

Review

# What Do We Know about Water Scarcity in Semi-Arid Zones? A Global Analysis and Research Trends

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**Abstract:** Water supply is strategic for the development of society. The water distribution in nature follows patterns linked to geographic and territorial issues. Climate fluctuations aggravate shortage problems in semi-arid regions. This study aims to develop a systematic review of research on water scarcity in semi-arid areas through bibliometric methods that allow the analysis of its structure, performance, evolution, and future trends. The methodology considers three phases: (i) literature review, (ii) data cleaning and processing, and (iii) analysis of the research field and future trends. The intellectual structure of water scarcity in semi-arid zones covers 2206 documents with the collaboration of sixty-one countries, distributed in studies carried out in 54 years (1967 to 2021). This field of research has been growing, especially since the 21st century (93.1% of the documents). The countries that study the issue the most are those with high population rates and large consumption patterns, such as the United States and China. There are two central areas of interest led by the terms "water scarcity" and "water stress" due to the intensive use of the resource for agriculture and the management of the water–energy–climate nexus. Thus, the most significant journals studied relate remote sensing to resource management, and the most cited are related to agriculture. This research made it possible to consider future topics such as the study of anthropogenic effects and climate change, the accuracy and applicability of models, and future trends in conventional and unconventional agriculture and resources.

**Keywords:** water scarcity; water stress; semi-arid zone; bibliometric analysis; intellectual structure



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## 1. Introduction

Water scarcity is a high-impact global risk [1]. Over the last 100 years, water use has accelerated, with the current growth rate being 1% per year [2]. Water scarcity refers to the relationship between the supply of water resources and demand [3,4]. Thus, when discussing scarcity, we also discuss water's uneven temporal and spatial variations [5–7]. Regions with scarcity correspond to a third of the population of developing countries, or a quarter of the world population [8,9].

Population growth, economic development, and consumption patterns intensify the problem of scarcity [9,10]. Added to this is the contamination of groundwater due to agricultural load, wastewater and salinization [11–14]. Furthermore, climate change can also affect demand and precipitation [2,15–17]. These problems lead to the search for solutions to conserve the quality and quantity of water, especially in semi-arid areas [18],

such as the management, conservation and monitoring of groundwater [19,20]; wastewater treatment for pollution reduction, sustainable use and human development [2,21,22]; land use management [23]; and technologies for capturing and reserving water [13].

In semi-arid regions, water scarcity is aggravated, threatening food production, ecosystems and health [8,24–26]. A rapid expansion of semi-arid areas of the northern Mediterranean, southern Africa, and North and South America is expected [27]. Therefore, understanding the consequences of hot weather and semi-arid conditions is essential to generating development strategies. The semi-arid climate refers to the fluctuations between the dry and rainy seasons [28]. The countries with the most severe development problems are those where climate affects access to water [15,29].

Access to water to satisfy the basic needs of humanity is a fundamental condition for survival and the first step towards sustainable water use [30,31]. However, globally, water is trading on the market [32], and water resources are increasingly scarce, which causes socio-hydrological impacts on water distribution processes [33,34]. Therefore, it is essential to understand how these water–human systems evolve in the face of water scarcity [35,36] through participatory and sustainability criteria [37–40].

The studies mentioned in this article have addressed the issue of water scarcity from different perspectives, such as future scarcity, scarcity modelling and especially its interaction with climate change, food security, management policies and economics [8,17,23,28,31,41]. Nevertheless, due to the seriousness of this problem, it is necessary to explore the intellectual structure of water scarcity in semi-arid zones [42]. Therefore, a bibliometric study in this field would be an additional contribution to existing research on the subject.

This study analyses the scientific literature on water scarcity using bibliometric techniques to comprehensively assess the structures and development of the field [43,44]. The analysis of water scarcity is essential to identify current and future research areas, given the growing and aggravating need to supply, especially in semi-arid regions.

This article aims to explore: what has been the development of research trends on water scarcity in semi-arid areas? Which are the most productive and influential contributors (countries and journals) in the field of water scarcity in semi-arid zones? What are the most influential publications in this field? What are the areas of interest associated with this intellectual structure? Therefore, the aim is to develop a systematic review of research on water scarcity in semi-arid areas using bibliometric methods that allow the analysis of its structure, performance, evolution, and future trends in this field of study.

## 2. Materials and Methods

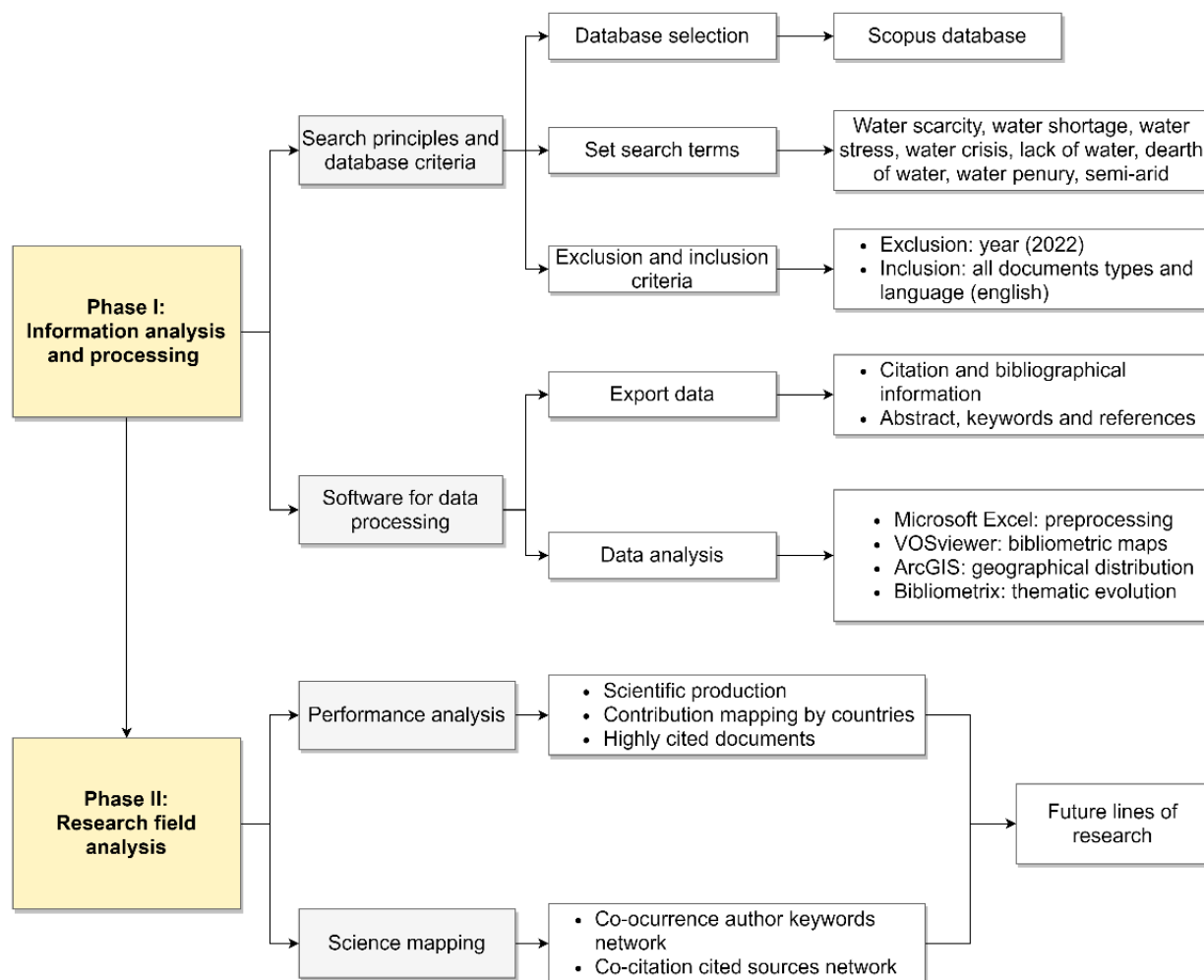
The research structure presents two phases, as detailed in Figure 1. The first phase corresponds to a literary review of the subject, cleaning and processing of information downloaded from the chosen databases. The second phase uses bibliometric techniques in conjunction with science mapping in VOSviewer (software version 1.6.18). Finally, this phase presents the analysis and interpretation of the data, the conclusions, and the future lines of research.

### 2.1. Phase I: Information Analysis and Processing

The systematic review is a methodology that allows for exploring areas of research through data collection and synthesis criteria that must be reproducible [45,46]. This procedure is like the one presented in the bibliometric analysis. One of these bibliometric studies pioneers is Derek J. de Solla Price, who considers that the network of articles creates patterns of research trends [47].

Bibliometric analysis is a quantitative method synthesising finding from the research area and representing them spatially [48,49]. This method covers various areas of knowledge such as environmental sciences [19,50–52], social sciences [53], geosciences [54] or interdisciplinary fields [55].

This phase encompasses two steps:



**Figure 1.** Outline of the research methodology.

### 2.1.1. Search Principles and Database Criteria

The application of the bibliometric method requires the choice of a database. The most-recognised multidisciplinary databases are WoS and Scopus [56,57]. Both databases rank journals by their productivity and the total number of citations to obtain an impact value, thereby acquiring journal activity, coverage and influence [58].

In this study we employed the Scopus database, the most widely used academic database due to its broad coverage of titles, journals and areas of knowledge [59,60]. This database is critical and robust due to its coverage and impact [61,62]. In addition, Scopus has more research in the field of earth sciences than other databases [54] and has a broad coverage of journals favouring the natural sciences, biomedical and engineering [63].

The bibliographical research allowed to establish the search terms for scarcity by supply and demand. However, the search does not cover drought since it is considered a natural and transitory event [64]. Instead, the search considers the terms: water scarcity, water shortage, water stress, water crisis [7,64–66], lack of water, dearth of water, or water penury [28,67–69] and the possible variations of the semi-arid.

The database download made in Scopus, dated January 2022, had the following search formula: ((TITLE-ABS-KEY (“water shortage\*”) OR TITLE-ABS-KEY (“water stress”) OR TITLE-ABS-KEY (“water crisis”) OR TITLE-ABS-KEY (“lack of water”) OR TITLE-ABS-KEY (“dearth of water”) OR TITLE-ABS-KEY (“water penur\*”) OR TITLE-ABS-KEY (“water scarcit\*”) AND NOT TITLE-ABS-KEY (drought\*))) AND ((TITLE-ABS-KEY (“semi-arid”) OR TITLE-ABS-KEY (“semi-arid”) OR TITLE-ABS-KEY (“semi arid”))), obtaining a total of 2395 documents.

This equation comprises inclusion and exclusion criteria. First, the search included English, the most frequent language [57], covering 93.1% of the documents. Additionally, the study covers all types of documents for better research results [70]. Finally, the search established exclusion criteria for the year 2022 because it is the current year. With this, the final search decreases to 2210 papers for 54 years (1967 to 2021).

### 2.1.2. Data Processing Software

The result of the Scopus search is a database of 2210 documents exported in CSV (Comma Separated Value) file format. The download includes citations, bibliographical information, abstract and keywords fields, and references. The data analysis included three software: Microsoft Excel, VOSviewer and ArcGIS.

- i. Microsoft Excel (software version 2207 Build 16.0.15427.20182, Microsoft Corporation, Redmond, WA, USA) allowed executing a pre-processing of the data, in which programming errors, erroneous records and documents discordant with the theme are corrected or eliminated [71,72]. Under these considerations, the pre-processing obtained 2206 papers. This software also allowed performance analysis of scientific production by reviewing authors, subject area, years, and countries [43].
- ii. VOSviewer (software version 1.6.18, Leiden University's Centre for Science and Technology Studies (CWTS), Amsterdam, The Netherlands) is free software that allows processing information to obtain bibliometric networks maps based on bibliographic information downloaded from database (e.g., Web of Science, Scopus) or data retrieved through the Application Programming Interface (API) (e.g., Crossref). The software is used to establish relationship maps between different units of analysis (author, document, journal, country, keywords, institutions) using bibliometric techniques (bibliographic coupling, co-author, co-citation, co-word) [73]. This software categorises the themes to graphically represent the lines of research [74–76]. Its use covers various research areas such as management [77–80], medicine [81,82], environmental sciences [83–85] and the field of earth sciences [43,86,87].
- iii. ArcGIS (software version 10.5, ESRI, Redlands, CA, USA) is a visualisation tool that allows scientific publications to be geographically located [88]. As a result, the high numbers of publications show the most active countries in the field of research [89].
- iv. Bibliometrix R-Tool (software version 3.2.1, software developed by University of Naples, Naples, Italy): It is an open-source software developed in R language, which allows qualitative research of data and its visualization in the structures of conceptual, intellectual and social knowledge [90–92]. The software has been used in various bibliometric studies related to earth sciences, environmental sciences and management [93–96].

### 2.2. Phase II: Research Field Analysis

The analysis of the research field comprises two approaches [97]:

- i. The performance analysis is a descriptive method that evaluates the productivity and impact of a research area of interest [98]. Performance analysis was used to study the scientific production and evolution of the research on water scarcity in semi-arid zones, using base indicators of publications such as number of documents, countries' contributions, institutions, journals and authors.
- ii. Scientific mapping allows spatial representation of how the different units of bibliometric analysis (e.g., documents, authors, keywords) are related to each other [99]. In this research, we used co-citation (journal) and co-occurrence (author's keywords) analysis [60]. Co-citation analysis allows connecting documents, authors or journals, based on joint appearances in the reference list [37,48]. On the other hand, co-occurrence analysis connects keywords when they appears in the title, abstract, list of keywords or author-generated keyword lists [100]. Both analyses are used to evaluate and obtain an overview of the structure and evolution of research topics [101]. The mapping used a threshold of 40 citations to produce ordered maps [102].

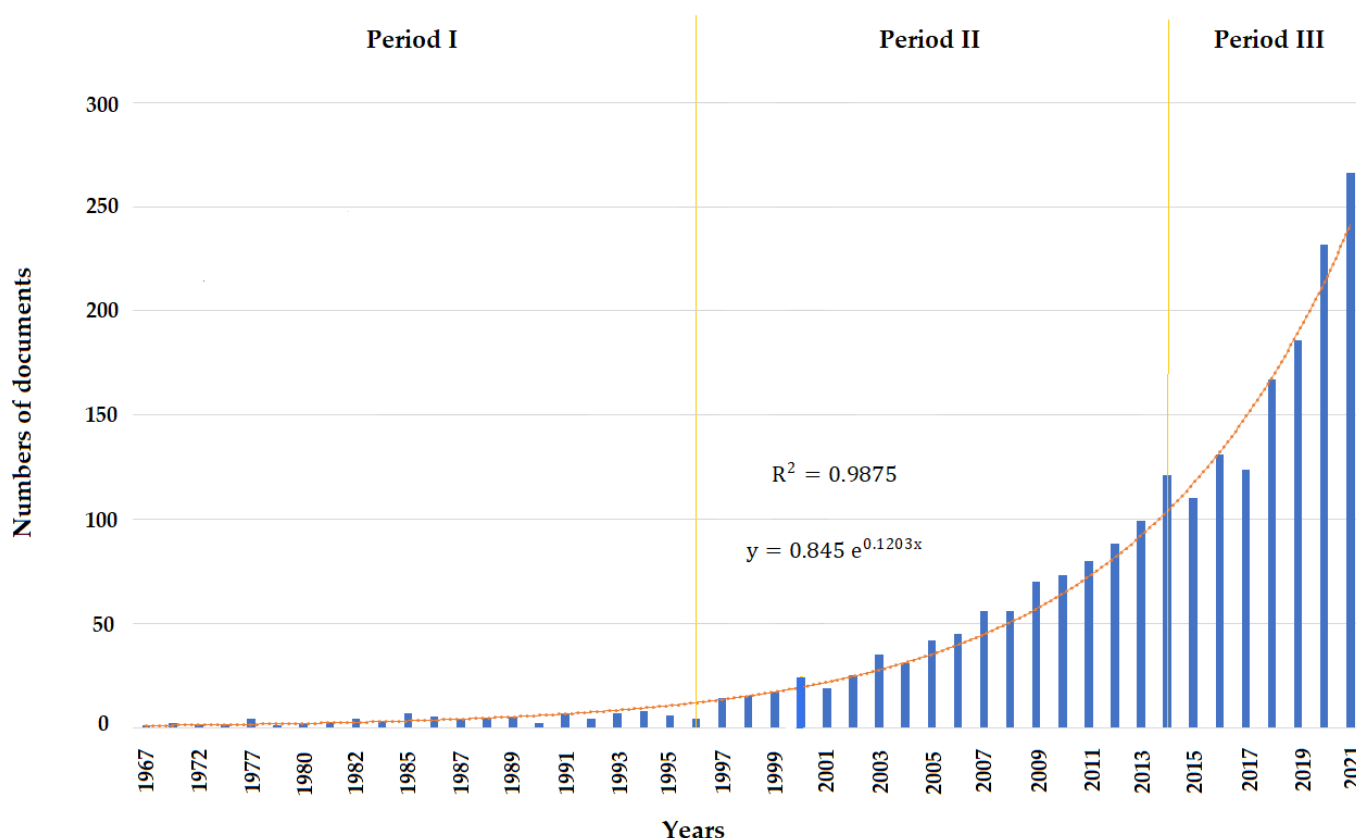
Journal co-citation allows analysing of the most-cited journals, and the keywords co-occurrence analyses the themes associated with the field of study. This keyword co-occurrence analysis helps to establish future research lines.

### 3. Results

#### 3.1. Performance Analysis

##### 3.1.1. Scientific Production

Scientific production covers 2206 documents in 54 years (1967 to 2021), divided into three periods according to the behaviour of the curve—the first period is for introduction, the second for development and maturity (Figure 2).



**Figure 2.** Annual scientific production on water scarcity in semi-arid areas.

#### 1. Period I (1967–1996)—Introduction.

In this period, 83 investigations were published, representing 3.71% of the scientific production of this field of study, with 2470 citations. The first investigations focused on plants' water requirements for agricultural production efficiency—groundwater management for the supply industrial sector and human consumption [103]. Techniques for the optimal use of water resources, such as irrigation, runoff or desalination, are examined [104–106]. Additionally, in conditions of hydric stress, the species' adaptability [107].

Other researchers analyzed the influence of water scarcity on trophic interactions [108], productivity [109], as well as crop yield and biomass [110]. Influence, which implies the analysis of the optimal use of water resources, especially in agriculture [111]; and in the study of the adaptation processes of plants to periods of scarcity in semi-arid and arid lands, such as fructan production [112], the gradual fall of plant leaves [113], efficient irrigation and optimal use of fertilizers [114], adaptation to saltwater consumption [115,116], patterns of water consumption between pastures and shrubs [117], reversible photoprotective mechanisms [118].

## 2. Period II (1997–2014)—Development.

This period is characterized by greater research development with 909 publications, representing 41.11% of the total. These publications concentrate the majority of citations in this field of study (70.09%). In this period, there is a growing interest in climate change adaptation, satellite mapping, modelling, water management and agriculture. Some research addresses climate change and its effects on ecosystems and species [119], grasslands [120], steppe [121], land use [122,123] and agricultural soils [124], as well as the effects of climate change on water resources [125,126], water stress [127], soil water availability [120], evapotranspiration [128], runoff farming [129]. Other researchers address the use of satellite mapping to map the use of water resources [130], evapotranspiration [131,132], vegetation dryness [133] and groundwater [134].

In this period, some relevant studies are presented on mechanisms and technologies that seek to improve water use efficiency in agriculture [135], given the food production projections [136]. One of the most important studies in this field is the satellite mapping of evapotranspiration in agriculture [131]. In addition, research studies the influence of mountainous areas on the supply of water resources [137], environmental degradation as an aggravating factor of water scarcity [138], and the places where arid lands expand and increase [27].

## 3. Period III (2015–2021)—Maturity.

Finally, the third-period analysis shows a growing interest on the part of the scientific community in the subject of study, due to the increase in publications, with a total of 1214 (55.18%) and 12,937 citations (Figure 2). The average annual production exceeds 170 documents, registering a peak in 2021 (266 documents). Evidence corroborates that this field of study is booming. Some studies cover the selection of suitable vegetation for reforestation [139] and replanting species' positive and negative effects [140]. Furthermore, food sustainability strategies improve crop yields under stress conditions [141,142]. Solutions and best practices in water resource management [143] adopt measures such as wastewater management for the circular economy [144]. Likewise, water use models and basin monitoring allow knowing their fluctuations [145] and vulnerability and promote the sustainable use of freshwater [20,146,147]. In this period, some topics observed in the previous period continue to be investigated, as well as new additions, such as water stress [148–152], water scarcity [153–157], water use efficiency [158–162], irrigation deficit [158–164], evapotranspiration [165–167], climate change [168–170] and remote sensing [158,171–174].

To assess whether the scientific production in water scarcity in semi-arid zones fits the Price's Law of exponential scientific growth [175], it has been tested with regression models to obtain the model with the best adjustment to data. The increase in production adjusts to an exponential curve (according to the equation  $y = 0.845e^{0.1203x}$ , Figure 2) given that the value of  $R^2$  (coefficient of determination) is 0.9875, according to Price's law [175]. The value of the coefficient close to one guarantees that the field of research is growing [176].

### 3.1.2. Language and Type of Documents

About the documents analysed, the thematic area of most significant interest is agriculture and biological sciences (31.1%) since sustainable agriculture is one of the most critical challenges facing water scarcity [177,178]. The following fields are environmental sciences (29.5%) and earth and planetary sciences (12.9%). The publications comprise 10 languages, where 93.1% are written in English and 3.4% in Chinese [179,180]. The predominance of English is because it is a language that facilitates international collaborations among researchers [135,181]. Other minor languages are Portuguese, Spanish, French, Persian, German, Italian, Japanese, and Russian. Regarding the type of documents, 83.8% correspond to scientific articles. Figure 3 shows other documents used in this knowledge structure, where a smaller group of documents (0.5%) corresponds to books, notes, erratum, and short surveys.

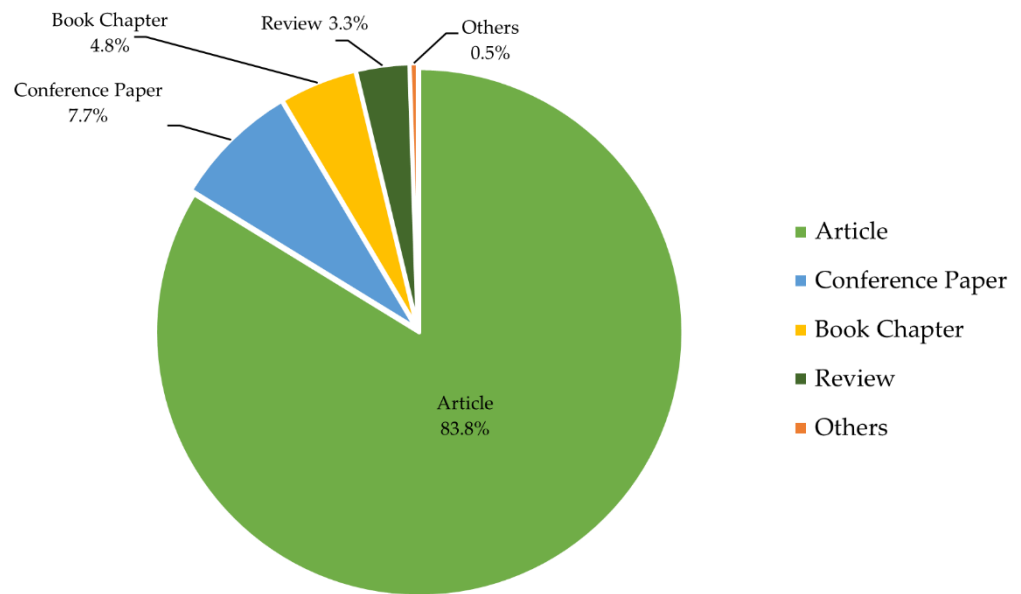


Figure 3. Distribution of scientific production according to the type of document.

### 3.1.3. Contribution by Countries

The review of scientific production by country allows knowing the regions/countries with the highest number of scientific publications related to the research field using the affiliation location of the authors [182,183]. The study covers 61 countries, with the most significant contribution coming from developed countries compared to developing countries. The map in Figure 4 presents a colour classification of production by country. ArcGIS 10.5 software generated this map.

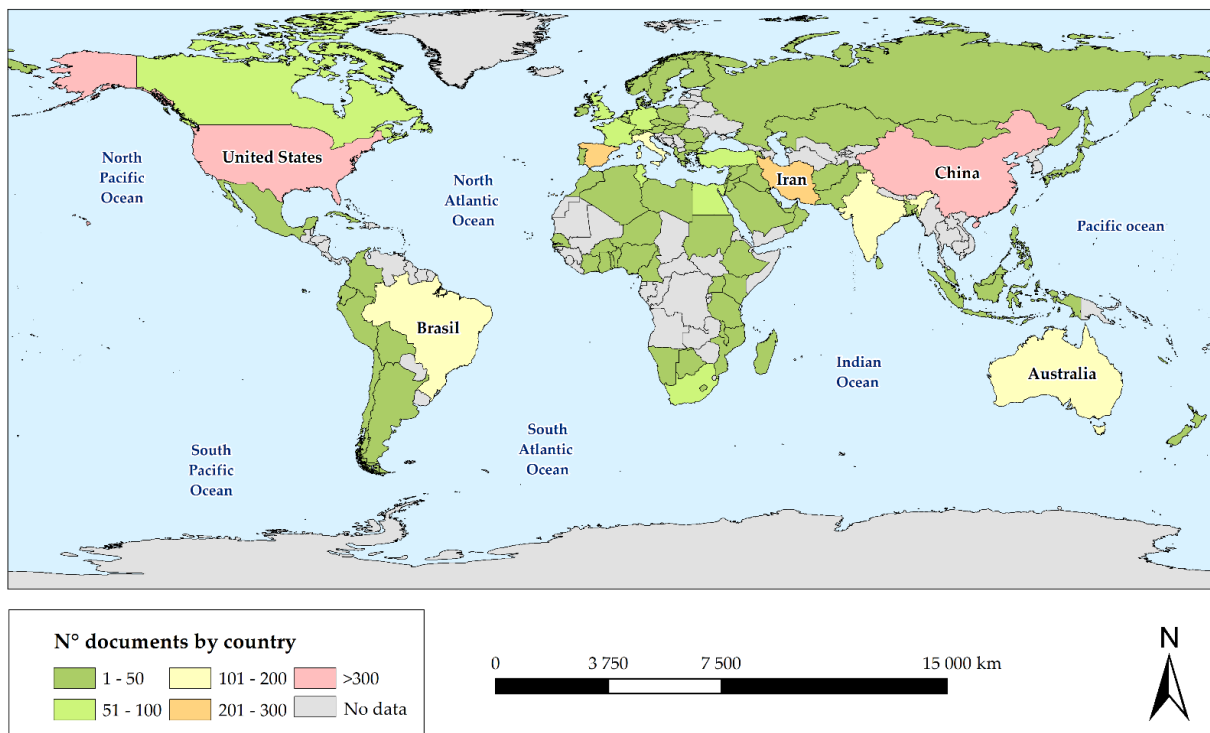


Figure 4. Distribution of scientific production by country.

The results indicate that the United States and China have the most considerable contribution, followed by Spain, Iran, Brazil, India, and Australia, in hierarchical order. The

top-three contributing countries also have the highest citation rates, followed by Australia and France. Research indicates projected scarcity conditions for 2050 in southern Mexico, southern and midwestern United States, northern Africa and China, eastern and central Asia, the Middle East, and north-western Brazil [184,185]. These aggravating conditions estimate social impacts that require immediate actions [27].

The collaboration between the first three countries (United States, China and Spain) established an evolutionary review of irrigation techniques for sustainable agriculture [186]. The United States and China present the most significant collaboration with 74 documents. The most-cited cooperation is a study that determines the expansion of drylands [27]. In addition to the analysis of efficient reforestation in China [138], they collaborate in research on models for decision-making [145,171,187,188], especially in agricultural issues such as water absorption and optimal irrigation in plants [189–195].

The United States collaborates on 18 documents with Spain, the most-cited research being the treatment and use of wastewater [196]. In addition, these countries investigate the effects of climate change in the Mediterranean [197] and the interaction between plants and irrigation [198–203]. Furthermore, the United States and Iran study the effects of water stress on plants [148,204,205] and collaborate with Brazil to investigate adaptation strategies to water demands [206,207]. Finally, the collaboration with Japan on satellite mapping of evapotranspiration is its most-cited research [131].

China and Spain investigate soil moisture and plant restoration [208]. In addition, China has collaborations with other Asian countries, such as India and Pakistan, where it researches management strategies for agriculture [162,209,210], climate change [211,212], water stress mitigation, and efficient water use [213,214]. The most-cited research from China has collaboration with France [140].

### 3.1.4. Most-Cited Documents

Citations of publications allow the evaluation and identification of studies in the field [37]. The scientific production analysed covers 2206 documents with 51,518 citations. Table 1 presents the 10 most-cited documents. These documents represent 10.8% (5585) of the total citations. The studies investigate global satellite mapping [27,131,137], effects of climate change [119,138,140] and especially agriculture [120,135,136,215]. Of these investigations, four are from journals from the United Kingdom [119,120,140,215], three are journals from the Netherlands [135,136,138], and three were from the United States [131,137] and one from Germany [27].

**Table 1.** Most cited documents.

Rank	Autor	Article	Journal	CIT <sup>1</sup>
1	Allen R.G., et al [131]	Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)-Model	Journal of Irrigation and Drainage Engineering	1095
2	Feng X., et al [140]	Revegetation in China's Loess Plateau is approaching sustainable water resource limits	Nature Climate Change	663
3	Viviroli D., et al [137]	Mountains of the world, water towers for humanity: Typology, mapping, and global significance	Water Resources Research	617
4	Deng X.-P., et al [135]	Improving agricultural water use efficiency in arid and semiarid areas of China	Agricultural Water Management	573
5	Hughes L. [119]	Climate change and Australia: Trends, projections, and impacts	Austral Ecology	538
6	Feng S., Fu Q. [27]	Expansion of global drylands under a warming climate	Atmospheric Chemistry and Physics	458
7	Ward S.J.E., et al [215]	Responses of wild C4 and C3 grass (Poaceae) species to elevated atmospheric CO <sub>2</sub> concentration: A meta-analytic test of current theories and perceptions	Global Change Biology	455
8	Liu W., et al [120]	Predominant role of water in regulating soil and microbial respiration and their responses to climate change in a semiarid grassland	Global Change Biology	412
9	Cao S., et al [138]	Excessive reliance on afforestation in China's arid and semi-arid regions: Lessons in ecological restoration	Earth-Science Reviews	387
10	Wallace J.S. [136]	Increasing agricultural water use efficiency to meet future food production	Agriculture, Ecosystems and Environment	387

<sup>1</sup> CIT: Citations.





addition, these studies assess how water depletion affects crop yields [234,245,247,248] and evapotranspiration as a function of reforestation and biomes [249,250].

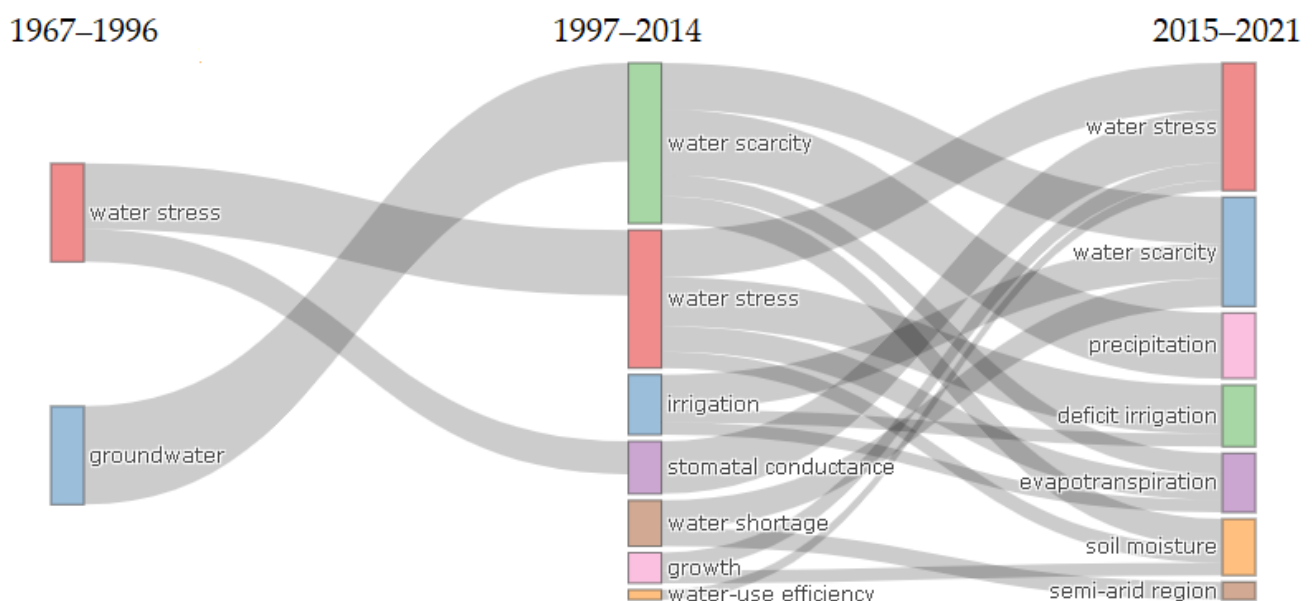
Cluster 4 (yellow colour) “water stress” presents water stress and water footprint as prominent terms, out of 10 items with 365 occurrences. In this cluster, the adaptation of plants to limited water availability is studied [112,178]. The analysis of the effects of water scarcity on food and meat production [207,251–253] and the evaluation of the impact on water consumption and use by human activities [185,254], land use [230], rainfall variability and aquifer recharge [255–257].

In cluster 5 (purple colour), “water productivity”, the terms water productivity, dry-land and food security stand out. This cluster comprises nine items with 145 occurrences. The research relates crop productivity prediction models to drainage simulation, evapotranspiration and nutrient regulation [150,225,258]. Also, efficient crop, water and soil management is studied [209,245,259], especially for food security [153,224,260,261].

Cluster 6 (light blue colour) “soil moisture” comprises seven items with 122 occurrences, where soil moisture and soil water content are its most relevant terms. This cluster includes water conservation, humidity and soil degradation research, given its close relationship with plant cover [194,262–264]. Studies suggest vegetation influences drainage networks, runoff, and hydrological patterns [265–268]. In addition, the effects on crops against nutrient content and carbon uptake are studied [269–271].

Cluster 7 (orange colour), called “model application”, encompasses six items with 87 occurrences and presents the terms modelling and nitrogen among the most important. The articles in this cluster analyse models that include simulations in conjunction with field observations. These models study the relationships between soil, water, atmosphere and plants for predictions of changes and behaviours [236,272–275]. In addition, the studies analyse management models for allocating water resources [188,276]. Finally, the research evaluates the relationship between soil type, water/nutrient use, and seasonal changes related to crop productivity [204,215,277–279].

When considering the evolution of the various topics in this field of study, it was visualized using a Sankey diagram (see Figure 6), which allows multiple attributes to be observed under the same graph [91]. This diagram was made with the Bibliometrix R-Tool software, using the Biblioshiny library. Figure 6 shows the evolution of the different themes in periods I (1967–1996), II (1997–2014) and III (2015–2021).



**Figure 6.** Sankey diagram showing the thematic evolution of water scarcity in semi-arid zones.

In the first period, it is observed how water stress and groundwater stand out as the main research topics. In the second period, these main themes are broken down into water stress related to stomach conductance and groundwater with water scarcity. The latter was the largest field of research and appeared to new topics such as irrigation, water shortage, growth, and water-use efficiency. Water shortage appears as a concept related to scarcity driven by the average availability of water per inhabitant, which differs from water stress when the demand for the resource exceeds the amount available. In the last period, the two themes of water stress and water scarcity continue to be a topic of interest. However, new themes such as precipitation appear, which are related to changes in the extreme climatic events that the planet experiences, a phenomenon that is intensified in the semi-arid region. This period is important because it shows how climate change generates other problems for the scientific community, such as increasing the irrigation deficit and its relationship with food security.

Additionally, Figure S1 exhibits the evolution of the themes that the scientific community has used with a frequency of 10 keywords. This figure highlights how germination issues are displaced by applications of Geographic Information Systems (GIS) tools. GIS has undergone advances in its use, generating new topics of interest, such as the Soil and Water Assessment Tool (SWAT). SWAT develops hydrological models to address environmental problems. His study in recent years is opening a critical potential line of research.

### 3.2.2. Journal Co-Citation

Co-citation is the frequency with which two journals are cited together [280]. Since citations are a measure of influence, this allows for mapping the flow of research [48,218] and insight into the intellectual structure of the field [43,281]. Thus, the more frequent the citation, the more likely there is a similarity between their research fields. This analysis results in the academic community of the area in question [43,282].

Cluster 1 (red colour) "Hydric resource management" encompasses 46 journals with 8576 citations, where the following stand out: Journal of Hydrology (J. Hydrol., 1692 citations), Desalination (600), Water Resources Management (Water Resour. Manag., 579) and Science of the Total Environment (Sci. Total Environ., 518 citations). These journals originate in the Netherlands and cover hydrology, environment, and management strategies.

Cluster 2 (green colour) "water management in agriculture" presents 10,711 citations in 42 journals. In this cluster, the journals with the most citations are Agricultural Water Management (Agr. Water Manage., Netherlands, 3484 citations), Irrigation Science (Irrig. Sci., Germany, 798), Journal of Experimental Botany (J. Exp. Bot., United Kingdom, 629). These journals address topics related to agriculture, irrigation, and plant sciences.

Cluster 3 (blue colour) "production agriculture" includes 34 journals with 6916 citations. In this cluster, the following stand out for their number of citations: Journal (Agron. J., United States, 1234), Field Crops Research (Field Crops Res., Netherlands, 842) and Plant and Soil (the Netherlands, 687). These journals present experiments and models of crops, ecology, and plant-soil interactions.

Cluster 4 (yellow colour) "natural and social water sciences" has 34 journals with 8379 citations. His most notable journals are Water Resources Research (Water Resour. Res., United States, 911 citations), Agricultural and Forest Meteorology (Agr. Forest Meteorol., Netherlands, 900), and Remote Sensing of Environment (Remote Sens. Environ., United States, 812). These journals deal with water, plant, and soil science topics, sometimes using remote sensing as a prominent factor.

Cluster 5 (purple colour) "ecology and environment" has 28 journals that include 4,752 citations, among which the following stand out: Oecologia (Germany, 540 citations), Journal of Arid Environments (J. Arid Environ., United States, 498), Tree Physiology (the United Kingdom, 483). The studies of these journals include models and applications of ecology, botany, ecosystems, and the environment.

Cluster 6 (light blue colour) "engineering in agriculture" comprises eight journals with 929 citations. Transactions of the Asabe (Trans. Asae, United States, 222 citations), Journal

of Irrigation and Drainage Engineering (J. Irrig. Drain. Eng., United States, 176), Irrigation and Drainage (Irrig. Drain., United Kingdom, 156). These journals present topics on the application of technologies for water management in agriculture.

#### 4. Discussion

The intellectual structure of water scarcity in semi-arid zones encompasses 2206 documents with 51,518 citations, distributed over 54 years of studies (1967 to 2021) with the collaboration of 61 countries. This scientific production presents 10 languages, highlighting English and publications of the type of scientific articles.

Research in this field has shown a growing interest on the part of the academic world, given that inefficient management of water resources, soil and crops are often added to water scarcity [209]. Thus, scientific production presents two periods of progress, defined for the 20th and 21st centuries. This last period registers an accelerated increase in research (93.1%), marked by the relationship between climate change and water scarcity [187,228,283], global trends in resource consumption patterns, technological development and population growth [66,227,234,284].

The countries with the most significant contribution to this scientific production are the United States and China (Figure 4). Both are close collaborators due to their high population rates and their patterns of water resource consumption, among which massive agricultural production stands out [254,285,286]. However, the most outstanding journals and research on the subject belong to the Netherlands, United Kingdom, United States and Germany.

The networks of co-occurrence of keywords and co-citation of journals served to analyse the intellectual structure of the research.

The keyword network presents a bimodal model that exhibits two central areas of interest, led by the terms “water scarcity” and “water stress” (Figure 5). This duality may be due to the pressure exerted on water, especially by extracting this resource for agricultural consumption (70%) and managing the water–energy–climate nexus [147,227,286]. In this figure, the red cluster led by water scarcity presents 42% of the co-occurrences of the topics related to the management of conventional and unconventional water resources [187,221,226,228,233]. In turn, water stress appears as the most popular term, with 9.7% of the co-occurrences. The terms water stress, evapotranspiration and water use efficiency are closely related to the efficient use of soil-water and crop productivity [159,214,234,237,245,273,287]. The cluster themes “model application”, “soil moisture”, and “water productivity” (orange, light blue and purple) function as a link between the main themes (Figure 5) [187,246,260,288].

Four groups stand out in the network of journals (Figure 7). The first is the red and yellow groups; these relate remote sensing to water resource management and concentrate the most considerable number of journals (24%). The green and blue groups are the second; these represent journals related to agriculture. The green cluster contains the most significant citations (26.6%). The third, the purple set, shows a close relationship with the yellow and green groups, which allows relating themes of botany, forest agriculture and ecology. Furthermore, the fourth, the light blue cluster (in-engineering), functions as a link between the journals on water resource management and agriculture (red and green, respectively).



- The reduction of future precipitation in arid and semi-arid zones and measurements of hydric stress [181,245].
- 3D aquifer models and groundwater potential mapping [246,247].
- Models for the allocation and management of water resources [248].
- In agriculture, future trends are:
- Accurately detecting water stress by varying environmental conditions and hydrological flow control factors [149,250].
- Development and application of irrigation techniques for the efficient use of water, control in the use of fertilizers and mitigation of soil contamination [163,191,291].
- Use of conventional and unconventional water resources for supply. Trends include:
- New alternatives of unconventional resources and studying their environmental impacts [292].
- Use of alternative energy sources, development, adaptation and improvement of desalination models and techniques, depending on the place of application [243,293].
- Sustainable groundwater extraction, water transfer, rainwater harvesting, and aquifer recharge structures [294–296].
- Recycling treated wastewater as a circular economy for irrigation and groundwater protection [157,297].

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/w14172685/s1>, Figure S1. The main trend topic keywords are associated with the literature on water scarcity in semi-arid zones in the Scopus database.

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