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Review

Sustainable Water Use in Agriculture: A Review of Worldwide Research

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Abstract: Sustainability of water use in agriculture is a line of research that has gained in importance worldwide. The present study reviewed 25 years of international research on sustainable water use in agriculture. A bibliometric analysis was developed to sample 2084 articles. Results indicate exponential growth in the number of articles published per year, with research in this field having acquired a global scale. Environmental Science and Agricultural and Biological Sciences are the main categories. Three journals—Agricultural Water Management, Water Resources Management and Nongye Gongcheng Xuebao Agricultural Engineering—published the most of the articles. China, the U.S., Australia, India and Germany produced the most research. The three institutions that published the most articles were all Chinese (Chinese Academy of Sciences, China Agricultural University and Northwest A&F University). The most cited authors were Ridoutt, Hoekstra and Zhang. The keywords most frequently used include: water-use, irrigation, water-management, water-supply, and sustainability. A network map shows three clusters that focus on the environmental, agronomic and management aspects. The findings of this study can assist researchers in this field by providing an overview of research on the sustainability of hydric resources.

Keywords: sustainability; water use; agriculture; bibliometric analysis; Scopus

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1. Introduction

Water forms the basis of wetland and marine ecosystems. Water is essential for other ecosystems, particularly agricultural ecosystems. Agricultural ecosystems are the main consumer of hydric resources worldwide [1,2] as they use approximately 80% of hydric resources, with regional variation derived from economic development and climatology [3,4]. In developed countries, water consumption for irrigation uses approximately 60% of available hydric resources, while this can reach 90% in developing countries [5]. The estimated 275 million hectares worldwide that is devoted to irrigated crops increases by 1.3% per annum [4]. This accounts for only 23% of cultivated land, although 45% of total food production is obtained from this type of crop [6–8]. To meet food demand by 2050, worldwide production needs to increase by 70% [9]. This projected increase in world food production implies an extension of cultivated land, an intensification of supplies under current cultivated land or the search for integrated management systems [10]. In low production scenarios, an increase of 53% in the consumption of hydric resources and an increase of 38% in worldwide cultivated land would be necessary to satisfy the target for the food demand by 2050 [11]. Increases in irrigation water consumption to meet those food demands are estimated to be 50% in developing countries and 16% in developed countries [12]. Intensification in water consumption can cause biodiversity loss; soil salinization; soil flooding; loss of complementary services; inequality between users; increases in vulnerability; and the deterioration of water sources and ecosystems [13–15]. Global climate change threatens the availability of hydric resources and agricultural systems. Change is predicted in precipitation cycles; increased frequency and intensity of extreme phenomena; and variations in soil moisture, evapotranspiration flows and surface runoff [16,17].

To deal with these challenges, many studies apply "sustainability science" (defined as "a discipline that points the way towards a sustainable society" [18] and "aimed at understanding the fundamental character of interactions between natural, human, and social systems, covers a wide range of academic disciplines" ([19], p. 116)) to the development of agricultural systems and sustainable water use [20]. The concept of sustainable development was first applied to ecosystems at the end of the twentieth century and was defined as the ability of ecosystems to maintain continuous service flows despite environmental, economic and social alterations [21]. Since then, many institutions and initiatives have included sustainability proposals in their objectives, reports and declarations. For example, the 2030 Agenda for Sustainable Development of United Nations includes 17 sustainable development goals among which there is one specific goal for clean water and sanitation (SDG 6) as well as other goals focusing on water scarcity to water use efficiency [22]. Furthermore, in the Horizon 2020 research and innovation program, the European Parliament introduced the requirement of sustainable production [23].

Before the focus on sustainable water use in agriculture, the concept of sustainability was progressively applied to different environmental, biophysical and agronomic fields. With reference to hydric resources, sustainability was defined in 1999 as the set of systems designed and managed with the purpose of satisfying the current and future objectives of society, without prejudice of environmental, ecological and hydrologic integrity [24]. In terms of agriculture, sustainability is focused on the development of safe practices that do not damage the environment [25]. When applied to the management of hydric resources in agriculture, sustainability is viewed as the set of practices that increase crop production while minimizing water losses [26]. The objectives of sustainable management of hydric resources in agriculture consider the continuity of the agrarian system from a physical-biological perspective, economic efficiency in the use of resources and social participation in decision-making processes [27]. A global field of research has emerged using this conceptual framework, generating a volume of literature on sustainable water use in agriculture (SWUA) that is relevant to scientists and stakeholders. However, there has been no analysis on the dynamics of world research on SWUA until now.

The research objective in this paper is a quantitative analysis on the dynamics of global SWUA research in the last 25 years. Bibliometric methods were employed to achieve this objective. Bibliometric analysis is used for identifying, organizing and analyzing the main elements of a research topic [28]. This analysis used mapping techniques to represent the bibliographic information available in the different database and determine the trends of a research field derived from statistical and mathematical methods [29,30]. The obtained results are useful for experts when introducing and evaluating scientific activity within a field of study as well as for analysts and managers in the decision-making process [31,32]. The methodology highlights the most productive agents in a research field, such as authors, institutions or countries [33], which identifies the driving forces in a field of study. Furthermore, through the use of different tools, the collaborative relationships between different productive agents can be established [19]. The bibliometric method is employed in Engineering, Medicine, Energy, Management and Biology. In the specific case of sustainability research, different bibliometric studies have been used for analysis, such as sustainable development at national and institutional levels [34]; sustainability and innovation in the car industry [28]; energy efficiency and sustainability in public buildings [35]; and interdisciplinarity of research on sustainability [36].

2. Methodology

The Scopus database was used to develop the bibliometric analysis. Scopus is the world's largest abstract and citation database of peer-reviewed research literature, which includes the most cited journals in each field of study. It is comprised of approximately 15,000 publications, 265 million webpages and 18 million patents [28]. Therefore, Scopus guarantees the representation of the final sample of documents within a field of study and the quality and originality of the data [37]. Scopus provides a wide variety of data on each of the publications, allowing the comparison of different analysis and the downloading of useful information for the analysis process in different formats [38]. Recent bibliometric studies have used the Scopus database [35,39–41].

To select the sample of articles analyzed in this study, a search was performed in January 2018 using the following terms: (TITLE-ABS-KEY ("water use" OR "water-use" OR "use of water"); AND TITLE-ABS-KEY (sustainability OR sustainable); AND TITLE-ABS-KEY (irrigation OR agricultur* OR farm* OR crop* OR agroecosystem)). Searches were limited to the period of 1993–2017. In the final sample, documents without a rigorous review process were rejected, such as working documents, books and conference papers [42]. Review articles were excluded to avoid duplication in the sample [43]. The final sample contained 2084 articles. The variables analyzed were: publication year of articles; categories; journals; countries; institutions; authors; and keywords.

Bibliometric studies distinguish three types of indicators [32]: quantity indicators that refer to productivity; quality indicators that refer to impact of publications; and structural indicators that measure the connections established between the different agents (authors, institutions and countries). In this study, these three types of indicators were analyzed. In addition to the different counts to measure the productivity of authors, institutions and countries, different indicators used to measure research impact were the number of citations; the H index; and the SCImago Journal Rank (SJR) impact factor.

The analysis was completed with networking maps to provide values for international collaboration and the hotspots trends for this field of study. The networking map tools reveal the collaboration links established between different agents involved in a field of study. In this work, we used VOSviewer (version 1.6.5., Leiden University, Leiden, The Netherlands) to show the international collaboration between the different countries and the research trends through keywords. VOSviewer is a software tool for the processing of keywords and the grouping analysis used for the visualization of topographic network maps through a coincidence matrix, which allows grouping by co-authorship and by co-occurrence [44]. VOSviewer is widely used for showing maps of global scientific collaboration [28,45–48].

3. Results and Discussion

3.1. Evolution of Main Variables

The analysis of the number of articles published during 1993–2017 proves that research on SWUA has attracted increased attention throughout the years (Table 1). In particular, the number of articles published (A) grew from 4 in 1993 to 267 in 2017. Figure 1 shows how the number of articles published has grown exponentially within this thematic field. Figure 2 has been created in order to compare the publication trends of articles versing on water as a general topic and articles specifically studying SWUA. Logarithms have been applied to both series for homogenization purposes. The average rate of cumulative growth has been calculated. Results show that published articles on water have increased at an annual average rate of 6.14%, whereas the SWUA studies achieve a rate of 19.13%. These data highlight the fact that the publication increase on SWUA is superior to the one of water as a general theme. The growing interest in this field is also shown by the increase in the number of authors, journals and countries. The number of authors (AU) increased from 4 in 1993 to 1110 in 2017. The number of journals (J) increased from 3 to 147. The number of countries (C) increased from 3 to 69. The participation of 6170 authors, 597 journals and 115 countries in the publication of the 2084 articles included in the sample shows the growth of this field of study, demonstrating that it has become an important global issue. The number of references (NR) included in the articles expanded. In 1994, the number of references was 120, while this was 11,773 in 2017, which resulted in the average number of references per article increasing from 20.1 to 44.1. The total number of citations accumulated (TC) grew from 1 in 1994 to 5638 in 2017, which resulted in an increase in the average number of citations per article (CTC/CA) from 0.1 to 15.4.

Table 1. Evolution of the main characteristics of the articles.

Year	A	AU	J	C	NR	NR/A	TC	CTC/CA
1993	4	4	3	3	ND	ND	0	0.0
1994	6	9	5	4	120	20.1	1	0.1
1995	7	17	6	6	231	33.0	6	0.4
1996	11	17	10	8	126	11.5	8	0.5
1997	18	46	14	14	456	25.3	21	0.8
1998	14	34	13	11	300	21.4	38	1.2
1999	25	61	14	14	863	34.5	61	1.6
2000	17	43	17	13	462	27.2	82	2.1
2001	38	114	26	19	998	26.3	107	2.3
2002	26	75	22	12	889	34.2	192	3.1
2003	50	152	37	29	1177	23.5	253	3.6
2004	37	113	27	25	1046	28.3	268	4.1
2005	40	119	33	24	975	24.4	364	4.8
2006	57	202	46	21	1467	25.7	491	5.4
2007	76	244	54	35	2267	29.8	620	5.9
2008	82	258	56	34	2473	30.2	809	6.5
2009	112	389	79	38	4079	36.4	1086	7.1
2010	127	435	84	46	4307	33.9	1420	7.8
2011	140	523	94	48	5312	37.9	2015	8.8
2012	138	493	89	49	4889	35.4	2365	10.0
2013	172	694	110	55	7183	41.8	3106	11.1
2014	196	756	137	49	7831	40.0	3773	12.3
2015	210	867	116	56	8517	40.6	4262	13.3
2016	214	910	126	59	9273	43.3	5117	14.6
2017	267	1110	147	69	11,773	44.1	5638	15.4

A: The annual number of total articles; AU: the annual number of authors; J: the annual number of journals; C: the annual number of countries; NR: the number of references in total articles; NR/A: the annual number of references per article; TC: the annual number of citations in cumulative articles; CTC/CA: annual total citation per cumulative article.

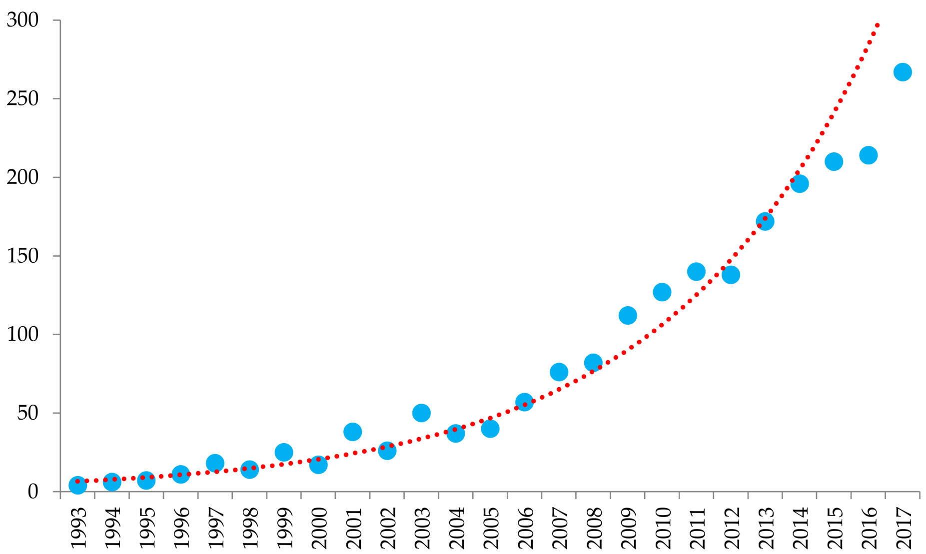

Figure 1. Trend in the number of articles.

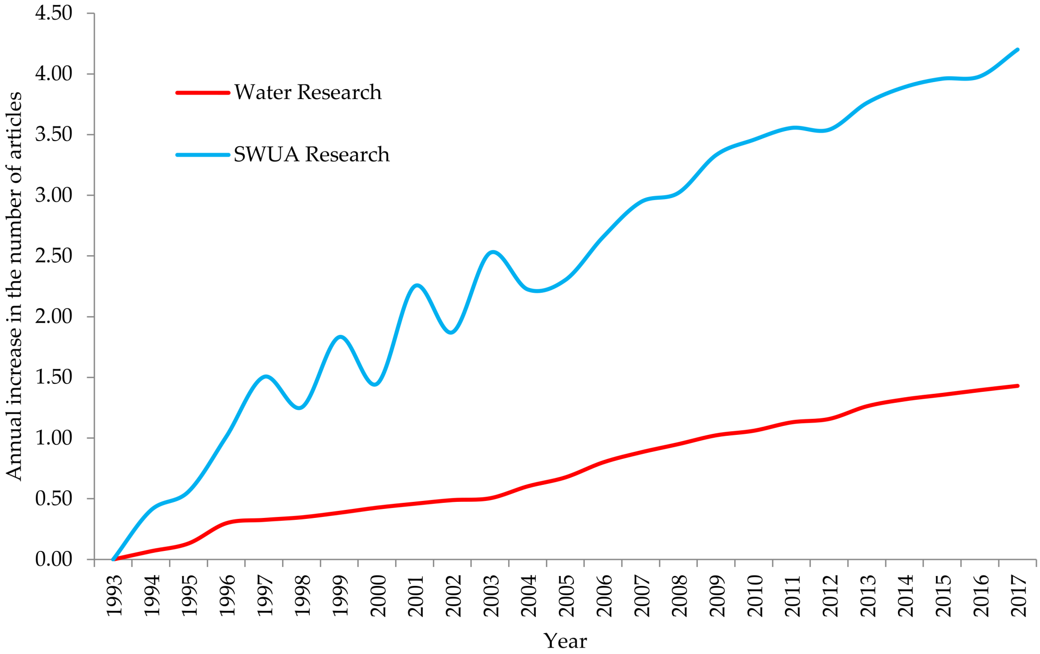

Figure 2. Comparative trends in the number of articles of Water and Sustainable Water Use in Agriculture SWUA research.

3.2. Thematic Areas and Journals

The articles published on SWUA were classified in 25 different categories, although an article can be simultaneously classified into different thematic areas. During the entire study period, the main categories were Environmental Sciences as well as Agricultural and Biological Sciences, which published 61.2% and 50.5% of the total number of published articles, respectively. This was followed by Earth and Planetary Sciences with 18.3%, Social Sciences with 14.5%, Engineering with 10.8% and Energy with 7%. Sustainability is an inherently multidisciplinary concept, which needs the intervention of Natural and Social Sciences for its analysis [1,49]. The Social Sciences category only included 14.5% of the total number of articles of the sample, while Economics, Econometrics and Finance represented 2.7%. Business, Management and Accounting represented 2.6%, Multidisciplinary 1.2% and Decision Sciences 0.6%. Figure 3 shows the evolution of the main subject areas according to the Scopus classification for the period of 1993–2017.

Table 2 shows the most productive journals for SWUA research. In these journals, the different indicators related with production and impact are displayed. This group of journals accumulated 27.1% of the total of articles published, indicating that a wide variety of journals publish articles on SWUA. The journal with the highest number of articles published in this research field was Agricultural Water Management, with a total of 159 articles. Since the beginning of the period chosen, this journal led the ranking. There is a group of journals that was published on this field recently (they published their first article on SWUA in 2011–2013). Nevertheless, they were first in terms of the most productive journals. For example, the journal Sustainability joined the SWUA publications most recently, but achieved the seventh position in the entire period and the third position in the last five-year period (2013–2017), thus surpassing journals with a longer history of SWUA research.

With respect to impact indicators, Agricultural Water Management is the journal that accumulated the highest total number of citations of 4367, followed by Agriculture Ecosystems and Environment with 1101, Water Resources Management with 1020 and Field Crops Research with 942. The journals with the highest number of citations per article are Agriculture Ecosystems and Environment with 45.9, Agricultural Water Management with 27.5, Field Crops Research with 26.2 and Journal of

Environmental Management with 25.8. As the H index is conditioned by the number of articles, the comparison between some of these journals according to this index does highlight interesting cases, although there is no clarification. Despite publishing a relatively high volume of articles, journals that joined this thematic area more recently have not accumulated enough citations to increase their H index yet, as an article will not generate a high number of citations until some years after publication. This is the case for journals such as Sustainability, Water or Science of the Total Environment. However, there are journals with a high number of articles and higher tradition in this topic that also showed relatively reduced indexes. This is the case for journals, such as Wit Transactions on Ecology and the Environment, Shengtai Xuebao and Irrigation and Drainage. With respect to the SJR index, the most important publication is the Journal of Hydrology, followed by Science of the Total Environment, Journal of Cleaner Production as well as Agriculture, Ecosystem and Environment. The journals in which more articles on SWUA were published were high quality, as all of them occupied the first and second quartile of their categories within the SJR, with the exception of one journal.

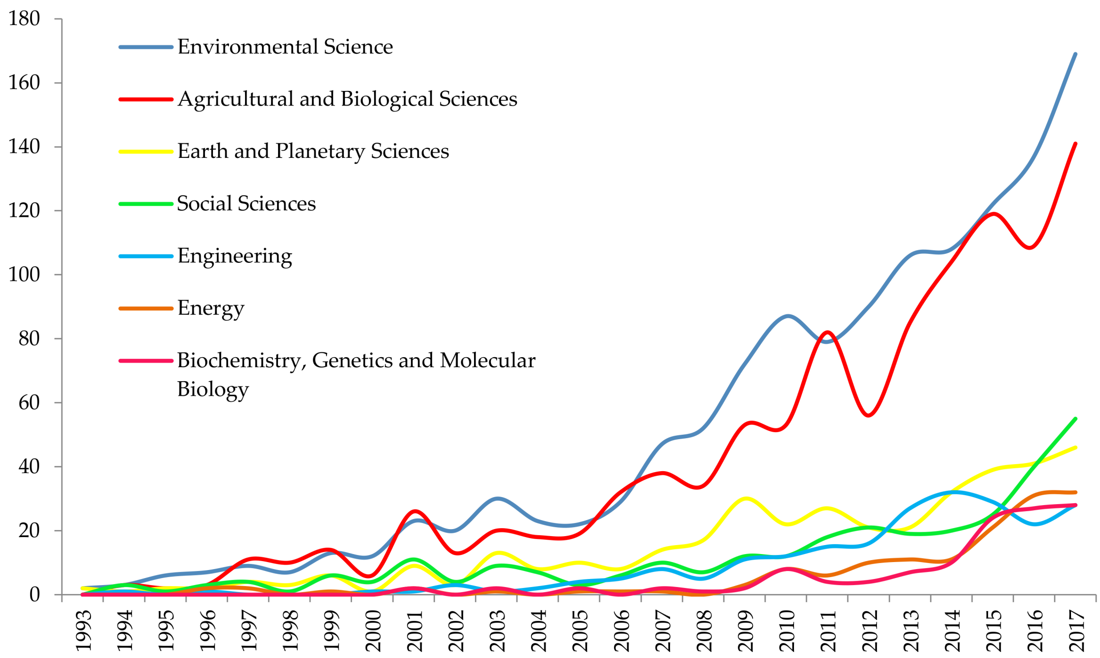

Figure 3. Evolution of the main subject areas.

Regarding the group composition of journals that publish most on SWUA, it is interesting to point out that they come from very different theme categories. We can find journals devoted to agriculture, water, management and ecology. This diversity lies in the multidisciplinary character of the water sustainability study in agriculture. The concepts of efficiency and ecosystemic services are tightly linked to the sustainable management of water for irrigation. In fact, it is necessary to improve efficiency in order to reach sustainability. Moreover, efficiency should guarantee services beyond food supply and assure erosion prevention, CO^2 capture and improvement of water quality. The study of these current questions requires the use of new methodologies and the establishment of collaborations among disciplines like Agronomy, Biology, Ecology, Economics and Social Sciences [50].

Table 2. Characteristics of the main journals.

Journal	A	SJR	C	TC	TC/A	H	1st A	R (A)				
								1993–1997	1998–2002	2003–2007	2008–2012	2013–2017
Agricultural Water Management	159	1.264 (Q1)	The Netherlands	4367	27.5	39	1997	7 (1)	1 (12)	1 (22)	1 (51)	1 (73)
Water Resources Management	51	1.355 (Q1)	The Netherlands	1020	20.0	18	2000	0	10 (2)	6 (6)	3 (21)	6 (22)
Nongye Gongcheng Xuebao Agricultural Engineering	37	0.372 (Q2)	China	140	3.8	7	2011	0	0	0	13 (7)	4 (30)
Field Crops Research	36	1.577 (Q1)	The Netherlands	942	26.2	17	1998	0	6 (3)	15 (3)	10 (8)	6 (22)
Wit Transactions on Ecology and the Environment	35	0.123 (ND)	the United Kingdom	18	0.5	2	2006	0	0	4 (7)	2 (25)	65 (3)
Water	33	0.548 (Q2)	Switzerland	75	2.3	4	2012	0	0	0	90 (1)	2 (32)
Sustainability	31	0.524 (Q2)	Switzerland	94	3.0	6	2013	0	0	0	0	3 (31)
Shengtai Xuebao Acta Ecologica Sinica	29	0.177 (Q4)	China	73	2.5	5	2008	0	0	0	4 (18)	14 (11)
Science of the Total Environment	28	1.621 (Q1)	The Netherlands	214	7.6	10	2012	0	0	0	90 (1)	5 (27)
Journal of Cleaner Production	27	1.615 (Q1)	The Netherlands	396	14.7	12	2006	0	0	43 (1)	16 (5)	8 (21)
Journal of Hydrology	26	1.745 (Q1)	The Netherlands	536	20.6	13	2004	0	0	28 (2)	5 (11)	11 (13)
Irrigation and Drainage	25	0.433 (Q2)	the U.S.	134	5.4	8	2003	0	0	8 (4)	6 (10)	14 (11)
Agriculture Ecosystems and Environment	24	1.612 (Q1)	The Netherlands	1101	45.9	13	2000	0	10 (2)	8 (4)	16 (5)	11 (13)
Journal of Environmental Management	24	1.141 (Q1)	the U.S.	618	25.8	16	2000	0	10 (2)	15 (3)	7 (9)	18 (10)

A: the annual number of total articles; SJR: Scopus Journal Ranking; C: country; TC: the annual number of citations in total articles; TC/A: total citation per article; H: H index; 1st A: first article of SWUA research by journal; R: ranking position.

3.3. Countries, Institutions and Authors

Table 3 shows the main productivity and impact indicators in the 10 countries with the highest number of articles published on SWUA. China ranked first with 432 articles, followed by the U.S. with 423, Australia with 221, India with 181 and Germany with 120. The U.S. was the country with the highest total number of articles published on SWUA during the study period until 2013 when China became the leading country for this ranking. The rest of the countries alternated in other positions within the leading group, except for France, which occupied the eleventh position in the last five-year period and Canada, which occupied the tenth position before joining the top ten group. The table also shows the number of published articles on SWUA per million inhabitants in each country (APC: number of articles per 1 mill. inhabitants). If we weight the number of published articles regarding the country population, in the first position, we can find Australia, followed by The Netherlands and Spain, whereas the last positions are occupied by China and India.

With respect to impact indicator, the U.S. is the country with the highest number of accumulated citations in its articles on SWUA with a total of 9315 citations. It is followed by China with 5382, Australia with 4583, India with 2813 and The Netherlands with 2617. However, if the average number of citations per article is considered, The Netherlands ranked first with a total of 26.7 citations. It is followed by France with 23.2, the U.S. with 22, Italy with 20.8 and Australia with 20.7 citations per article. To visualize the correlation between H index and the number of articles published by each country, Figure 4 shows the regression model that links these two variables.

Table 3. Characteristics of the main countries.

Country	A	APC	TC	TC/A	R (A)				
					1993–1997	1998–2002	2003–2007	2008–2012	2013–2017
China	432	0.313	5382	12.5	8 (1)	4 (8)	2 (38)	2 (99)	1 (286)
the United States	423	1.309	9315	22.0	1 (10)	1 (34)	1 (50)	1 (102)	2 (227)
Australia	221	9.160	4583	20.7	3 (3)	2 (17)	3 (37)	3 (82)	4 (82)
India	181	0.137	2813	15.5	4 (2)	3 (13)	4 (24)	4 (48)	3 (94)
Germany	120	1.452	2020	16.8	8 (1)	5 (5)	5 (15)	5 (37)	7 (62)
Spain	117	2.519	2004	17.1	0	0	5 (15)	6 (32)	5 (70)
Italy	104	1.716	2166	20.8	0	0	12 (7)	8 (31)	6 (66)
The Netherlands	98	5.758	2617	26.7	4 (2)	5 (5)	7 (14)	10 (24)	8 (53)
the United Kingdom	92	1.402	1554	16.9	2 (5)	10 (3)	9 (8)	6 (32)	9 (44)
France	64	0.957	1483	23.2	0	7 (4)	15 (5)	9 (25)	11 (30)

A: the annual number of total articles; APC: number of articles per 1mill. inhabitants; TC: the annual number of citations in total articles; TC/A: total citation per article; R: ranking position.

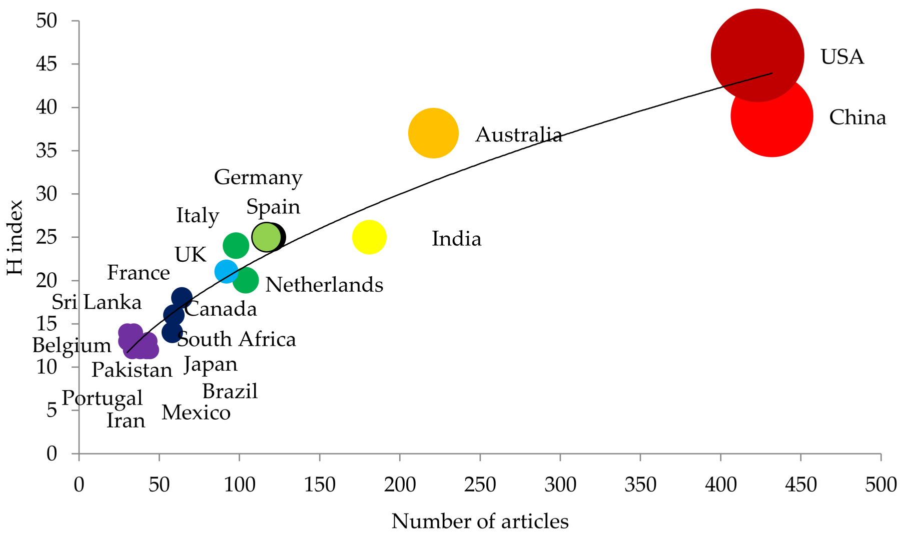

Figure 4. Correlation between H index and number of articles by country.

Table 4 shows the percentage of international collaboration (IC), the number of countries forming a collaboration network (NC) and the five main collaborators from each of the most productive countries (classified in descending order with respect to the number of collaborations). France had the highest percentage of works with international collaboration at 68.75% of the total, followed by Germany at 68.33%, The Netherlands at 65.31% and the United Kingdom at 63.04%. The U.S. had the largest network of collaborations, with a total of 55 different collaborating countries, followed by Germany with 50 and China with 43. The table also includes the average number of citations of each country (TC/A) for articles completed with international collaboration (IC) and without international collaboration (NIC). International collaboration created higher impact for the articles published (measured through the number of citations) in all of the cases except for The Netherlands, the United Kingdom and France.

Figure 5 shows a network map of the different collaborations between countries. The set of countries with the highest number of connections was chosen to make the map. The size of each circle represents the number of articles of each country. The thickness of each line represents the number of collaborations between countries. The different colors group the different clusters formed by sets of countries. Four clusters can be differentiated. The first cluster (Blue) is formed by the main productive countries, which are China, the U.S. and Australia, together with Argentina and Canada. The second cluster (Yellow) is formed by India, Ethiopia, Thailand, Bangladesh and Japan. The third cluster (Green) represents Germany with Brazil, Iran, Uzbekistan, Sweden and Switzerland. The fourth cluster (Red) includes the set of Western Europe countries (The Netherlands, Belgium, Portugal, Spain, the UK, France and Italy) together with South Africa, Mexico and New Zealand.

In order to detect the main differences between research trends, articles in collaboration with the leading researching countries—China and the United States—have been reviewed. Regarding China, articles in collaboration with the group built by Australia and the United States have been firstly analysed; and, secondly, those written together with its main European partners—Germany, The Netherlands and the United Kingdom. In both cases, most articles are devoted to domestic Chinese issues, 83% and 95%, respectively. Within the first group (China with Australia and the United States), researchers focus on the efficient use of water, whereas in the second group (China and European countries), the main topic is groundwater. Regarding the collaboration between the United States and its main European partners—Germany, Italy, Spain and the United Kingdom—a balance of the study territory has been found. They are equally devoted to American and European areas, as well as to third countries. The research focus varies from water use and supply to water management for irrigation and sustainability.

Table 4. International collaboration of the main countries.

Country	IC (%)	NC	Main Collaborators	TC/A	
				IC	NIC
China	37.73	43	the United States, Australia, Canada, Japan, the United Kingdom	18.0	9.1
the United States	45.39	55	China, India, Australia, Germany, Mexico	27.7	17.3
Australia	43.89	41	China, the United States, Pakistan, India, Spain	22.6	19.3
India	29.28	27	the United States, Australia, The Netherlands, Bangladesh, Philippines	34.9	7.5
Germany	68.33	50	the United States, Uzbekistan, China, Austria, Ethiopia	18.6	13.0
Spain	41.88	23	Italy, the United States, Australia, Portugal, the United Kingdom	19.4	15.5
Italy	38.46	33	the United States, Spain, France, Morocco, Portugal	35.3	11.8
The Netherlands	65.31	40	China, Australia, Germany, India, South Africa	22.7	34.2
the United Kingdom	63.04	40	China, the United States, Spain, Germany, India	15.4	19.4
France	68.75	37	Italy, Morocco, Australia, Belgium, Germany	21.4	27.0

IC: international collaborations; NC: total number of international collaborators; TC/A: total citation per article; NIC: no international collaborations.

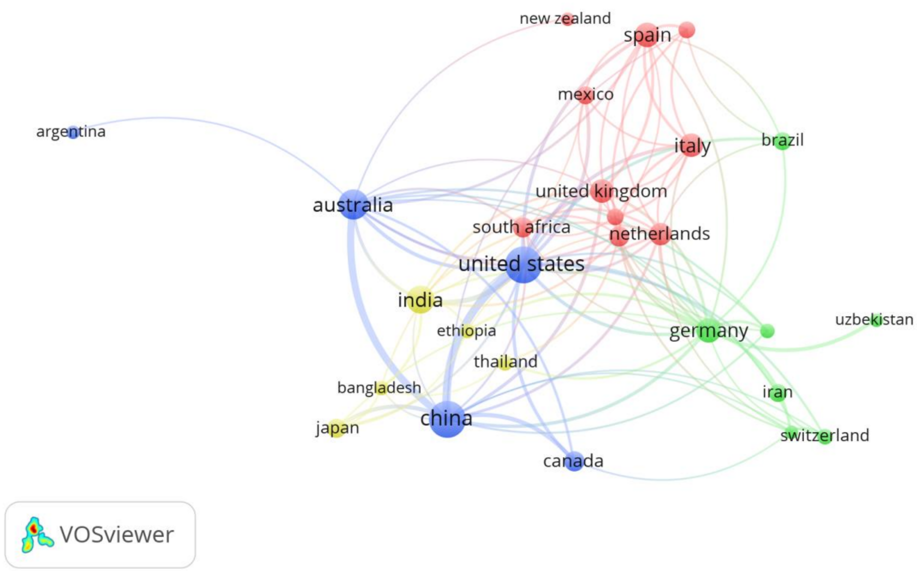

Figure 5. Countries' network.

Table 5 shows the main production and impact indicators of the institutions with the highest number of publications on SWUA. The Chinese Academy of Sciences ranked first with a total of 134 articles published between 1993–2017. It is followed by the China Agricultural University with 63, the Northwest A&F University (from China) with 59 and the Wageningen University and Research Centre of The Netherlands with 46. With respect to the number of citations, the Chinese Academy of Science had 2195 citations, followed by the Wageningen University and Research Centre of The Netherlands with 1243, the United States Department of Agriculture (USDA) Agricultural Research Service with 1058 and China Agricultural University with 1032. If we consider the average number of citations per article, the USDA Agricultural Research Service ranked first with 27.8 citations. The Wageningen University and Research Centre occupied the second position with 27 citations per article and the CSIRO Land and Water of Australia had the third position with 26.6 citations. Similar to the case found with countries, the H index was not a determining indicator due to the difference in the number of articles published by the different institutions. However, the Chinese Academy of Sciences also showed the highest H index (27). The Wageningen University and Research Centre is the institution that had articles with the most international collaboration (73.91%), followed by the University of Western Australia (56%) and the China Agricultural University (52.38%). In all of the cases, except the University of Western Australia, the articles published by these institutions with international collaboration had a higher impact when measured through the number of citations received.

Table 5. Characteristics of the main institutions.

Institution	C	A	TC	TC/A	H index	IC (%)	TC/A	
							IC	NIC
Chinese Academy of Sciences	China	134	2195	16.4	27	34.33	23.5	12.7
China Agricultural University	China	63	1032	16.4	18	52.38	16.5	16.3
Northwest A&F University	China	59	712	12.1	14	35.59	19.0	8.2
Wageningen University and Research Centre	The Netherlands	46	1243	27.0	17	73.91	27.9	24.7
USDA Agricultural Research Service	the U.S.	38	1058	27.8	18	31.58	34.8	24.7
Institute of Geographical Sciences and Natural Resources Research Chinese Academy of Sciences	China	35	743	21.2	12	34.29	39.5	11.7
CSIRO Land and Water	Australia	33	878	26.6	15	48.48	40.7	13.4
Ministry of Agriculture of the People's Republic of China	China	29	178	6.1	8	24.14	12.6	4.1
Beijing Normal University	China	28	371	13.3	10	32.14	24.1	8.1
University of Western Australia	Australia	25	426	17.0	10	56.00	14.3	20.5

C: country; A: the annual number of total articles; TC: the annual number of citations in total articles; TC/A: total citation per article; IC: international collaborations; NIC: no international collaborations.

Table 6 includes the most productive authors on SWUA and shows the main variables related to production (A) and the impact of their articles (TC) in addition to the affiliation, the country (C), the year of publication of their first (1st A) and last article on this topic (Last A). Half of these authors belong to Chinese research centers and, generally, are frequently the recent members of the SWUA research cohort. The author with the oldest publication is Luis S. Pereira from Portugal, who published his first article on SWUA in 1996. All authors published their last article in SWUA between 2015 and 2017, indicating that they continue to work on this topic. The only exception is the case of Frank A. Ward, whose last article is dated from 2012.

Bradley G. Ridoutt is the author with the highest number of articles published on SWUA. His work on the water footprint is the most relevant with respect to the number of citations [51–53]. The author with the second highest number of articles is Arjen Y. Hoekstra, who stands out for his works on water footprint and for the large number of countries he has studied, such as China, Kenya, France, the UK, Malawi and Latin America. His more relevant articles are available in references [54–56]. Xiying Zhang has the same number of articles published, but his work in the North China Plain is more agronomic. His most cited articles are references [57–59]. These three authors have the highest number of citations, have accumulated the highest average number of citations per article and have the highest H index. Based on these data, these three authors are considered as models in this line of research.

3.4. Keyword Analysis

An analysis of the keywords was used to identify hotspots within a research field. The 20 most frequently used keywords in articles on SWUA are displayed in Table 7 for the period of 1993–2017. The period was divided into five-year sub-periods, which show the evolution of keywords. The values that appear in the table refer to the position that keywords occupied in each sub-period compared with the total number of keywords of the sample, the number of articles in which it appeared [R (A)] and the repetition percentage (%). The 20 most frequently used keywords included terms related to water (Water-Use, Water-Management, Water-Supply, Water-Resources, Water-Use-Efficiency, Water-Conservation, Groundwater and Groundwater-Resources); sustainability (Sustainability, Sustainable-Development and Climate Change); crops and agricultural practices (Irrigation, Agriculture, Crops, Irrigation-System, Crop-Yield, Crop-Production, Triticum-Aestivum, Evapotranspiration and Zea-Mays).

Table 6. Characteristics of the main authors.

Author	A	TC	TC/A	H Index	C	Affiliation	1st A	Last A
Ridoutt, Bradley G.	13	548	42.2	10	Australia	Commonwealth Scientific and Industrial Research Organization	2009	2017
Hoekstra, Arjen Y.	10	456	45.6	9	The Netherlands	University of Twente	2007	2017
Zhang, Xiying	10	541	54.1	9	China	Institute of Genetics and Developmental Biology Chinese Academy of Sciences	2003	2015
Jat, MangiLal	9	180	20.0	5	India	International Maize and Wheat Improvement Centre	2009	2016
Lamers, John P.A.	8	68	8.5	6	Germany	Universitat Bonn	2010	2016
Wang, Dong	8	27	3.4	3	China	Shandong Agricultural University	2010	2017
Wu, Pute	8	35	4.4	4	China	Northwest A&F University	2010	2017
Yang, Yonghui	8	311	38.9	6	China	Chinese Academy of Sciences, Key Laboratory of Agricultural Water Resources	2002	2017
Chen, Fu	7	82	11.7	5	China	China University of Mining Technology	2010	2015
Huo, Zailin	7	44	6.3	3	China	China Agricultural University, College of Water Resources and Civil Engineering	2012	2017
Pereira, Luis S.	7	168	24.0	5	Portugal	Technical University of Lisbon, Instituto Superior de Agronomia	1996	2017
Ward, Frank A.	7	261	37.3	6	the U.S.	New Mexico State University Las Cruces	2007	2012

A: the annual number of total articles; TC: the annual number of citations in total articles; TC/A: total citation per article; C: country; 1st A: first article of SWUA research by author; Last A: last article of SWUA research by author.

Table 7. Evolution of the main keywords.

Keywords	1993–2017		1993–1997		1998–2002		2003–2007		2008–2012		2013–2017	
	A	%	R (A)	%	R (A)	%	R (A)	%	R (A)	%	R (A)	%
Water-Use	697	33.45	9 (6)	13.04	3 (29)	24.17	3 (89)	34.23	2 (255)	42.57	3 (318)	30.03
Irrigation	691	33.16	1 (11)	23.91	1 (35)	29.17	1 (104)	40.00	4 (207)	34.56	1 (334)	31.54
Water-Management	668	32.05	4 (8)	17.39	2 (33)	27.50	2 (97)	37.31	3 (216)	36.06	4 (314)	29.65
Water-Supply	661	31.72	3 (10)	21.74	7 (13)	10.83	8 (50)	19.23	1 (263)	43.91	2 (325)	30.69
Sustainability	572	27.45	15 (4)	8.70	5 (21)	17.50	4 (74)	28.46	5 (191)	31.89	6 (282)	26.63
Water-Resources	547	26.25	7 (7)	15.22	5 (21)	17.50	5 (68)	26.15	7 (152)	25.38	5 (299)	28.23
Water-Use-Efficiency	477	22.89	12 (5)	10.87	9 (9)	7.50	9 (49)	18.85	6 (160)	26.71	7 (251)	23.70
Sustainable-Development	475	22.79	4 (8)	17.39	4 (24)	20.00	7 (67)	25.77	8 (134)	22.37	8 (242)	22.85
Agriculture	342	16.41	21 (3)	6.52	12 (8)	6.67	12 (39)	15.00	11 (81)	13.52	9 (211)	19.92
Water-Conservation	311	14.92	21 (3)	6.52	51 (3)	2.50	24 (22)	8.46	9 (106)	17.70	10 (177)	16.71
Crops	281	13.48	0	0.00	25 (5)	4.17	14 (34)	13.08	13 (79)	13.19	12 (161)	15.20
Groundwater	279	13.39	33 (2)	4.35	9 (9)	7.50	11 (41)	13.46	12 (81)	13.52	14 (141)	13.31
Irrigation-System	267	12.81	0	0.00	19 (6)	5.00	30 (18)	6.92	10 (93)	15.53	13 (150)	14.16
Crop-Yield	228	10.94	72 (1)	2.17	19 (6)	5.00	15 (27)	10.38	15 (72)	12.02	16 (122)	11.52
Crop-Production	209	10.03	0	0.00	43 (4)	3.33	29 (19)	7.31	17 (69)	11.52	17 (118)	11.14
Triticum-Aestivum	197	9.45	33 (2)	4.35	16 (7)	5.83	13 (38)	14.62	18(68)	11.35	26 (80)	7.55
Climate-Change	192	9.21	0	0.00	51 (3)	2.50	81 (7)	2.69	21 (57)	9.52	15 (125)	11.80
Evapotranspiration	176	8.45	0	0.00	43 (4)	3.33	25 (21)	8.08	30 (46)	7.68	18 (105)	9.92
Groundwater-Resources	175	8.40	33 (2)	4.35	25 (5)	4.17	30 (18)	6.92	23 (56)	9.35	22 (94)	8.88
Zea-Mays	171	8.21	72 (1)	2.17	43 (4)	3.33	21 (23)	8.85	22(57)	9.52	25 (86)	8.12

A: the annual number of total articles; R: ranking position.

Irrigation ranked first for most of the period. The group formed by these 20 keywords was the set of most frequently used terms in articles on SWUA, although they changed their position according to the relevance given to each one by research in the different sub-periods. The most repeated keywords in the 1993–1997 sub-period were: Irrigation, Water-Supply, Water-Management, Environmental-Protection, Sustainable-Development and Developing-Country. The most used geographical terms were Asia and the Middle East. In this first period, research was directed towards the conservation and environmental protection as well as the agricultural development in developing countries, mainly in the Middle East and Asia. Outstanding methodological terms did not appear.

In the second five-year period (1998–2002), research preferences for keywords changed. In the 1993–1997 period, the focus was on developing regions, whereas, in the 1998–2002 period, specific countries appear among the first positions of the most used terms (India in the 10th position, Australia in the 11th position, China in the 12th position and the U.S. in the 13th position). Unlike the first period, terms referring to arid and semi-arid regions were highlighted in the second period. Terms related to sustainability continue to appear between the two periods. However, terms referring to crops, which were barely used previously, increased in importance during the second period, including Triticum-Aestivum, Crops, Crop-Yield and Crop-Production. Research focused on more agronomic aspects and the field of study was set at the watershed and exploitation level.

The period of 2003–2007 signified the current configuration of the framework with respect to keywords. In addition to the terms already mentioned and related with sustainability and agronomy, words related with hydric resources were diversified (Water, Groundwater, Groundwater-Resources, Catchments, Rain, Aquifers and Rivers). The main crops were Zea-Mays and Wheat. By region, Eurasia, Asia and Europe were respectively ranked in the fifth, ninth and sixteenth positions in the entire keywords sample. By country, China occupied the 16th position and Australia the 19th position. The term World appeared for the first time in the 17th position, which referred to the global scale of the topic analyzed. Mathematical-Models was the most repeated methodological term. The link between Economic and Social Sciences in this field of study was relevant in this period because the term Economic-And-Social-Effects was frequently used.

Trends from 2003–2007 continued through 2008–2012. The main difference was the appearance of terms, such as Drought, Water-Stress and Water-Scarcity. These appeared as a consequence of increasing concerns about the consequences of climate change. This situation was extended to the next period (2013–2017), in which Climate-Change was within the group of the twenty most used words for the first time. Food security was a priority in this field, represented by the terms Food-Security and Food-Supply. The studied crops were Zea-Mays, Wheat and Rice, while the field of study was focused on the watershed level. The most mentioned methodology among the keywords was Water-Footprint.

As far as the keyword evolution is concerned, the term Climate Change stands out. It has moved forward from the 81st to the 15th place. In order to picture the term trends, 192 articles with this keyword have been analysed. The main reason for the increase of its use lies in the growing social interest in the effects of climate change on various fields. One of the key milestones that fostered research on climate change was the creation of the Intergovernmental Panel on Climate Change in 1988. Since then, this platform has published reports about the state of climate change that serve as guidelines for the research needs. The coming into force of the Kyoto Protocol in 2005 meant another huge impulse for the research on climate change. The growing interest in climate change has brought about some research trends on SWUA, the most relevant ones being: sustainability of food and water supply for the growing world population; soil management sustainability based on hydrographic basins; climate change impacts on crops and their sustainability; and planning measures and decision-making processes related to the effects of climate change on the effective use of water for agriculture.

Figure 6 shows the network map that links the keywords to the entire sample of the articles analyzed. The size of the circle represents the number of articles in which each keyword appears and the color represents the cluster in which the keyword is included based on the number of co-appearances.

There are three main clusters that represent three different viewpoints on SWUA. The first (Red) is focused on environmental aspects, including terms related to environmental protection and conservation. It is closely related to the socio-economic aspect of sustainability and is associated with the U.S. and Africa. The second (Green) represents the largest agronomic trend on SWUA. It includes different crops and agricultural management practices that influence agricultural sustainability and is associated with China and Australia. The third (Blue) represents hydric resources management that follows resource optimization and the balance between the source availability and the satisfaction of the different demands. This trend is associated with the European and Asian regions.

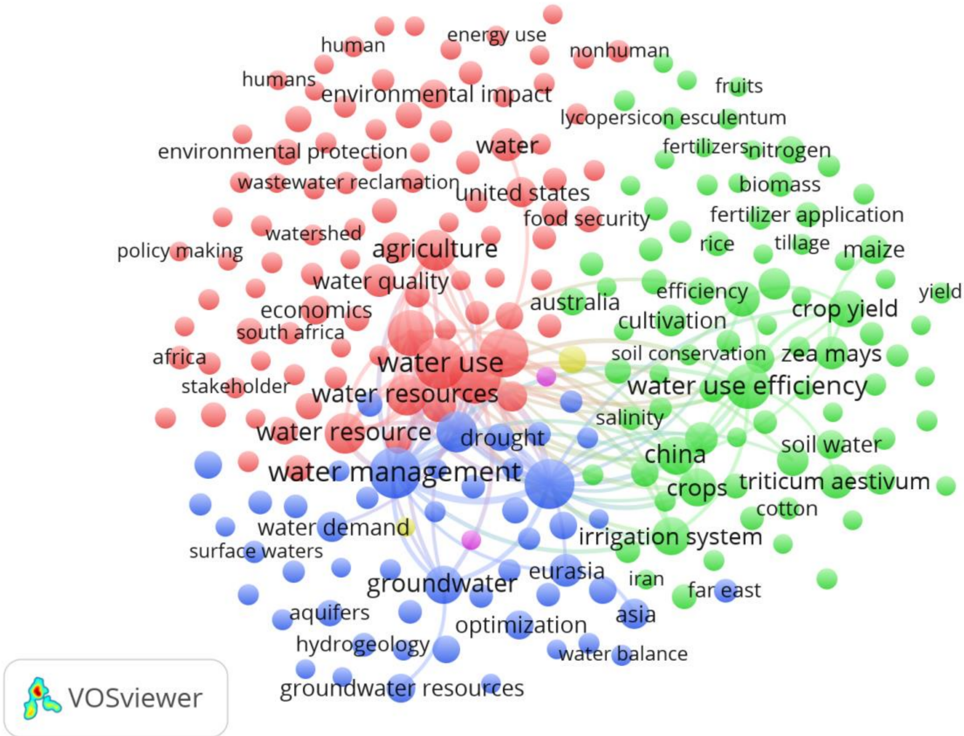

Figure 6. Keywords network.

Table 8 shows the five most frequently used keywords by the five most productive countries on SWUA. These terms signify the main hotspots for each of these countries. This analysis permits identification of the different research trends based on the features of each country. In general, all of the countries shared the same keywords, although there are some differences. The U.S., Australia and Germany displayed differences only on one keyword. The U.S. and Germany had the same keywords, while Australia included the name of the country among the most used keywords and did not include Water-Supply. For China and India, the most repeated keyword was the name of its country itself. China is the only country that included Water-Resources and the country that gave less importance to Water-Management and Sustainability. Chinese works were focused on water availability and water use efficiency. India was the only country that did not include Irrigation, but it was focused on the sustainable management of water use and its efficiency.

In order to verify underlying trends, 432 articles from China and 181 from India have been studied. It has been proven that 91.7% of the Chinese articles focus on domestic issues as well as 83.6% of the Indian ones. This highlights the fact that Indian and Chinese authors concentrate almost exclusively on domestic issues.

Table 8. Main keywords by country.

Country	Keyword 1	Keyword 2	Keyword 3	Keyword 4	Keyword 5
China	China	Water-Supply	Water-Resources	Water-Use-Efficiency	Irrigation
the United States	Water-Supply	Irrigation	Water-Use	Sustainability	Water-Management
Australia	Water-Use	Australia	Irrigation	Sustainability	Water-Management
India	India	Sustainability	Water-Management	Water-Use	Water-Use-Efficiency
Germany	Water-Management	Water-Use	Irrigation	Water-Supply	Sustainability

4. Conclusions

The aim of this study was to review 25 years of international research on sustainable water use in agriculture. A bibliometric analysis was developed to sample 2084 articles published between 1993 and 2017. A productivity, impact and structural study was carried out based on the number of articles, journals, thematic categories, authors, affiliation and countries. This work was completed with the analysis of the main hotspots' trends based on the keywords used in the articles.

Results indicated that research on sustainable water use in agriculture achieved exponential growth in the number of articles published and has become a global issue. It has been proven that the number of published articles on this topic is increasing much more than articles on water in general terms. It highlights that this research line has become a relevant study field within the general water question.

The main categories, which included articles on sustainable water use in agriculture, were Environmental Sciences (60.2%) and Agricultural and Biological Sciences (50.5%). The concept of sustainability had repercussions at environmental, socio-cultural and economic levels. Many authors stated the need for multidisciplinary approaches to deal with environmental resource sustainability. However, in the case of sustainable water use in agriculture, only 14.5% of the articles published used the Social Sciences approach; 2.7% were included in the Economics, Econometrics and Finance category; 2.6% in Business, Management and Accounting; 1.2% in Multidisciplinary; and 0.6% in Decision Sciences. The sustainability concept applied to the use of water in agriculture is directly linked to the water use efficiency and water ecosystemic services concepts. We find it necessary to create holistic analysis approaches that include technical, environmental and socio-economic aspects. They will be able to generate needed information for sustainable planning and management of hydric resources. The decision-making process has to be able to incorporate stakeholders' preferences, as well as keep ecosystem integrity and their service flow.

The countries that published the most articles were China, the U.S., Australia, India and Germany, although the countries that published the articles with the highest impact were The Netherlands, France, the U.S., Italy and Australia. It has been proven that there are relevant differences when comparing the absolute number of published articles and the weighted average number regarding population per country. In this sense, the countries that stand out are Australia, The Netherlands and Spain. The countries that published the most articles with international collaboration were France, Germany, The Netherlands, the United Kingdom and the U.S. Different research trends have been observed per country. China and India focus their efforts on domestic issues, even when they work together with other countries, whereas European countries, the United States and Australia show balanced national and international research issues. The variety of leading research topics could also be identified per country. The research aims of the United States and China vary according to the country with which they are collaborating.

The analysis of keywords showed that the use of the term Climate Change has seen the most growth in the last few years. It highlights the fact that concerns about climate change risks are becoming greater in scientific communities. Four main research trends have been identified within this issue. We find it necessary to include climate change impacts on the studies of water use in agriculture if we want to obtain realistic and useful information in decision-making processes.

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