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Review

Analysis of Hotspots in Subsurface Drip Irrigation Research Using CiteSpace

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Abstract: To investigate the research hotspots and development trends of subsurface drip irrigation (SDI) over the past 20 years, this study analyzed relevant literature from the Web of Science Core Collection spanning from 2002 to 2022. The data were visualized using CiteSpace, showcasing the publication volume trends, countries, keywords, cited references, authors, and affiliated institutions. Based on 1079 articles, the annual publication volume showed an overall upward trend. The United States had the most extensive research coverage and highest publication volume, whereas China had the fastest growing publication rate in recent years. However, relatively little cooperation occurred among research teams and institutions. Over time, research topics became increasingly diverse, with water conservation and yield increases being the primary research objectives. In addition to improving irrigation and fertilizer use efficiency, SDI has also been applied in research on the safe utilization of unconventional water resources (wastewater and salt water) and the optimization of soil conditions. Among these, aerated irrigation technology—aimed at improving root growth in the rhizosphere—may become a new branch of SDI research. Currently, the main research focus in the field of SDI is the diffusion and distribution of water in the crop root zone, for which Hydrus model simulation is a particularly important method.

Keywords: subsurface drip irrigation; CiteSpace software; hotspot analysis; frontier analysis

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1. Introduction

The rapid rate of urbanization and population growth continually increases the global imbalance between water supply and demand for agriculture, industry, and the environment. The scarcity of irrigation water has become a major challenge for agricultural development worldwide [1]. According to projections by the United Nations, the global population is expected to reach 9.55 billion by 2050, corresponding to a 70% increase in food demand and 19% increase in water use in agricultural irrigation [2–4]. Traditional irrigation methods, such as flood irrigation, exhibit low water resource utilization efficiency and exacerbate water wastage [3]. Therefore, the development of water-saving irrigation technologies has become a priority. Simultaneously, improving grain yield while reducing agricultural water consumption has emerged as a prominent topic in contemporary agricultural development [5].

In 1920, Lee O. Charles from California developed and patented a basic subsurface drip irrigation (SDI) system that utilized tile pipes [6]. However, owing to technological limitations at the time, the SDI system had no practical applications. In recent years, owing to escalating environmental pollution, water resource crises, and technological and material advances, SDI technology has been implemented for various crops with considerable economic benefits. Generally, an SDI system comprises a water source, head pivot, main pipe, capillary channels, and emitters. A head pivot typically includes a pumping station, fertilization device, testing device, and several filtering devices to remove impurities from the effluent and provide pressure for transporting water over long distances. This ensures uniform water flow to the field and facilitates the supply of water and fertilizer to the root zone of crops through capillary channels and emitters [7].

SDI technology is renowned for its water- and fertilizer-saving abilities and high degree of automation. Water and fertilizer are delivered directly to crop roots through pipes buried in the tilled layer. As shown in Figure 1, compared with other irrigation methods, SDI can significantly reduce water loss through surface evaporation, enhance irrigation efficiency, improve crop net photosynthesis, and reduce crop transpiration [8]. In addition, SDI can effectively control weed growth, inhibit the proliferation of soil diseases and insect pests, reduce pesticide use, and significantly improve crop yield and quality [9,10]. In this study, we analyzed the literature on SDI in the core collection of the Web of Science to provide insights into research trends and emerging issues in the field. Our study elucidates the current issues of concern and provides informed directions for development in the field of SDI.

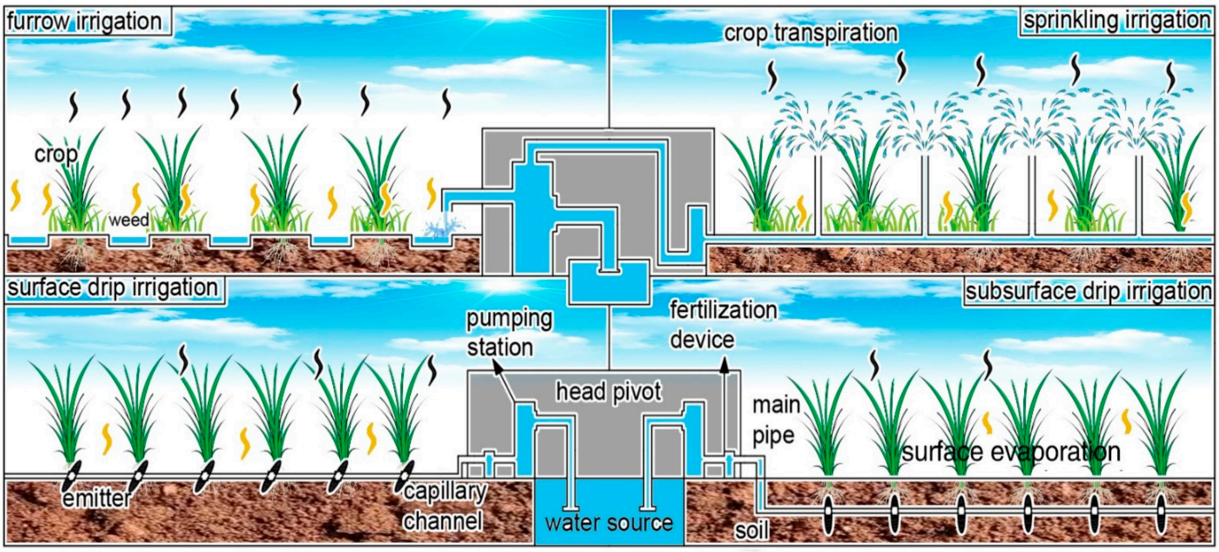

Figure 1. Schematic diagram of four different irrigation methods.

2. Materials and Methods

2.1. Data Sources

To ensure the accuracy and authority of the data, we used the core collection of the Web of Science to retrieve data based on the topic (with the retrieval term "subsurface drip irrigation") and limited the retrieval period to between January 2002 and December 2022. The article type was set to "article" and "review article". A total of 1080 articles were obtained and the article data, including full records and cited references, were imported into CiteSpace (v.6.1.R6, 64-bit) in text (.txt) format.

2.2. Research Methods

CiteSpace is a data visualization software developed by Prof. Chen Chaomei using the Java platform. CiteSpace can analyze input data from papers and generate a visual map of the focus and relationships between papers in a given field of research.

We screened the imported literature in CiteSpace, with the time slice set to one year and threshold (top N per slice) set to 50; the Pathfinder clipping method was used to simplify the atlas. During this step, an article that was officially published in 2023 but had been pre-published online was excluded. In the following results, we elucidated the development trend and widespread application of research interest in subsurface drip irrigation through annual publication volume and countries of origin. We examined the collaboration among various research teams in the field of SDI through the analysis of institutions and authors. The topic hotspots and research directions were expressed through the examination of keywords, while the research scope and orientations were explored through reference co-citation analysis. Apart from specific mentions, all the analyses were conducted based on the data from 41 reviews and 1038 articles.

In the knowledge maps, the greater the node range, the more frequently an object appears or is referenced. The thickness of the lines connecting the nodes indicates the degree of co-occurrence or co-citation. To assess the importance of the nodes in the network, betweenness centrality (BC) was estimated, as shown in purple on the knowledge map, with a value between 0 and 1. The median is generally considered to have a BC > 0.1. Clustering is another way to analyze research areas and distinguish unique topics. In clustering analysis, a modularity (Q) > 0.3 indicates that the clustering results are significant, while a silhouette (S) > 0.5 indicates good clustering and (S) > 0.7 indicates great clustering [11]. Finally, the burstiness of keywords can be used to determine the research hotspots (citation bursts) and analyze the direction of SDI development.

3. Results

3.1. Analysis of Annual Publication Volume and Countries of Origin

Annual publication volume is a critical indicator of a particular research field's developmental trends, based on the level of research activity and interest in a specific area [12]. Figure 2 illustrates the annual publication volumes for studies relating to SDI and the associated countries. Overall, the number of publications steadily increased over time. However, a slight decrease in the number of publications was observed in 2005, 2012, and 2017. The highest number of publications occurred in 2021, suggesting that the issue of agricultural water shortages is gaining increasing attention, and research on SDI is expanding.

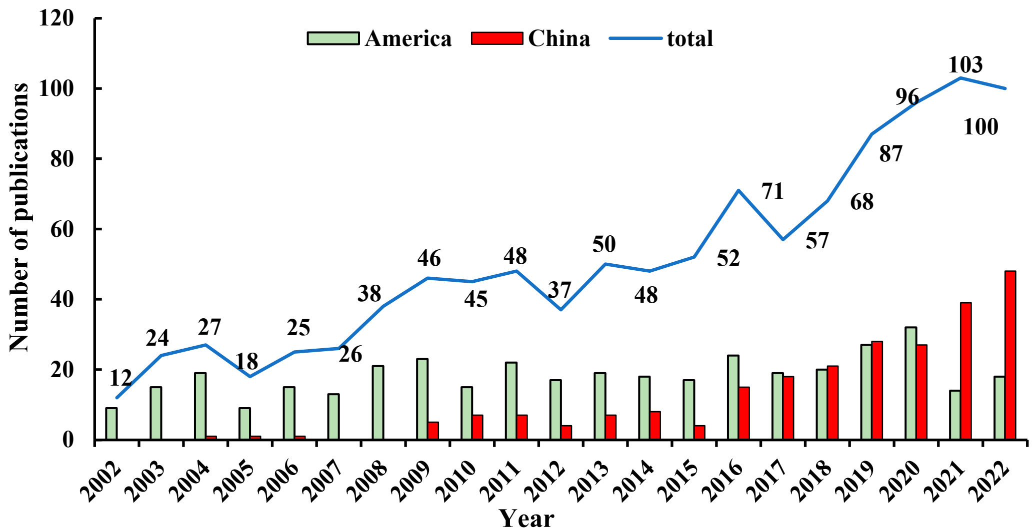

Figure 2. Annual circulation of publications.

Table 1 presents the number of publications according to location over the past 20 years. The United States led research on SDI, with the highest centrality and largest circulation of publications. Chinese publications ranked second in circulation, starting in 2004 and slowly growing until 2016 when publication rates surged. By 2022, the number of Chinese publications reached 48, accounting for ~50% of the total number of published articles that year. As the most populous country in the world, China produces 25% of the world's food with only 10% of the world's arable land and thus faces considerable challenges in agricultural water usage; thus, food security and water shortage may be the reasons behind China's substantial research investment in water-saving agriculture [13–15].

Table 1. Publication volume per country.

Rank	Number of Papers	Percentage %	Centrality	Burst	Country
1	386	35.78	0.57	28.42	USA
2	241	22.34	0.17		China
3	73	6.77	0.25		Spain
4	72	6.67	0.12	5.67	Brazil
5	56	5.19	0.07	4.02	Egypt
6	48	4.45	0.12	3.68	Israel
7	47	4.35	0.08		India
8	46	4.25	0.14		Iran
9	45	4.15	0.04	8.08	Australia
10	40	3.70	0.02		Turkey
11	40	3.70	0.14		Saudi Arabia
12	28	2.59	0.11		Italy
13	23	2.13	0.00	3.68	Canada
14	19	1.76	0.10		Germany
15	17	1.57	0.06	4.05	Greece
16	15	1.39	0.01		Pakistan
17	14	1.29	0.09		England
18	14	1.29	0.10		South Africa
19	13	1.20	0.14		France
20	13	1.20	0.13		Portugal

3.2. Analysis of Publishing Institution and Authors

The analysis of publishing institutions and authors is essential for understanding the structural developments and changes in the research field [16]. As shown in Table 2, 12 institutions published more than 20 publications each. Regarding publication volume and centrality, the US Department of Agriculture Agricultural Research Service was the most productive institution and published 9.54% of all publications. The institution with the second-highest publication volume was Northwest A&F University, which also had the highest publication volume and citation burst in the past five years. Several research institutes in the United States have published in the field of SDI, such as the University of California, Davis; the University of Arizona; and the University of California, Riverside.

Table 2. Top 12 institutions with the largest number of publications in SDI research.

Frequency	Centrality	Burst	Institution
103	0.25	7.27	US Department of Agriculture Agricultural Research Service
49	0.01	9.74	Northwest A&F University
34	0.04		University of California, Davis
30	0.06		China Agricultural University
28	0.07		Chinese Academy of Science
27	0.04	4.78	University of Arizona
26	0.08		University of California, Riverside
24	0.02	5.04	Texas A&M University
22	0.04		Ben Gurion University of the Negev
22	0.03		King Saud University
21	0.02		China Institute of Water Resources and Hydropower Resources
20	0.02		Kansas State University

Most of the institutions with the highest number of publications were from the United States or China, emphasizing their significant roles in SDI research.

Figure 3 illustrates the author contributions, consisting of 645 nodes and 581 lines with a density of 0.0028. Notably, although numerous research teams appeared in the author visualization map, each team operated independently. The fragmented nature of SDI research calls for strengthened communication and cooperation among institutions to form an interactive support network that utilizes the unique strengths of each research group and ultimately enhances research efficiency and depth.

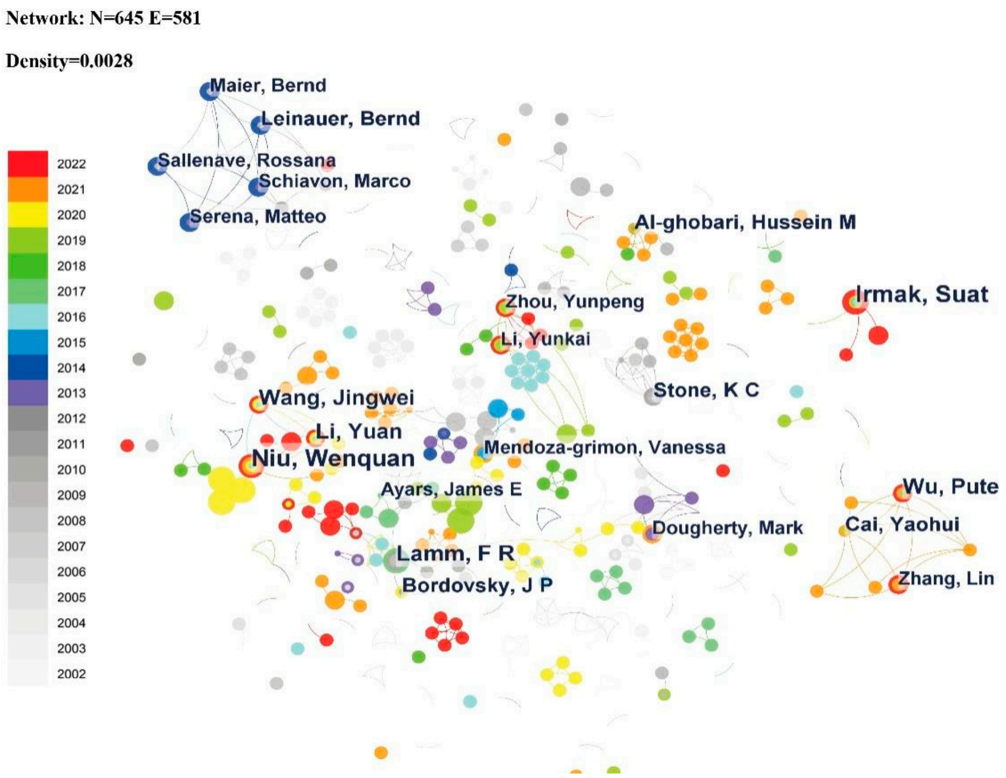

Figure 3. Author co-occurrence map for authors producing literature relating to SDI.

3.3. *Keyword Analysis*

3.3.1. Exploration of Hot Topics in Review Articles

To comprehensively explore the research hotspots and directions in the field of SDI, we manually analyzed the keyword information from 41 reviews based on the literature data and presented the results in Table 3 (the numbers following "*" represent the frequency of the keyword occurrence). Review articles are based on primary research data and information, representing the perspectives of other scholars on the advancements of subsurface drip irrigation in the respective field. The frequency of keywords in review papers can reflect the research focuses of other scholars in the SDI domain. A higher occurrence of keywords of the same type indicates a higher level of attention towards that particular area. Through the analysis of review paper keywords, we observed that, besides the category "irrigation methods", which is closely related to the search term, the distribution of soil moisture, environmental pollution, and crop cultivation have received the most attention. This suggests that SDI has been widely adopted in numerous crop cultivations, while also potentially posing challenges in controlling agricultural pollution. Investigating the water distribution and hydraulic characteristics of SDI under different irrigation and soil conditions is a popular research topic. In contrast, the topic of economic benefits discussion appears to be relatively limited, indicating that economic factors receive less attention in the research and development of SDI. Moreover, advancements in new technologies have provided opportunities for SDI, generating extensive discussions on enhancing water use efficiency, utilizing unconventional water resources, and increasing crop yields.

Table 3. Statistical analysis of keyword information in review articles.

Tags	Keywords	Count
Irrigation method	subsurface drip irrigation × 9; irrigation × 6; micro irrigation × 5; irrigation methods × 4; trickle irrigation × 3; deficit irrigation × 3; drip irrigation × 3; irrigation systems × 2; SDI × 2; sprinkler irrigation × 2; surface irrigation × 2; limiting flow; furrow irrigation; spray irrigation; subsurface irrigation	45
Soil moisture distribution and changes	water-table; soil moisture distribution pattern; wetting pattern; transport; drying-rewetting frequency; soil water; water movement; hydraulic conductivity; integrated water; variably saturated flow; one dimensional infiltration; surface point source; dependent linearized infiltration; unsaturated hydraulic conductivity; steady state flows; groundwater; soil water potential; soil water potential threshold; soil hydraulic properties; root water uptake; soil management; root distribution; root water; root zone water; fine root; sorption; evapotranspiration;	27
Environmental issues and pollution	microbial contamination; environmental health; microbial activity; oxide emissions; denitrification; nitrogen-fixation; similarity solutions; soil properties; heavy metals; boron toxicity; steady state; excess boron; chemigation; soil contamination; pathogens; health risks; soil contamination; ammonia volatilization; N_2O; CO_2; CH_4; C_2H_2	22
Crop	lettuce; cotton; wheat cropping system; winter-wheat; rice; grassland soils; pomegranate; tomato root distribution; cropping systems; cotton; sugarcane; plant; vitis vinifera; wine; plant growth; plant conditioners; corn; interspecific interaction; niche differentiation; plant breeding; plant roots; winter wheat	22
New technologies	remote sensing × 3; discharge rate; technical parameters; wireless sensor networks; soil-moisture; precision agriculture; screenhouse; automation; innovation and technology; low energy precision application; tensiometer; soil water potential sensor; walled carbon nanotubes; ground penetrating radar; electrical conductivity	17
Water use efficiency	water use efficiency × 7; water saving × 2; water requirements; water use productivity; crop water productivity; water use; crop productivity; water productivity; water resources	16
Nonconventional water resource utilization	treated wastewater × 3; water quality; wastewater reuse; low quality water; virtual water; unconventional water resources; site waste water; wastewater; salinity; soil salinity; nonuniform transient salinity; coal salt tolerance; n-mineralization	15
Yield	Yield × 3; crop production × 2; aril colour; fruit quality; plant growth; physical properties; waste of water and feed; crop quality; yield response; grain-yield	13
Irrigation strategy and management	water management × 3; management; management strategies; irrigation management strategies; design; operation systems; irrigation schemes; irrigation management × 2; irrigation scheduling	12

Table 3. *Cont.*

Tags	Keywords	Count
Agricultural development	Sustainability × 3; conservation agriculture × 2; protected cultivation; residue management; zero tillage; cereal system; sustainable irrigation; agriculture	11
Climate change and water resources	climate change × 3; groundwater depletion; drought; environmental impact; micro-climate regulation; heat stress; temperature	9
Region and terrain	coastal-plain; India; basin tillage; ceramic pots; sub-Sahara; ogalla aquifer; indo-gangetic plains of India	7
Fertilizers and nutrition	Fertigation × 2; controlled release fertilizers; macronutrients; nutrients; nutrient source	6
Economic benefits	payoff period; runoff; water pricing and rationing	3
Others	LEPA; uniformity; prisma-p; semi-permeable membrane; nitrogen isotope; semifield; conservative numerical-solution; finite-element method; conservative numerical-solution; finite-element method, meta-analysis; bibliometric analysis; Green-ampt analysis	13

3.3.2. Analysis of Keyword Co-Occurrence

Analyzing the keywords of a certain field of research can be useful in elucidating research hotspots and core content within that field [17]. Figure 4 shows a keyword co-occurrence map containing 596 nodes, 2509 connections between the nodes, and a density of 0.0142. Table 4 presents high-frequency keywords, where the top 10 keywords have a frequency > 100. By combining these keywords, we observed that water use efficiency and yield were prominent research directions related to SDI.

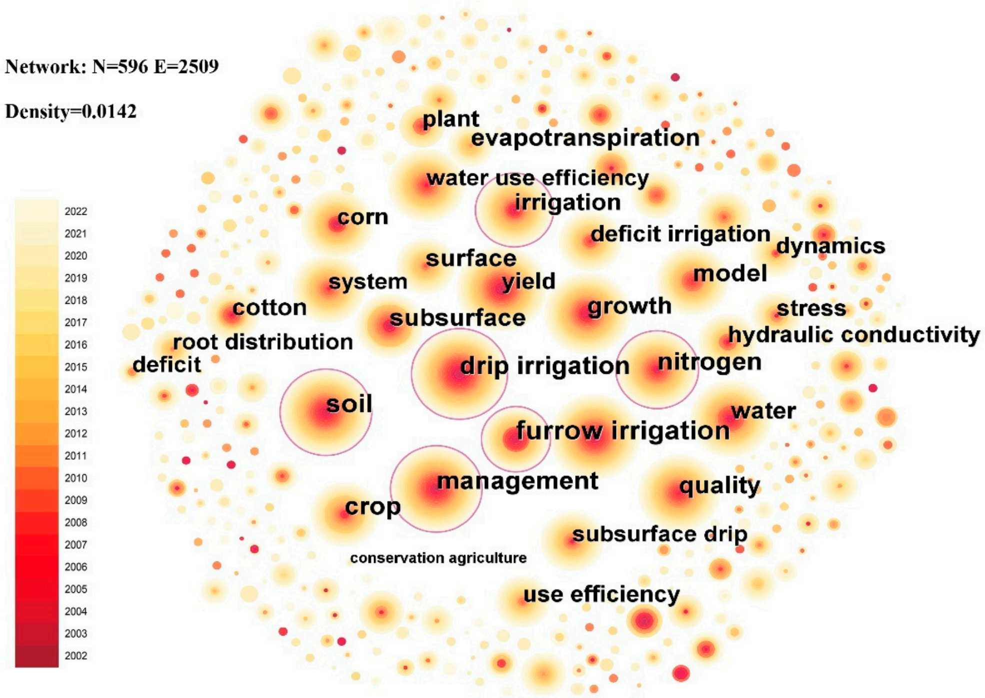

Figure 4. Keyword co-occurrence map displaying the most frequently used words associated with SDI research.

Table 4. Top 30 most frequently cited keywords used in literature pertaining to SDI.

Rank	Count	Centrality	Burst	Keyword
1	380	0.02		subsurface drip irrigation
2	244	0.06		yield
3	174	0.05		water use efficiency
4	170	0.11		drip irrigation
5	161	0.06		growth
6	155	0.10		management
7	151	0.17		soil
8	122	0.06		water
9	117	0.06		deficit irrigation
10	113	0.09		quality
11	93	0.08		use efficiency
12	88	0.05		system
13	71	0.10		irrigation
14	67	0.05		model
15	66	0.10		nitrogen
16	61	0.08		crop
17	59	0.07		subsurface drip
18	55	0.05		corn
19	53	0.01		simulation
20	51	0.07		surface
21	48	0.05		cotton
22	44	0.04		fruit quality
23	43	0.04		dynamics
24	43	0.03		field
25	43	0.07		subsurface
26	41	0.07		evapotranspiration
27	41	0.04		hydraulic conductivity
28	39	0.05		stress
29	38	0.03	5.36	flow
30	35	0.13	5.48	furrow irrigation

Keywords with a high BC represent the most important research areas in SDI. Figure 4 shows six keywords with high centrality: soil (0.17), furrow irrigation (0.13), drip irrigation (0.11), irrigation (0.10), management (0.10), and nitrogen (0.10). Soil is a fundamental component of crop production. The physical and chemical properties of soil have a considerable influence on the effectiveness of SDI. Based on the degree of permeability, sandy soil is more suitable for SDI compared to the more compact clayey soil, which is also vulnerable to uneven water and fertilizer distribution [18]. Soil temperature, pH, and salt content affect the ability of plants to absorb and utilize water and nutrients [19,20]. Furrow, drip, and irrigation were closely associated with the search terms used in this study. Compared with other irrigation methods, SDI yields higher water use efficiency, less soil erosion, and greater water conservation and is more conducive to improving crop yield and quality. Furthermore, it also reduces labor intensity [21,22]. SDI management encompasses irrigation scheduling, fertilization, system maintenance, and soil crop management. Effective management strategies are essential for enhancing crop yield and quality, maintaining soil health, improving water and fertilizer use efficiency, and achieving sustainable crop production [23]. Nitrogen is an important nutrient in crop growth and directly affects yield. Variations in irrigation methods can significantly affect nitrogen use efficiency. Studies have demonstrated that SDI can improve nitrogen utilization efficiency while reducing nitrogen loss [24,25]. Additionally, SDI can be combined with other measures, such as soil testing, mulch planting, and crop rotation, to optimize nitrogen use efficiency [24–26].

3.3.3. Keyword Clustering Relating to SDI Literature According to Time of Citation

A keyword clustering map is a valuable tool for characterizing nodes with similar themes [17]. As shown in Figure 5, the Q of keyword clustering was 0.4584, and the S was 0.7546. The selection of keywords and the log-likelihood ratio utilized by the clustering algorithm generated 14 labels, in which 588 out of 596 nodes were classified; each node's label was unique. The thickness of the lines between nodes within a cluster indicates the correlation between research directions (the denser the lines, the stronger the correlation) [27].

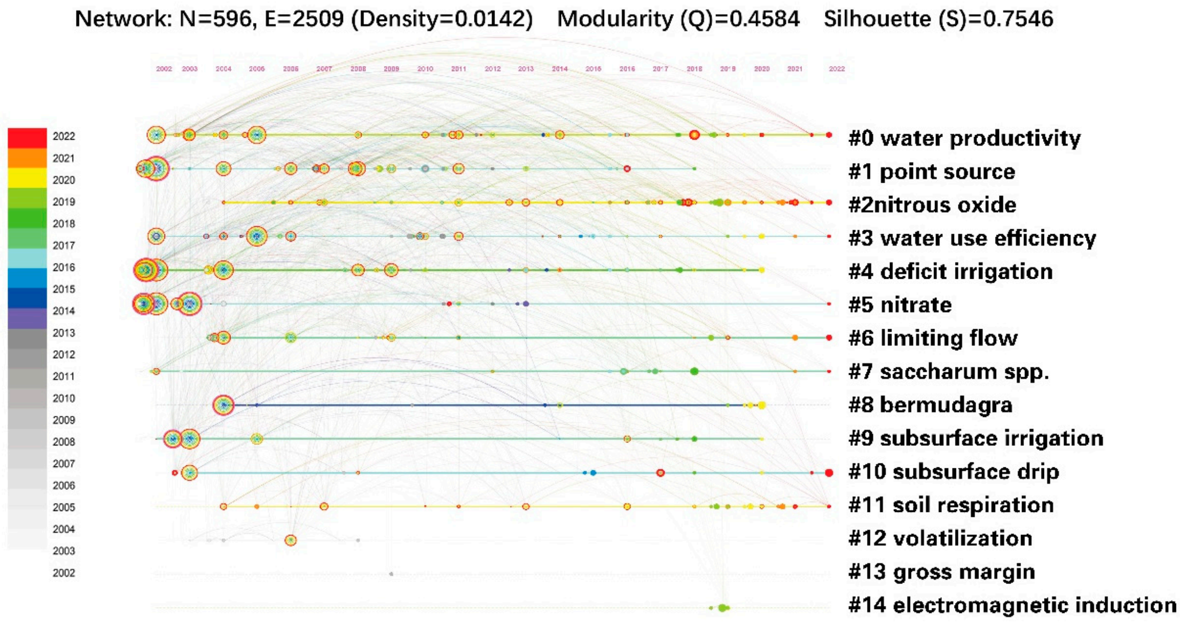

Figure 5. Keywords timeline clustering map for keywords relating to SDI research.

To further refine the research content and identify research hotspots, tags with the same theme were summarized into nine parts (tags #9 and #10 were excluded because of their close association with the search term). Part 1 (#0 water productivity and #3 water use efficiency) includes 126 nodes, and the main years of #0 and #3 were 2012 and 2011, respectively. Part 2 (#2 nitrous oxide and #5 nitrate) contained 109 nodes, and the main years for #2 and #5 were 2016 and 2007, respectively. Part 3 (#4 deficit irrigation and #6 limiting flow) had 90 nodes, with the main year being 2010. Part 4 (#7 *Saccharum* spp. and #8 Bermudagra (Bermuda grass)) had a total of 73 nodes, and the main years of #7 and #8 were 2013 and 2012, respectively. Part 5 (#1 point source) appeared in 2009 and contained 65 nodes. Part 6 (#11 soil respiration) had 30 nodes and appeared in 2015. Part 7 (#12 volatilization) had 19 nodes, and the main year was 2005. Part 8 (#13 gross margin) had six nodes, and its main year was 2009. Finally, Part 9 (#14 electromagnetic induction) comprised six nodes, and its primary year was 2019.

Among the nine parts, water use efficiency in Part 1 contained the highest number of nodes, indicating that crop water absorption and utilization efficiency has been a major focus of research in SDI. Part 2, which considers nitrogen, is divided into two periods. The earlier period focused on the effect of nitrogen fertilizer on crop yield, while the latter dealt with the avoidance of the adverse effects of nitrate on the environment. The precise control of nitrogen fertilizer dosage through SDI can promote crop growth while avoiding pollution and uncontrolled emissions of greenhouse gases (CO_2 and N_2O, among others) [26,28]. Part 3, deficit irrigation, is an important water-saving strategy in arid and semiarid regions [29] that aims to limit input while promoting yield and quality, thereby achieving an efficient balance between irrigation volume (input) and crop yield (output) for maximum profit [30–32]. Part 4, crop, indicates the beneficial impact of SDI on *Saccharum* spp. and Bermudagra (Bermuda grass) crop yield and quality while reducing water and fertilizer usage [33–36]. Part 5, the study of point sources, relates to the design of SDI systems and crop planting methods for optimized efficiency. The distribution of point sources not only has a significant impact on soil water depletion and moisture peak, but also limits the amount of tilling and crop spacing [37–40]. However, the timeline node distribution indicated that point source research was initially a hot topic but has gradually become less popular in recent research. Part 6, soil respiration, was evenly distributed throughout the research period, and its popularity increased slightly with the development of oxygation (oxygenated irrigation water). In general, irrigation saturates the spaces between soil particles and reduces air content, resulting in reduced respiration in the crop root zone. The oxygenation of irrigation water can effectively improve respiration in the root zone, thus increasing yield and quality [41–44]. Part 7, node distribution and connection, indicated that the study of evapotranspiration is outdated, albeit closely related to other parts. Evaporation is an important parameter for determining crop water demand. Based on crop water demand and local water supply conditions, efficient planning for precipitation and irrigation can achieve the best economic, social, and ecological outcomes [45–47]. In Part 8, profit studies were observed to be rare and do not overlap with other categories. However, from a commercial perspective, the complicated operating mode of SDI requires higher investment costs, which may inhibit its application and marketing [21]. Part 9, the application of sensor technology in agriculture, developed rapidly. Sensor technology provides a means to locate and monitor the distribution of water and nutrients in the soil and automate the functioning of the SDI system. The combined use of electromagnetic induction technology can further optimize irrigation and fertilization strategies to improve water and nutrient use efficiency and crop yield [48,49].

3.3.4. Analysis of Keyword Bursts

A keyword burst refers to a significant change in the frequency of a keyword over time. Keywords with strong and long-lasting burst intensities may represent a new research direction [50].

Figure 6 shows that the burst intensity for words before 2007 were strongly correlated with the search terms used in this study. “Trickle irrigation” had the highest burst intensity, whereas “subsurface” had the longest burst duration. Between 2002 and 2022, research focused on the characteristics of SDI. In 2010, three keywords showed a high burst intensity, among which “irrigation” appeared in 2004 and was associated with several burst words of the previous publication period. The studies of drip distribution in irrigation systems and water infiltration distribution also gained attention during this period. Finally, the close association in the burst timing of “water productivity”, “grain yield”, and “performance” represents the latest hot topics in SDI research. Therefore, we expect that SDI system research and development will continue to focus on improving yield and water conservation.

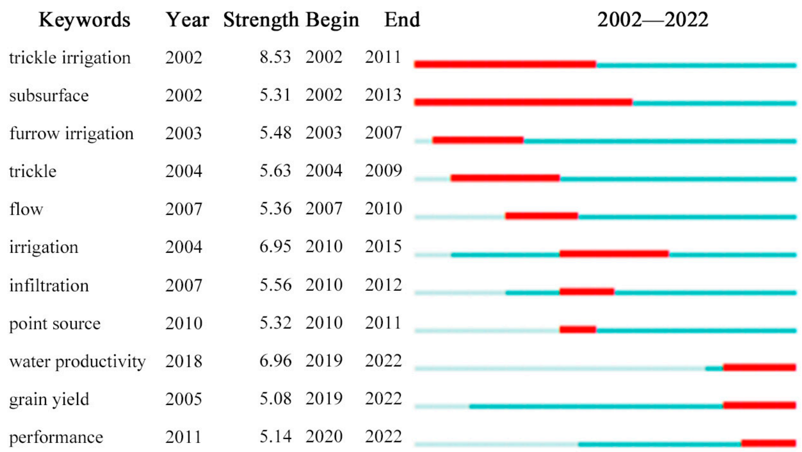

Figure 6. Top 11 keywords relating to SDI with the strongest citation bursts over the period between 2002 and 2022.

3.4. Analysis of Reference Co-Citation

We assessed the topic trends and temporal development of SDI research through a reference co-citation analysis. Reference co-citation refers to the overall number of citations for a particular paper [16]. Because some references were published before the papers screened in our study, the analysis of reference co-citation includes some studies before 2002. Table 5 highlights citations with high frequency or strong centrality, and Figure 7 shows a cluster analysis of citations over time. Each node in the figure represents a cited article and its size reflects the proportion of citations [51].

Table 5. Publications on SDI with high co-citation frequencies.

Frequency	Centrality	Burst	Author	Source	Year
29	0.05	10.43	Ayars, J.E.	*Agr. Water Manag.*	2015
25	0.00	10.27	Lamm, F.R.	*Trans. ASABE*	2016
19	0.01	6.66	Ben-Noah, I.	*Agr. Water Manag.*	2016
18	0.08	6.36	Simunek, J.	*Vadose Zone J.*	2016
17	0.02	5.29	Du, Y.D.	*Agr. Water Manag.*	2018
16	0.00	7.49	Li, Y.	*Soil Sci. Soc. Am. J.*	2016
15	0.25	7.40	Kandelous, M.M.	*Agr. Water Manag.*	2010
15	0.17	5.24	Irmak, S.	*Irrig. Sci.*	2016
13	0.15	4.04	Cai, Y.H.	*Agr. Water Manag.*	2017
13	0.24	7.93	Lamm, F.R.	*Irrig. Sci.*	2003
11	0.22	5.65	Simunek, J.	*Vadose Zone J.*	2008
10	0.20	4.40	Dabach, S.	*Agr. Water Manag.*	2015
10	0.11	5.79	Gardenas, A.I.	*Agr. Water Manag.*	2005
8	0.22	4.79	Kandelous, M.M.	*Soil Sci. Soc. Am. J.*	2011
6	0.21	3.13	Payero, J.O.	*Agr. Water Manag.*	2006
6	0.13	3.59	Kandelous, M.M.	*Agr. Water Manag.*	2012
4	0.15		Thompson, T.L.	*Soil Sci. Soc. Am. J.*	2002
4	0.20		Ajdary, K.	*Agr. Water Manag.*	2007
4	0.13		Evett, S.R.	*Agr. Water Manag.*	2002
3	0.22		Abou Lila, T.S.	*Irrig. Sci.*	2013
3	0.12		Bekele, S.	*Agr. Water Manag.*	2007
3	0.11		Selim, T.	*Soil Sci. Soc. Am. J.*	2013
2	0.12		Thompson, T.L.	*Soil Sci. Soc. Am. J.*	2002

We divided the timeline map into four parts. The first part covered the period before 2002, during which the research directions included #7 clay deposit, #13 potato crop, #16 precision flow control, and #19 *Prunus dulcis*. The second part spans 2002–2008, comprising the research directions #5 stem yield, #9 soil moisture sensors, #3 Wyoming, #10 gross margin, #12 antioxidant activity, #15 quality assurance standard (QAS), #14 economic benefits, and #18 energy balance. The third part spans 2008–2014, comprising the research directions #11 soil water balance, #4 irrigation water productivity, #6 crop coefficients, #1 aerated irrigation, #2 alfalfa, #20 *Saccharum officinarum* L., and #22 organic fertilizer application. Finally, the research directions of the fourth part, spanning 2014–2022, comprised #0 partial root-zone drying, #1 aerated irrigation, #2 alfalfa, #8 Hydrus, #17 redistribution, and #21 subsurface drainage.

Analysis of the timeline map revealed that the scope of SDI research has broadened over time. The earliest node of import occurred in Category #7, which pertains to the proper management of clay deposits. This is a key factor in the effective use of SDI because clay deposits may clog emitters and reduce the flow of water and nutrients to crop roots [52]. Al-Eter et al. [16] demonstrated that the use of clay deposit amendments in sandy soils improved soil water storage and promoted root growth and yield. Three categories produced key nodes in the second period. The earliest category was #5, which addressed stem yield and showed that SDI contributed considerably to the yield of root and tuber crops (sweet potatoes, onions, and potatoes). Although #10 gross margin produced three nodes of importance, the keyword analysis in Section 3.3.2 suggested that profit is not the most important factor in the development of subsurface drip irrigation. This is likely related to the high input cost, high technical threshold of operation and maintenance, and long income cycle of SDI. Furthermore, the optimization of and improvement in SDI equipment mainly focuses on enterprise transformation, with relevant information stored as part of the core enterprise data. Considering the distribution of nodes over time, #3 Wyoming emerged because of the impact of coalbed sodic water on agriculture in Wyoming, United States. Because of large-scale coal mining in the area, salty water has been injected into the coal seam and has forced farmers to use slightly saltier water for irrigation [53–55]. SDI, with its completely closed pipeline and precisely controlled flow rate, offers significant advantages in the use of nonconventional water resources (wastewater and saltwater) for irrigation. This setup can prevent the transfer of pollutants while maintaining the levels of nutrients, such as nitrogen, phosphorus, potassium, and organic matter, required for crop growth [56,57]. Brackish water irrigation is mainly applied to sandy loam with good drainage and leaching conditions in arid areas. In salinized soils, a decrease in soil water content promotes soil salinity, but brackish water irrigation can increase soil water content and dilute soil salinity [15,58–61]. The third period encompassed the largest number of research categories. The two key nodes were #6 (crop coefficients) and #4 (irrigation water productivity). The research focus during this period was on developing appropriate irrigation strategies according to the water demand cycles of different crops. Aerated irrigation, a new branch of research, emerged during this period. The fourth phase focused on the infiltration distribution of irrigation water in the root zone of crops, which is commonly associated with the Hydrus model for water movement simulation in SDI.

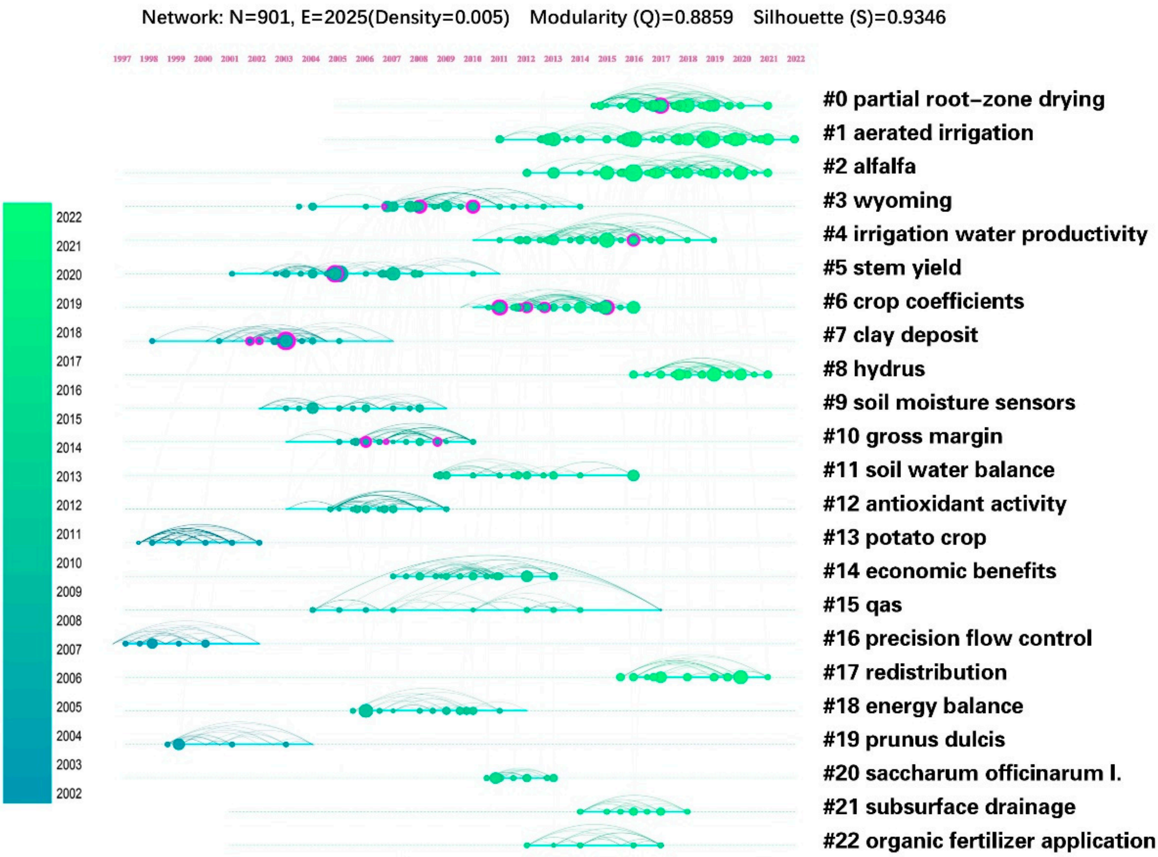

Figure 7. Reference clustering according to time.

Early research on SDI primarily focused on traditional techniques, such as precise control, water conservation, yield increase, and soil and water conservation. In recent years, with the emergence and development of new technologies, some new research methods and branches have entered the research scope of SDI. For example, Hydras is a simulation software for groundwater and soil water movement, mainly used to study and simulate soil moisture, infiltration and transportation, hydrological processes, and soil hydrochemical reactions [62–64]. SDI research now considers different soil types and water management practices to predict and optimize soil moisture and ultimately enhance agricultural productivity [65]. Aerated irrigation is an innovative development that increases the feeding capacity of crop roots by infusing irrigated water with oxygen or air, allowing plants to absorb more water and nutrients, and reducing the need for frequent watering. This results in water conservation and improved plant health [4,44,52,66,67]. Among application crops, alfalfa has become a hot topic in SDI research. Alfalfa thrives in cool and humid climates, and SDI can reduce the occurrence of soil surface crusting and soil erosion, which are unfavorable for the growth of alfalfa. Therefore, SDI has broad prospects for application in alfalfa planting and the forage industry [68,69].

4. Discussion

In recent years, the application of subsurface drip irrigation in water-saving agriculture has increased considerably. In the United States, the area of SDI application increased by over 167% between 2003 and 2018, mainly for crops such as corn, onions, cotton, and tomatoes [21]. The integration of water and fertilizer is one of the main advantages of SDI, which enables consistent and evenly distributed fertilizer and pesticide application throughout the entire growth cycle [24]. SDI is characterized by low water flow rates, where water is released from emitters and diffuses through capillary action and gravity to the root zone of crops. This closed irrigation method minimizes the occurrence of water spreading on the soil surface, effectively reducing the leaching and runoff of fertilizers and pesticides. Consequently, SDI mitigates their movement within the soil, thereby mitigating pollution and environmental contamination [9]. This can improve fertilizer and water use efficiency while limiting nutrient loss, which ultimately promotes yield and limits the impact on the environment. SDI has demonstrated excellent performance in saline water irrigation. Under favorable drainage conditions, continuous SDI induces leaching of the soil beneath the emitters, preventing salt accumulation near the root zone and mitigating the negative impact of salinity on crops [70]. A large number of research results in the above research fields have been published in journals related to agronomy, water resources, and environmental sciences, such as *Agricultural Water Management*, *Agronomy*, *Agriculture*, *Water*, and other excellent journals.

The development of internet technology has led to the intelligent and precise transformation of SDI. Against the backdrop of current agricultural production shifting towards intensification and automation, there has been rapid progress in the development of extensive, non-destructive, and fast detection techniques for assessing soil moisture, nutrient levels, and crop losses in agricultural fields [71]. The utilization of big data and satellite remote sensing technology enables the refinement and intelligentization of irrigation strategies. Through real-time monitoring and data analysis, timely information on meteorological changes, soil temperature and moisture, and surface evaporation can be obtained. By evaluating the water status of agricultural fields in conjunction with crop growth and water requirements, targeted irrigation recommendations can be provided [49,72]. Soil sensors and the Internet of Things have significantly improved the monitoring, management, and maintenance of SDI systems [17,73]. Because the working parts of an SDI system, such as pipes and irrigators, are buried underground, blockages and pipeline leakages can be challenging to detect. Delayed maintenance can lead to small-scale droughts or flooding, which reduces irrigation efficiency and results in crop loss. Enhanced monitoring devices can accurately sense and control the operational status of SDI systems and assess soil health, thereby providing effective assistance in system management and irrigation strategy formulation.

Enhancing the operational lifespan poses a significant challenge to the development of SDI systems. Compared to other irrigation methods, SDI has higher maintenance and operating costs, and the economic viability of SDI systems relies on achieving a lifespan of 15 to 20 years [22]. Blockages and pipeline damage are frequently encountered issues in SDI systems. Clogging primarily occurs in the emitters of subsurface drip irrigation systems and is caused by particle blockage, deposition from chemical reactions between fertilizers, and the aggregation of microorganisms in confined spaces [74]. Regular flushing or periodic flushing can effectively prevent clogging in pipelines and emitters [75]. The anti-clogging performance of emitters depends on factors such as channel shape, dimensions, materials, and other factors. Increasing the fluid velocity and turbulence inside the emitters can contribute to improved anti-clogging performance. Computational Fluid Dynamics (CFD)-based numerical simulation techniques have been widely applied in the design and development of emitters, playing a significant role in optimizing channel design and enhancing anti-clogging capabilities [76]. Pipeline damage can result from multiple factors: aging of the pipeline material, breakage caused by expansion and contraction under varying temperatures, damage inflicted by plowing equipment, and damage from rodents [20]. Implementing appropriate pipeline layout and land cultivation strategies can help prevent damage to SDI systems during plowing operations. However, traditional SDI pipe materials are plastic and rubber, which are susceptible to UV- and temperature-mediated aging. Composite and ceramic materials have recently emerged as alternatives for manufacturing SDI pipes and emitters [77]. These materials can reduce the long-term losses and maintenance costs of SDI, while improving environmental friendliness and energy efficiency.

The economic benefits of SDI systems should be evaluated based on specific circumstances and considerations. SDI is recognized for its water-saving effects; however, it may not deliver superior economic benefits when compared to other conventional irrigation methods [78]. As revealed by keyword mapping, relatively few studies have assessed the economic benefits of SDI. From the perspective of economic competitiveness, SDI may not be suitable for all crops. For example, root crops (such as sweet potatoes, onions, and potatoes), as well as certain vegetable crops (such as tomatoes), have demonstrated significant increases in yield using SDI; however, cereals have not exhibited sufficient yield increases to justify the advantages of SDI over other irrigation methods [79–81]. Notably, there has been an increase in research on the use of SDI in alfalfa cultivation. This is due to the precise water and nutrient control offered by SDI. Excessive or inadequate soil moisture levels and fertilization can reduce alfalfa yields. The application of SDI systems allows for effective control of production costs and enhances forage production [82]. The application of SDI systems involves considerable financial investment and requires the design, construction, and management of specialized equipment by technically trained personnel. Moreover, SDI systems rely on electricity to drive water pumps and valves, among other devices, which increases running costs. Since subsurface drip irrigation systems are susceptible to damage from plowing equipment, they are more suitable for low-tillage or no-tillage cropping models [78]. Crop rotation may not be suitable for SDI because the fixed burial depth and spacing of drip heads may be inconsistent with crop row spacing and planting depth, thus reducing irrigation efficiency. In practice, considering crop type, land topography, and water resources. Further research is needed to evaluate the economic benefits of SDI systems under different scenarios [83].

5. Conclusions

In this study, CiteSpace was used to examine the trends in the research field of subsurface drip irrigation. Research on SDI has garnered increasing attention in recent decades, its applications have continued to expand, and it has demonstrated considerable potential in improving the yields of a variety of crops. Based on statistical analysis of publication numbers, the United States and China have been the most influential countries in SDI research. Research on SDI is relatively dispersed among various research institutions and teams. It is anticipated that by enhancing collaboration, research efficiency and depth can be improved. Current SDI research focuses on improving water use efficiency and increasing crop yield, with the distribution of water in the crop root zone being a research hotspot. The Hydrus model plays a significant role in studying the movement of soil moisture peaks and nutrient substances under SDI conditions. To optimize the productivity of the root zone, aerated irrigation may emerge as a new branch of SDI. The significant potential demonstrated by SDI in water-saving irrigation and the nonconventional water resources (wastewater and saltwater) positions it as a promising solution for increased application in arid regions. The development of new technologies and materials presents opportunities for the widespread adoption of SDI, facilitating the formulation of precision irrigation strategies and extending system longevity. In order to control costs and increase yields, SDI is likely to be increasingly applied in the cultivation of forage crops, such as alfalfa, in the livestock industry. Despite certain limitations, such as high investment costs and complex management and maintenance, SDI shows great potential in the development of water-saving and production-increasing technologies to meet future food demands, while limiting costs related to both long-term operation and environmental impact.

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