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Review

Sustainable Irrigation in Agriculture: An Analysis of Global Research

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Abstract: Irrigated agriculture plays a fundamental role as a supplier of food and raw materials. However, it is also the world's largest water user. In recent years, there has been an increase in the number of studies analyzing agricultural irrigation from the perspective of sustainability with a focus on its environmental, economic, and social impacts. This study seeks to analyze the dynamics of global research in sustainable irrigation in agriculture between 1999 and 2018, including the main agents promoting it and the topics that have received the most attention. To do this, a review and a bibliometric analysis were carried out on a sample of 713 articles. The results show that sustainability is a line of study that is becoming increasingly more prominent within research in irrigation. The study also reveals the existence of substantial differences and preferred topics in the research undertaken by different countries. The priority issues addressed in the research were climatic change, environmental impact, and natural resources conservation; unconventional water resources; irrigation technology and innovation; and water use efficiency. Finally, the findings indicate a series of areas related to sustainable irrigation in agriculture in which research should be promoted.

Keywords: sustainable irrigation; bibliometric analysis; climate change; innovation and technology; water use efficiency; unconventional water resources

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1. Introduction

The current global context is conditioned by the growth of the world's population and the progressive and continuous deterioration of the environment. This creates the challenge of ensuring the supply of basic resources, such as food and water, and sustainable development [1], where water plays an essential role in the survival of human society [2] and contributes to the provision of a wide range of services on which the wellbeing of society is based [3–5]. However, water resources are subject to severe degradation due to many factors, such as the consequences of global climate change, alterations in the use of land, agricultural and urban expansion, and overexploitation due to economic development [6–8]. In parallel with this degradation and overexploitation of ecosystems and water resources, the demand for the services supplied by these resources is expected to increase.

Agricultural ecosystems are the principal suppliers of food, but they are also the main users of water resources on a global level [9,10]. These ecosystems use between 60% and 90% of the available water, depending on the climate and economic development of the region [11,12]. The global area dedicated to irrigated crops is estimated to be 275 million hectares, with an upward growth trend of 1.3% per year [13]. This accounts for just 23% of farmed land; however, 45% of total food production is obtained through these types of crops [14,15]. It has been estimated that in order to satisfy the food demand in 2050, world production must increase by 70% [16]. In a scenario of low production, in order to fulfil this objective, it will be necessary to increase the use of water resources on a global level by 53% [17]—around 50% in developing countries and 16% in developed countries [18]—keeping the current values of variables like productivity and technology.

Currently, different approaches are being used to address the challenges of food provision and the supply of water for different uses and to maintain an environmental balance. Some works point to the development of measures to control demand so that irrigation water sustainability can be reached. The development of efficient water markets can be an optimal measure in underdeveloped areas and with a high level of water scarcity, like in South Africa [19,20]. The implementation of joint restrictions based on the establishment of quotas and the payment of fees can be an effective control system for the use of agriculture water in developed regions specialized in the production of high-quality crops and where overexploitation of water resources is currently taking place [21]. Regarding water supply, many authors recommend the joint use of different water resources and the development of infrastructures as nonconventional water sources [22,23]. Another line of research is focused on the improvement of the efficiency of water use and the development of clean production models that guarantee sustainability from social and economic perspectives [24,25]. In order to achieve this objective, the whole irrigation process must be analyzed. This process covers different phases beginning with the water source and ending with its use for agriculture. Zhang et al. [26] identified three phases in irrigation: The first includes the extraction of water from the source and its transfer through channels to the point of use; the second consists of the distribution of the water to the root system to facilitate its absorption by crops (this includes both traditional irrigation using floods and furrows and modern irrigation through drip systems and microsprinklers); and the third covers the whole crop-growing process, whereby the water is transported from the roots to the rest of the plant. The goal is to save resources through minimizing water losses during these three phases and to improve the efficiency in the use of water resources.

The so-called "Science of Sustainability" also studies how to address these challenges. It is defined as "a discipline that points the way towards a sustainable society" and is "aimed at understanding the fundamental character of interactions between natural, human, and social systems, covers a wide range of academic disciplines", for the development of agricultural systems and the sustainable use of water [27–29]. At the end of the 1990s, sustainability was used as a characteristic to describe ecosystems, referring to the capacity to maintain the flow of services in different environmental, economic, and social contexts [30]. When it is applied to the management of water resources in agriculture, sustainability is considered to be a series of practices that increase crop yield and minimize water losses [31]. The objectives of the sustainable management of water resources in agriculture consider the continuity of the agricultural system from physical and biological perspectives, as well as the economic efficiency of the use of the resources and social participation in the decision-making processes [32]. An evaluation of a change in water use requires, therefore, a multidisciplinary approach that includes an analysis of the body of water under study in order to understand the possible impacts on the quantity and quality of the water and the timetable of the different uses. A comprehensive evaluation of the marginal productivity of water is also required, together with an analysis of its nonmarketable value, such as that derived from ecosystem services [33].

In recent years, there has been an increase in the number of studies analyzing agricultural irrigation from the perspective of sustainability with a focus on its environmental, economic, and social impacts. The objective of this study is to analyze the dynamics of the research on sustainable irrigation in agriculture over the last twenty years. In order to fulfil this objective, a two-fold analysis was undertaken: quantitatively through a bibliometric analysis; and qualitatively through a systemic review based on keyword analysis. The study analyzes the evolution of the number of articles published, the main authors, institutions and countries that promote this research field, the disciplines involved in the research, the main lines of research, the differences in academic approach and the countries considered, and the main issues that affect the research in this field.

Bibliometric analysis was introduced by Garfield in the 1950s [34], and its objective is to identify, classify, and evaluate the principal components within a specific research field [35]. Bibliometry combines tools of quantitative analysis to study the trends of a research topic and identify the main driving agents and the relevance of their publications [36,37]. In bibliometric analyses, three types of indicators can be distinguished, which were defined by Durieux and Gevenois [38]: productivity indicators, relevance indicators, and structural indicators. In addition to these indicators, different approaches exist in bibliometric analysis. Co-occurrence, co-citation, and bibliographic coupling analysis are among the traditional approaches. This extended methodology can be considered as a new one in some research areas. This has also continuously been developing. In this sense, this work introduces some new methodological aspects which provide a contribution regarding previous works—in fact, the sample search process, a mixed quantitative and qualitative review, and the production of keyword networks to identify main trends per country. The results of this study provide a basis on which to establish priorities and to develop new projects in future research on this topic.

2. Methodology

In order to conduct this study, a traditional approach based on co-occurrence was selected, which included the assessment of productivity, quality, and structural indicators. In this approach, first, the agents with the highest number of publications were identified, and second, the impact of the publications of these authors was analyzed. This type of analysis, particularly with respect to journals, is highly interesting for researchers, given that it constitutes a way to assess the relevance of the journals in which authors publish their studies [39]. Finally, we used mapping techniques to analyze the structure of the network between different agents. The Scopus database was used to select the sample of studies to analyze. This database has proven to be the most suitable for our area of study, enabling us to ensure the selection of a representative sample of the studies carried out on sustainable irrigation (SI). Furthermore, it is easy to access, allows the visualization and analysis of data, and allows data to be downloaded in different formats for subsequent processing using software applications [40]. Nevertheless, if some works on SI are not indexed in the Scopus database, they have not been considered in our sample.

The term used to carry out the search was "sustainable irrigation", and this selection was based on previous studies on the same topic [41–43]. This term was searched for under authors' keywords and titles. The study period selected was 1999 to 2018. Research activity in this topic peaked during these years. Furthermore, this period immediately followed the 1st World Water Forum held in Marrakesh in 1997, which is considered to be one of the main landmarks in this field. Only documents until 2018 were included so that complete annual periods could be compared. In order to avoid duplication, the sample only included original articles [44]. It is worth pointing out that a different search query could give rise to different results. The search was carried out in January 2019. The sample of this study was composed of 713 articles. In addition, a search of articles on "irrigation" was also carried out with the same restrictions in order to analyze the relative importance of sustainability within this general theme. Figure 1 shows an outline of the methodology on which this study was based.

The analyzed variables were the number of articles, their years of publication, all of the authors of the articles, the institutions and countries of all of the authors, the subject areas in which Scopus classifies the studies, the name of the journals in which they were published, and the keywords. After downloading this information, the first task was to eliminate duplications. The names of authors and institutions can be found in different formats. This can lead to errors when counting these records. Therefore, these two variables were analyzed, and the different records were regrouped so that the same author and institution were not counted more than once. Once the information had been refined, different tables and figures were drawn up, and the analysis of the data was conducted. The programs used were Excel (version 2016) and SciMAT (v1.1.04) (University of Granada, Granada, Spain). The tool used to create the network maps was VOSviewer, which is widely used in this type of study [42]. Finally, keyword analysis was used to extract the principal research trends [45]. The terms were regrouped in order to eliminate duplications due to plurals, hyphens, words in upper case letters, etc. For the grouping of keywords by topics, standardized grouping algorithms were used with the following tools: Vosviewer (Association strength) and SciMAT (network analysis).

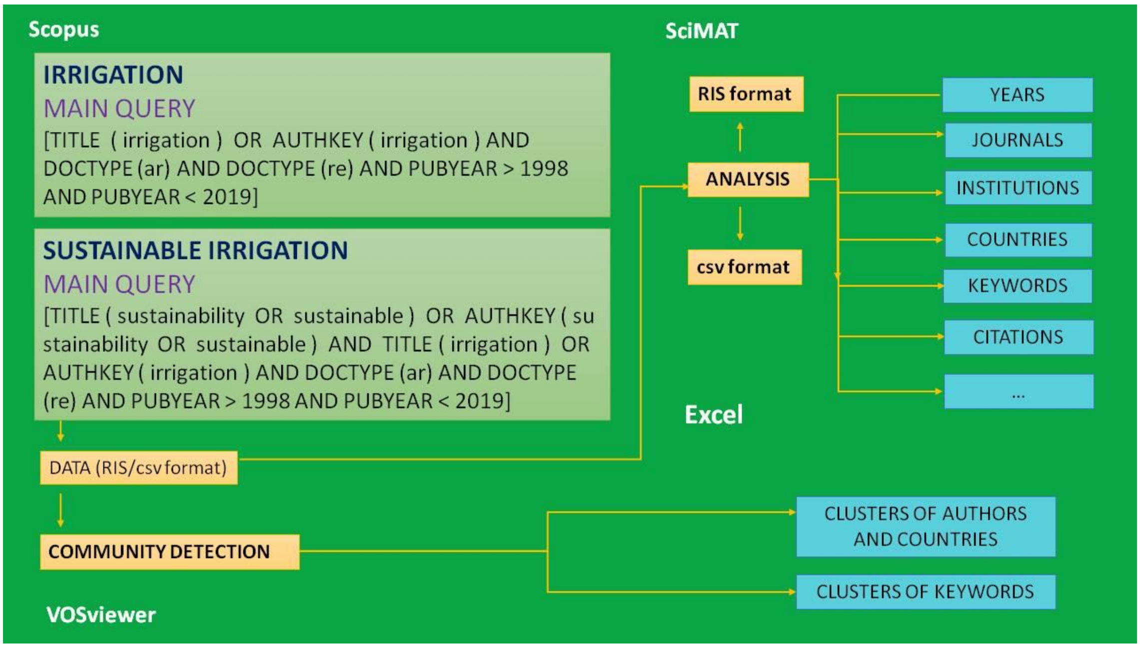

Figure 1. Outline of the methodological development of this study.

As for the methodology, this work includes some novel aspects compared to previous studies dealing with a similar topic. Firstly, regarding the sample selection of articles to be analyzed, some previous studies made a search based on titles, abstracts, and keywords [41–43,46,47]. In this work, the search was conducted in the fields of title and authors' keywords. Furthermore, before getting the final sample, it was checked that all included articles were related to the actual SI research. Secondly, most works on bibliometric reviews include the analysis of keywords. Nevertheless, this is the first search analysis which aims at detecting SI research trends based on the disciplinary approach of the study and the country where the research was conducted. Finally, the work includes a quantitative review based on a bibliometric analysis, as well as a qualitative one based on the traditional review.

3. Results

3.1. Evolution of the General Characteristics of Research on Sustainable Irrigation (SI)

Table 1 shows the evolution of the main variables related to research on SI during the period 1999–2018. During the studied period, relevant events like international declarations and congresses decisively influenced on the sustainability research. The Kyoto Protocol (UNFCCC, 2008), which commits world countries to reduce greenhouse gas emissions, should be highlighted, as well as the Economics of Ecosystems and Biodiversity of 2010; the Rio +20 of 2012; the Millennium Development Goals of the United Nations (UN, 2015), which provides guidelines for improving livelihoods and the environment globally; or the Paris Agreement on Climate Change of 2016; among others. These happenings additionally stimulate research on this topic [48]. This could also explain the existence of peaks regarding the publication of articles on SI research, like in 2017. A further reason explaining the higher number of published articles in 2017 compared to 2018 is that the sample selection was conducted in January 2019. The Scopus database updates itself continuously and, at the time of the sample search, not all published articles in 2018 had been registered. If the sample selection were to be performed at the end of 2019, the number of published and indexed articles on SI in Scopus in 2018 would increase.

Table 1. Main characteristics of sustainable irrigation (SI) research.

Year	Articles	Authors	Journals	Countries	Citation	Average Citation [1]
1999	6	13	6	5	0	0.0
2000	11	22	9	7	14	0.8
2001	15	30	11	10	5	0.6
2002	15	43	11	14	14	0.7
2003	12	24	12	11	35	1.2
2004	15	33	15	13	47	1.6
2005	20	57	16	15	76	2.0
2006	35	112	23	25	130	2.5
2007	22	68	19	15	181	3.3
2008	31	89	24	20	211	3.9
2009	25	56	18	21	289	4.8
2010	47	135	39	29	331	5.2
2011	37	118	31	29	442	6.1
2012	37	107	26	22	517	7.0
2013	45	149	38	27	650	7.9
2014	63	214	47	38	743	8.5
2015	53	202	46	30	901	9.4
2016	68	244	55	34	1268	10.5
2017	88	325	58	37	1515	11.4
2018	68	292	45	42	1707	12.7

[1] Total number of citations accumulated to date divided by the total number of articles published to date.

In general terms, we observed a growth trend in all of the variables analyzed, which indicates the development of this line of research. More than 45% of the total number of studies in the sample are concentrated in the last five years of the period analyzed. In order to confirm the growth of this field of study, the evolution of the number of articles on SI during the period of analysis was compared with all of the articles published on irrigation and all of the articles published on sustainability. Figure 2 shows the percentage of annual variation in the number of articles published in these lines of research. The average annual growth of the articles on irrigation was 1.6%, the one of articles on sustainability 3.8%, while that of articles on SI was 5.2%. This enabled us to confirm that SI is a line of study that is becoming increasingly more prominent within research in irrigation and in sustainability in general. These results agree with other works on water and sustainability [1,39,49].

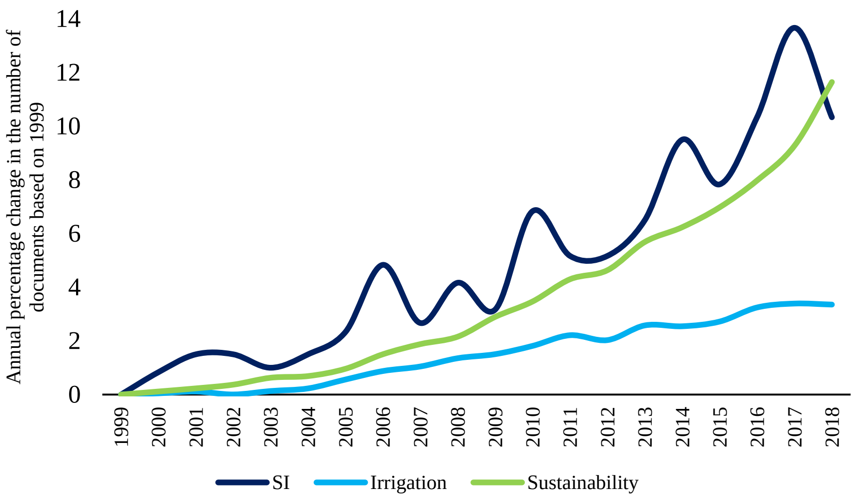

Figure 2. Comparative trends in irrigation, sustainability, and SI research.

With respect to the rest of the variables included in Table 1, the average number of authors per article doubled from two at the beginning of the period to four at the end. The number of journals in which articles on SI were published increased from six in 1999 to 45 in 2018. The number of countries also grew during the period analyzed (from five in 1999 to 42 in 2018). The annual number of references increased from 0.8 in 2000 to 12.7 in 2018.

3.2. Evolution of Research in SI by Subject Area

Figure 3 shows the evolution of the main subject areas into which the articles on SI included in the Scopus database were classified. It should be noted that an article may belong to more than one category. From the beginning of the period, the category in which the highest number of studies were classified was Environmental Sciences, which accounted for almost 65% of the total sample. The second largest block of studies was classified in the Agricultural and Biological Sciences category, with 44.3% of the total sample. In third place was the Social Sciences category with 21.1% of the articles. These three categories have dominated research on SI since the beginning of the studied period. However, in contrast to some previous works [37,39,48], our results revealed that over the last five years, the Earth and Planetary Sciences, Engineering, Energy, and Economics categories have begun to gain relevance, although none of them include more than 15% of the total articles in the sample. The Scopus classification distinguishes between the following categories: Business, Management, and Accounting; and Economics, Econometrics, and Finance, which also differ from Social Sciences. For the purpose of simplification, we grouped these two categories into only one and termed it "Economics".

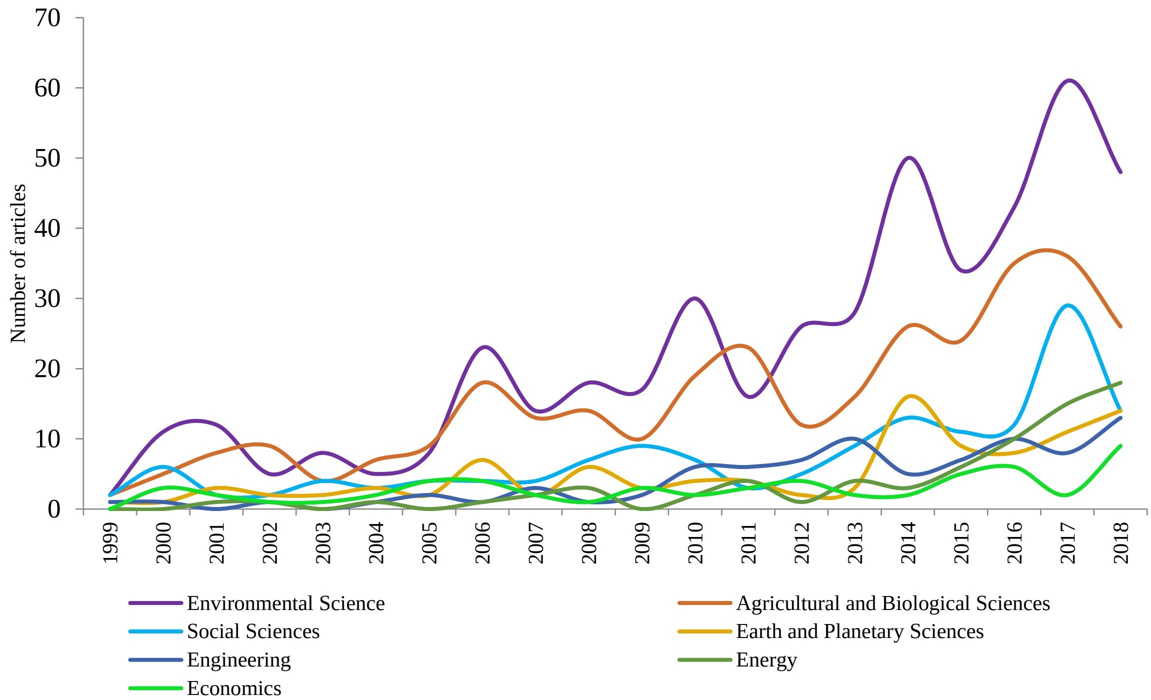

Figure 3. Comparative trends of subject categories related to SI research.

The keyword analysis revealed that there is a series of commonly used terms in research on SI, irrespective of the approach of the study. These terms include, among others, agriculture, alternative agriculture, climate change, crops, groundwater, irrigation system, salinity, sustainable development, water conservation, water management, water resources, water supply, water use, water use efficiency, and water quality. When we took the analysis beyond these terms, we identified a group of keywords used specifically by each discipline.

In the studies classified in the category of Environmental Sciences, there was an emphasis on the state of the soil (soils, soil moisture), aquifers, and surface water. With respect to processes, from the environmental approach, recycling and wastewater reclamation were prominent. In terms of methodology, the keywords that stood out were numerical model and decision making, particularly related to the management of the available water resources (water budget, water availability). With regard to the geographical dimension, China, the United States, and India were particularly prominent, as were the regions of Eurasia and Asia.

In the studies classified within the category of Agricultural and Biological Sciences, technical terms were predominant. Studies in this category mostly focused on soils and groundwater. There was particular emphasis on different types of crops (Triticum aestivum, Zea mays, fruit, Gossypium hirsutum, and rice) and irrigation processes (deficit irrigation, drainage, drip irrigation, leaching, waterlogging, agricultural irrigation). Furthermore, from the agronomic perspective, the environmental dimension was also considered (Environmental Impact). In these studies, China and the United States stood out, together with the regions of Africa and Asia.

The studies carried out from a Social Sciences approach had a more multidisciplinary perspective. They focused primarily on the stakeholders, water demands, and food security. However, technical concepts were also prominent, particularly those related to irrigation and water management (drip irrigation, sustainable water management), crops (Triticum aestivum), and economics (water economics). Unlike the over categories, land use was found to be one of the prominent subjects of this group of studies. A focus on management and decision making at different levels was also characteristic of these studies (governance approach, water planning, policy making, resource management, decision support system). With respect to geographical distribution, the United States, China, India, Spain, and Australia were among the most cited countries, and Asia, Europe and Africa stood out on a regional level.

Finally, the studies carried out based on an economic approach (Economic Sciences) were the most multidisciplinary, including technical, social, and environmental aspects. Among the main themes analyzed in these studies, we found food supply, food security, the development and innovation of irrigation systems (agricultural technology, irrigation performance) and management processes (integrated resource management, managed change, project management, strategic change, strategic management, strategic planning, decision making), and issues related to economic and social management (efficiency, investment, performance, economic and social effects) and the environment (environmental impact, environmental sustainability).

3.3. Most Relevant Journals in the Research on SI

Table 2 shows the main characteristics of the most prolific journals in the field of SI. The group of journals with the highest number of articles published on SI accounted for 25.7% of the total articles in the sample. This indicates that there is a high level of dispersion in terms of the journals that publish articles on this subject area. The leading journal in terms of the total number of articles published during the whole period analyzed was *Agricultural Water Management*, with a total of 52 articles on SI. This journal has the highest H index and the most citations of the journals with articles published in this area, and a Scimago journal rank (SJR) factor of 1.272. It published its first issue on this subject in 2001. Since then, it has remained among the top positions in terms of the number of articles published on SI, becoming the leader in 2014. The journal in second place was *Irrigation and Drainage*, with a total of 30 articles on SI. This journal published its first article on SI in 2001 and was the most prolific journal until 2005. It has the second highest H index, an average of 10.4 citations per article and an SJR index of 0.342. The third journal was *Sustainability*, with 17 articles on SI. This journal is among the most recently incorporated journals, as its first article on SI was published in 2013. However, in only five years, it rose to third position in terms of the number of articles for the whole of the period of study. It has an average of 3.8 citations per article, an H index of 6 and an SJR of 0.537. The journal with the highest average number of citations per article was *Science of the Total Environment* with 33.8; followed by the *Journal of Hydrology* with 31.5 and *Water Resources Management* with 29.4.

Table 2. Main characteristics of the most active journals related to SI research.

Journal	Articles	SJR [1]	H index [2]	Country	Citation	Average Citation [3]	1st Article	Last Article
Agricultural Water Management	52	1.272 (Q1)	21	Netherlands	1128	21.7	2001	2018
Irrigation and Drainage	30	0.342 (Q2)	10	USA	313	10.4	2001	2018
Sustainability	17	0.537 (Q2)	6	Switzerland	65	3.8	2013	2018
Water	15	0.634 (Q1)	8	Switzerland	129	8.6	2009	2018
Water Policy	11	0.461 (Q2)	6	UK	74	6.7	2005	2018
Water Resources Management	11	1.185 (Q1)	9	Netherlands	323	29.4	2000	2015
Acta Horticulturae	10	0.198 (Q3)	2	Belgium	17	1.7	2011	2018
Journal of Hydrology	10	1.832 (Q1)	8	Netherlands	315	31.5	2010	2017
Journal of Cleaner Production	9	1.467 (Q1)	5	Netherlands	49	5.4	2015	2018
Journal of Irrigation and Drainage Engineering	9	0.521 (Q2)	4	USA	47	5.2	2007	2017
Science of The Total Environment	9	1.546 (Q1)	6	Netherlands	304	33.8	2004	2018

[1] Scimago Journal Rank 2017; [2] only sample documents; [3] total number of citations divided by the total number of articles.

3.4. Most Relevant Countries in Research on SI

Table 3 shows the principle characteristics of the articles on SI from the most prolific countries. During the analyzed period, the United States was the leading country in research on SI in terms of the number of articles, with a total of 143. The country with the second highest number of articles was India, with a total of 74. This was followed by Australia with 67, Spain with 61, and Italy with 55. Due to the differences in terms of the size and economic development of the different countries, these data were analyzed to determine the number of articles per capita, measured as the number of articles per million inhabitants. Based on this variable, Australia was shown to be the most productive country with 2.7 articles per million inhabitants. This was followed by the Netherlands with 1.5, Spain with 1.3, Italy with 0.9, and the United Kingdom with 0.8. France was shown to be the country with the most citations per article, with 23.9, followed by the United Kingdom with 22.5, Iran with 21.9, the Netherlands with 18.6, and the United States with 18.1.

Table 3. Main characteristics of the most active countries related to SI research.

Country	Articles	Average per Capita Articles [1]	Citation	Average Citation [2]	H Index [3]	1st Article	Last Article	% of Cultivated Area Equipped for Irrigation (Ranking Countries) [4]
USA	143	0.439	2585	18.1	25	1999	2018	16.94 (72)
India	74	0.055	688	9.3	14	1999	2018	41.54 (38)
Australia	67	2.724	941	14.0	17	2000	2018	5.72 (110)
Spain	61	1.310	815	13.4	14	2004	2018	21.61 (64)
Italy	55	0.908	359	6.5	9	2002	2018	44.22 (35)
China	52	0.038	791	15.2	15	2004	2018	51.48 (28)
UK	51	0.772	1147	22.5	16	1999	2018	3.41 (126)
Germany	36	0.435	509	14.1	12	2004	2018	5.65 (111)
France	29	0.432	692	23.9	10	2000	2018	14.53 (82)
Japan	26	0.205	347	13.3	8	2001	2017	54.96 (25)
Netherlands	26	1.518	483	18.6	11	2001	2018	46.85 (31)
Brazil	22	0.105	163	7.4	6	2006	2018	5.79 (108)
Canada	22	0.599	179	8.1	8	2005	2018	2.44 (134)
Iran	19	0.234	416	21.9	8	2009	2018	51.88 (27)
South Africa	19	0.335	109	5.7	7	2002	2018	12.93 (83)

[1] Total number of articles per million inhabitants; [2] total number of citations divided by the total number of articles; [3] only sample documents; [4] FAO Aquastat (2019), last available data.

The percentage of cultivated area ready for irrigation per country has been included in the last column of the table, as well as the position they have in the world ranking regarding this variable. It can be stated that these countries do not occupy leading positions as far as irrigation-equipped cultivated land is concerned. From the available information about 177 countries, Japan is the country with the highest percentage of irrigation-equipped land surface—54.96%—, reaching the 25th place—followed by Iran with 51.88% (27th place), China with 51.48% (28th place), and Netherlands with 46.85% (31st place). However, some countries leading research on SI place themselves on lower positions within the irrigation-equipped cultivated surface ranking. This is the case for the USA with 16.94% (72nd place), Australia with 5.72% (110th place), or the UK with 3.41% (126th place).

Table 4 shows the principal variables related to the international collaboration of countries with the highest numbers of articles. The average percentage of articles carried out through international collaboration was 50.3%. The countries with the highest percentage of studies carried out in collaboration were Canada with 81.8%, France with 79.3%, Germany with 75.1%, the Netherlands with 65.4%, and China with 55.8%. The United States was found to have the largest collaboration network, with 33 different collaborators. In addition, similarly to Australia, this country forms part of the group of the main collaborators of 10 of the 15 countries in the table. These data reveal the global nature of research in this subject area, with very high percentages and extensive collaboration networks on a global level. The majority of the countries obtained a higher average number of citations per article when they worked in collaboration with other countries. The articles produced through collaboration obtained an average of 14.6 citations as opposed to 13.5 citations of noncollaborative articles. When comparing these results to those of related works on irrigation and water [37,39,48], it can be observed that studies on sustainability trigger a higher level of international cooperation.

Table 4. International collaboration of the most active countries related to SI research.

Country	Percentage of Collaboration [1]	Number of Collaborators	Main Collaborators	Average Citation	
				Collaboration [2]	Noncollaboration [3]
USA	45.5	33	China, Italy, Mexico, Canada, Sweden	23.1	13.9
India	21.6	15	USA, Ethiopia, France, UK, Australia	11.6	8.7
Australia	52.2	22	China, Canada, Spain, USA, Bangladesh	18.6	9.1
Spain	40.9	18	Portugal, Australia, Germany, Italy, Belgium	22.1	7.3
Italy	40.0	19	USA, Netherlands, Spain, France, South Africa	5.0	7.5
China	55.8	16	USA, Australia, Canada, Bangladesh, Germany	15.7	14.6
UK	47.1	28	India, Italy, Netherlands, Philippines, Spain	22.3	22.6
Germany	75.1	30	Uzbekistan, USA, Spain, Switzerland, Australia	15.6	9.9
France	79.3	21	India, USA, Australia, Belgium, Italy	19.1	42.2
Japan	38.5	9	Thailand, USA, Vietnam, Australia, Egypt	9.9	15.5
Netherlands	65.4	16	Italy, Australia, China, Germany, Pakistan	23.6	9.1
Brazil	31.8	7	Spain, USA, Argentina, Germany, Italy	14.7	4.0
Canada	81.8	13	Australia, China, USA, Denmark, India	9.2	3.3
Iran	26.3	4	Australia, USA, Germany, Netherlands	2.2	28.9
South Africa	52.6	13	Australia, Italy, Belgium, Bolivia, Denmark	6.2	5.2

[1] Number of articles made through international collaboration divided by the total number of articles; [2] number of citations obtained by articles made through international collaboration divided by the number of articles; [3] number of citations obtained for articles not made through international collaboration divided by the number of articles.

Figure 4 shows a network map of the collaborations carried out between countries, where the size of the circle represents the number of documents per country and the color corresponds to the cluster formed by the different groups of countries. Three clusters can be distinguished, led by the United States, Australia, and Spain in terms of the number of articles. The first (shown in blue) includes some of the most prolific countries, such as India, Italy, China, France, Japan, and the Netherlands, and others, such as Mexico, Egypt, and Bangladesh. Together with Australia, the second cluster (shown in red) includes Canada, Iran, South Africa, Sweden, Switzerland, Pakistan, Sri Lanka, and Uzbekistan. The group led by Spain (shown in green) includes some European countries, such as the United Kingdom, Germany, Belgium, Portugal, and Greece, as well as countries in the Mediterranean basin, such as Israel, Jordan, Morocco, and Turkey, and others, such as Brazil, Thailand, and New Zealand.

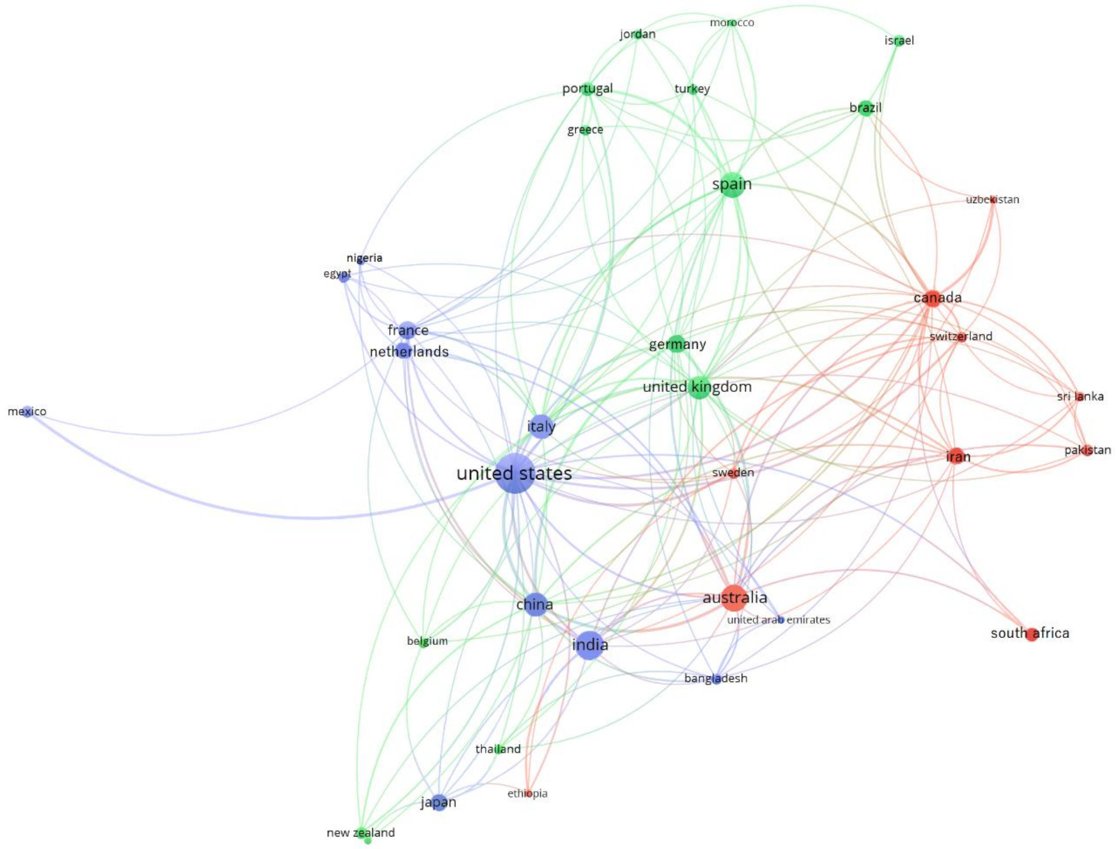

Figure 4. Main relationships between countries in SI research.

A keyword analysis was used to detect the preferences in the research conducted by the countries included in Table 4 (Table 5). We established that there is a group of terms that make up a general line from which the different specific topics are derived.

In the studies conducted in the United States, the central themes included food supply and food security (food-supply, food-security), the conservation of natural resources and environmental impacts (conservation-of-natural-resources, environmental-impact), and land use (land-use). Agronomic issues, such as crop evapotranspiration and productivity, were prominent. Both surface water and groundwater were studied with special emphasis on the availability of the resource, the water budget, the water table, and water stress (surface-water, water-budget, water-availability, water-table, water-stress). The term most used in relation to methodology was numerical model (numerical-model), and the term most used with regard to crops was Zea mays (Zea-mays). No noteworthy geographical terms other than the United States were identified.

Table 5. Main keywords of the most active countries related to SI research.

Country	Keywords
USA	crop-yield, surface-water, alternative-agriculture, numerical-model, food-security, water-budget, wastewater-reclamation, water-availability, food-supply, evapotranspiration, conservation-of-natural-resources, environmental-impact, water-table, water-stress, Zea-mays, land-use
India	optimization, irrigation-planning, water-table, waterlogging, drainage, Maharashtra, irrigation-projects, rice, arid-regions, ecosystems, fertilizers, nutrient, vegetables, waste-water, South-Asia, surface-water
Australia	Australasia, wastewater, irrigation-efficiency, Murray-Darling-basin, environmental-protection, evapotranspiration, food-supply, hydrogeology, runoff, water-availability, controlled-study, hydrology, water-treatment, rice, recycling, Canada
Spain	energy-efficiency, fruit, irrigation-networks, semiarid-region, profitability, southern-Europe, soil-moisture, deficit-irrigation, carbon-dioxide, drip-irrigation, water-economics, economic-analysis, water-productivity, decision-support-systems, energy-resources, stakeholder
Italy	deficit-irrigation, decision-support-system, southern-Europe, farms, fruit, orchard, Mediterranean-environment, forestry, stem-water-potential, crop-yield, dicotyledon, stomatal-conductance, water-stress, drainage, decision-making, environmental-impact
China	alternative-agriculture, Zea-mays, Triticum-aestivum, Xinjiang-Uygur, North-China-plain, decision-making, irrigation-district, evapotranspiration, environmental-protection, hydrological-modelling, ecology, landforms, soil-moisture, integrated-approach, water-availability, uncertainty
UK	alternative-agriculture, environmental-impact, water-treatment, drainage, Africa, environment, wastewater, cost-benefit-analysis, rice, wetland, recycling, runoff, drainage-and-irrigation, arid-regions, crop-yield, hydrocarbon
Germany	food-supply, Triticum-aestivum, Uzbekistan, alternative-agriculture, arid-region, fertilizer, oasis, climate-models, economic-and-social-effects, drip-irrigation, agricultural-intensification, food-security, leaching, common-pool-resource, cropping-system, greenhouse-gas
France	farming-system, stakeholder, groundwater-overexploitation, evapotranspiration, deficit-irrigation, decision-making, environmental-policy, governance-approach, surface-water, public-private-partnership, pricing-policy, water-economics, chemical-composition, dynamic-model, linear-programming, ecophysiological-responses
Japan	irrigation-development, water-users'-organization, rainfall, sustainable-rice-production, institutional-development, Triticum-aestivum, Zea-mays, water-policy, participatory-irrigation-management, saline-water-irrigation, soil-water-salinity, sorghum, electrical-conductivity, semiarid-region, sorghum-bicolour, drought
Netherlands	drainage, Triticum-aestivum, food-production, recirculations, well, groundwater-abstraction, agricultural-extension, smallholder, agricultural-development, food-supply, agricultural-management, decision-making, rain, alternative-agriculture, catchments, networking-system
Brazil	biofuel, expansion, water-availability, environmental-impact, bioenergy, biomass-power, Cerrado, sugar-cane, glycine-max, sustainable-production, Saccharum-officinarum, carbon-dioxide, chemistry, evapotranspiration, metabolism, rainwater
Canada	alternative-agriculture, water-policies, sensitivity-analysis, stochastic-programming, decision-making, environmental-protection, uncertainty-analysis, water-availability, water-stress, Gossypium-hirsutum, food-security, global-perspective, food-production, Triticum-aestivum, water-sharing, yield-response
Iran	crop-yield, cropping-pattern, economic-and-social-effects, rainfall, food-supply, Zea-mays, FAO, optimum-decision, surface-water-resources, recycling, genetic-algorithm, GHG-emission, irrigation-district, farmers-motivation, untreated-wastewater-irrigation, Bayesian-networks
South Africa	Sub-Saharan-Africa, wastewater, evapotranspiration, water-economics, drought, simulation, controlled-study, electric-conductivity, economic-and-social-effects, GIS, water-balance, computer-simulation, food-supply, project-management, mine-water, environmental-impact

The articles from India were found to place more emphasis on new alternative agriculture systems (alternative-agriculture) and the agricultural activity in arid areas (arid-regions) on an ecosystem level (ecosystems). Agronomic aspects such as the nutrition and fertilization of crops (fertilizers, nutrient) and their productivity (crop-yield, productivity) were also prominent. Both surface and groundwater were studied (surface-water), as was the planning and development of irrigation projects for optimizing the resource (irrigation-planning, irrigation-project, optimization), with particular emphasis on irrigation processes (drainage, waterlogging, water-table) and alternative water sources (wastewater). The term most used in relation to methodology was numerical model (numerical-model), and with regard to crops, the most used terms were rice and vegetables (rice, vegetables). Prominent geographical terms, such as the State of Maharashtra or the region of South Asia, were identified.

The studies conducted in Australia covered food supply (food-supply), runoff (runoff), and environmental protection (environmental-protection). Agronomic issues, such as crop evapotranspiration (evapotranspiration) and irrigation efficiency (irrigation-efficiency), were prominent. With respect to water resources, particular emphasis was placed on the availability of the resources, the water budget (water-availability, water-budget), and the use of alternative sources through recycling and wastewater treatment (wastewater, water-treatment, recycling). From a methodological point of view, the hydrological and geological approaches were prominent (hydrology, hydrogeology), as were controlled studies (controlled-study), and in terms of crops, the prominent term was rice (rice). Noteworthy geographical terms, such as the basin of the river Murray–Darling (Murray-Darling-basin), the region of Australasia and the country of Canada, were identified.

In the case of Spain, relevant topics were the management of the use of energy resources (energy-efficiency, energy-resources), the productivity of water (water-productivity), efficiency (efficiency), semiarid regions (semiarid-regions), and environmental protection (environmental-protection). Agronomic issues such as soil moisture (soil-moisture) were prominent, as were innovations in agricultural and irrigation systems (alternative-agriculture, irrigation-networks, drip-irrigation, deficit-irrigation) and irrigation efficiency (irrigation-efficiency). In terms of methodology, the economic approach was prominent (water-economics, economic-analysis, profitability), as was the social approach (stakeholders, decision-support-systems). With respect to crops, fruit was the most relevant term (fruit). Noteworthy geographical terms, such as the regions of Southern Europe and Eurasia (Southern-Europe, Europe, Eurasia), were identified.

The studies conducted in Italy were similar to those conducted in Spain. The main differences were found in certain agronomic terms related to crops (crop-yield, dicotyledon, stomatal-conductance, stem-water-potential) or irrigation (drainage, soil-moisture). The studies were carried out on a farm level (farms, orchard) and focused on the Mediterranean environment. In terms of methodology, the numerical models focused on decision making (decision-making) were noteworthy. With respect to crops, as well as fruit (fruit), Zea mays was also prominent. The central themes included water stress (water-stress), the environmental impact (environmental-impact), and forestry (forestry).

The articles conducted in China placed greater emphasis on environmental protection (environmental-protection), agricultural activity in arid regions (arid-regions), decision-making processes (decision-making), and issues at the district level (irrigation-district). Agronomic issues such as crop evapotranspiration (evapotranspiration) and crop productivity (crop-yield) were also prominent. With respect to water, the central theme was the level of water resources (water-level), while in the methodological area, hydrogeological models were prominent (hydrogeological-modelling). With respect to crops, rice, corn maize and wheat were found to be noteworthy (rice, Zea-mays, Triticum-aestivum, maize). The most prominent geographical terms were the regions of the North China Plain and Xinjiang Uygur.

The central themes in the studies conducted in the United Kingdom were crop yield (crop-yield); the environment and the assessment of the environmental impact (environment, environmental-impact), particularly in arid regions (arid-regions); and hydrocarbon (hydrocarbon). Processes related to water and irrigation, such as drainage (drainage), runoff (runoff), and the recycling of water in wetlands and wastewater treatment (water-treatment, wastewater, wetlands-recycling), stood out. The most prominent term related to methodology was cost benefit analysis (cost-benefit-analysis), and in terms of crops, the study of rice was predominant (rice). This may be due to the country's connection with Asian countries (Asia, Eurasia, and South Asia).

The articles conducted in Germany, as in the case of other countries, were conditioned by its collaborative ties with other nations. The main themes included food supply and food security (food-supply, food security); the new alternative agricultural systems and the intensification of agricultural activity (alternative-agriculture, agricultural-intensification); agricultural activity in arid regions (arid-regions, oasis); and the effects of agricultural activity on economic and social levels and environmental pollution (economic-and-social-effects, greenhouse-gas, particle-size). The prominent agronomic aspects were fertilizers (fertilizers), leaching (leaching), and drip irrigation (drip-irrigation). The most commonly used term with respect to methodology was related to the study of the effects of climate change: climate models (climate-models). Further fields of interest are common pool resources; and, with respect to crops, studies on wheat (Triticum-aestivum). One of Germany's principal collaborators was China, which is why this country appeared prominently among the keywords of German studies. Similarly, Uzbekistan is one of Germany's main trading partners and also appears among the keywords.

The studies carried out in France particularly focused on the policy and institutional dimension (environmental-policy, decision-making, governance-approach, public-private-partnership, pricing-policy). French studies analyzed the level of exploitation (farming-system) and contemplated the different agents involved (stakeholders). The priority issues included the overexploitation of groundwater and surface water (groundwater-overexploitation, surface-water); the chemical composition (chemical-composition); crop evapotranspiration (evapotranspiration) and the response to possible alterations (ecophysiological-responses); and deficit irrigation (deficit-irrigation). In terms of methodology, dynamic models and linear programming were prominent (dynamic-model, linear-programming), together with economic issues related to water (water-economics).

Studies conducted in Japan considered issues such as the development of irrigation, particularly through participative processes on both institutional and irrigation water user levels (irrigation-development, water-users'-organization, participatory-irrigation-management, institutional-development, water-policy). The Japanese studies analyzed aspects related to the salinity of irrigation water and soil (saline-water-irrigation, soil-water-salinity) and the electrical conductivity of water (electrical-conductivity). Water shortages due to drought, particularly in semiarid regions, were also found to be relevant issues (drought, semi-arid-region). The studies from this country analyzed the use of rainwater as a source for irrigation (rainfall). It is the country with the highest number of crops, and the study of the sustainable production of rice was found to be particularly relevant (sustainable-rice-production, Triticum-aestivum, Zea-mays, sorghum, sorghum-bicolour).

In the Netherlands, the primary topics identified were the management and development of agriculture, particularly towards the use of new alternative systems (agricultural-development, agricultural-management, alternative-agriculture), and there was special emphasis on the extension of agricultural practices (agricultural-extension). Other subject areas of many of this country's studies were the security and production of food (food-supply, food-production). The crop that is most studied was wheat (Triticum-aestivum). The articles focused on groundwater and rainwater with respect to water resources (well, groundwater-abstraction, rain), recirculation processes and network development (drainage, recirculations, networking-system) and the studies on the level of the basins were predominant (catchments). On a social level, the point of view of the small farmers (smallholders) was given special attention, particularly in relation to the decision-making processes (decision-making).

The studies conducted in Brazil contemplated the environmental impacts (environmental-impact), water availability (water-availability), and the expansion of the agricultural activity (agricultural-expansion). With respect to crop processes, evapotranspiration, metabolism, sustainable production, and carbon dioxide were prominent (carbon-dioxide, sustainable-production, evapotranspiration, metabolism). This country has published a large number of studies on the use of rainwater for irrigation (rainwater). Particularly noteworthy is the research on crops related to the use of biomass for different purposes (biofuel, bioenergy, biomass-power, sugar-cane, glycine-max, saccharum-officinarum). On a geographic level, studies in the region of Cerrado were predominant. Additionally, the most prominent methodological approach was found to be chemistry (chemistry).

In Canada, the most relevant themes were the new forms of agriculture (alternative-agriculture), environmental protection (environmental-protection), food security (food-security, food-production), and decision making (decision-making, water-policies). The global perspective of this line of research (global-perspective) was found to be noteworthy. From a methodological point of view, the sensitivity models, stochastic programming, and uncertainty analysis were prominent (sensitivity-analysis, stochastic-programming, uncertainty-analysis). The predominant terms with respect to water were water availability, water stress, and water sharing. With regard to crops, wheat and cotton stood out (Gossypium-hirsutum, Triticum-aestivum).

In the case of Iran, concern for the food supply was found to be prominent, despite its relationship with the FAO—Food and Agriculture Organization of the United Nations (food-supply, FAO, crop-yield). On a methodological level, genetic algorithms stood out (genetic-algorithm), together with processes for optimizing decisions (optimum-decision), and Bayesian networks (Bayesian-networks). The economic and social levels were represented through the motivation of farmers and the assessment of the economic and social effects (economic-and-social-effects, farmers-motivation). In the agronomic field, cropping patterns and the use of untreated wastewater were priority areas (cropping-pattern, untreated-wastewater-irrigation). In addition to wastewater, the combined integral use of surface water, recycled water, and rainwater for irrigation was prominent (rainfall, surface-water-resources, recycling).

Finally, the articles from South Africa were based on controlled studies, geographical information systems, and computer simulations (computer-simulation, simulation, controlled-study, GIS). The environmental impacts (environmental-impact), particularly those related to the use of mine water and wastewater (mine-water, wastewater); food supply (food-supply); project management (project-management); and the economic and social effects related to irrigation (economic-and-social-effects) were priority themes. With respect to the agronomic dimension, the evapotranspiration processes, drought, electric conductivity, and water balance stood out (evapotranspiration, drought, electric-conductivity, water-balance).

3.5. Most Relevant Institutions in Research on SI

Table 6 shows the main characteristics of the institutions with the highest number of articles on SI. The Chinese Academy of Sciences holds the first position with 14 articles. This institution has accumulated a total of 376 citations in these articles, with an average of 26.9 citations per article and an H index of 7. The institution with the second largest number of articles is the Commonwealth Scientific and Industrial Research Organisation—Land and Water (CSIRO Land and Water), with a total of 12 studies published. It has 212 citations, an average of 17.7 citations per article, and an H index of 8. In third place is the University of South Australia, with 10 articles. This institution has accumulated a total of 24 citations, an average of 2.4 citations per article, and an H index of 3. The institution with the largest number of citations and the highest average citations per article in its studies on SI is the University of Texas, with a total of 562 citations and 93.7 citations per article.

With respect to the international collaboration of institutions, the average percentage of articles carried out jointly was 46.6%. The institutions with the highest percentage of articles carried out in collaboration were the IHE Delft Institute for Water Education and the Universidade de Lisboa (University of Lisbon) with 83.3%. These two institutions were followed by the University of South Australia with 80.1%, Columbia University with 75.1%, China Agricultural University and Texas A and M University with 66.7%, and the University of California with 62.5%. The average number of citations of the jointly-written articles of the group of 22 institutions was 18.3 as opposed to 16.7 citations for the rest. The institutions with the highest number of citations in articles written in collaboration were the University of Texas, the University of California, and China Agricultural University.

Table 6. Main characteristics of the most active institutions related to SI research.

Institution	Country	Articles	Citation	Average Citation [1]	H Index [2]	Percentage of Collaboration [3]	Average Citation	
							Collaboration [4]	Noncollaboration [5]
Chinese Academy of Sciences	China	14	376	26.9	7	35.7	22.2	29.4
CSIRO Land and Water	Australia	12	212	17.7	8	41.7	21.2	15.1
University of South Australia	Australia	10	24	2.4	3	80.1	2.5	2.0
USDA Agricultural Research Service, Washington DC	USA	9	86	9.6	5	22.2	8.5	9.9
Wageningen University and Research Centre	Netherlands	9	117	13.0	6	55.6	16.2	9.0
Indian Institute of Technology Kharagpur	India	9	163	18.1	7	33.3	6.0	24.2
University of California, Riverside	USA	8	406	50.8	5	62.5	49.6	52.7
Columbia University in the City of New York	USA	8	97	12.1	5	75.1	13.2	9.0
Universidad de Cordoba	Spain	7	73	10.4	7	28.6	14.5	8.8
University of California, Davis	USA	7	87	12.4	3	42.9	26.0	2.3
Università degli Studi della Basilicata	Italy	7	16	2.3	3	14.3	0.0	2.7
Harran Üniversitesi	Turkey	6	77	12.8	3	0.0	0.0	12.8
University of Texas at Austin	USA	6	562	93.7	5	50.0	110.7	76.7
China Agricultural University	China	6	104	17.3	3	66.7	26.0	0.0
Universidad de Almeria	Spain	6	40	6.7	4	50.0	2.7	10.7
Texas A and M University	USA	6	42	7.0	3	66.7	5.5	10.0
IHE Delft Institute for Water Education	Netherlands	6	142	23.7	5	83.3	22.2	31.0
Ben-Gurion University of the Negev	Israel	6	66	11.0	6	16.7	6.0	12.0
Alma Mater Studiorum Università di Bologna	Italy	6	155	25.8	3	16.7	13.0	28.4
Commonwealth Scientific and Industrial Research Organization	Australia	6	92	15.3	3	50.0	16.7	14.0
Northwest A & F University	China	6	42	7.0	5	50.0	7.0	7.0
Universidade de Lisboa	Portugal	6	65	10.8	5	83.3	13.0	0.0

[1] The total number of citations divided by the total number of articles; [2] only sample documents; [3] the number of articles produced through international collaboration divided by the total number of articles; [4] the number of citations obtained by articles produced through international collaboration divided by the number of articles; [5] the number of citations obtained for articles not made through international collaboration divided by the number of articles.

3.6. Most Relevant Authors in Research on SI

Table 7 shows the main characteristics of the authors who have produced the highest numbers of articles on SI. A large number of authors published articles on SI within the study period, but the number of publications per author was small. The three authors with the most articles were Henning Bjornlund from the University of South Australia, Bartolomeo Dichio from the Università degli Studi della Basilicata, and Ajay Kumar R. Singh from the Indian Institute of Technology Kharagpur. Although they published the same number of articles, there were large differences in terms of the relevance of the publications of the different authors. Bjornlund has a total of 20 citations for his articles, Dichio 11, and Singh 145. James D. Oster of the University of California was the author with the largest number of citations with a total of 369; and the highest average number of citations per article with 73.8. He was followed by Mohammad Valipour from the Islamic Azad University, with a total of 366 citations and 73.2 per article. In third place was Dennis Wichelns from the Stockholm Environment Institute with 189 total citations and 37.8 citations per article. The author with the oldest publication was Bart Schultz of the IHE Delft Institute for Water Education, who published his first article in 2001. This author, who has written four articles on SI, has accumulated a total of 122 citations and published his last article on this subject in 2005. The authors who have made more recent contributions to this line of research are P. Amparo López-Jiménez and Modesto Pérez-Sánchez from the Universitat Politècnica de València.

Table 7. Major characteristics of the most active authors related to SI research.

Author	Articles	Citation	Average Citations [1]	H Index [2]	Country	Affiliation [3]	1st Article	Last Article
Bjornlund, Henning	6	20	3.3	2	Australia	University of South Australia	2010	2017
Dichio, Bartolomeo	6	11	1.8	2	Italy	Università degli Studi della Basilicata	2010	2018
Singh, Ajay Kumar R.	6	145	24.2	5	India	Indian Institute of Technology Kharagpur	2010	2017
Oster, James D.	5	369	73.8	3	USA	University of California	2003	2013
Scholz, Miklas	5	49	9.8	4	UK	University of Salford	2006	2018
Valipour, Mohammad	5	366	73.2	5	Iran	Islamic Azad University	2015	2017
Wichelns, Dennis	5	189	37.8	4	Sweden	Stockholm Environment Institute	2002	2014
Xiloyannis, Cristos	5	11	2.2	2	Italy	Università degli Studi della Basilicata	2010	2018
Annandale, John George	4	28	7.0	3	South Africa	Universiteit van Pretoria	2002	2017
Aydogdu, Mustafa Hakki	4	15	3.8	3	Turkey	Harran Üniversitesi	2015	2017
López-Jiménez, P. Amparo	4	50	12.5	3	Spain	Universitat Politècnica de València	2016	2018
Montanaro, Giuseppe	4	9	2.3	1	Italy	Università degli Studi della Basilicata	2010	2018
Pérez-Sánchez, Modesto	4	50	12.5	3	Spain	Universitat Politècnica de València	2016	2018
Schultz, Bart	4	122	30.5	4	Netherlands	IHE Delft Institute for Water Education	2001	2005
Vico, Giulia	4	46	11.5	3	Sweden	Swedish University of Agricultural Sciences	2011	2018

[1] Total number of citations divided by the total number of articles; [2] only sample documents; [3] last verified affiliation.

3.7. Main Issues in SI Research

The most relevant issues in SI research were determined based on the analysis of keywords. These issues included the concern for the state of natural resources, including water and soil and their conservation; the impact of agriculture on the environment and the consequences of climate change; the use of nonconventional water resources as an alternative for irrigation, including desalinated seawater, reused water, and harvested rainwater; the developments in innovation and technology for irrigation systems, particularly drip irrigation and deficit irrigation; and, finally, the improvements in the efficiency of the use of irrigation water. Below is an overview of the research carried out on these four priority issues. The weight of each priority research line has been established through the repetition number of the main keywords within each research line as the article average of the sample. It has to be taken into account that an article can be classified under different topics. For example, an article which analyzes water efficiency regarding nonconventional water resources shows as the most weighted research line climatic change, environmental impact, and natural resource conservation, with a 56.8% out of the total sample works; followed by water use efficiency with 42.5%, irrigation technology and innovation with 37.6%, and unconventional water resources with 31.2%.

3.7.1. Climatic Change, Environmental Impact, and Natural Resource Conservation

It is predicted that the consequences derived from global climate change will be alterations in precipitation cycles, triggering long-term droughts, more frequent and more intense extreme phenomena, and water supply imbalances [39,50]. Furthermore, these consequences will be reflected in agriculture by way of variations in soil humidity and in the evapotranspiration and runoff flows [14,51]. The United Nations report on the development of global water resources of 2015 estimates that there will be a drinking water shortage of 40% on a global level by the year 2030 [52].

Bad practice in agriculture produces a series of impacts that can have consequences on environmental, economic, and social levels. As well as water use, current irrigation agriculture requires the addition of fertilizers and other chemical products [53]. When the use of chemical products is incomplete or inefficient or when excessive water is applied, the resulting filtration ends up in drainage systems or in the groundwater recharge areas under the cultivated land [54]. The most deteriorated ecosystems currently include the majority of the groundwater bodies on a global scale. These water resources have enabled the development of agricultural activity in arid and semiarid regions and also in more humid regions where there are mismatches between precipitation and the needs of the crops [55]. In recent decades, the intensification of agriculture has given rise to a fall in piezometric levels, the development of salinization processes, seawater intrusion, and pollution by agricultural nitrates, among other effects [23].

Due to the estimated increase in the amount of fresh water required to meet the future irrigation demands, a drastic reduction in biodiversity is expected to take place, together with an increase in the salinity or flooding of soil, a loss in the flow of complementary services provided by the ecosystems, and the degradation of water sources and ecosystems in general [56,57]. On a social level, an increase in the vulnerability and inequality between users is expected [58,59].

In order to mitigate these adverse effects and to contribute to the conservation of the ecosystems, important legislation is currently being developed on a global level. Among the objectives established by the United Nations for the Horizon 2030 on Sustainable Development is one specifically related to water and sanitation (ODS 6), which addresses aspects ranging from water shortage to water use efficiency [60]. The Horizon 2020 Plan of the European Parliament includes the requirement for sustainable production in agricultural systems [61]. Many countries, including the United States, China, India, and Costa Rica, have consolidated payment systems for environmental services provided by agricultural ecosystems with the objective of conserving water resources in good condition.

3.7.2. Unconventional Water Resources

The current scenario is one in which so-called conventional water sources are being exhausted and degraded in large parts of the world. These water sources include both surface water (rivers, lakes, reservoirs) and groundwater (aquifers). The principal option for increasing the water supply for irrigation consists of using alternative sources, also called nonconventional water sources [23]. These other sources include the reuse of urban and industrial water, the desalination of seawater, and rainwater harvesting. In recent years, water from nontraditional sources has become a competitive option in the supply of quality water for irrigation, particularly in arid and semiarid regions [62] The use of these types of resources has a series of advantages—two in particular. First, the contribution of these new water sources represents an increase in the supply of the resource, which is capable of satisfying the growing demand of the different sectors (urban supply, agricultural activity, tourism sector, industrial sector, and environmental requirements) [63]. Second, the use of water from alternative sources should serve to diminish the use of traditional water sources so that the state of deterioration of the wetlands, rivers, and aquifers can be restored or at least alleviated [64]. If these two advantages are to be efficient, they have to be accompanied by demand control. In addition to these two principal functions, the use of nonconventional water resources gives rise to other advantages. They provide a greater reliability in the supply, they supply higher quality water, they can generate increases in crop yields, they contribute to ensuring the stability of agricultural incomes, and they can have positive effects on seawater intrusion processes in the aquifers [65–67].

The use of each of these alternatives also gives rise to a series of limitations and disadvantages. Evidently, the construction of seawater desalination plants is only feasible in coastal areas. A wastewater treatment plant requires a volume of a large enough size for the facility to be viable [64]. Therefore, the use of this resource is not possible in areas where the activities generating wastewater (population nuclei, industrial facilities, livestock farms, etc.) do not have sufficient water use [63]. Thus, despite water reuse being the ideal way of maintaining continuous use of the resource, this type of facility is not appropriate for many rural areas where the population is dispersed. The main problem of rainwater harvesting systems is the low volume of water that can be supplied in comparison with the demand [67]. Furthermore, the seasonality of rain in many regions means that the water must be stored for long periods of time for use when needed. To these limitations we must also add the high cost of water derived through these systems. The installation costs are usually very high, and we must also take into account the cost of production. In the case of desalination and reuse, these costs usually establish a price for water that is much higher than the price of conventional resources [68]. This means that many farmers throughout the world are not willing to pay the price of the water unless there is no alternative available. Studies have been carried out on experience with the use of desalinated seawater, reused water or harvested rainwater all over the world [69–75].

3.7.3. Irrigation Technology and Innovation

Irrigation technology has evolved continuously over the last few decades. Flood irrigation, sprinkler irrigation, furrow irrigation, and drip irrigation are some of the methods that have emerged, and their advantages and disadvantages have been studied with respect to different types of crops, soils, and climatic conditions. New technologies have given rise to the development of comprehensive automated systems that combine the use of tensiometers, lysimeters, software applications, and even geographical information systems. However, drip irrigation and deficit irrigation are the terms that appear among the most used keywords.

De Wrachienb et al. [76] date the beginning of drip irrigation systems to the 1940s in Australia. The development of this system came about after the emergence of polypropylene tubes. It was not until two decades later that this system was improved in Israel, from where it was exported all over the world. Currently, thanks to automation and the use of microcontrollers, sensors, and integrated systems, this method has been perfected, and the drip irrigation system is now considerably more advantageous than traditional systems such as flood irrigation or sprinklers [77–79]. The main contribution of this system is that it enables a substantial saving in the use of water for irrigation, which enables the development or expansion of agricultural activity in arid and semiarid regions, where it would not be possible otherwise [80,81]. Another advantage is that it can prevent evaporation, as it supplies water directly to the roots of plants [82]. Different studies show that the use of drip irrigation increases the marketable yield and quality of crops and stabilizes production when deficit irrigation is used and that fertigation through drip irrigation helps to reduce the use of fertilizers and, therefore, the risk of pollution due to leachate [80,83]. Salvador and Aragüés [84] analyzed the advantages and disadvantages of the use of underground drip irrigation systems. They demonstrated their usefulness, profitability, and sustainability and indicated that the design, handling, and maintenance of this system, together with the quality of the irrigation water and type of soil, are fundamental aspects that determine their sustainability. On the other hand, Puy et al. [85] indicated that this type of system can have harmful consequences in terms of the degradation of the soil or the production of greenhouse gas emissions.

Deficit irrigation was introduced as a measure to limit the vegetative growth of crops [86]. This irrigation technique has been fully developed, and it is used extensively [87]. This method has been used with both drip irrigation and microsprinkling on different crops and can be combined with remote sensing technology or infrared techniques to produce significant water savings while crop yields remain unaffected. Du et al. [88] analyzed the use of deficit irrigation as a sustainable strategy for managing water resources in agriculture for food security in China. These authors concluded that the current understanding of physiological processes enables the deficit irrigation methods to be adjusted to different crops and environments in order to increase water use efficiency and the yield and quality of crops. Many studies have been carried out on this subject area [89–93].

Though many authors support drip irrigation as a sustainability measure, some recent studies question it. Perry et al. [94] confirm the "zero-sum game" hypothesis which argues that the impact of high-technology watering in a farm increases the demand of local water and land production at the expense of water availability and production in other places. Furthermore, due to the advantageous effects of drip irrigation, it makes water more affordable and, at the time, it allows irrigating larger areas, obtaining greater profits, and shift to more valuable crops. The most foreseeable impact of water efficiency improvement will be the increase of current water demands. In this sense, water scarcity would remain difficult to manage. Paul et al. [95], in their review of the rebound effects on the management of land and cultivation soils, found evidence for the presence of rebound effects and the Jevons paradox, together with productivity increases and efficiency of irrigation water due to technological innovations. Further studies agree with these results [96,97].

3.7.4. Water Use Efficiency

All of these innovations have the objective of improving water use efficiency for irrigation. In the year 2000, Kofi Annan, the Secretary General of the United Nations, proposed a "Blue Revolution in Agriculture" that was proposed to be capable of increasing productivity per unit of water. This strategy became known by the slogan "more crop per drop" [24]. According to Yang [98], obtaining the ideal water efficiency for irrigating crops involves the reduction of losses caused by evaporation, runoff, and underground draining while increasing production. Zhang et al. [26] indicated that the use of technology to save irrigation water not only saves water and increases production but also improves the nutritional value of agricultural products and guarantees food safety by improving the environmental conditions. Water use efficiency in agriculture generally implies a reduction in water use to meet a specific production objective or to increase the production of a specific water supply [99]. The aim of improving water use efficiency is to increase food production, boost financial gains, and guarantee the supply of ecosystem services at lower social and environmental costs per unit of water used [100,101]. The practices used to achieve this objective include rainwater harvesting, complementary irrigation, deficit irrigation, and the use of precision irrigation techniques and practices to conserve groundwater [24,102]. The priority areas where it is possible to significantly increase the productivity of water include areas with a high level of poverty and a low level of water productivity; areas with physical water shortage, where competition for water is high; areas with limited development of water resources, where the high yields of additional water have a considerable impact; and areas with degraded ecosystems driven by water, such as depleting water tables and dried-up rivers [103,104].

Among the different improvements developed over the last few decades, the use of drip irrigation has been fundamental in the improvement of water use efficiency and saving. Different studies have shown that drip irrigation has a water-saving potential of between 18% and 75%. According to Narayanamoorthy [82], drip irrigation saves an average of 25 to 75% of water compared to flood irrigation. Similar results were found, although with different percentages, in studies by Ibragimov et al. [105], Maisiri et al. [106], Yazar et al. [107], or Peterson and Ding [108], Abdulai et al. [109], Cremades et al. [110], and Jalota et al. [111].

4. Conclusions

This study presented the dynamics of global research in sustainable irrigation in agriculture over the last two decades, the main agents promoting it, and the topics that have received the most attention. The main concerns stated in the Introduction section related to the improvement of irrigation water use in order to increase food production, the world overexploitation of water resources, and the effects of global climate change. Our analysis verified how these questions are addressed by countries taking into account interdisciplinary approaches, and it also proved how these questions are mirrored in the main research lines on SI.

The results of the analysis of the principal variables revealed that the study of sustainable irrigation has grown in recent years in all of the variables considered: articles, authors, journals, institutions, and countries. Despite the fact that the growth trend in this topic is higher than that of general research in irrigation, an even greater research effort using a sustainability-based approach is required to further knowledge in this area. Traditionally, studies on sustainability have focused on one of the areas of which it is composed, namely, the environmental, social or economic dimensions. In the study of irrigation, the dominant area has been the environmental dimension, far more than the social or economic perspectives. The studies that analyzed just one of these dimensions provide highly useful information, but this information is only partial. It is necessary to integrate the three aspects of sustainability in order to gain full knowledge of the feasibility of certain practices, not only in terms of their environmental impacts but also with respect to income generation for farmers and the wellbeing of the community.

The keyword study revealed the existence of diversity between studies carried out using specific approaches and in different countries. In general, the study of environmental impacts and climate change, water availability, the improvement in efficiency, sustainable development, food supply, and the conservation of water bodies, particularly aquifers that have deteriorated, are common themes. However, certain practices, such as deficit irrigation or drip irrigation and aspects related to energy consumption and certain crops, are priority issues for particular countries. The methodological approaches used and the tools applied are other points of differentiation of the research carried out by each country. The keyword analysis showed four main research lines on SI: climatic change, environmental impact, and natural resource conservation; unconventional water resources; irrigation technology and innovation; and water use efficiency. Due to the large number of analyzed documents and the scope of this work, an in-depth content analysis per topic has not been undertaken. It will be highly interesting for future studies in order to provide more detailed information of these four specific topics.

As a final conclusion, we believe that certain aspects of the research on sustainable irrigation in agriculture in each of the dimensions of sustainability should be promoted. From a technical point of view, innovation and technology have furthered the development of irrigation systems and new available water sources that can contribute to improving the efficiency of water use and the sustainability of rural areas, particularly agricultural activity in arid regions. However, effort should be made to make this technology accessible, as its cost is economically unfeasible for small-scale agriculture in many countries. New water sources, such as those derived from desalination, reuse and rainwater harvesting systems, are very expensive for farmers compared to traditional sources. The production processes for desalination and reuse should be improved, particularly with respect to energy consumption in order to bring down the final price of the water. Furthermore, although the use of these nonconventional water resources has proved to have a series of advantages for the crops and the soil, this knowledge has not been transmitted to the farmers, and therefore, they are still reluctant to use it for irrigation. Greater effort should be made to communicate the results of the research to society. Finally, greater knowledge of the environmental impacts of irrigation-related practices in different areas on plot, district, basin and regional levels is needed. Water bodies are connected to each other, so certain practices that generate a small impact on river source areas can have a multiplying effect and be experienced in the underground bodies of coastal areas.

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