive amounts of nitrogen (N) and phosphorus (P) in the water have exceeded their reasonable threshold ranges, directly leading to eutrophication of the water, excessive algal growth, and fish death [1–3]. Currently, the impact of agricultural drainage water quality represents a significant concern [4,5].

In response to this situation, scholars from around the world have proposed a series of physical, chemical, and biological techniques to treat agricultural drainage water [6,7]. For instance, fertilizer management, cover crops, perennial crops, groundwater management, constructed wetlands, buffer strips, drainage ditches, saturated buffer zones, and bioreactors [8–14]. Among them, agricultural drainage water ditches and bioreactors have received widespread attention from scholars worldwide due to their unique advantages. Currently, research on agricultural drainage water treatment has evolved from a single discipline to a multidisciplinary one, which emphasizes the strong contribution of research developments in Engineering and Environmental Engineering to the study of agricultural drainage water treatment.

Agricultural drainage water ditches represent a direct link between farmland and natural water bodies, which play an important role in agricultural production [15–17]. In addition, agricultural drainage water ditches have been demonstrated to be suitable tools for mitigating agricultural pollution. Previous research has indicated that vegetated drainage ditches provide a suitable mechanism for the effective removal of nutrients, suspended solids, and organic matter from water bodies compared to unvegetated drainage ditches [18–23]. The cost of removing nitrates from agricultural drainage water using nitrification bioreactors is low, making it another proven technology that has been successfully applied in many places in addition to agricultural drainage water ditches [24]. In summary, although the environmental cost of agricultural drainage water is high, and the treatment methods are diverse, it is unquestionable that it can be used to help farmers achieve higher yields by controlling crop water status [25,26].

To date, few have investigated the entire knowledge domain of agricultural drainage water treatment, including how they change over time and the potential factors influencing such changes. To fill these research gaps, this paper downloaded all relevant English-language scientific publications from the Web of Science Core Collection (WOSCC) and visualized the research in the field of agricultural drainage water treatment using CiteSpace, a literature metric software based on computational and statistical methods (Chen, 2017). This paper visualizes knowledge graphs of countries, institutions, authors, disciplines, and terms, aiming to provide a clear overview of the overall research status of agricultural drainage water treatment, summarize and describe the current situation, predict possible research focuses in the future, and provide some references for future researchers and related policymakers.

2. Data Sources and Analytical Methods

2.1. Data Sources and Screening

Web of Science (WOS) is an accurate scientific and technical knowledge literature indexing tool that provides insights into the most important areas of scientific and technical research, and WOS is often considered one of the best sources of data collection for global bibliometric analysis [27,28]. In addition, Web of Science and search tools such as Scopus are of equal strength and have their own strengths, and the content of search tools such as Scopus also overlap with Web of Science. Therefore, we chose Web of Science as our literature search tool [29–31].

The data sources used for the recent study were the Science Citation Index Expanded (SCIE), the Emerging Science Citation Index (ESCI), the Social Science Citation Index (SSCI), the Citation Index to Conference Proceedings-Science (CPCI-S), the Citation Index to Conference Papers-Social Sciences and Humanities (CPCI-SSH), Current Chemical Reactions (CCR-Expanded), and the Index Chemist (IC) under the umbrella of WOS Core Collection (WOSCC) databases. The data were obtained on 1 March 2023.

The search keywords were as follows: (TS = ("agricultural drainage water" OR "agricultural drainage" OR "farmland drainage")) AND TS = ("purification" OR "purify" OR "decontamination" OR "treatment" OR "remove" OR "dispose" OR "remediation"). We obtained 311 literature records, and from the data obtained above, we refined the data by removing "revised" literature and selecting the literature language as "English". The data were downloaded as plain text to form a local database and imported into CiteSpace (6.1.R6.64-bit) http://cluster.ischool.drexel.edu/~cchen/citespace/download/ (accessed on 25 January 2023) for automatic software de-duplication to obtain 282 documents and the pre-processed data as the basis of our study.

2.2. Analytical Methods

The emerging and innovative method for bibliometric investigations contains a visualization of scientific contributions based on social network analyses and colored graph theory. Among numerous tools/methods established for scientometric analyses, Java-based software (CiteSpace) was used to visualize and map the scientific knowledge domain. It is freely available software and was initially established at Drexel University in the United States by Dr. Chen Chaomei [32]. Given the large number of publications we identified, it would be difficult to manually extract their information, so it was necessary to use the software. At the same time, CiteSpace has visualization capabilities that can help us solve these problems [33]. Therefore, we chose the CiteSpace software (version 6.1.R6.64-bit) as the main tool, thus providing a comprehensive analysis of the selected literature.

CiteSpace was used to explore publications and collaborative networks, agricultural drainage water research development, and collaboration and distribution among countries, research institutions, and authors. It was carried out by setting the node types in the CiteSpace software to "country", "institution", "author", "keyword", etc., to achieve this goal. Since a remarkable correlation exists between country and institution nodes (an institution is a subset of a country), country and institution nodes were shown in the same graph. The node type was changed to "Category" and the specialized software was used to conduct a timeline analysis, which facilitated the visualization of the progression of the research themes within the field. Modifying the node type configuration made it possible to conduct a co-citation analysis. For this academic article, a co-citation was defined as the occurrence in which papers A and B cited paper C. This method enabled the identification of influential papers and the extraction of pertinent data from them. By "term" clustering and co-occurrence analysis, it was possible to identify pioneering research and areas of intense focus at various phases of the development of the field. The integration of these analyses allowed for the identification of overarching trends in the evolution of agricultural drainage water research and the forecasting of upcoming issues and advances requiring future attention. The flow of data processing, as well as analysis of the article, is shown in Figure 1.

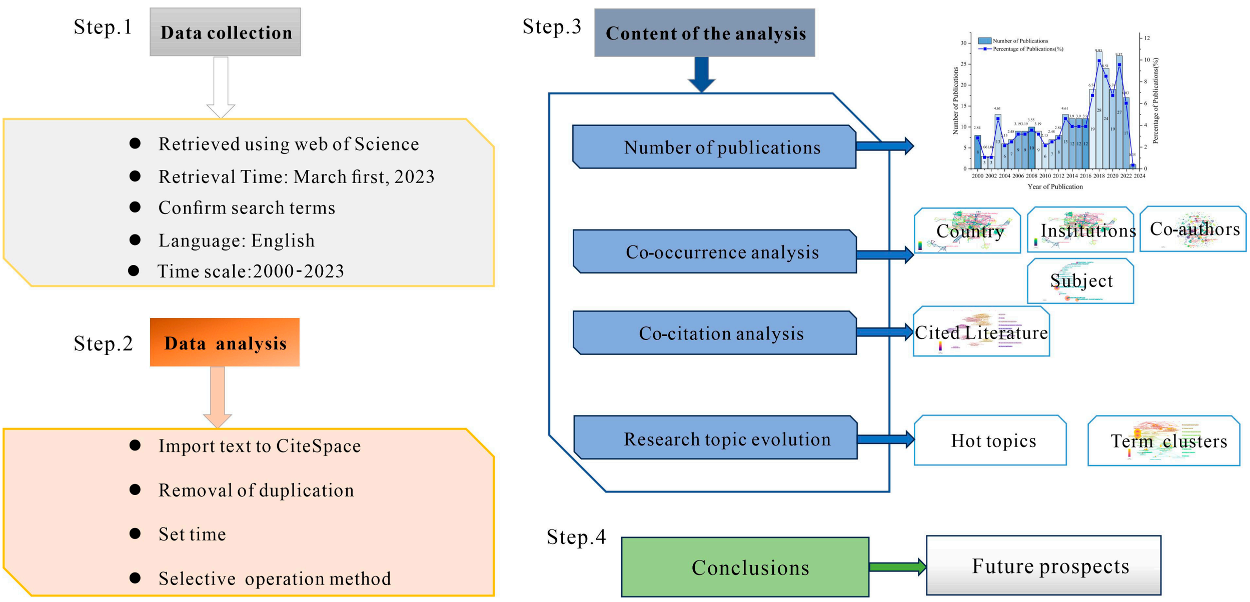


Figure 1. Data processing and analysis flow of this article.

3. Result and Discussion

3.1. Basic Situation Analysis

3.1.1. Publication of Papers at Different Stages

We analyzed 282 publications from 1 January 2000 to 1 March 2023 based on the available data (Figure 2). The number of publications was divided into two stages. During the 10 years, from 2003 to 2012, the number of publications accounted for only 39.4% of the total, and no more than 10 papers were published in any year during this stage except for 2003. Although this phase was not extensive in research, the acceptance of the agricultural drainage water treatment definition and research methods laid the theoretical foundation for subsequent studies. Consequently, the aforementioned 13-year duration can be categorized as the developmental phase of research pertaining to farmland drainage. Between 2013 and 2022, the number of published papers in the field of agricultural drainage water increased to 7.7 times the number in 2013, accounting for 64.9% of the publications during our study period. We call this the "high growth" agricultural drainage water research phase. During this stage, research in agricultural drainage water has become an active area of research for many scholars, with more than 10 papers published each year. During the 4 years from 2018 to 2021, about 20 articles were published each year, especially in 2018, a year in which the number of articles published reached a peak of 28 during the research period. During this stage, some scholars conducted case studies on agricultural drainage water [34,35]. Most scholars recognize that agricultural drainage water is the largest part of pesticide-contaminated water, and therefore, removing all pesticides from it is necessary. In the current study, the main focus is on the effects of different measures on the migration and transformation processes of pollutants in drainage ditches [36]. Meanwhile, some scholars have also focused on other related aspects, such as the effect of agricultural drainage water on the greenhouse effect of agricultural systems [19].

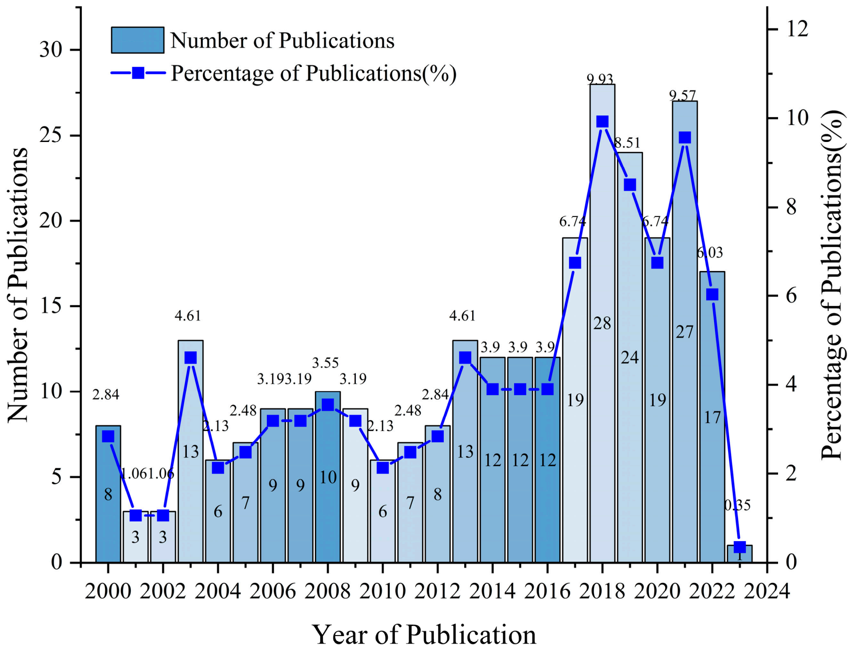


Figure 2. Number of publications in the field of agricultural drainage water treatment per year from 2000 to 2023. The data for 2023 are until 1 March 2023.

As for 2023, the data for this year are not representative, since we only collected the data until 1 March 2023.

3.1.2. Cooperation Networks

By analyzing the cooperation networks among countries and institutions, it was possible to identify key countries and research institutions with a large number of publications and a strong influence in the field of agricultural drainage water and to identify the cooperative relationships among them. We found two hundred and ninety-four institutions from forty countries or regions involved in research on agricultural drainage water with five countries and eighteen institutions publishing a more significant number of papers (Figure 3).

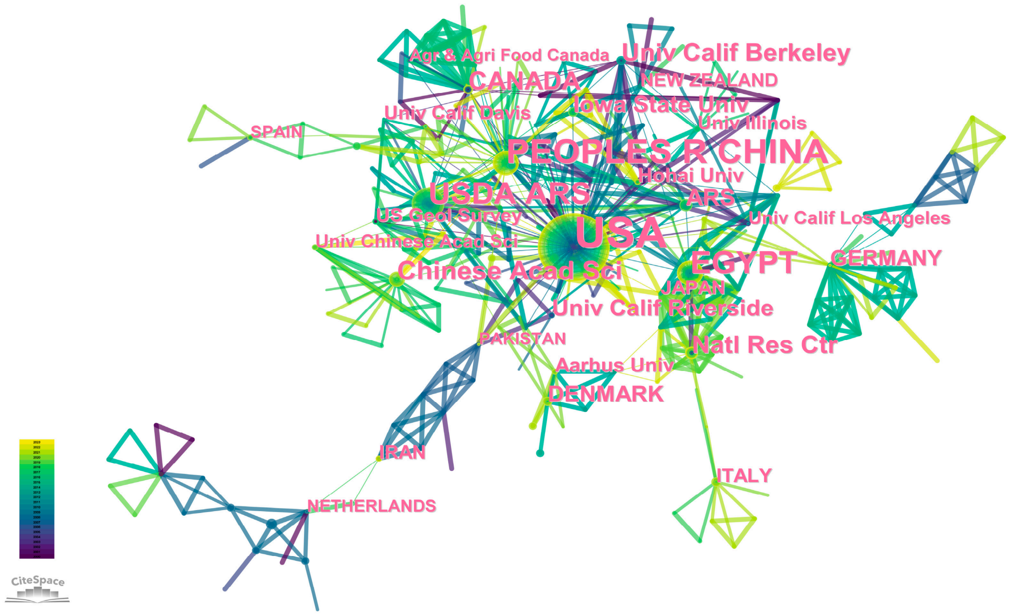


Figure 3. Visualization result of the productive institution and country with their collaborative links.

We list the top 20 leading countries for articles related to agricultural drainage water treatment in Table 1. Among them, the United States (Number of publications [Count] = 142) and China (Count = 49) are the dominant countries. Figure 4 shows in detail the top ten countries in terms of the number of articles issued in recent years.

Table 1. The top 20 active institutions for articles related to agricultural drainage water treatment.

Sr.No.	Count	Centrality	Year	Institution	City	Country
1	29	0.22	2002	USDA ARS	Washington	America
2	17	0.05	2017	Chinese Academy Science	Beijing	China
3	14	0.08	2000	University California Berkeley	Berkeley	America
4	14	0.04	2003	National Research Centre	Paris	French
5	12	0.16	2010	U.S Agricultural Research Service	Washington	America
6	12	0.05	2009	Iowa State University	Ames	America
7	11	0.00	2003	University California Riverside	Riverside	America
8	8	0.02	2015	Hohai University	Nanjing	China
9	8	0.02	2013	Aarhus University	Aarhus	Denmark
10	8	0.07	2000	University California Davis	Davis	America
11	7	0.02	2000	U.S. Geological Survey	Reston	America
12	7	0.00	2014	University Illinois	Urbana	America
13	6	0.02	2003	University California Los Angeles	Los Angeles	America
14	6	0.05	2017	University Chinese Academy Science	Beijing	China
15	5	0.10	2010	Alexandria University	Alexandria	Egypt
16	5	0.04	2006	Agriculture & Agri Food Canada	Guelph	Canada
17	5	0.04	2013	Tokyo Institute Technology	Tokyo	Japan
18	4	0.00	2000	University Waterloo	Waterloo	Canada
19	4	0.05	2004	Southern Illinois University	Carbondale	America
20	4	0.03	2000	California Department of Water Resources	Sacramento	America

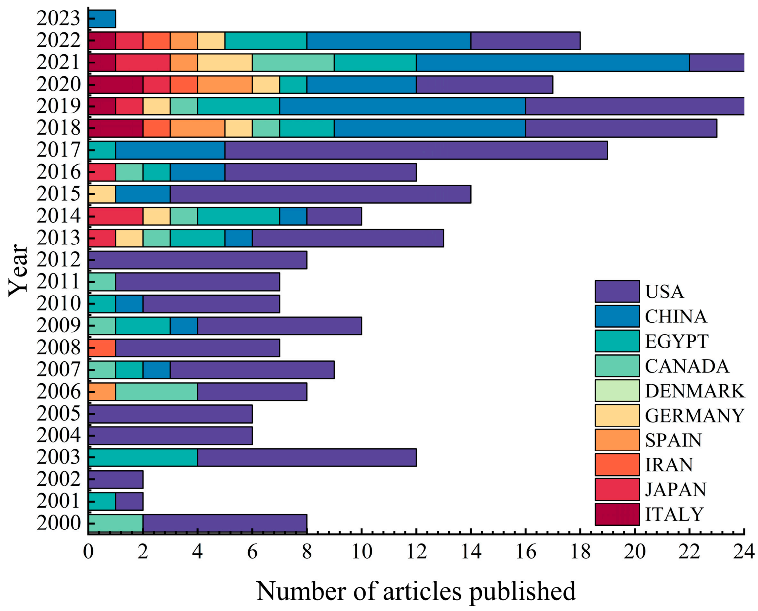


Figure 4. Top ten countries in the area of agricultural drainage water treatment in terms of the specific stack of publications in each year from 2000 to 2023. The data for 2023 are through 1 March 2023.

The top 20 active institutions for articles related to agricultural drainage water treatment are listed in Table 2. The U.S. has a more significant number of research institutions on agricultural drainage water, such as the USDA Agricultural Research Service, the National Laboratory for Agriculture and the Environment (USDA ARS, 29 papers), the University of California, Berkeley (14), the National Research Center (USA) (14), the U.S. Agricultural Research Service (12), Iowa State University (12), and the University of California, Riverside (11), etc. Each institution has published more than 10 papers in the above list of American institutions. Among them, the USDA ARS ranks first in the number of publications in this field in the U.S. and worldwide. In contrast, Chinese research results are concentrated in a few major research institutions, such as the Chinese Academy of Sciences (17), Hohai University (8), and the University of Chinese Academy of Sciences (6). The Chinese Academy of Sciences ranks first in terms of the number of publications in this field in China and second worldwide.

From the perspective of cooperative networks, intermediary centrality is important. Mediation centrality refers to the strength of the number of connections a node has with other nodes in the network; high Mediation centrality represents that the node has a strong influence within the network and is a critical node in the network relationships [33]. The United States has the highest degree of centrality (Degree of centrality [Centr] = 0.55), followed by China (Centr = 0.53). There is also a certain amount of cooperation between the two countries. Furthermore, these two countries have also established cooperative relationships with other countries, such as Egypt and Canada.

We analyzed the number of papers and collaborative networks among authors and discovered that 524 authors are actively engaged in researching agricultural drainage water (Figure 5). Among these authors, twenty-seven authors have published three or more articles. A more detailed list of the top 20 active authors of articles related to agricultural drainage water treatment is displayed in Table 3. Among these highly productive researchers, Norman Terry from the University of California, Berkeley, was one of the earliest to focus on this field. Z.H. Ye from the School of Life Sciences at Sun Yat-sen University in China was one of the earliest Chinese scholars to study this area. In addition, three Chinese Academy of Sciences authors have published two or more papers. The network of authors resembles a sky filled with stars, appearing more scattered.

Table 2. Top 20 dominant countries for articles related to agricultural drainage water treatment.

Sr.No.	Count	Centrality	Year	Countries
1	142	0.55	2000	USA
2	49	0.53	2009	China
3	30	0.36	2001	Egypt
4	16	0.00	2000	Canada
5	10	0.00	2013	Denmark
6	9	0.31	2013	Germany
7	7	0.01	2013	Japan
8	7	0.18	2006	Spain
9	7	0.00	2018	Italy
10	7	0.24	2008	Iran
11	6	0.00	2001	New Zealand
12	5	0.38	2003	Pakistan
13	5	0.17	2000	The Netherlands
14	4	0.00	2018	Czech Republic
15	4	0.00	2000	France
16	4	0.00	2005	Denmark
17	4	0.09	2007	Sweden
18	4	0.31	2002	Australia
19	3	0.00	2014	Korea
20	3	0.00	2009	England

Table 3. Top 20 active authors of articles related to agricultural drainage water treatment (note that the year here refers to the time when this author's first relevant article appeared during our search using Web of Science).

Sr.No.	Count	Institution	Authors	Year
1	6	University of California	Terry, N.	2000
2	5	USDA—Agricultural Research Service National Sedimentation Laboratory	Moore, M.T.	2008
3	5	University of California	Frankenberger, W.T.	2003
4	5	Alexandria University	Fleifle, A.	2013
5	4	National Ground Water Association USA	Allred, B.J.	2012
6	4	Southern Illinois University Edwardsville	Lin, Z.Q.	2000
7	4	University of California	Cohen, Y.	2006
8	4	Alexandria University	Elzeir, M.	2013
9	4	Egypt-Japan University of Science and Technology (E-JUST)	Tawfik, A.	2013
10	3	Aarhus University	Elsgaard, L.	2021
11	3	University of California	Rahardianto, A.	2006
12	3	University of Bologna	Blasioli, S.	2018
13	3	University of Bologna	Braschi, I.	2018
14	3	University of California	William, T.	2007
15	3	Iowa State University	Christianson, L.	2013
16	3	USDA—Agricultural Research Service National Sedimentation Laboratory	Cooper, C.M.	2008
17	3	Kansas State University	Bhandari, A.	2013
18	3	University of California	Mccool, B.C.	2010
19	3	University of California	Zhang, Y.Q.	2004
20	3	Southern Illinois University Edwardsville	Lin, Z.Q.	2006

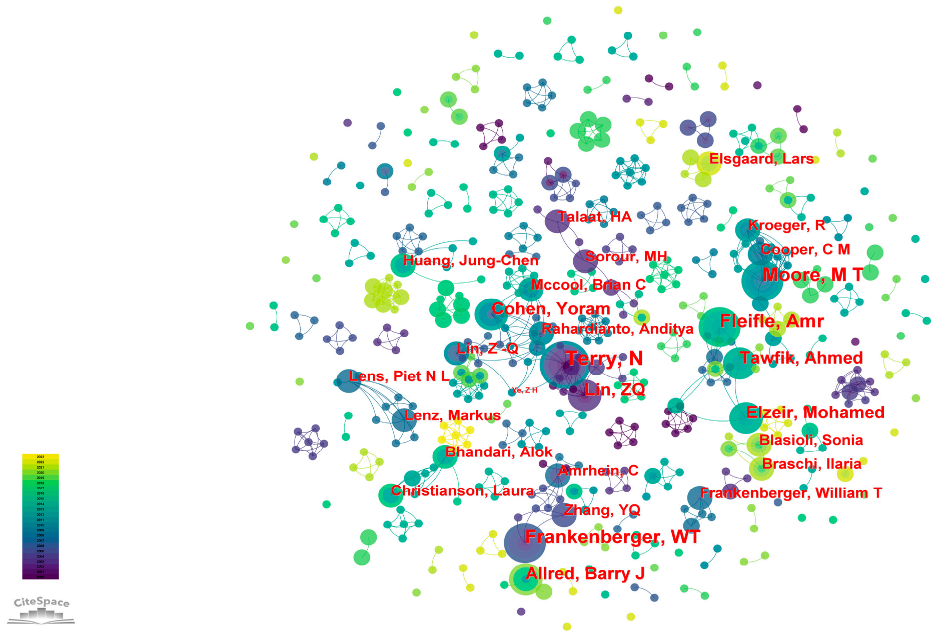


Figure 5. Visualization result of the productive authors with their collaborative links.

In contrast, the strong connections are shown by national and institutional collaborations. Some small-scale fixed cooperative relationships demonstrate the emergence of cooperative groups. Among them, the largest collaborative group is the University of California Berkeley research group, with Norman Terry and other scholars as the core. Z. H. Ye, a scholar from the School of Life Sciences at Sun Yat-sen University in China, collaborates with the U.C. Berkeley research group centered on Norman Terry and other scholars.

3.1.3. Subject Evolution

Through co-occurrence analysis of the subjects in the publications, we constructed a subject network for agricultural drainage water research, showcasing the evolution of mainstream and interdisciplinary disciplines in this field (Figure 6, Table 4). In general, the study of treating agricultural drainage water has evolved from being primarily focused on environmental sciences and water resources to encompassing a range of disciplines. In 2000, agricultural drainage water research appeared in environmental science (Count = 177, Centr = 0.39) and water resources (Count = 82, Centr = 0.35). At this time, it is well known that frequent human agricultural activities and the widespread use of pesticides have led to substantial agricultural water pollution and environmental pollution. In addition, with the maturity of modern environmental ecology theories and methods, the use of environmental ecology concepts and methods to solve the environmental problems caused by this situation have become the focus of scholars.

Currently, environmental science and water resources are still the main topics of agricultural drainage water research, accounting for 91.8% of the research papers in this field. Since 2000, with the development of social economy, science, and technology, agricultural drainage water treatment began to appear in engineering, environmental engineering, and chemistry. Among them, the connection between agricultural drainage water research and engineering is very close, so their intermediary centrality is high (Centr = 0.33).

Subsequently, agricultural drainage water treatment developed into a multidisciplinary approach. In 2004, research on agricultural drainage water treatment began to appear in agriculture. Since 2006, agricultural drainage water research has appeared in various natural or social disciplines, such as geography, energy, and economics. Soil science (Count = 11, Centr = 0.77) and green and sustainable science and technology (Count = 7, Centr = 0.08) also show a relatively high frequency and centrality. Certainly, the development of various disciplines has contributed to the research process to some extent.

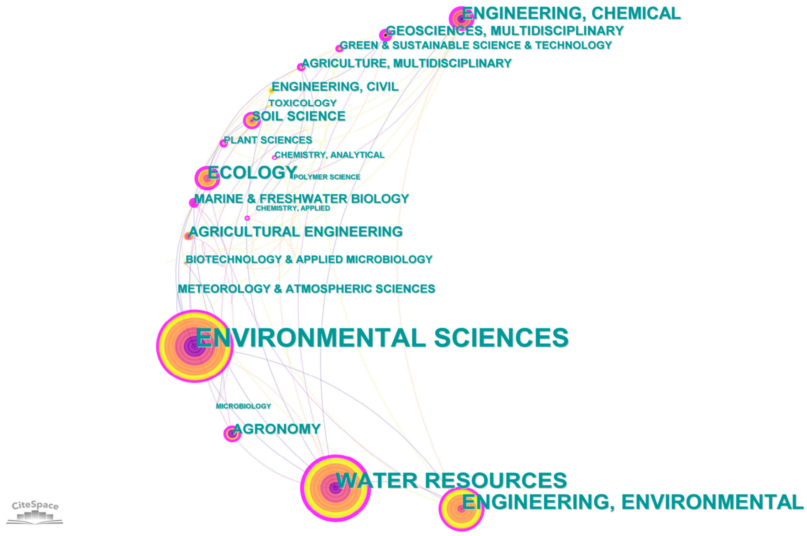


Figure 6. Visualization result of the productive subject with their collaborative links (produced by CiteSpace).

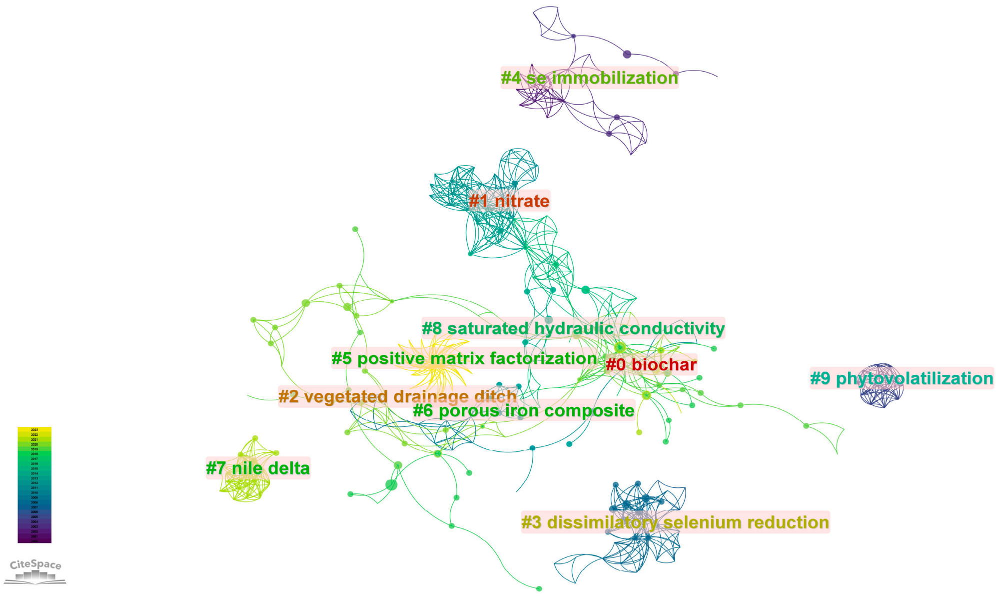
Table 4. The evolution of disciplines in the field of agricultural drainage water treatment (Top 20 by frequency).

Sr.No.	Count	Centrality	Year	Subject Category
1	177	0.39	2000	Environmental Sciences
2	82	0.35	2000	Water Resources
3	58	0.19	2001	Engineering, Environmental
4	31	0.12	2000	Ecology
5	25	0.33	2003	Engineering, Chemical
6	15	0.05	2006	Agronomy
7	13	0.01	2004	Agricultural Engineering
8	12	0.17	2000	Geosciences, Multidisciplinary
9	11	0.07	2000	Soil Science
10	9	0.01	2000	Engineering, Civil
11	9	0.11	2000	Marine and Freshwater Biology
12	8	0.00	2003	Meteorology and Atmospheric Sciences
13	8	0.14	2002	Agriculture, Multidisciplinary
14	7	0.08	2001	Biotechnology and Applied Microbiology
15	7	0.08	2006	Green and Sustainable Science and Technology
16	6	0.00	2003	Toxicology
17	6	0.00	2003	Plant Sciences
18	4	0.24	2014	Chemistry, Analytical
19	3	0.00	2001	Microbiology
20	3	0.00	2003	Chemistry, Applied

3.2. Knowledge Base Analysis

3.2.1. Co-Citation Clustering

Co-citation analysis can assist in identifying the papers that are commonly read and cited in agricultural drainage water treatment research. According to the statistical information extracted from our data by CiteSpace, the 282 publications we analyzed cited 710 papers. Publications cited more than once are shown in Supplementary Materials Table S1. By clustering the cited publications (based on their frequency) and selecting the top five clusters, we were able to identify the knowledge base of agricultural drainage water treatment research to some extent (Figure 7).



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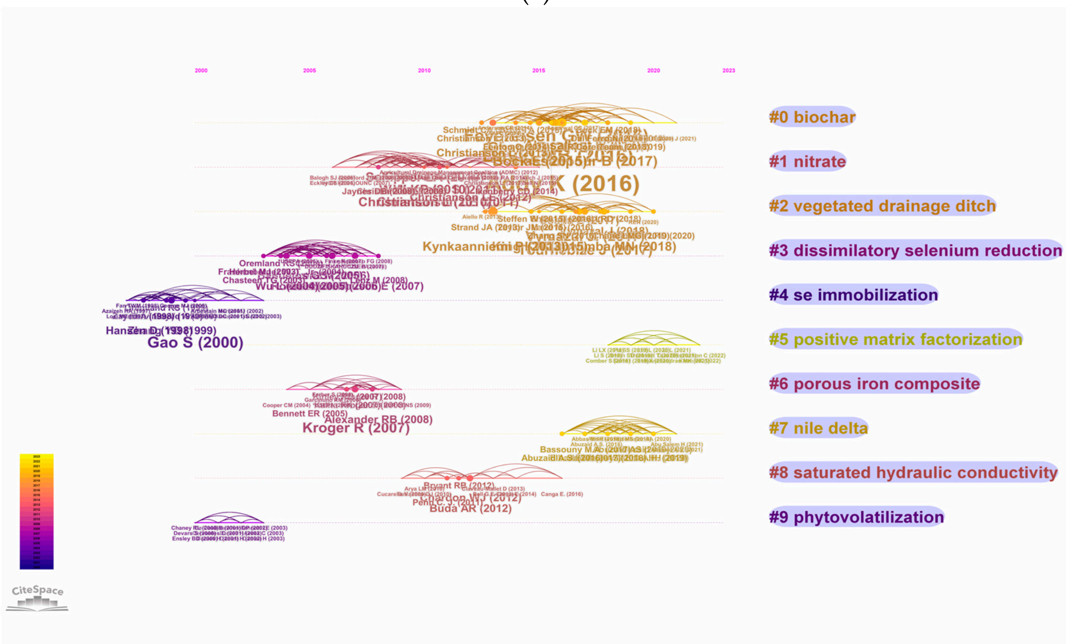

(**b**)

Figure 7. Clustering of frequently co-cited literature in the field of agricultural drainage water treatment. ((**a**) Clustering diagram of co-citations; (**b**) Timeline diagram of co-citation clusters, produced by CiteSpace).

The "selenium fixation" cluster began in 1997. This is due to the fact that selenium may be present in agricultural drainage, and selenium fixation through chemical and biological reduction processes can remove selenium from agricultural drainage water and address possible agricultural water pollution during the process [37]. Current research has shown that plant uptake of selenium may be an effective means of removing selenium from drainage sediments [38]. The cluster "dissimilatory selenium reduction" started in 2003 and lasted until 2008, ranking fourth among the clusters we analyzed. In addition, selenate was also a common pollutant in selenium-containing agricultural drainage, which could be converted into elemental selenium nanoparticles under the action of microorganisms [39]. To some extent, it further reflects the current attention paid to selenium in the field of agricultural drainage water treatment.

The largest cluster is "biochar", which emerged from 2013 to 2021, lasting for 9 years. At the same time, it also indirectly reflects the application of biochar in agricultural drainage water treatment. To date, the utilization of biochar as a means of adsorbing pollutants in agricultural drainage water continues to be a significant aspect of the agricultural drainage water treatment process. Global scholars actively seek biochar types with higher adsorption efficiency and relatively low cost. In this cluster, "biochar" is closely related to agricultural drainage water treatment and has become a keyword in research papers. The "nitrate" cluster lasted the longest (2006–2015) and focused on case studies such as the use of denitrification bioreactors for reducing nitrate nitrogen in agricultural drainage [40].

The presence of vegetation in water bodies serves to purify pollutants, resulting in the formation of a cluster known as a "vegetated drainage ditch", which has demonstrated a relatively prolonged lifespan. Agricultural drainage water is an important cause of eutrophication in rivers, lakes, reservoirs, and coastal areas. The vegetated drainage ditch is a promising technology for eliminating nutrients and suspended matter from agricultural drainage. The results of some studies have shown that a vegetated drainage ditch is comparable to an artificial wetland in terms of nutrients, and suspended and organic matter treatment efficiency [11,41].

Meanwhile, keywords such as "green agriculture", "green development", and "sustainability" provide ideas for the determination and implementation of agricultural drainage water treatment methods.

3.2.2. Frequently Cited Literature

We found twelve papers with more than five citations in the co-citation graph (Figure 8), which to some extent shows the development of the discipline to date, general patterns of research, interdisciplinary cooperation, research patterns, and methods. The 12 most frequently cited publications contribute to accumulating the knowledge base of agricultural drainage water.

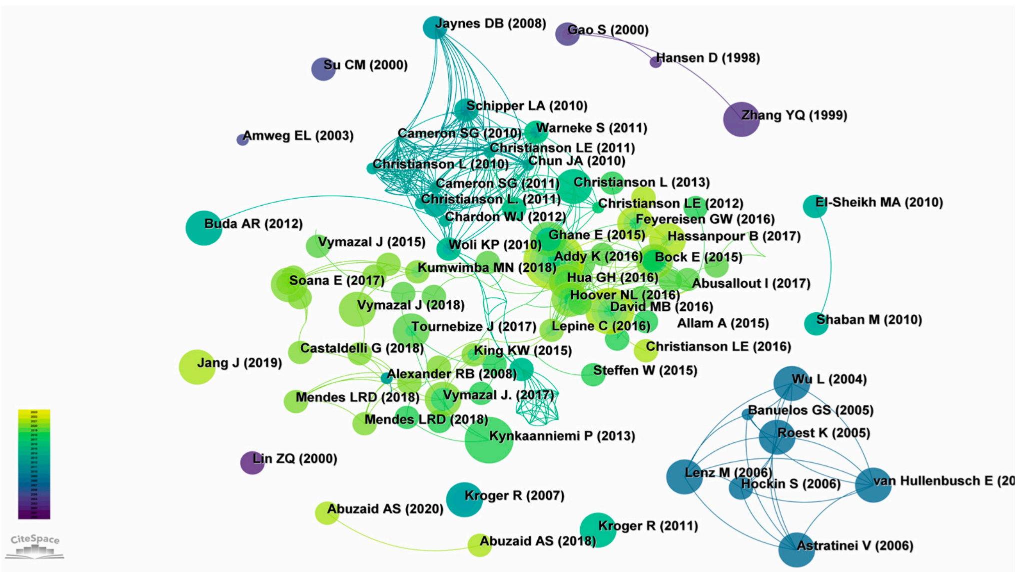

Figure 8. Map of frequently co-cited references in the field of agricultural drainage water treatment.

Among the 12 most frequently cited publications, 16.7% were journal articles that provided a perspective or viewpoint of the literature review. Tournebize, Addy, and other researchers mentioned solutions for nitrate removal in their articles, but they exhibited variations in their approaches and proposed remedies [42,43]. Tournebize et al. analyzed that specific substances and artificial wetlands effectively remove nitrate and pesticides from agricultural drainage water [42]. Addy et al. used meta-analysis to synthesize the first quantitative denitrifying wood chip bioreactor to assess nitrate removal under environmental and design conditions from 26 published studies. In his paper, he points out the promise of denitrifying bioreactors as a strategy for degrading nitrate and reducing water quality degradation in the treatment of agricultural drainage water and other wastewater, while presenting his view on the orientation of future work in this field, thus becoming the most cited publication (18 citations) [43].

The case study accounted for 66.6% of the 12 most frequently cited publications, and these papers served as a reference for the methodology and content of the subsequent research. Some scholars have pointed out that denitrifying bioreactors utilizing woody material as a carbon substrate is highly effective in removing nitrate and ammonia nitrogen from agricultural drainage water [44,45]. Hoover et al. evaluated the performance of bioreactors under different controlled conditions, including woodchip age, hydraulic retention times (HRTs), and temperature, among others, and their findings provided information to help improve the design of woodchip denitrification bioreactors under specific climatic conditions and existing NO_3-N loads [44]. Hassanpour and Bock, among others, added woody material and wood chip-biochar to the bioreactor during the experiment. They found that adding biochar improved the removal of both NO_3^- and P from denitrifying bioreactors (DNBRs) and reduced N_2O emissions [45,46]. This result suggests that variations in biochar materials may improve the removal efficiency of pollutants such as bacteria, pesticides, or drugs. This finding also opens up possibilities for future research on investigating internal fill materials in bioreactors.

These scholars are still actively exploring more efficient methods for removing excessive nitrate and ammonia nitrogen from agricultural drainage water [44–48]. The study conducted by Feyereisen et al. replaced wood chip media with agriculturally derived media to compare and test the nitrate removal rate (NRR) of denitrification bioreactors under warm and cold temperatures. Using the temperature of early spring drainage in the northern United States as the time point, some nitrate removal profiles could be expected under field conditions at the first drainage, with agricultural-derived media performing better than wood chips [44]. Kröger, Hoover, Hua, and others conducted case studies on agricultural drainage water in the Midwest region, the Mississippi River, New York State, and Iowa, respectively. Their research findings have provided references for subsequent research [44,48,49].

The proportion of papers focusing on models and methods is 16.7%, which is not high but still reflects the extent that scholars in this field are aware of the importance of exploring innovative modeling methods. Among them, Ghaneet al. conducted experiments on denitrification beds by modeling the treatment of agricultural drainage water in denitrification beds, and the results showed that the greenhouse gas emissions on the surface of denitrification beds were low. The model evaluation statistics showed a satisfactory prediction of bed outflow nitrate concentration during subsurface drainage flow of agricultural drainage water. The model provides a favorable value for designing efficient denitrification beds, thus improving agricultural drainage water quality [50]. Mark B. David et al. installed two temperature and substrate-controlled woodchip bioreactors for the treatment of agricultural drainage water in the Shibras River watershed in east-central Illinois, USA, which tested the performance of the nitrate load [51]. In addition, the development of biological and chemical disciplines has provided important support for agricultural drainage water research.

3.3. Research Topic Evolution

3.3.1. Hot Topics during Each Stage of the Discipline's Development

Term co-occurrence indicates a situation where two keywords simultaneously appear in multiple articles. The term co-occurrence analysis can reflect the frontiers and hot spots in the research and evolution of agricultural drainage water treatment in different research periods, thus revealing the hot changes in this research topic. We manually classified thirty-four research topics (Supplementary Materials Table S2) into five categories based on the terminology counted by the CiteSpace software (version 6.1.R6.64-bit), which appeared five or more times: research purpose, research topic, research content, research method, and research factor. During the period spanning from 2000 to 2012, it was observed that while the quantity of papers published annually did not reach significant levels, the quantity of terms utilized was not insignificant. Between 2013 and 2023, along with the increase in the number of papers, there was also an increase in the number of new terms (it should be noted that the number of papers and terms in 2023 is low due to our data collection as of 1 March 2023). Between 2013 and 2023, 60.6% of articles of the total were published, and the number of new terms in this period represents 50.8%. Despite the increase in research papers, the number of new terms is particularly high due to some terms already having been defined before 2013.

Among the studies on the treatment of agricultural drainage water that appeared from 2000 to 2012, 68.6% were related to "content", followed by "factors" (18.4%) and "methods" (7.65%). Themes and objectives received less attention, resulting in lower representation for both categories. Terms classified under "topic" have been available since 2000, while there are only 12 terms classified under "purpose". From 2000 to 2012, the term "agricultural drainage" appeared multiple times (71 times) and exhibited high mediating centrality (Centr = 0.34), which serves as a significant node in terms of co-occurrence. Agricultural drainage water emerged as a crucial theme throughout this phase. During this period, the "removal of excessive selenite" from agricultural drainage [52] became a significant research purpose and appeared multiple times. "Pretreatment" became a more important methodological term in this phase, which reflects to some extent that researchers had already considered pretreatment as a means of improving water quality in agricultural drainage water treatment processes at an early stage.

From 2013 to 2023, the number of papers increased, as did the topic of agricultural drainage water treatment research, with 42.5% of new terms appearing in this period. "Research content" remains the most prominent topic of interest; it accounts for 74.5% of the total number of terms in this period, while "research factors" remain the second most popular (13.8%), but "research topic" and "research purpose" are still relatively small, accounting for only 2.8% and 2.1%, respectively, while "research method" accounts for 7.9%. Nitrate removal (15 times, Center = 0.07) is the most important new term under "research purpose" at this stage, indicating that researchers are very concerned about how to efficiently remove excessive nitrate from agricultural drainage water, which, of course, also indicates that "desalination" is still a focus of researchers, rather than only existing in the early stage of this field of research [53,54]. In addition, water quality [55] and removal efficiency [56] became two hot topics in this phase. Agricultural drainage water (63 times, Center = 0.42) [57] was the most frequent and mediated centrality term under the "research topic" category, reflecting the continuity and continued interest in the research topic. Agricultural chemicals emerged as an important "research factor". In particular, the large-scale use of agricultural chemicals (pesticides) has become an important factor in the pollution of agricultural drainage water. At the same time, the proportion of "research purpose" is deficient, at only 2%, and the removal of pollutants such as nitrogen and phosphorus from agricultural drainage water and the achievement of good overall ecological benefits are the main purposes at this stage [41,58]. It also indicates that research scholars are paying more attention to its impact on the overall ecological environment. In terms of the "research method", the chemical remediation method (e.g., activated carbon adsorption of pollutants in agricultural drainage) and bioremediation method (e.g., plant adsorption) [11] were used. Denitrification bioreactors [59], especially those based on wood chips as a substrate [60] have also become a method of treating excessive substances in agricultural drainage water.

3.3.2. Evolution of Term Clusters

By clustering the terms, we identified the top ten clusters (Figure 9). The timeline mapping generated by CiteSpace shows that the longest-lasting cluster is "macrophyte-based systems" (2000–2023), and it is also the largest cluster, which existed throughout the study period (Figure 9b). The early terminology of this cluster is mostly agricultural in theme, such as agricultural land, agricultural run-off, and agricultural ditches. In the middle of the cluster's development, terms such as agricultural drainage water were increasingly emphasized. Some scholars found differences in the nutrient mitigation capacity of agricultural ditches with and without vegetation, which may also have an impact on the sorption capacity of pesticide chemicals [61,62].

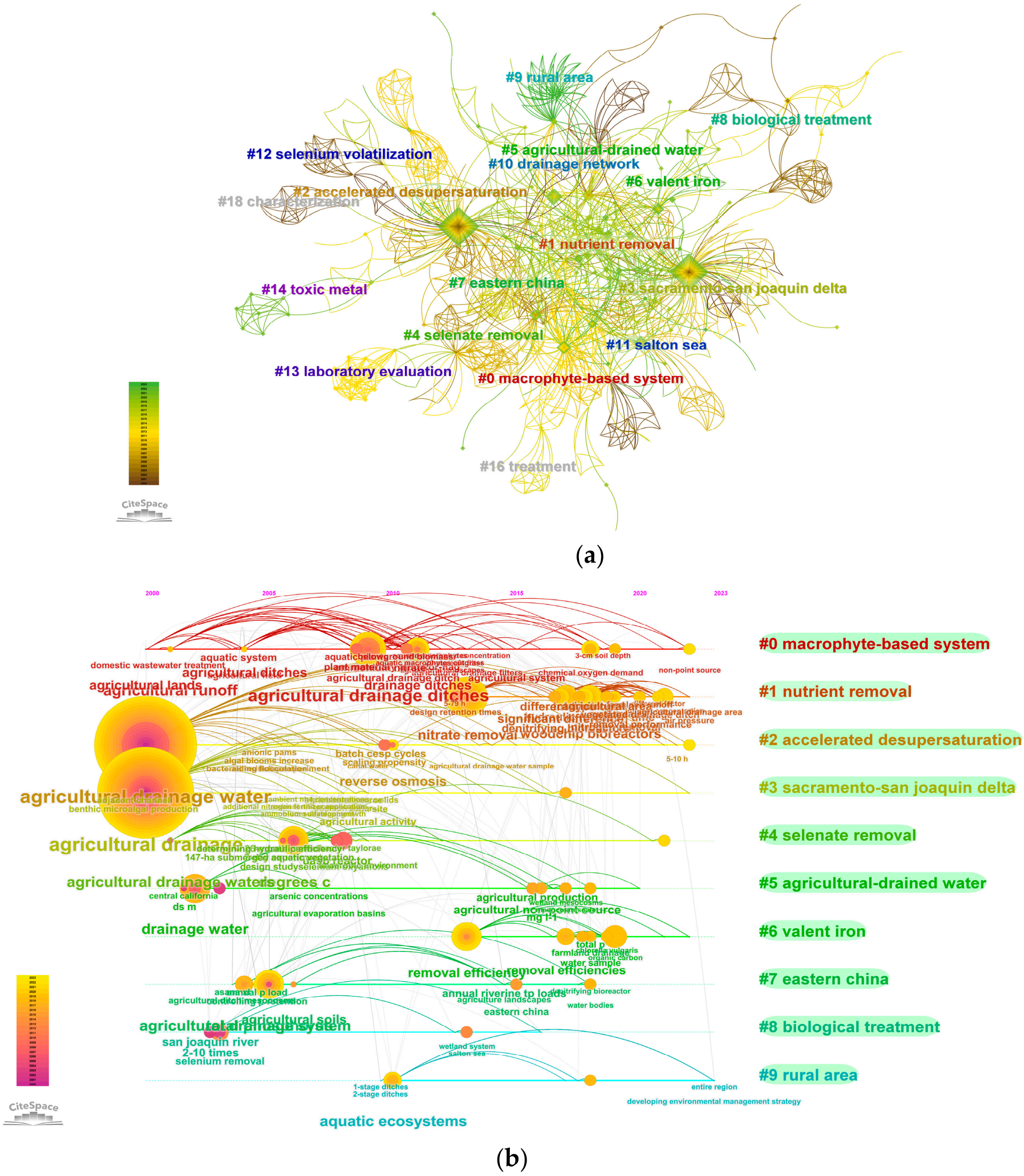

Figure 9. Clusters of agricultural drainage water treatment research based on the terms. ((**a**) clustering diagram for term analysis; (**b**) timeline diagram for term clustering.).

"Nutrient removal", "accelerated desupersaturation", and "Sacramento-sanjoaquin delta" are three clusters that were more important during the research period and will remain important for a long time. The eutrophication of water in agricultural drainage water is a common problem, and "nutrient removal" [63] primarily addresses the issue of water eutrophication, such as removing excessive nitrates from agricultural drainage water. Through the analysis of the cluster "accelerated supersaturation", it was found that accelerated supersaturation has a certain impact on water treatment in agricultural drainage. For example, Anditya Rahardianto et al. used a two-step chemically-enhanced seeded precipitation (CESP) process, which was demonstrated for the accelerated desupersaturation of antiscalant-containing, gypsum-supersaturated model solutions, which mimicked reverse osmosis (R.O.) concentrate from the R.O. desalting of agricultural drainage water of high mineral scaling propensity. Experimental studies have demonstrated that accelerated desupersaturation can enhance the recovery rate of agricultural drainage water [64]. The cluster pertaining to the removal of selenate remains a significant area of investigation among scholars, as evidenced by our observations on co-occurrence. Later, two relatively small clusters emerged, “rural areas” (2010–2023) and “biological treatment” (2003–2016), which also appeared relatively late. It is inevitable for “rural areas” to form top-ten clusters, and agricultural drainage water primarily occurs in rural areas. Consequently, the water environmental issues arising from it also require urgent attention and treatment. “Biological treatment” has been favored by researchers as an important treatment method to deal with excess pollutants in agricultural drainage water. Within this cluster, the term “wetland system” has become a frequent term, and researchers have found that wetland systems may effectively remove pollutants from agricultural drainage water [65].

4. Conclusions and Future Prospects

In this study, we conducted a comprehensive and systematic visual analysis of agricultural drainage water treatment research by CiteSpace. We revealed the current status of the field, as well as the characteristics of literature citations and research topics. Agricultural drainage water treatment research has made some achievements in terms of theory, methodology, framework, and case studies. Developing countries have emerged as a new focus of research. The research has evolved from laying theoretical foundations to practical applications and from a single-discipline focus on water resources to a multidisciplinary approach.

The study of the current status and characteristics of agricultural drainage water treatment, along with a review of the current state of development and a summary of the primary methodologies and frameworks, provides researchers with a basis on which to focus and from which to draw conclusions. The removal of salts (nitrates, selenate), particularly through denitrification bioreactors, has become an important research hotspot in agricultural drainage water treatment. In the contemporary context of environmental protection, the topics of salt removal, nitrogen removal, and phosphorus removal will continue to be relevant for researchers and factors.

Based on our research findings, we propose the following directions for future research, aiming to provide new insights for researchers and government managers, with the confidence that they will be useful in decision-making:

(1) Currently, there is a higher prevalence of case studies in developed countries such as the United States, while case studies in developing countries are relatively limited. In the future, developing countries should conduct more case studies, drawing upon the experiences of developed countries. Simultaneously, researchers should expand the scope of case studies to include agricultural areas near urban regions, aiming to explore the variations in pollution types and removal effectiveness between these areas and rural agricultural development regions.

(2) Looking ahead, the overall goal of future research may shift from how to treat the excess pollutants present in agricultural drainage water bodies to how to achieve good overall ecological benefits through agricultural drainage water treatment.

(3) Achieving high-quality agricultural drainage water treatment in rural agricultural development areas poses challenges for developing countries, influenced by various factors such as treatment costs. Currently, most agricultural areas in developing countries adopt low-cost drainage ditches and natural ponds, while developed countries employ bioreactors, large artificial ecological ponds, various types of drainage ditches, etc. It is believed that measures and methods for agricultural drainage water treatment in developing countries will become more enriched with the development of the economy and technology.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr11102952/s1, Table S1: Publications cited more than once; Table S2: Research topics.

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