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Review

Advances in Water Use Efficiency in Agriculture: A Bibliometric Analysis

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Abstract: Water use efficiency in agriculture (WUEA) has become a priority given increasing limitations on hydric resources. As a result, this area of research has increased in importance, becoming one of the most prolific lines of study. The main aim of this study was to present a review of worldwide WUEA research over the last 30 years. A bibliometric analysis was developed based on the Scopus database. The sample included 6063 articles. The variables analyzed were: articles per year, category, journal, country, institution, author, and keyword. The results indicate that a remarkable growth in the number of articles published per year is occurring. The main category is environmental science and the main journal *Agricultural Water Management*. The countries with the highest number of articles were China, the United States of America, and India. The institution that published the most articles was the Chinese Academy of Sciences and the authors from China also were the most productive. The most frequently used keywords were irrigation, crop yield, water supply, and crops. The findings of this study can assist researchers in this field by providing an overview of worldwide research.

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

1. Introduction

A series of variables limit the availability of hydric resources that can be used in agriculture [1–6]. Within this context of scarcity, improving water use efficiency has become a priority [7–9]. Water Use Efficiency in Agriculture (WUEA) usually involves consuming less water to reach a specific production goal or increasing the production of a given water supply [10]. This concept can be addressed through different scientific disciplines [11]. From the physiology viewpoint, WUE is defined as a measure of carbon gain through transpirational water loss [12]. Irrigation scientists use this term to describe the relationship between the water used in crops and the water lost from the source; therefore, it is expressed in volume per water volume. Agronomists are mainly concerned about maximizing biomass production or crop yield per water unit used. The main difference in the efficiency concept between physiologists and agronomists is that the former do not consider possible water loss during crop production. From an economic point of view, water irrigation efficiency is the irrigation level that maximizes yield by considering all the costs, prices, and the response of crop yield to irrigation. The multidisciplinarity of this concept requires the integration of different viewpoints when addressing the global challenges that researchers face when referring to water use [13,14].

The goal of improving WUEA is increasing food production and income, improving the financial gains, and guaranteeing the supply of ecosystem services at a lower social and environmental cost per water unit used [13,15]. An increase in WUEA might result in better nutrition for families, higher income, and more productive employment, especially in regions with arid and semi-arid climates.

The practices used to achieve this aim include water collection, supplementary irrigation, shortfall irrigation, precision irrigation techniques, and practices for soil water conservation [8,16]. The priority areas where significant increases in water productivity are possible include: (1) areas where poverty is high and water productivity is low, (2) areas of physical water shortage where competition for water is high, (3) areas with limited development of hydric resources where high yields from additional water have a considerable impact, and (4) ecosystem degradation areas driven by water, such as the fall of water tables and the drying up of rivers [14,17]. The evaluation of an action on the change of water use requires a multidisciplinary analysis that includes a water examination to understand the changes in water quality and quantity, and the timing of different uses as well as a comprehensive evaluation exercise to evaluate marginal water productivity and non-marketable values associated with water use, such as those derived from ecosystem services [18]. Through this analysis, the improvement of WUEA requires a holistic approach that includes both the biophysical and socioeconomic spheres [19].

Research on WUEA began in the 1960s [20] and since then, the number of contributions has increased steadily. This line of research has reached an important development level; therefore, analyzing the evolution of water research is necessary. However, to our knowledge, no studies have analyzed the dynamics of global WUEA research. The objective of this work was to fill this knowledge gap through the development of an analysis of the performance and trends in worldwide WUEA research. To achieve this objective, a systematic and quantitative study was completed using the bibliometric method. In the case of hydric resources, this method has been used to study wetlands [21], hydrology [22], hydrogeology [23], desalination [24], and water footprint [25].

The article is organized as follows. After this introduction, the methodology used in the development of this article, the data sources and the analyzed variables are described in Section 2. The main results together with their discussion are shown in Section 3. The main conclusions obtained from this research are shown in Section 4.

2. Materials and Methods

2.1. The Bibliometric Method

The bibliometric analysis is a statistical method used to identify, organize and analyze the main components within a specific research field [26,27]. It was introduced by Garfield in the mid-twentieth century, since then it has been generalized in the scientific research and has contributed during decades to review knowledge across multiple disciplines [28]. The bibliometric method has been widely used in Biology, Energy, Engineering, Medicine and Management areas. Hereby statistical and mathematical methods are involved to represent, thorough mapping techniques, bibliographic information available on databases and identify trends in a specific field of research [29,30]. This methodology allows researchers evaluate the contribution of the involved researching agents such as countries, institutions and authors. The relevance of the scientific production can also be assessed [31]. Moreover, it can also identify main drivers of a research field. Though several tools, collaboration relationships between involved agents can be clarified [32]. Links between authors from different disciplines, institutions and countries can be studied. This is especially relevant in fields of specialization with a global impact, as it is the case of WUEA, where internationalization and collaborations need to be analyzed [33]. For this reason, the bibliometric method has been used in our research.

Regarding potential interested readers and users of this analysis, it can be stated that results are useful for experts when assessing scientific production on a specific topic. They can easily identify what has already been studied and this method can help them determine better opportunities for future publications [28]. Information about new technologies and investment options can also be gathered for analysts and decision-makers [34].

Bibliometric approaches include co-occurrence analysis, co-citation and bibliographic coupling. In our study, the keyword co-occurrence approach has been considered as the best suited one for our pursued objectives. Since the apparition of "Statistical Bibliography", the study of metadata related to scientific publications is frequent. Data like year of publication, citations, theme categories and keywords are considered for the analysis and mapping of information in review works [35]. Current techniques have evolved to information visualization through text and data mining techniques, mapping techniques and tool developments based on routine types of automatized software [28,35]. According to Durieux y Gevenois [36], three types of indicators can be found in bibliometric studies. Quantity indicators refer to productivity; quality ones to publication impact; and structural indicators measure established connections. In the present work, these three types of indicators have been taken into account. Apart from counting to measure the productivity of authors, institutions and countries, further indicators have been used to value impact. Network maps have been produced to visualize international collaborations and trends of access points in this study field.

2.2. Data and Processing

For bibliometric analysis development, the Scopus database was used, which is considered as the world's largest abstract and citation database of peer-reviewed research literature. Furthermore, Scopus is available for free [37]. The Scopus database has also been used in many previous bibliometric analysis [38–42].

The search range focused on the period of 1988 to 2017 and was performed with the following parameters: [TITLE-ABS-KEY ("water use efficiency" OR "efficiency of water use") AND TITLE-ABS-KEY (irrigation OR agricultur* OR farm* OR crop*)] in January 2018. The publications were limited to the categories of Agricultural and Biological Sciences to ensure undesired subject matter was not analyzed in this study. Only works until 2017 were included to compare complete annual periods. The sample was limited to articles to avoid duplicity in the works analyzed [43]. Notably, a different search could provide different results. The final sample analyzed in this work included 6063 articles. The records obtained were properly processed using spreadsheets and creating corresponding graphics to permit sorting of the results.

Publications on WUEA were evaluated considering the following factors: number of articles per year, author, institution where authors are members, country, subject area, name of the journal, and keywords. After downloading this information, we first eliminated the duplications. The same author and the institution, or a reference to the title, were found in different formats in different documents, which can lead to errors when counting these records. For this reason, all information was analysed and the different records were regrouped, so that the same author, institution, keyword, etc., were not counted more than once. When all the information was clear, different tables and figures were created to correctly view and analyse the data using different computer programmes. VOSviewer was the tool chosen to create the network maps; this tool is useful for this type of work. Finally, the analysis of keywords was used to elicit the main research movements related to WUEA.

Different quality indicators were used to evaluate the different records. In addition to the number of citations, the H index and the SCImago Journal Rank (SJR) impact factor were included. The H index for an author or country is the h number of documents of an author or the number of publications of a country (Np) that has at least h citations in each one [44]. SJR is a measure of the weighted citations received by the journal, where the weight of the citations depends on the thematic field and the prestige of the journal from which the citation was obtained [45].

3. Results and Discussion

3.1. Evolution of Scientific Production

Table 1 shows the evolution of the main characteristics of the research works on WUEA published from 1988 to 2017, divided by articles, authors, references, citations, journals, and countries. The number of articles published has increased in recent years, proving that WUEA studies are attracting increasing attention. WUEA studies have grown from 20 articles in 1988 to more than 600 in 2017. Therefore, during the first two decades of the period analyzed (1988–2007), only 27% of the total number of works was published, whereas from 2013 to 2017, 45% of the total works of the period was published. Figure 1 shows how this line of research has attracted interest since its origin, growing exponentially in recent years. The filled points represent the annual articles from 1988 and the curve simulates the growth pattern of global articles.

Table 1. Major characteristics of the articles on Water Use Efficiency in Agriculture (WUEA) research from 1988 to 2017.

Year	A	AU	AU/A	NR	NR/A	TC	TC/CA	J	A/J	C
1988	20	47	2.4	358	17.9	7	0.4	17	1.2	12
1989	30	83	2.8	576	19.2	14	0.3	21	1.4	18
1990	40	111	2.8	719	18.0	32	0.4	25	1.6	16
1991	31	85	2.7	621	20.0	50	0.4	20	1.6	17
1992	32	83	2.6	793	24.8	96	0.6	18	1.8	17
1993	43	100	2.3	915	21.3	121	0.6	22	2.0	18
1994	45	118	2.6	736	16.4	130	0.5	26	1.7	14
1995	38	106	2.8	1182	31.1	142	0.5	26	1.5	19
1996	54	166	3.1	988	18.3	313	0.9	33	1.6	24
1997	78	218	2.8	1724	22.1	335	0.8	42	1.9	20
1998	76	219	2.9	1710	22.5	387	0.8	49	1.6	32
1999	83	240	2.9	1675	20.2	512	0.9	36	2.3	29
2000	88	281	3.2	2207	25.1	546	0.8	52	1.7	34
2001	102	332	3.3	2239	22.0	698	0.9	47	2.2	35
2002	101	322	3.2	2790	27.6	869	1.0	49	2.1	27
2003	121	382	3.2	3067	25.3	1035	1.1	52	2.3	35
2004	124	402	3.2	3015	24.3	1310	1.2	57	2.2	37
2005	161	535	3.3	3906	24.3	1663	1.3	72	2.2	40
2006	180	599	3.3	4459	24.8	1988	1.4	71	2.5	43
2007	227	823	3.6	6049	26.6	2934	1.8	86	2.6	54
2008	247	848	3.4	6150	24.9	3145	1.6	100	2.5	49
2009	340	1188	3.5	9643	28.4	4365	1.9	122	2.8	50
2010	343	1282	3.7	9978	29.1	5019	1.9	127	2.7	61
2011	431	1563	3.6	12,352	28.7	6455	2.1	152	2.8	69
2012	367	1364	3.7	11,546	31.5	7198	2.1	142	2.6	58
2013	462	1764	3.8	14,175	30.7	8722	2.3	147	3.1	62
2014	476	1917	4.0	16,012	33.6	9935	2.3	176	2.7	63
2015	501	1993	4.0	16,316	32.6	11,510	2.4	184	2.7	66
2016	604	2368	3.9	20,551	34.0	13,072	2.4	207	2.9	68
2017	618	2397	3.9	22,366	36.2	13,926	2.3	195	3.2	74

A: The annual number of total articles; AU: the annual number of authors; AU/A: the average number of authors per article; 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; TC/CA: annual total citation per cumulative article; J: the annual number of journals; A/J: the annual number of articles in an individual journal; C: the annual number of countries.

With respect to the number of authors, a total of 13,861 authors participated in the creation of the 6063 articles analyzed. The annual calculation verifies that the number of authors constantly increased over the entire period, growing from 47 in 1988 to 2397 in 2017. The average number of authors per article almost doubled throughout the whole period, increasing from 2.4 to 3.9. The number of references also increased steadily. In 1988, the total number of references was 358, whereas in 2017, it was 22,366. The average number of references per article increased from 17.9 to 36.2. With respect to the number of citations in the articles published on WUEA during the entire period, the 6063 articles analyzed accumulated a total of 96,529 citations, which is an average of 15 citations per article. This variable increased exponentially from seven citations in 1988 to 13,926 citations in 2017, and almost 60% of all citations were concentrated in the most recent five-year period. The table also shows the average number of citations per article (TC/CA) as well as the total number of citations accumulated until the end of the period divided into the total number of articles published to date. The average number of citations per article increased constantly, growing from 0.4 in 1988 to 2.3 in 2017. The number of journals where articles on WUEA were published grew from 17 in 1988 to 195 in 2017.

The average number of publications per journal increased from 1.2 to 3.2 articles per journal. Finally, the number of countries that have published articles about WUEA increased quickly over the study period, beginning with 12 countries in 1988 and reaching a maximum of 74 in 2017. The participation of a growing number of countries in this field of study shows that WUEA is becoming an important global issue.

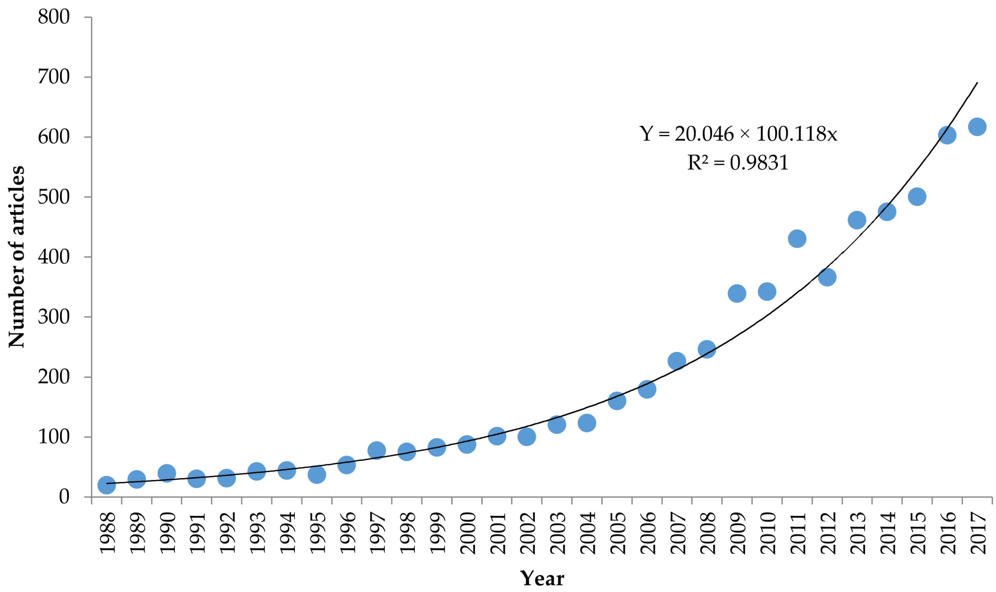

Figure 1. Annual number of articles on WUEA research from 1988 to 2017.

The reasons, which are pushing forward the WUEA research expansion, are various. World population is more and more conscious about the need to preserve this essential good in order to keep the current way of life. The impacts of global climate change on water-based agro-systems are increasingly present in the global society concerns. Asian and African coastal mangroves, as well as the agroforestry systems in Eastern Africa are social and ecological areas from which local population depend and whose survival is being threated. Mediterranean agriculture and the one from Australia, China and United States of America are in serious risk due to new climatic patterns with droughts and heavy rains. In the politic sphere, national and international decision makers have echoed this social concern. Already in 2000, Kofi Annan, Secretary-General of the UN, stated the need to carry out a "Blue Revolution in Agriculture" based on the productivity increase per water unit. Its well-known motto was "more crop per drop" [8]. The UN Agenda 2030 on Sustainable Development includes 17 goals for a sustainable development among which one specific aim is devoted to water and sanitation (SDG 6), ranging from water scarcity to efficiency in water use [46]. At the time, the European Parliament introduced in Horizon 2020 the requirement of a sustainable production in agro-systems [47]. Countries like United States of America, China, India or Costa Rica have implemented since decades environmental services under payment in agriculture aiming at preserving hydric resources. Local, national and international stakeholders need to gather more information which help them to make decisions on an efficient management of hydric resources, especially in agriculture since it is the main consumer of water.

3.2. Distribution of Production by Subject Categories and Journals

Figure 2 shows the evolution of the main thematic areas into which the articles published on WUEA were classified according to Scopus classification, and were linked to the main category of Agricultural and Biological Sciences. Notably, only one study can be indexed in more than one category. Since our research aims at showing the links between the different disciplines, it cannot be considered a selection bias that an article is classified under various categories. During almost all of the study period, the main category was Environmental Science which published 31% of the total number of published works. This was followed by Earth and Planetary Sciences with 16%; Biochemistry, Genetics and Molecular Biology with 10%; and Engineering with 7% of the total number of articles. The rest of the categories did not reach more than 2% of the total number of published articles. This hierarchy was maintained throughout the study period.

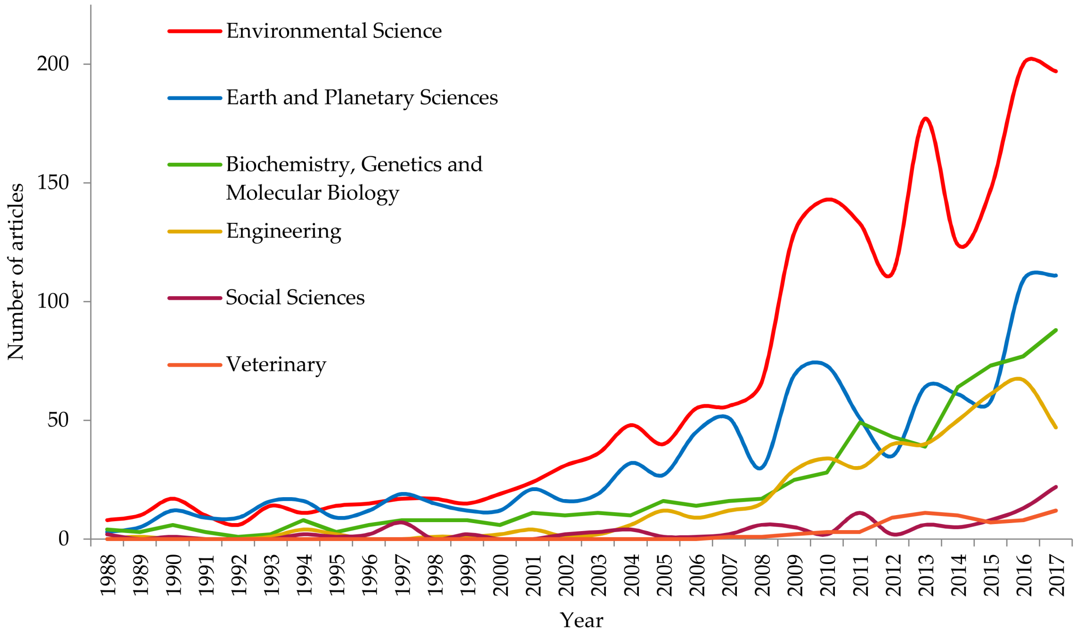

Figure 2. Comparisons of the growth trends of articles on WUEA research by subject categories from 1988 to 2017.

Despite the economic concept of efficiency being a priority when determining water use, the Economics, Econometrics and Finances and Business, Management and Accounting categories represented a residual percentage in the research studies on WUEA, accounting for less than 0.6% of the articles published. Also, the articles published belonging to the categories of Multidisciplinary and Decision Sciences were insignificant, representing only 0.1% of the total number of published articles. These categories were considered as representative of the unifying nature of the research. However, these categorizations of databases may not truly represent the multidisciplinary publications [48].

Table 2 shows the 15 journals with the highest number of articles published on WUEA during the period of 1988 to 2017. To facilitate the analysis of the dynamics throughout the period, three sub-periods were created (1988–1997, 1998–2007, and 2008–2017). The journal with the highest number of articles published on this research field was *Agricultural Water Management*, with a total of 752 articles that represent 12.4% of the total number of published articles. This journal published its first article on WUEA in 1988, and has led the ranking of publications since nearly 1990, and from 2002, this journal significantly outpaced the remainder of the journals. Furthermore, it accumulated the highest number of citations, having a higher SJR index and a higher average number of citations per article (26.5). The next journal in terms of number of articles was *Nongye Gongcheng Xuebao Transactions of The Chinese Society of Agricultural Engineering*, with a total of 276, and the third was *Field Crops Research* with 218.

One Chinese journal, *Shengtai Xuebao Acta Ecologica Sinica*, has been publishing an increasing number of articles in this field, leading it to occupy the eighth position, but its SJR index is still small, placing it in occupying the fourth quartile. The journal with the highest SJR index was *Agricultural and Forest Meteorology*. This journal occupies twelfth position with respect to the number of articles published within the period analyzed, but has the highest number of citations per article with 33. The first 10 journals in this ranking account for 34.8% of the total number of published articles, forming the core of scientific production on WUEA.

Table 2. Most productive journals for WUEA research from 1988 to 2017.

Publication	R (A)	SJR *	C	TC	TC/A	1st A	R (A)		
							1988–1997	1998–2007	2008–2017
Agricultural Water Management	1 (752)	1.264 (Q1)	Netherlands	19,949	26.5	1988	1 (41)	1 (189)	1 (522)
Nongye Gongcheng Xuebao	2 (276)	0.372 (Q2)	China	1557	5.6	1999	0	4 (47)	2 (229)
Field Crops Research	3 (218)	1.577 (Q1)	Netherlands	6162	28.3	1989	3 (23)	5 (42)	3 (153)
Indian Journal of Agronomy	4 (165)	0.394 (Q2)	India	588	3.6	1996	12 (8)	2 (86)	8 (71)
Chinese Journal of Applied Ecology	5 (133)	0.189 (Q4)	China	597	4.5	1992	35 (2)	11 (24)	5 (107)
Irrigation Science	6 (123)	0.978 (Q1)	Germany	3070	25.0	1988	2 (24)	8 (29)	10 (70)
Indian Journal of Agricultural Sciences	7 (117)	0.260 (Q3)	India	409	3.5	1996	28 (3)	3 (53)	13 (61)
Shengtai Xuebao Acta Ecologica Sinica	8 (114)	0.177 (Q4)	China	346	3.0	2007	0	73 (3)	4 (111)
Agronomy Journal	9 (108)	0.741 (Q1)	USA	2438	22.6	1996	20 (5)	6 (32)	8 (71)
Scientia Horticulturae	10 (104)	0.770 (Q1)	Netherlands	1919	18.5	1988	12 (8)	16 (15)	6 (81)
Acta Horticulturae	11 (88)	0.18 (Q4)	Belgium	359	4.1	1998	0	16 (15)	7 (73)
Agricultural and Forest Meteorology	12 (74)	1.976 (Q1)	Netherlands	2439	33.0	1988	4 (19)	33 (8)	17 (47)
European Journal of Agronomy	12 (74)	1.336 (Q1)	Netherlands	2043	27.6	1998	0	19 (13)	13 (61)
Soil and Tillage Research	14 (72)	1.353 (Q1)	Netherlands	2116	29.4	1989	9 (12)	8 (29)	29 (31)
Journal of Food Agriculture and Environment	15 (68)	0.214 (Q3)	Finland	249	3.7	2007	0	118 (1)	11 (67)

*: SJR 2016. R: ranking position; 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; 1st A: first article of WUEA research by journal.

3.3. Distribution of Production by Countries, Institutions and Authors

Table 3 shows the evolution of the number of articles on WUEA in the 10 countries with the highest number of articles published during the period of 1988 to 2017. China is the country with the highest total number of articles published on WUEA during the period of 1988 to 2017, followed by the U.S., India, Australia, and Spain. Between 1988 and 2004, the U.S. was the country that published the most articles on this topic. After 2004, China became the leading country for this ranking.

Table 3. Most productive countries for WUEA research from 1988 to 2017.

Country	R(A)	TC	TC/A	R (A)		
				1988–1997	1988–1997	1988–1997
China	1 (1626)	19,160	11.8	13 (8)	3 (211)	1 (1407)
United States	2 (991)	22,988	23.2	1 (113)	1 (243)	2 (635)
India	3 (749)	6071	8.1	2 (62)	2 (225)	3 (462)
Australia	4 (502)	14,397	28.7	3 (57)	4 (125)	4 (320)
Spain	5 (303)	8437	27.8	9 (10)	5 (64)	5 (229)
Italy	6 (247)	5163	20.9	14 (7)	9 (46)	7 (194)
Brazil	7 (246)	2406	9.8	18 (5)	16 (19)	6 (222)
Iran	8 (195)	1848	9.5	30 (2)	16 (19)	8 (174)
Turkey	9 (191)	3032	15.9	22 (3)	6 (51)	10 (137)
Germany	10 (188)	3781	20.1	18 (5)	11 (36)	9 (147)

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

The country with the highest total number of citations from 1988 to 2017 was the U.S. with 22,988 citations, followed by China with 19,160, Australia with 14,397, and Spain with 8473. However, Australia was the country with the highest average number of citations per article with 28.7, followed by Spain with 27.8, the U.S. with 23.2, Italy with 20.9, and Germany with 20.1. When we compared the percentage of articles and the number of citations per country to the total number of published works and citations within the period, significant differences were found. The U.S., Australia, and Spain were the three countries with the highest positive differences between the number of articles and citations. This could be viewed as a sign of recognizing the publications from these countries based on the citations. Conversely, China and India were the countries with the lowest number of citations compared to the number of works published.

Studies have shown that the H index is correlated with the total number of published articles [44]. Figure 3 shows the relationship between the H index and the total number of publications. A model was used to simulate the increase in H index with the increase in the total number of publications per countries over the 30 years analyzed. A high correlation was observed (R^2 = 0.7234) between the adaption line based on the numeric equation and the statistical data points that were extracted from the dataset in this study.

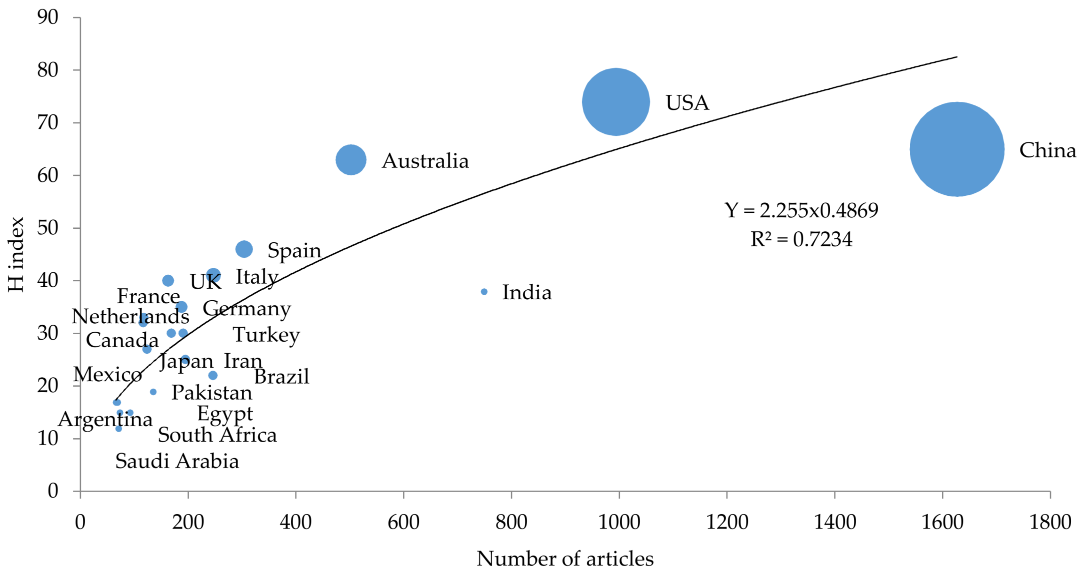

Figure 3. Quantitative relationship between the H Index and total number of articles by country for WUEA research from 1988 to 2017.

Table 4 shows the percentage of articles for each country through international collaboration (IC), the number of countries with which collaborations have been made (NC), and the main five collaborators of each country, classified in descending order with respect to the number of collaborations. The countries with the highest percentage of works completed with international collaboration were Germany, the United States, Australia, Italy, and Spain. The U.S. was the country with the largest network of collaborations, with a total of 65 different collaborating countries among which China, Australia, Canada, Spain, and Brazil are highlighted. The United States stands out because it belongs to the main group of collaborators of all the countries that form the top 10, and it is the main collaborator for six out of these 10 countries (China, India, Spain, Brazil, Turkey, and Iran). In all cases, except for Australia and the U.S., articles published in collaboration with other countries had a higher number of citations than those without collaboration (NIC).

Figure 4 shows a network map of the collaborations between the most productive countries, where the size of the circle represents the number of documents per country and the color corresponds to the cluster formed by different groups of countries. Five main clusters can be differentiated, led by China, the U.S., India, Italy, and Turkey with respect to the number of articles. The first cluster mainly links China and Hong Kong with Canada and Australia. In the second cluster, the main relationships were established between the U.S., Spain, Brazil, Mexico, and Argentina. The third is formed by India, Germany, the United Kingdom, Japan, and the Netherlands, among others. In the group for Italy, European countries such as Austria, Denmark, and France are found, together with Iran, Morocco, and Jordan. In the fifth group are Turkey, Egypt, Pakistan, Saudi Arabia, and South Korea.

Table 4. International collaboration for the most productive countries in WUEA research from 1988–2017.

Country	IC (%)	NC	Main Collaborators	TC/A	
				IC	NIC
China	23.19	53	U.S., Australia, Canada, Japan, Netherlands	19.5	9.5
United States	59.23	65	China, Australia, Canada, Spain, Brazil	20.2	27.5
India	13.48	33	U.S., Australia, Philippines, Japan, Bangladesh	13.2	7.3
Australia	44.42	52	China, U.S., India, Pakistan, France	25.7	31.1
Spain	33.33	37	U.S., Italy, U.K., Australia, Mexico	33.2	25.1
Italy	38.06	44	France, Spain, U.S., Netherlands, Syria	30.8	14.8
Brazil	18.29	26	U.S., Portugal, U.K., Argentina, Canada	23.3	6.8
Iran	26.67	27	U.S., Australia, Syrian Arab Republic, Italy, Japan	14.0	7.8
Turkey	15.71	10	U.S., U.K., Germany, Pakistan, Austria	19.0	15.3
Germany	69.15	58	China, U.S., Australia, France, Egypt	20.3	19.7

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

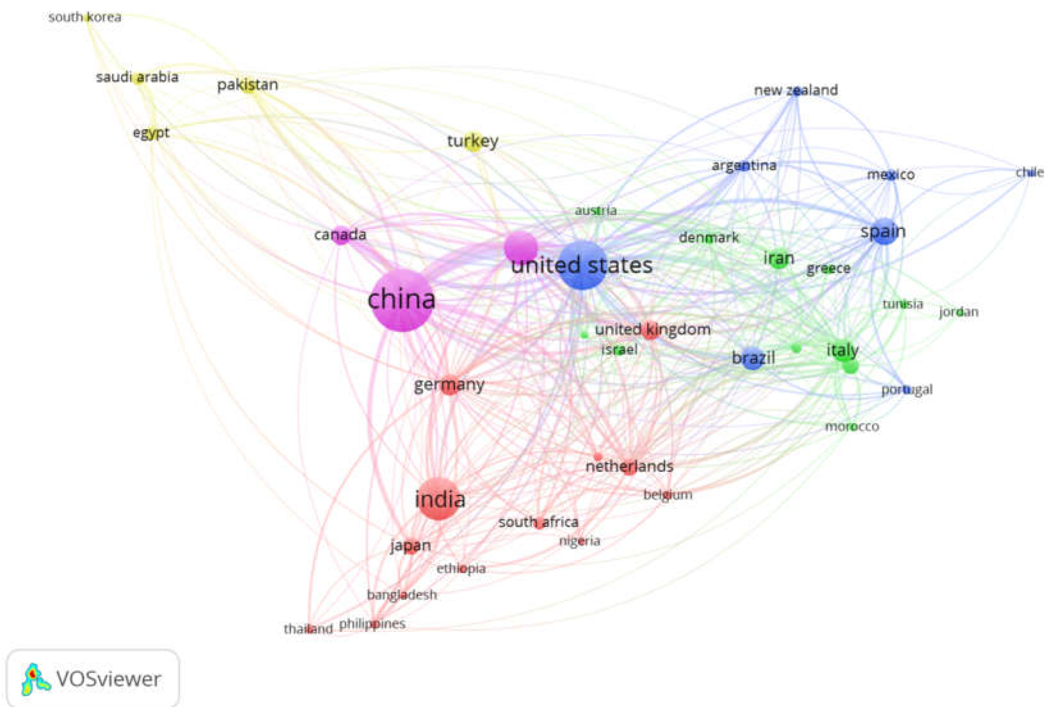

Figure 4. Cooperation based on co-authorship between countries for 1988 to 2017.

Table 5 shows the rankings of the 10 institutions with the highest number of publications about WUEA. All institutions are located in China, except for one center that belongs to the United States. The Chinese Academy of Sciences is ranked first with 362 articles, with the oldest publication dating back to 1992. Until 2002, the Chinese Academy of Sciences did not appear among the 10 most productive institutions, but thereafter it occupied the first position. It is followed by the Northwest A&F University, the China Agricultural University, and the United States Department of Agriculture (USDA) Agricultural Research Service with 312, 266, and 206 articles, respectively. The USDA is the only American institution within the group of the most productive institutions, occupying fourth position. It published on this topic for the first time in 1988. Since then, this institution led research about WUEA, and was ranked first until 2002. However, the USDA has the highest number of citations per article for the whole study period, with an average of 25.3 citations, and it has the second highest H index (42).

Table 5. Most productive institutions of WUEA research for 1988–2017.

Institution	C	A	TC	TC/A	H Index *	IC (%)	TC/A	
							IC	NIC
Chinese Academy of Sciences	China	362	6968	19.2	50	25.97	27.9	16.2
Northwest A&F University	China	312	3300	10.6	30	19.55	18.0	8.8
China Agricultural University	China	266	3724	14.0	34	31.95	17.5	12.4
USDA Agricultural Research Service, Washington, DC	USA	206	5204	25.3	42	30.58	31.9	22.4
Ministry of Agriculture of the People's Republic of China	China	137	798	5.8	16	21.17	9.3	4.9
Chinese Academy of Agricultural Sciences	China	129	1253	9.7	19	20.16	18.2	7.6
Institute of Soil and Water Conservation Chinese Academy of Sciences	China	123	1706	13.9	22	26.83	23.6	10.3
Shandong Agricultural University	China	110	741	6.7	13	7.27	7.4	6.7
Lanzhou University	China	99	2045	20.7	27	41.41	19.5	21.5
Ministry of Education China	China	97	970	10.0	18	23.71	13.3	9.0

* Only sample items. 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.

The Lanzhou University of China is the institution with the highest percentage of works completed through international collaboration with 41.41% of the total. It is followed by the China Agricultural University and the USDA, with 31.95% and 30.58%, respectively. Of all the institutions except one (Lanzhou University), the articles completed through international collaboration have a higher number of citations per article than those without collaboration. Therefore, international collaboration between research centres increases the impact of the published articles.

Table 6 shows the 15 authors with the highest number of articles published on WUEA. Although the authors wrote their first article in the 1990s, all authors pursued this line of research because they all published articles on WUEA in 2017. These results show that this field of study has matured, having a group of authors with a long research career and who are references.

The author with the highest number of articles is Shaozhong Kang from China Agricultural University with 56 articles, with 2155 accumulated citations from those studies, an H index of 26 in those publications, and an average of 38.5 citations per article. Yu Shi, a member of the Shadong Agricultural University of China, is the researcher who has more recently joined this line of research, with the first publication in 2011. Yu Shi occupies the ninth position in terms of the total number of articles, accumulating 103 citations within a total of 29 articles. The author with the highest number of citations per article is Xiying Zhang, a researcher who joined the Institute of Genetics and Developmental Biology Chinese Academy of Sciences, with an average of 45.9 citations per work. Terry A. Howell is the author with the oldest publication, dating back to 1989. Finally, all 10 authors who have published the most articles are Chinese, but if we consider the number of citations per article, then among the top 10 positions, authors from the U.S. and Denmark are included.

Figure 5 shows a network map with collaborations based on co-authorships, where the color corresponds to the cluster formed by different authors. From the results obtained, the set with the highest number of relationships is shown. A main core can be seen that is formed by different clusters that mainly link the Chinese authors, and among them, we found Kang, Yu, Shi, Zhang, Liu, Li, and Jia. Furthermore, a series of external groups was found, in which the remaining authors are placed.

Table 6. Most productive authors in WUEA research for 1988–2017.

Author	A	TC	TC/A	H Index *	C	Affiliation	First A	Last A
Kang, Shaozhong	56	2155	38.5	26	China	China Agricultural University	1998	2017
Yu, Zhenwen	42	220	5.2	9	China	Shandong Agricultural University	2008	2017
Li, Fengmin	41	734	17.9	14	China	Lanzhou University	2001	2017
Li, Fusheng	40	1017	25.4	20	China	Guangxi University	2002	2017
Jia, Zhikuan	40	480	12.0	13	China	Northwest A&F University	2006	2017
Zhang, Fucang	35	227	6.5	9	China	Northwest A&F University	2002	2017
Zhang, Yongli	34	128	3.8	8	China	Shandong Agricultural University	2009	2017
Zhang, Jianhua	33	1440	43.6	22	China	Chinese University of Hong Kong	1998	2017
Shi, Yu	29	103	3.6	7	China	Shandong Agricultural University	2011	2017
Wang, Dong	29	162	5.6	8	China	Shandong Agricultural University	2009	2017
Liu, Fulai	28	1028	36.7	15	Denmark	Kobenhavns Universitet	2004	2017
Zhang, Xiying	28	1284	45.9	18	China	Chinese Academy of Sciences	2003	2017
Evett, Steven R.	27	973	36.0	14	U.S.	USDA Agricultural Research Service	1997	2017
Howell, Terry A.	26	1128	43.4	17	U.S.	USDA Agricultural Research Service	1989	2017
Du, Taisheng	25	546	21.8	12	China	China Agricultural University	2005	2017

* Only sample items. A: the annual number of total articles; TC: the annual number of citations in total articles; TC/A: total citation per article; C: country.

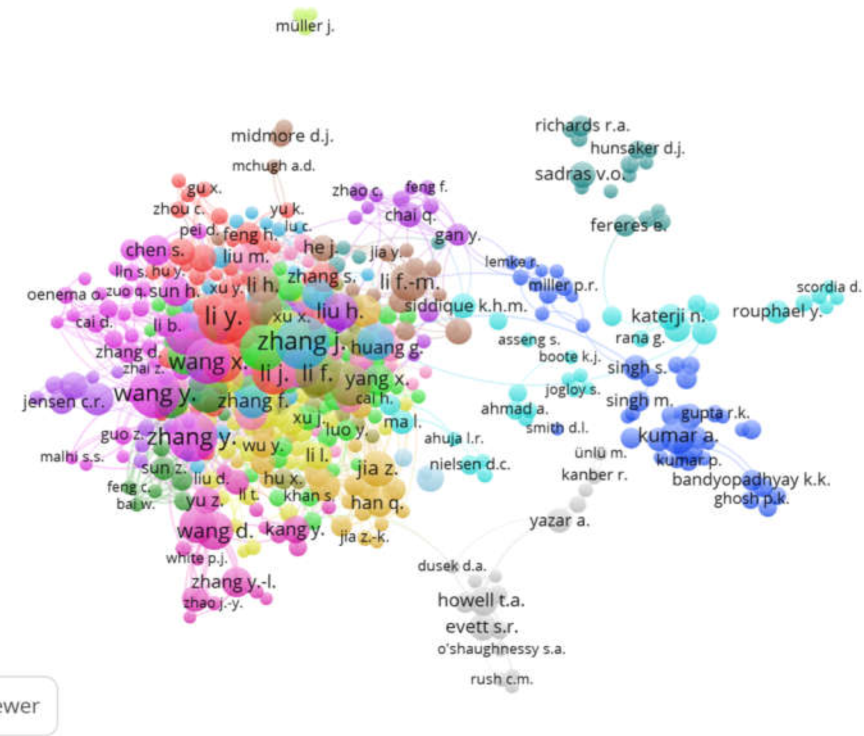

Figure 5. Cooperation based on co-authorship between authors for 1988–2017.

This huge increase of published articles by Chinese institutions and authors lies on economic and scientific reasons. China has experienced a significant economic growth based on intensive natural resources, being water one of the most relevant ones. During last years, the Chinese Government has brought about a productive change towards a more sustainable development model. An efficient use of water has become one of its main objectives. The governmental priority has pushed forward the increase of resources devoted to WUEA research [17,49]. On the other hand, in the last years new journals edited in China have been established to publish in Chinese. The most important are the following: Nongye Gongcheng Xuebao, Chinese Journal of Applied Ecology y Shengtai Xuebao Acta Ecologica Sinica. These journals configure the main diffusion channel of Chinese institutions and researchers. Nevertheless, scientific production coming from China has the potential to achieve better quality standards. Whereas the number of articles published by Chines institutions, authors and journals has significantly increased, when studying quality indicators (citations, H index, SJR) they show reduced values compared to other countries investigating on WUEA.

3.4. Keyword Analysis

A study of the keywords was completed to analyze the WUEA research trends. After regrouping the terms to avoid duplicates due to pluralization, words separated by dashes, words written in capital letters, etc., a total of 16,241 different keywords were obtained from the 6063 articles analyzed. The 20 most frequently used keywords that represent the research hotspots are shown in Table 7 for the total period analyzed and in three intervals of 10 years. Figure 6 shows trends of the ten most relevant keywords on WUEA research from 1988 to 2017. During this period, the 20 keywords appeared 17,853 times, providing an overview of the research trends during the analyzed period [44]. As expected, the term Water Use Efficiency was the most-used term during the entire analysis period. Notably, a series of up to 11 keywords that contain the term WUE, for example Irrigation Water Use Efficiency, were used. These other keywords were counted separately.

Table 7. Most frequently used keywords in WUEA research for 1988–2017.

Publication	1988–2017		1988–1997		1998–2007		2008–2017	
	A	%	R (A)	%	R (A)	%	R (A)	%
Water Use Efficiency	3528	58.19	1 (145)	32.88	1 (674)	53.37	1 (2709)	61.68
Irrigation	1787	29.47	2 (86)	19.50	2 (452)	35.79	2 (1249)	28.44
Crop Yield	1320	21.77	8 (20)	4.54	5 (239)	18.92	3 (1061)	24.16
Water Supply	1062	17.52	34 (8)	1.81	40 (53)	4.20	4 (1001)	22.79
Crops	876	14.45	11 (18)	4.08	4 (252)	19.95	8 (606)	13.80
Evapotranspiration	846	13.95	4 (29)	6.58	7 (180)	14.25	6 (638)	14.53
Triticum aestivum	813	13.41	8 (20)	4.54	3 (257)	20.35	9 (536)	12.20
Soil Moisture	704	11.61	19 (13)	2.95	50 (43)	3.40	5 (654)	14.89
Irrigation System	704	11.61	75 (4)	0.91	28 (64)	5.07	7 (637)	14.50
Yield	687	11.33	5 (27)	6.12	9 (154)	12.19	11 (506)	11.52
Wheat	639	10.54	6 (25)	5.67	8 (157)	12.43	15 (456)	10.38
Zea mays	625	10.31	18 (14)	3.17	11 (139)	11.01	14 (472)	10.75
Photosynthesis	590	9.73	10 (19)	4.31	16 (95)	7.52	13 (476)	10.84
Soils	588	9.70	15 (15)	3.40	12 (130)	10.29	16 (443)	10.09
Soil Water	577	9.52	25 (11)	2.49	21 (84)	6.65	12 (482)	10.97
Water Use	522	8.61	3 (39)	8.84	6 (199)	15.76	33 (285)	6,.49
Crop Production	518	8.54	106 (3)	0.68	24 (76)	6.02	17 (439)	10.00
Water	502	8.28	75 (4)	0.91	13 (123)	9.74	21 (375)	8.54
Maize	483	7.97	42 (7)	1.59	33 (59)	4.67	19 (417)	9.49
Water Management	482	7.95	25 (11)	2.49	21 (87)	6.89	20 (385)	8.77

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

The evolution of keywords revealed preferences in terminology. Water Use Efficiency and Irrigation were always ranked first and second over the 30 years analyzed. From 1988 to 1997, in addition to these two terms, the most-used terms were Water Use, Evapotranspiration, Yield, Wheat, Nitrogen, and Crop Yield. In this period, research focused on the use and efficiency of water irrigation to maximize production, especially in wheat, rice, and barley crops. Among the keywords referring to locations, the most repeated was India, which appears in 25th position. The following country that appeared the most was the Philippines occupying 75th position.

In the decade between 1998 and 2007, the most used terms, in addition to Water Use Efficiency and Irrigation, are *Triticum aestivum*, Crops, Crop Yield, Water Use, and Evapotranspiration. The main variation in this period was the research of crop varieties outside of production, in addition to soil development. The main crops that were studied were *Triticum aestivum* and *Zea mays*. The most-used geographical term in this decade was Eurasia, ranked in 10th position, followed by Asia in 13th position, and China in 22nd position.

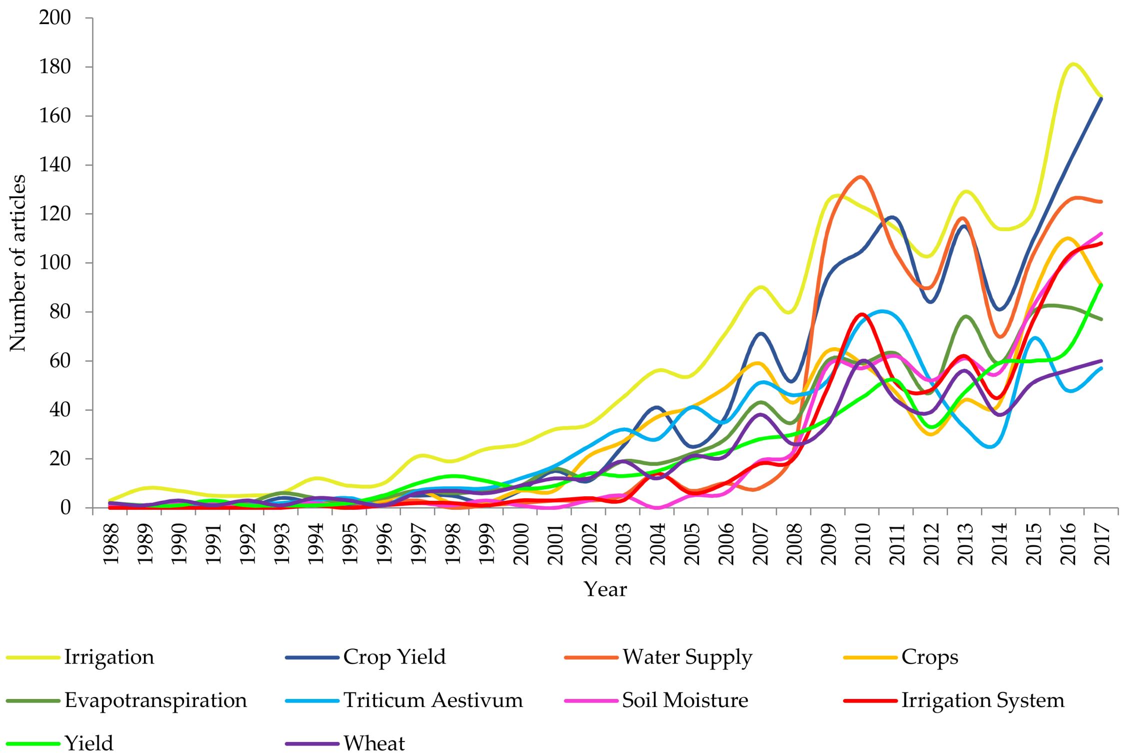

Figure 6. Trends of top ten keywords on WUEA research from 1988 to 2017.

In the decade between 2008 and 2017, the following terms experienced an increase in popularity: Water Supply moved from being ranked 40th in the past decade to 4th, Soil Moisture moved from 50th to 5th, and Irrigation System moved from 28th to 7th. The increasing crop intensification and shortage of hydric resources necessitated a focus on water supply. The technological and scientific advances allowed the development of new irrigation systems. The research thereafter focused on the development and evaluation of these systems. The retention, collection, and evaporation of water from soil was another focal point in this period. China was now the most-named geographical term, ranking 10th among the most used keywords, followed by United States (60th) and Australia (94th).

We created a network map of the incidence of keywords, based on keyword co-ocurrence, for the 100 terms with the highest number of links and a minimum of 50 coincidences. Figure 7 displays the resulting scientific landscape. The most popular terms are those that appear in bigger circles. The figure shows the link between those considered as hotspots in this research field, and three main groups are visible.

The first hotspot is represented by the term Irrigation, which is shown in blue. This cluster represents a management and decision-making viewpoint. In this cluster, a group of terms linked to irrigation appeared connected: irrigation, irrigation systems, irrigation waters, subirrigation, and drip irrigation. The following management terms are included in this cluster: agricultural management, decision making, economic analysis, irrigation management, management practice, water management, and water planning. The main crops represented are fruit and vegetable crops and the representative area is mainly the Mediterranean Basin. The keyword in the second cluster is Water, shown in green. This group provides a biophysical viewpoint. Here, we find terms related to hydric deficit and the water-soil relationship, including the terms water deficit, water stress, water uptake, transpiration, transpiration rate, drought, and drought stress. Concepts, such as crop improvement, adaptation, drought tolerance, drought resistance, plant transpiration, and plant-water relationship, are included in this cluster and reference plant-water relationships. Processes such photosynthesis, stomatal conductance, fertilization, physiology, and genetics are also included here. In this group, there are no noteworthy geographical references. The main keyword in the third cluster is Crop Yield, shown in red, and it includes the agronomic topic of water use. The different agronomic practices, systems, type of crop, and soil characteristics are included in this cluster. China in particular, and Asia and Eurasia in general, are the main geographic reference points.

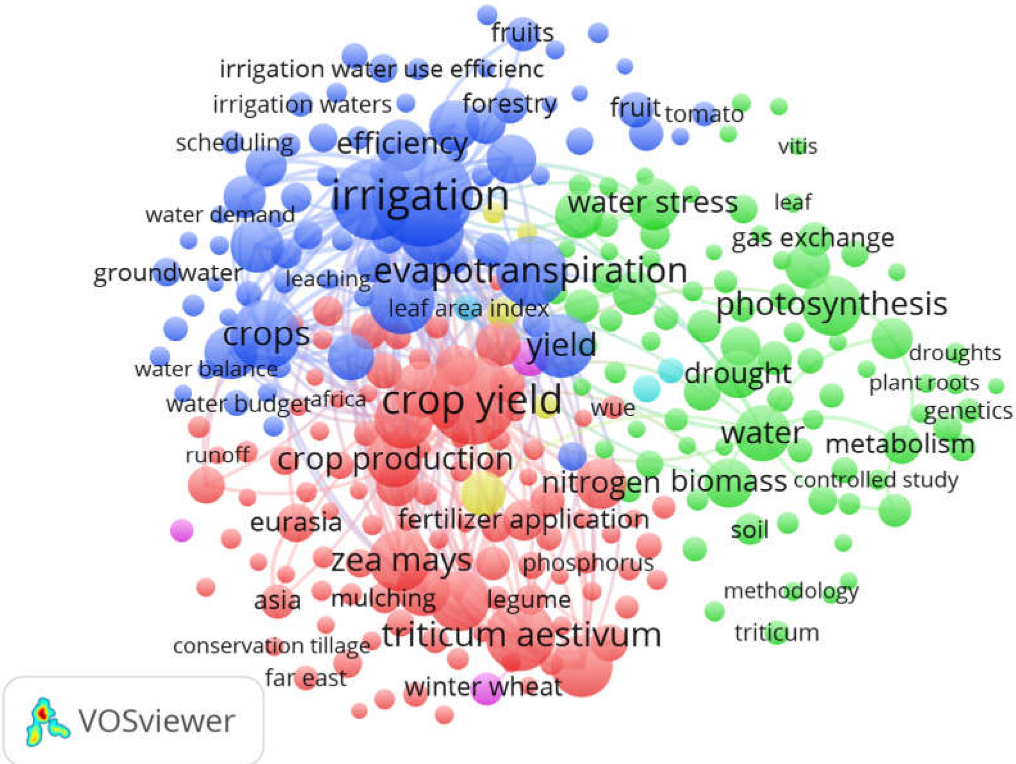

Figure 7. The concurrent network of the most common keywords in WUEA research for 1988–2017.

4. Conclusions

The main goal of this study was to present a review of worldwide WUEA research. To achieve this aim, a bibliometric analysis based on the Scopus database was performed for 1988 to 2017. The sample included 6063 articles. The analyzed variables were: number of articles per year, subject categories, journals, distribution by country, institutions, author, and keywords. The results indicated that a remarkable growth in the number of articles per year occurred, from 20 articles published in 1988 to more than 600 in 2017. This was particularly observable in the last five years, with 44% of the total number of WUEA articles being published in this period. The average number of authors per article almost duplicated, from 2.4 to 3.9, and the average number of references also increased from 17.9 to 36.2. The publication of articles on WUEA also extended to an increased number of journals, so that 17 journals published articles in this field of study in 1988 and 195 journals in 2017. WUEA research is becoming a global issue as an increasing number of countries are participating in this field of research, from 12 in 1988 to 74 in 2017. This WUEA research increase responds to the growing social awareness in the global context of climate change where the availability of hydric resources is at risk. Moreover, the food needs for the growing world population are more demanding since it is based on pattern of an intensive use of water. There is also an increasing demand of information from private and public institutions for their decision-making process regarding an efficient use of water.

Agricultural Water Management was the journal that had the highest number of articles published, followed by *Nongye Gongcheng Xuebao Transactions of the Chinese Society of Agricultural Engineering* and *Field Crops Research*. China is the country with the highest number of published articles, followed by the U.S., India, Australia, and Spain. The order would be different if the average number of citations per article was considered (Australia, Spain, United States, Italy, and Germany). The countries with the highest percentage of articles completed with international collaboration are Germany, the U.S., Australia, Italy, and Spain. The U.S. was the country with the highest network of collaborations, totaling 65 countries, and the U.S. forms a part of the group of main collaborators with all the countries research WUEA. The Chinese Academy of Sciences, the Northwest A&F University, the China Agricultural University, and the USDA Agricultural Research Service were the top four research institutions. The 10 authors who published the most articles in this field all come from China, but if we consider the number of citations per article, then among the top 10, there are authors from the U.S. and Denmark. Chinese institutions and authors are the most productive within this field of knowledge. However, the main diffusion channel for their publications are journals that publish only in Chinese and are difficult to be reached by the rest of the scientific community. This means lower impact indexes for their articles compared to the research in other languages. We consider that WUEA research could profit considerably if the Chinese institutions, researchers and journals ware more accessible.

An increasing number of studies have been conducted that are categorized under Environmental Science, Earth and Planetary Sciences, Biochemistry, Genetics and Molecular Biology and Engineering, accounting for 63% of the total number of published articles. The concurrent map of keywords identified the three main groups that can be considered as hotspots in this line of research: Irrigation (an approach from the management and decision making), Water (a biophysical approach), and Crop Yield (an agronomic approach). This highlights the lack of multidisciplinary integration on WUEA studies. Currently, the research on efficiency water use is not exclusive for the agronomy sector. Environmental sciences and eco-systemic services call for an improvement in the efficient use of irrigation water in order to face up the human challenges of the twenty-first century. For this reason, a number of measures should be implemented in the following three directions. Firstly, in the technological sector, research on new technologies to collect rain water, regulate soil humidity and the creation of alternative irrigation water resources should be fostered. Secondly, in the socio-cultural field, it is necessary to identify farmers' level of knowledge and readiness to introduce new technologies. It would also be of interest to know social preferences and possibilities to pay more for products coming from sustainable production systems. And, thirdly, regarding the environmental point of view, impacts on ecosystems and their services should be further studied. These holistic approaches will be able to provide useful information to socially plan and manage hydric resources for agriculture.

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