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Bibliometric Analysis of Groundwater's Life Cycle Assessment Research

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Abstract: Groundwater is an important water resource that accounts for 30% of the world's freshwater. 97% of this extracted groundwater is for drinking and human use. Due to anthropogenic activities, this resource is affected and, consequently, its life cycle is modified, changing its natural state. This paper aims to analyse the scientific production that deals with the study of groundwater's Life Cycle Assessment (LCA), using bibliometric methods. Thus, it contributes to the evolution of knowledge of this resource in terms of its use (environmental, economic and social). The methodological process includes: (i) selection and analysis of search topics in the Scopus and Web of Science (WoS) databases; (ii) application of Bibliometrix and Visualisation of Similarity Viewer (VOSviewer) software to the data collected; (iii) scientific structure of the relation of the topics groundwater and life cycle, considering programme lines and relations in their sub-themes; (iv) literature review of Author keywords. A total of 780 papers were selected, 306 being from Scopus, 158 from WoS and 316 published in both databases. The time evolution of the analysed data (publications) indicates that groundwater LCA studies have seen exponential growth (between 1983 and 2021). In addition, it has three development periods: introduction (years between 1983 and 2001), growth (between 2002 and 2011) and maturation (between 2012 and 2021). At the country level (origin of contributions authors), the USA dominates the total scientific production with 24.7%, followed by Denmark with 12.8% and 10.3% for China. Among the main topics of study associated with LCA are those focused on: the proposal of remediation methods, the application and development of technologies and the use of water resources by the urban community. This study allows establishing new trends in agricultural development issues about irrigation efficiency, wastewater reuse, mining and treatment, climate change in a circular economy scheme related to sustainability and life cycle assessment.

Keywords: aquifer; lifecycles; sustainability; co-occurrence analysis; scientometric analysis

1. Introduction

1.1. Overview

Freshwater accounts for 3% of the earth's available water resources [1]. Despite its small fraction, its contribution is significant in the face of increasing demand for this resource worldwide (1% growth since the end of the 20th century) [2], and in some places, it is the only source of this resource. This global water demand or scarcity is caused by climate change and poor management strategies [3,4]. Another cause is the unstoppable growth of the world's population, the urbanisation of new territories and increasing industrialisation [5–7]. In general, water is an irreplaceable and fundamental element that contributes to the development of human life and society, making it a subject of great interest in the last three decades [8–11].

Freshwater is in diverse ecosystems such as ice caps, lakes, rivers, swamps, soil moisture and groundwater. Groundwater is a natural resource hidden in the earth's crust, representing a not visible ecosystem to life on the surface. It is also considered a sustainable water resource that is part of the earth's water cycle, which flows or is recharged by the natural energy provided by the sun [12–14]. Groundwater has an important role in the storage or reserve of freshwater, accounting for 30.1% of the planet's total [15]. These reservoirs also contribute to lake and river formation by filtering fresh water to the land surface, forming flora and fauna ecosystems [16,17]. In addition, 97% of this extracted groundwater is used as a hydrological resource for developing the modern economy, mainly in human consumption, agriculture, domestic necessity and manufacturing [18–22]. Therefore, groundwater is in high demand worldwide, with approximately 800–1000 km^3 of water per year [23].

Physical and chemical methods exist for quality location and interpretation of these ecosystems in groundwater exploration [24–26]. There are also strategies for exploiting this resource, like natural production (i.e., springs or underground discharges, lakes, rivers) and artificial production (i.e., water wells with electric pumps or compressors) (e.g., [27–29]).

Living beings and renewable-non-renewable resources are part of a life cycle that hosts a start-to-finish process, understood as the whole process "from the cradle to the tomb" [30–32]. It encompasses conception, birth, adolescence, maturity, senescence and death [33]. At the beginning of the 20th century, the concept of the life cycle was of great interest in general biology, with studies focusing on the life cycle of an individual [34,35]. The life cycle is a maturational and general process of natural populations. This criterion has alternate conceptions such as lifespan and life-course, and they do not share the same meaning concerning reproduction that transcends an individual [36]. Life cycle theory is frequently used in production and industry, environmental impact assessment and has great significance in the mining industry [37]. In the industrial field, the life cycle considers the phases of a product from extraction, processing, distribution, transport, use and consumption to recycling and disposal [38].

Environmental problems and the limitation of natural resources strengthened the life cycle concept through global modelling research and energy audits [39]. Changes in weather patterns alter groundwater quality, like sea-level leading to saltwater intrusion [40–42]. On the other hand, anthropogenic activities affect the groundwater's life cycle, mainly by excessive fertilisers, animal manure, domestic water and solid waste [43,44]. Another activity is the industrialisation of mining in the exploration and production stages, which affects the groundwater environment, reducing the quality of these waters [45,46]. These factors mark an environmental and human health concern, as polluted water accumulates heavy metals in linked living systems [47]. Tackling groundwater contamination issues is key to environmental remediation, considering sources, possible reuse of contaminated resources, controls and mitigations of pollutant factors [48,49].

LCA is an internationally standardised methodology for assessing the environmental impact of products, processes and activities in all stages of the life cycle [50]. The relationship of groundwater to the life cycle is a key factor in sustainable development and special attention by governments, society and the scientific community. According to Lemming [51], LCA "is becoming an increasingly widespread tool in support systems for environmental decision-making regarding the cleanup of contaminated sites". LCA is considered the most appropriate way to achieve integrated sustainability from remediation projects like those of wastewater treatment [52,53]. In the case of groundwater, some authors [54] focus their analysis on a system boundary of the LCA study that contains: the construction of tube wells, groundwater abstraction, water distribution and disposal of the material after its useful life. The LCA of groundwater has several stages from the origin to the end of its use, such as extraction, treatment, consumption and reuse of resources [55,56]. This process has been applied in papers of the agricultural energy sector [57], primary and wastewater treatment [58] and urban water supply systems [59].

Bibliometric analysis is a field of scientific research that identifies the cognitive structure and intellectual relationships through quantitative analysis of performance, like documents, authors, countries, journals and institutions [60,61]. This analysis uses systematic techniques that make it easier to obtain transparent bibliographic information to know a specific field [62]. It also explores in-depth the topics that the scientific community considers relevant in social, economic and environmental sustainability [63]. In addition, bibliometrics has contributed to various academic fields like Earth Sciences [64], sustainability [65], environment [66], engineering [67] and industry [68].

In bibliometric studies oriented towards environmentally sustainable development and climate change, similar to those addressed in this paper, the contribution of this systematic approach allows for a better characterisation of these issues [40,41,43]. The Scopus and Web of Science (WoS) databases provide extensive coverage of scientific disciplines, ease of access and visualisation for the search and collection of scientific information [64,69]. For example, WoS has provided information since the beginning of the last century, hosting approximately 1300 prestigious journal articles [70] and 256 disciplines [71,72]. The database includes more than 8700 academic journals in various fields, like natural sciences, engineering, biomedicine, social sciences, arts and humanities [73]. In addition, it presents a wide range of bibliometric studies [74,75].

1.2. Aim and Scope

This paper aims to analyse the scientific production that addresses groundwater's life cycle analysis through bibliometric methods to contribute to the knowledge of subject evolution within the framework of its utilisation (environmental, economic and social).

The bibliometric study seeks to describe the groundwater life cycle from activity determination, problems and importance of the topic; a detailed description of data mining and a presentation and analysis of results based on the combination of bibliometric data to determine the performance, developments and trends in the study field.

2. Materials and Methods

The methodology proposed in this work comprises three phases that allow this analysis to be carried out (Figure 1): (i) selection and analysis of topics in Scopus and Web of Science (WoS) databases; (ii) application of Bibliometrix (developed by Massimo Aria, Naples, Italy) and VOSviewer software (developed by Jan van Eck and Ludo Waltman, Leiden, Netherlands); (iii) scientific structure; (iv) literature review of Author Keywords.

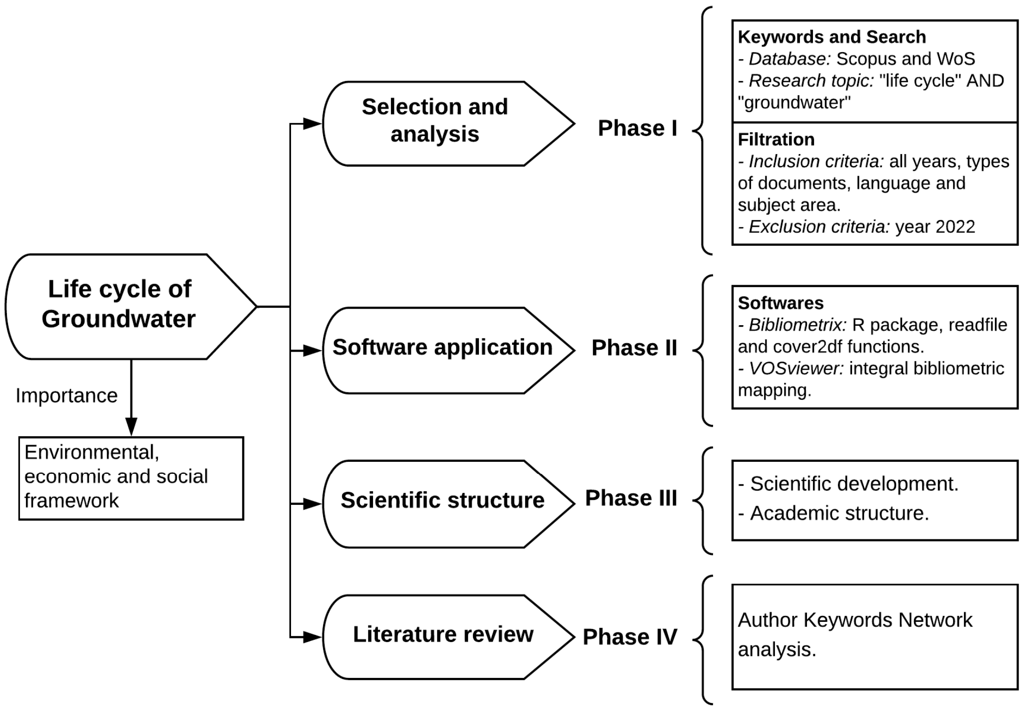

Figure 1. Diagram of study's methodology. Based on [76,77].

2.1. Phase I: Selection and Analysis

The relationship between groundwater and the life cycle has a broad scope in various fields of science (e.g., Environmental Science and Engineering). The search considered the topic search "life cycle" AND "groundwater", searching on titles, abstracts and keywords in the Scopus and WoS databases [78,79]. These databases have filtering mechanisms that allow grouping the information based on the criteria considered, such as the terms of inclusion (i.e., all types of documents, language, years and subject area) and exclusion (i.e., the current year 2022) [80]. They also allowed the selection of various download format options. According to the software to be selected, the present study collected files in Comma-Separated Values (CSV) and BibTex format in Scopus, Excel and Plain Text File in WoS for the processing-analysis of the information.

Files obtained from Scopus and WoS require cleaning records with inconsistencies prior to merging and using the information. The data were downloaded after filtering the information in the databases, obtaining 630 documents from Scopus and 474 from WoS. The data processing consisted of eliminating records without author names, titles and year of publication in CSV, Excel, BibTex and Plain Text File, finding eight inconsistencies in the Scopus formats, resulting in 622 Scopus documents and 474 WoS documents. Subsequently, this study considered eliminating Scopus publications found in WoS (316 duplicate documents) due to the diversity of subject areas [69] and the higher quartile quality of journals in WoS [70]. It also has an important data organisation that allows for complete and less inconsistent information [81]. After this process, the records were 474 documents in WoS and 306 in Scopus, generating 780 documents for the graphs of top author production over time, most relevant sources, country scientific production and keywords frequency, as well as the analysis of scientific production, Author Keywords and literature review. On the other hand, the subject area analysis used the 622 Scopus documents and WoS publications to involve their academic distributions.

2.2. Phase II: Software Application

- Bibliometrix: is an R package that allows analysing bibliometric data using specific tools [82,83]. This study used RStudio version 4.1.2, setting up the R environment package. Bibliometrix uses the functions readfile (loads and converts data into UTF-8) and convert2df (extracts and creates a data frame). The software processed the information through a codification in RStudio, which allowed the automatic cleaning of the records, considering keeping the WoS archives and eliminating duplicates from Scopus [84,85]. The data are generated using R's generic (plot) function [86].

- Visualisation of Similarity Viewer (VOSviewer): the clean CSV file was entered into the program for the generation of the Author Keyword map, indicating the link between the most frequent words related to the life cycle of groundwater. In recent years, this software has been applied in several different areas (e.g., [66,78]). This software made it possible to analyse the intellectual structure of this research field through the construction and visualisation of a comprehensive bibliometric mapping [87,88].

2.3. Phase III: Scientific Structure

This work is made up of two sections, the scientific development, which contains the intellectual approach, and the academic structure, which shows the intellectual links. The first one develops a knowledge analysis of scientific production, top author production over time and main journals-subject areas [89,90]. On the other hand, the academic structure makes it possible to visualise the intellectual environment to characterise the links between various disciplines and countries [91,92].

2.4. Phase IV: Literature Review of Author Keywords

This section is based on a systematic search and classification related to Author Keywords clusters analysis, considering all types of documents, such as scientific articles, books and conference papers. The review details the studies' importance or scientific interest on the same topic. Although the research results reflect various documents (780), the review compiles the publications based on the Author Keywords.

3. Results

The first phase of the search allowed the identification of 622 documents in Scopus and 474 in WoS that individually belong to this field of study. However, this information presents 316 duplicates that are eliminated, considering 780 publications in the processing or analysis. Therefore, this information corresponds to 306 documents only from Scopus and 158 from WoS, and 316 from both databases (Figure 2).

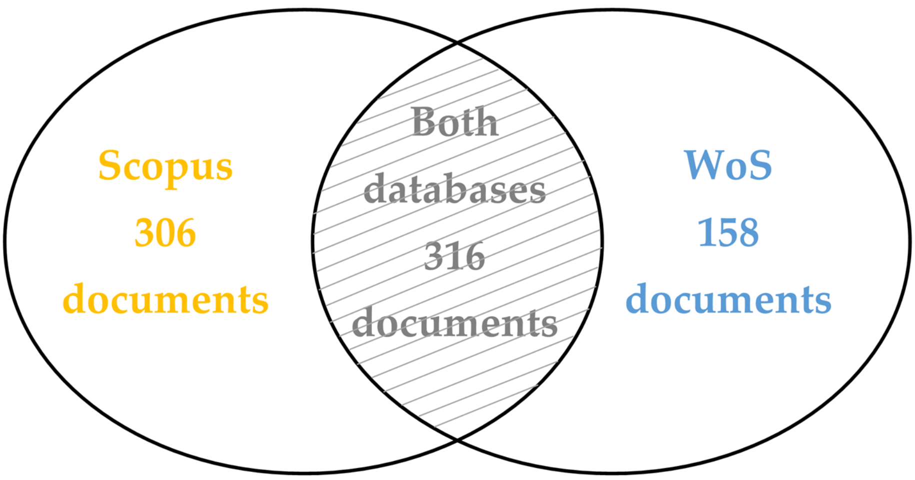

Figure 2. Total number of documents collected in the databases.

Table 1 shows an overview of the information used in the corresponding analyses, based on the data fusion obtained in the two databases' compilation.

Table 1. General information based on the two bases merger.

Items	Quantity
General Information	
Documents	780
Sources (Journals, Books, Conferences)	450
Average years from publication	7.72
Average citations per documents	23.76
Average citations per year per documents	2.906
Author's Keywords	2104
Authors' information	
Authors	2672
Authors of single-authored documents	61
Authors of multi-authored documents	2611
Authors' collaboration	
Single-authored documents	66
Documents per Author	0.292
Co-Authors per Documents	4.17

3.1. Scientific Development

3.1.1. Scientific Production

Figure 3 shows a distribution of publications over time. According to Price's Law [93], the subject presents an exponential growth due to the significant production in the last 16 years (2006–2021), marking the peak of this research field (86.5% of production).

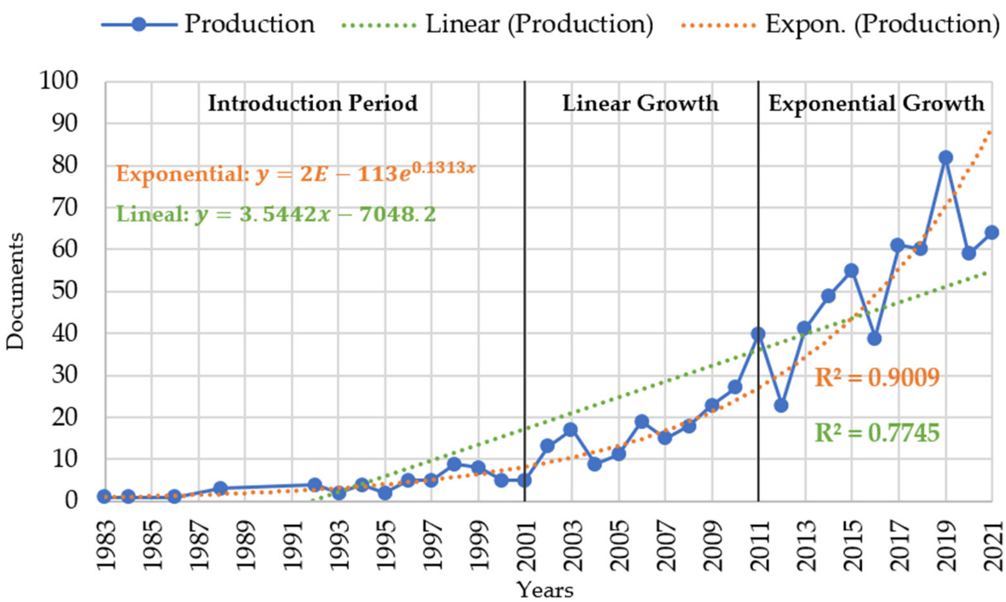

Figure 3. Scientific production of groundwater and life cycle relationship. Documents: 306 documents only from Scopus and 158 from WoS, and 316 from both databases.

The scientific production comprises three periods of development: introduction (1983–2001), linear growth (2002–2011) and exponential growth (2012–2021).

- Introduction period. The first period consists of 55 publications, representing 7.05% of the total. The results show that the interest in the groundwater theme with the life cycle started from the environmental problem–solution relationship and water trade, presenting studies of life cycle alterations in water ecosystems [94,95], contaminated resources treatment [96] and water desalination for urban distribution [97]. In subsequent years, research has concentrated on biological analyses in water ecosystems [98–100], hazardous waste transport [101], water abstraction mechanism [102] and groundwater risk assessment [103]. In addition, the first studies related to LCA of environments polluted by industrial and urban activities are starting [104,105].

- Linear growth period. This period shows 192 documents representing 24.6% of the total, with a growth that marks the scientific interest in this field of research. The information shows the importance of implementing LCA in groundwater ecosystems and related environments (river formation, lakes, lagoons), which are affected by climate change and anthropogenic activity [106–109]. Technological innovation has a relative contribution to solving these problems, like simulation programmes that project the behaviour of anthropogenic factors on natural resources [110,111]. Subsequently, it allows the generation of a detailed analysis for environmental remediation [112,113].
- Exponential growth period. The last period represents the key to exponential growth, grouping 533 documents (68.3% of the total). The year 2019 presents the highest number of publications (with 82 documents), followed by the year 2021 (with 64), making it a constant growth field (Figure 2). This period shows the strengthening of research in this academic field with various topics, like trichloroethene contaminated areas assessment [114–116], surface to groundwater transition [117], acid rock drainage to glacial ecosystems [118]; as well as LCA related to brine treatment [119], dispersed alkaline substrate technology [120], electrokinetic in situ remediation [121] and filtration systems [122]. In addition, there are many studies related to environmental problems caused by mining and agriculture (major share of world trade today) [123–126].

3.1.2. Top Author Production over the Time

The scientific field shows a total of 2672 authors since 1983. This analysis shows the top 20, ranked by production time, paper numbers and total citations (Figure 4). These authors have a remarkable contribution to papers and citations, with publications dating back to 2004.

- Time of production: some of the prominent researchers have a long time of production. However, other authors have a shorter time of scientific development with outstanding production (e.g., Verones F., Liu Y., Manfredi S., Bjerg P.L., Godskesen B.). These authors generate publications related to ecotoxic impacts assessment of heavy metal leaching [127–129], ecosystem problems due to water consumption [125,130,131], wastewater and water use sustainability in the context of environmental impacts [132–134] and landfills environmental assessment [135–137].
- Number of papers: some authors contribute consistently with an average of two papers per year (e.g., Christensen T., Hauschild M., Hellweg S.). These present authors' studies on sustainable transport using reusable equipment [138], environmental simulation systems and solid waste assessment models [139,140] and environmental impact assessment [141–143]. Other authors have an average production of 1 to 1.6 papers per year (e.g., Pfister S., Verones F., Bjerg P., Bayer P., Rygaard M., Chen Y.), with studies analysing future water limitation by uncontrollable consumption [144,145] and urban water supply alternatives [146,147].
- Total Citations (TC): the most cited authors received up to 38.67 citations per year (Hellweg S., Pfister S., Verones F.), marking an important contribution to the scientific field. Researchers with lower productivity have a significant number of citations, averaging 13.58 and 32.89 citations per year (e.g., Bjerg P., Margni M., Lemming G.).

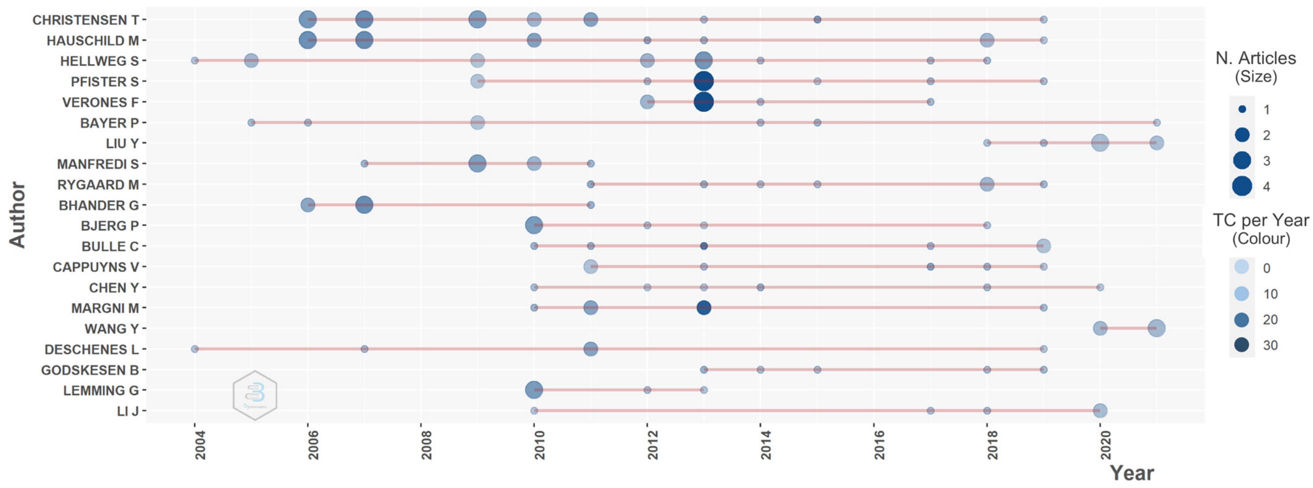

Figure 4. Number (N) of articles and the main authors' annual Total Citations (TC). Documents: 306 documents only from Scopus and 158 from WoS and 316 from both databases.

3.1.3. Most Relevant Sources

The analysis provides a general overview of the journals related to this academic field and the knowledge topics [148]. In general terms, the total output (780 documents) shows 450 journals from various subject areas. This section presents the top 20 sources from various subject areas with 249 papers (31.9% of the total) (Figures 5 and 6).

The groundwater and life cycle research rise are in journals, like Journal of Cleaner Production, International Journal of Life Cycle Assessment, Science of the Total Environment, Environmental Science & Technology, Waste Management and Water Research. These sources generate publications related to the areas of "Environmental Science", "Engineering" and "Chemistry" [149–151]. Other journals, like Sustainability, Water, Agricultural Systems and Resources, Conservation and Recycling, have a prominent participation in "Agricultural and Biological Sciences", "Social Sciences", "Energy" and "Economics, Econometrics and Finance" [152–155]. In addition, there are sources with less scientific production, like Energies and Applied Energy, belonging to the "Energy" area. However, these studies have an important collaboration in energy innovation, like biomass and friendly energy [156,157].

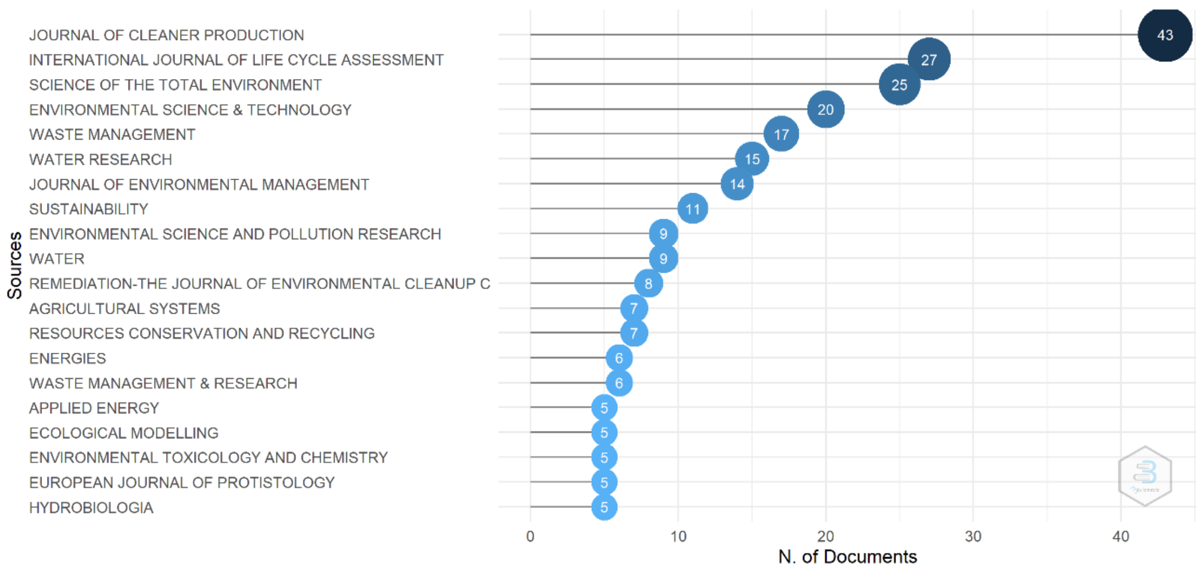

Figure 5. Journals with the highest number (N.) of documents in the field of study. Documents: 306 documents only from Scopus and 158 from WoS and 316 from both databases.

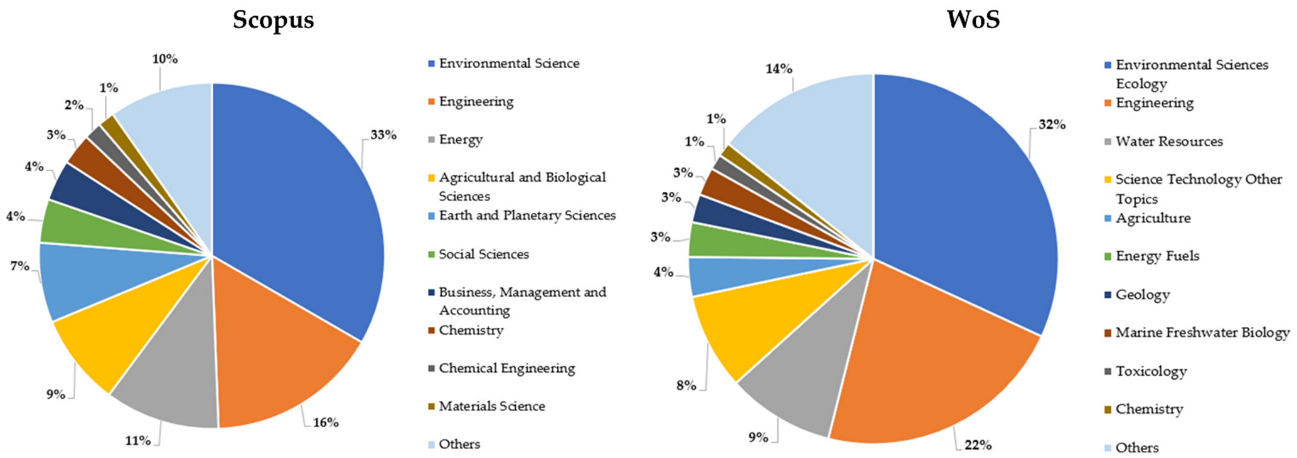

Figure 6. Main subject areas of the scientific field in Scopus and Web of Science (WoS). Documents: 622 Scopus and 474 WoS.

3.2. Academic structure

3.2.1. Author Keyword Co-Occurrence Network

This analysis allows the intellectual structuring of knowledge through a network of frequently occurring terms using the VOSviewer software [158]. The programme handled 2109 keywords using processing conditions through a thesaurus, such as similar words reduction, plural words and the number of keywords occurrences (five times) [159]. Therefore, 58 nodes comply with the variables mentioned above, forming seven clusters in total (Figure 7).

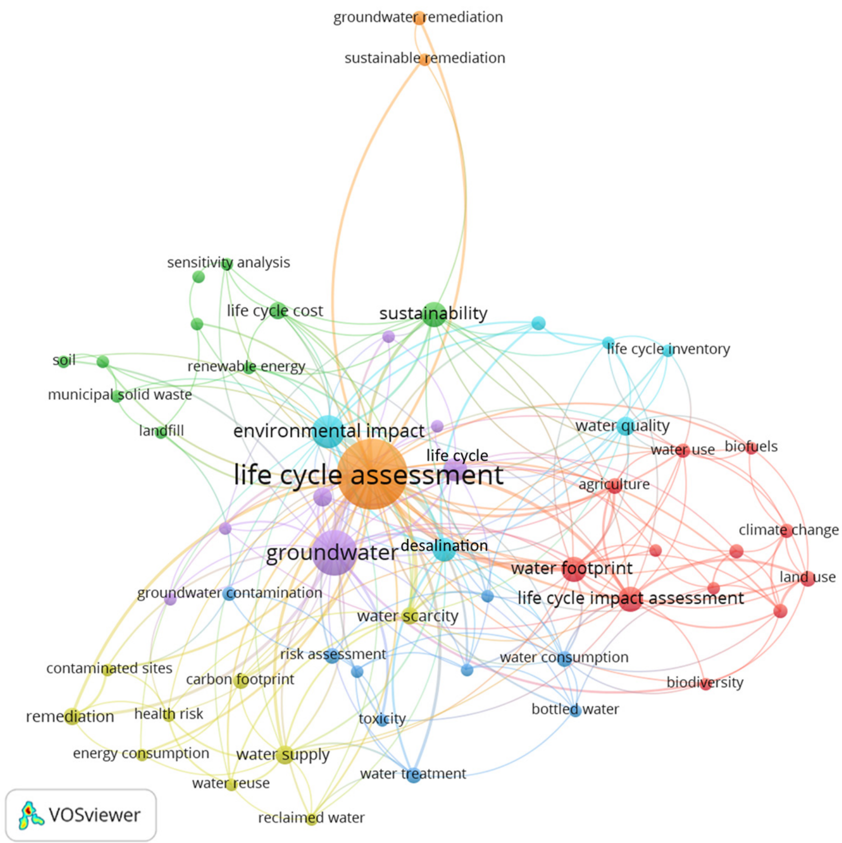

Figure 7. Author keywords network. Documents: 306 documents only from Scopus and 158 from WoS and 316 from both databases.

Cluster 1-"climate change and water use" (red colour), has the highest number of nodes (12 keywords) with 107 occurrences. This cluster presents studies related to water resources use, environmental issues and water distribution for energy production. Some researchers study the water supply mix in LCA [160], cause-effect to human health from contaminated water use [161], water footprint inventories [162,163] and Amazonian percussion by land and water use [164]. Other authors focus their studies on strengthening environmental impact assessment [133], environmental impact analysis for pollution and water consumption [145], ecosystem services assessment [165], biomass supply [166], economic decision-making [167], circular economy in water use [168] and environmental sustainability in agriculture [169].

Cluster 2-"sustainability" (green colour) is the second-largest cluster with 11 keywords and 74 occurrences. This node set presents municipal solid waste management and water treatment costs publications [170–172]. There are authors with studies characterising new perspectives for sustainable development, like the application of solar water heating systems [173], algal biodiesel [174], food system strategies [154] and multi-objective mixed integer linear programming [175].

Cluster 3-"mining and treatment" (blue colour), represents a set of nine nodes (60 occurrences). Topics are focused on water treatment for human consumption (bottling and drinking water system), like water quality analysis surveys [176], water footprint reduction [177], groundwater contamination by engineered nanoparticles [178], environmental impact assessment of water supplies [179] and primary water treatment for human consumption [180]. In addition, studies related to mining activity and its environmental consequences appear for the first time on a large scale [58,181,182].

Cluster 4-"water consumption and reuse" (yellow colour), integrates a total of nine nodes (69 occurrences) detailing a sequence of works on water pollution, remediation, reuse and scarcity. The researchers apply remediation systems for waste regeneration [183], potable water reuse for environmental and social benefits [184], technology assessment methods for water supply [185], nanotechnological remediation [186] and urban water management decision making [146]. Other studies present a monetary costs analysis of secondary impacts during environmental remediation [187].

Cluster 5-"wastewater reuse and groundwater pollution" (lilac colour), consisting of seven nodes (118 occurrences), deals with groundwater and the importance of protecting its life cycle, as well as topics related to wastewater, pollution and irrigation. Papers relate water reuse methods and agricultural-urban water use, such as tertiary treatment of wastewater in urban consumption [56,188], the water-energy nexus in energy-intensive systems and environmental impact [59] and absorption of nutrients from wastewater for agricultural irrigation [126]. On the other hand, there is work that focuses on sustainability in groundwater extraction through artificial production (submerged pumps) [189] and the application of sustainable adsorbents for wastewater defluorination [190]. Other studies analyse contaminant adsorption methods [132,191], the economic benefits of wastewater use [192] and Multiple Inlet Rice Irrigation [193]. In addition, some authors use simulators in agriculture for the water supply and anthropogenic control analysis [194].

Cluster 6-"environmental cycle" (light blue colour), has six nodes in total (82 occurrences). The works detail a similar content to other clusters (1 and 2), oriented to desalination, quality and environmental impact of water resources from groundwater ecosystems. Studies focus on ecological desalination with renewable sources [151,195], the environmental impact of industrial waters [196], economic-environmental development [128], shale gas development analysis [197], water footprint [198], life cycle inventory [199], expansion of urban water infrastructures [200] and dual-purpose pressure retarded osmosis desalination plants [201].

Cluster 7-"life cycle assessment" (orange colour) is the cluster with the smallest number of nodes (three). However, it has the highest frequency keyword in terms of the groundwater relationship with the life cycle, with 164 occurrences out of the total group (177). The section shows a variety of studies regarding LCA in an environmental, economic and social framework [202–206]. In addition, it presents studies of groundwater environmental remediation through various sustainable methods [183,207,208], the water-energy nexus in energy intensity and environmental impacts terms [59].

3.2.2. Country Scientific Production

The analysis presents an association rule between three variables that determine the relationship of an investigation [82,209]. This analysis shows the author-country-keyword intersection with a limit of 12 variables per category (Figure 8). A total of 72 countries have conducted scientific research on the life cycle of groundwater, led by the USA, Denmark, China, Germany and Switzerland:

- The USA has a contribution of 193 publications with the relevant participation of five authors and a presence of important keywords like "life cycle assessment" (in 62 papers), "groundwater" (54), "water quality" (19) and "water footprint" (7). This nation generates a work variety that focuses on the life cycle assessment of water resources in environmental impact areas, water quality, desalination and irrigation in agriculture.
- Denmark presents a contribution of 100 documents with the strong participation of six authors and seven main keywords. Like the USA, Denmark has an academic contribution to the life cycle and environmental impact assessment, contaminated water remediation and conventional desalination processes for urban and industrial consumption.
- China has 80 publications involving a contribution of 10 keywords and two relevant authors. In the academic literature, there are a variety of studies like those in the USA (e.g., life cycle assessment, groundwater, water footprint, remediation, water quality). However, the research boom began in 2015, determining its recent strength in this scientific field.
- Germany contributes with 67 papers featuring five main authors and seven highly related keywords. This nation shows a remarkable production (behind the USA), which determines the interest in studies on the environmental problem solutions and the groundwater life cycle protection.
- Switzerland presents a contribution of 59 publications with prominent authors (five) and keywords (three). This nation shows strength in sustainability studies linked to the environmental impact of water ecosystems, strongly involving assessment methods.
- Other countries also contribute to this scientific field (e.g., France, Canada, Australia, United Kingdom) and other remarkable production nations.

3.2.3. Keyword Frequency

This analysis presents the frequency of the main topics that allowed the selected study field's evolution (Figure 9). This section considers keywords that appear in at least three studies, placing the node in the year of the highest frequency. The information shows that scientific development begins with water treatment and biological studies of insects found in this resource. Subsequently, the work focused on pollution problems in groundwater ecosystems due to increasing socioeconomic demand at the global level. The issue involved the concepts of sustainable development, the management of toxic waste and the life cycle to ensure a balance between the protection of ecosystems and socioeconomic growth. However, the results were not significant, which allowed maintaining the environmental impact assessment processes and proposing new analysis strategies, such as life cycle assessment for water quality studies and decision making. This criterion is related to agricultural activities and urban water consumption, belonging to the keywords "water supply". On the other hand, water scarcity, water quality issues and energy demand have strengthened carbon, water footprint reduction studies, renewable energies implementation and wastewater reuse through water treatment methods. The information present in the last years (2020–2021) reflects a strong interest in the environment, wastewater reuse and circular economy issues.

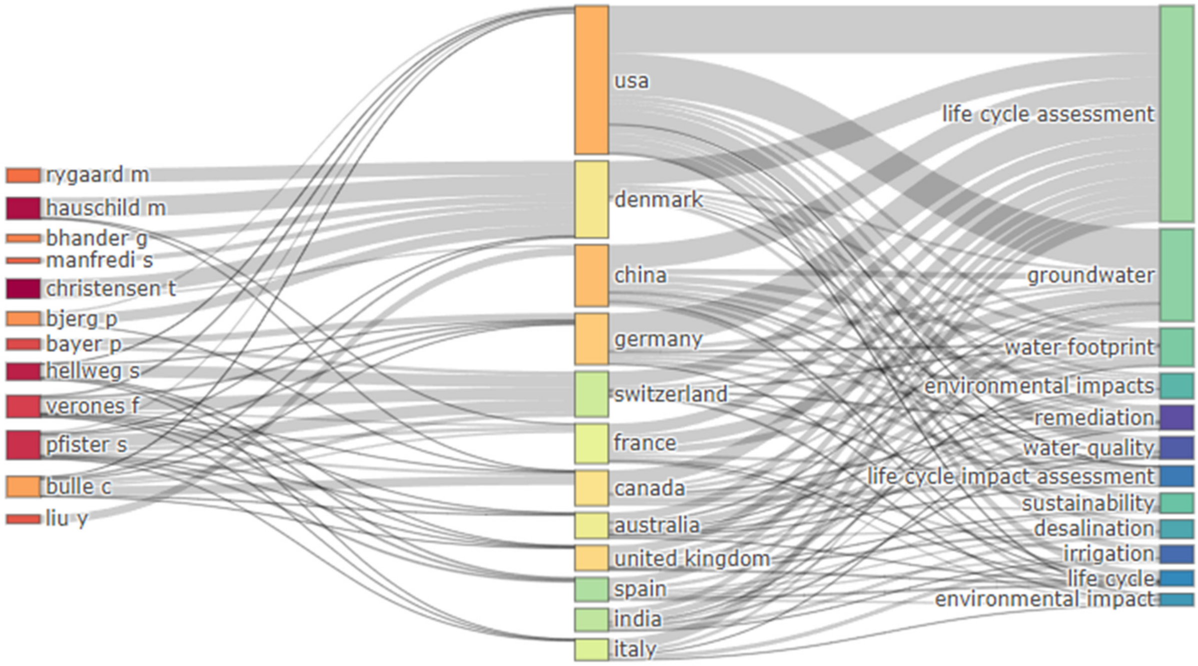

Figure 8. Three-fields plot (author, country, keyword). Documents: 306 documents only from Scopus and 158 from WoS and 316 from both databases.

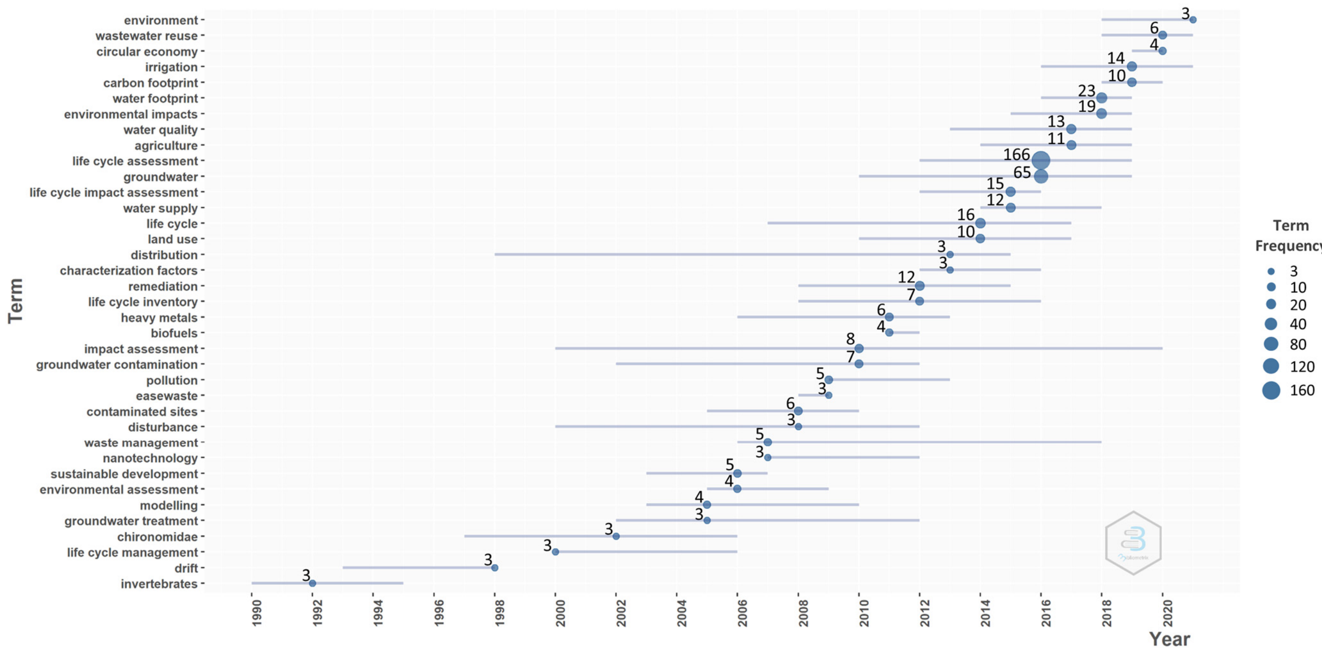

Figure 9. The trend of Keywords by year of the scientific field. Documents: 306 documents only from Scopus and 158 from WoS and 316 from both databases.

3.3. Literature Review of Author Keywords Clusters

This section identifies the findings of scientific works related to the keywords with the highest occurrence in each cluster. In general, the review presents the most representative papers of each cluster (1 to 3 publications), examining a total of 41 papers (Table 2). In addition, it is considered that the papers should respond to environmental, economic and social aspects.

Table 2. Literature review of Author Keywords in an environmental, economic and social aspect.

Clusters	Aspect	Author/Secondary Keywords	Description of Results	References
C 1 [1]	Environmental	Water footprint/water supply mix	Water supply mix (WSmix) benefits environmental profile and energy linkage, feasible in countries with different socio-economic conditions.	Leão et al. [160]
		Water footprint/amazonian percussion	The assessment methods identified that impacts from agricultural activity increase atmospheric and terrestrial fluxes. This study determined a lower impact intensification and the benefits of the water resources.	Lathuillière et al. [164]
	Economic	Water footprint/economic decision-making	Strengthens decision-making for growers and plant producers on the relationship between water resources and economic sustainability in terms of savings and financial gains.	Majsztrik et al. [167]
		Ecosystem services/circular economy	The study determines the importance of promoting the circular economy in water market initiatives, as it favours the reduction of the environmental footprint of water consumption.	Sauvé et al. [168]
	Social	Life cycle impact assessment, water footprint/ water consumption	It analyses the effects of water consumption, focusing on impact assessment methods: water scarcity, human health, ecosystem quality and resource depletion.	Pfister [145]
		Water footprint/human health, cause-effect	Cause-effect modelling improves the assessment of the harm to human health in the water footprint caused by polluted water consumption.	Mikosch et al. [161]
C 2 [2]	Environmental	Life cycle cost, renewable energy/solar water heating systems	In aquaculture, solar water heating systems have a less environmental impact in cold climates than electric power and other climates.	Kim & Zhang [173]
		Sustainability, life cycle cost/tertiary treatments	Tertiary wastewater treatment with favourable results and opportunity for groundwater recharge.	Akhoundi & Nazif [56]
	Economic	Sustainability/food system	The study shows that some current trends threaten the socio-economic and environmental sustainability of the US food system.	Heller & Keoleian [154]
		Life cycle cost/renewable systems	Wind energy use shows advantages in water scarcity problem areas, low economic resources and civil strife.	Bouzidi [171]
	Social	Sustainability/algal biodiesel	Analysis determines that algae biodiesel production improves energy security and creates new job opportunities.	Zhu et al. [174]
		Municipal solid waste/linear programming model	The development of multi-objective mixed-integer linear programming allows the design of an integrated municipal solid waste network, avoiding social and environmental problems.	Yousefloo & Babazadeh [175]
C 3 [3]	Environmental	Water treatment/nanoparticle concentrations	The artificial nanoparticles impact groundwater quality, so ultrafiltration techniques are needed to remove nanoparticle contamination in waters.	Troester et al. [178]
		Mining/environmental consequences	The water risk assessment showed that regions with nickel, copper and lead-zinc production alter the water balance, water quality and mining infrastructure.	Northey et al. [181]
		Water consumption/water footprint reduction	The production of algae feedstock for biofuel reduces the water footprint by 18%, presenting energy potential and salinity tolerance.	Mayer et al. [177]
	Economic	Water consumption/ water quiality	Social surveys indicate the importance of tap water quality in urban consumption, as it would reduce bottling, protect the environment and implement good circular economy practices.	Gambino et al. [176]
		Water consumption/ food balance	Using a balance of food consumption in countries worldwide would mean saving freshwater and developing the economy.	Blas et al. [152]
	Social	Risk assessment/ mining pollution	Abandoned mining areas pollute water resources for urban consumption, affecting the social and environmental relationship, and it is important to apply the LCA.	Feng et al. [45]

Table 2. *Cont.*

Clusters	Aspect	Author/Secondary Keywords	Description of Results	References
C 4 [4]	Environmental	Remediation/waste regeneration	The comparative evaluation of water treatment methods defines the importance of understanding the harmful substances' fate during incineration and the need for technologies to dispose of these substances.	Boyer et al. [183]
		Water reuse, water supply/environmental impact	Environmental impact assessment is crucial during water management decision-making in environments experiencing new urban settlements.	Rygaard et al. [146]
	Economic	Water supply/technology assessment method	The multi-criteria evaluation method argued that groundwater abstraction is the most sustainable supply technology in an economic or social framework.	Godskesen et al. [185]
		Remediation/decision support, secondary impacts of remediation	The probabilistic model indicates that the secondary impacts of remediation are converted into monetary costs. The methodology facilitates decision-making in remediation interventions.	Lemming et al. [187]
	Social	Remediation/nanotechnology	The analysis found that nanotechnology in agricultural products provide a controlled release of chemicals, preventing contamination of water sources.	Iavicoli et al. [186]
		Water supply, water scarcity, water reuse/environmental and social benefit	Quantitative and qualitative assessments showed that potable reuse has environmental and social benefits.	Haak et al. [184]
C 5 [5]	Environmental	Life cycle/ sustainable adsorbents	The study evaluates three adsorbents in water defluorination, presenting lower energy intensity by reducing the carbon footprint between two and 20 times concerning activated alumina.	Pan et al. [190]
		Groundwater, pollution, irrigation/simulator	The simulators make it possible to determine that it is necessary to create an optimal balance between the number of chemical fertilisers and water applied to crops.	Marinov & Marinov [194]
		Wastewater/adsorption method	The adsorption assisted by activated carbon, biochar, nanomaterials and clay minerals demonstrates a highly effective and environmentally friendly treatment.	Rasheed et al. [191]
	Economic	Wastewater reuse/ economic benefits	The reuse of treated wastewater benefits the economy of a territory. Sites with unsustainable exploitation of natural resources.	López & Rodríguez [192]
		Groundwater, irrigation/ Multiple Inlet	Multiple Inlet Rice Irrigation benefits agricultural activities, like reducing water consumption and production cost savings by 128%.	Shew et al. [193]
	Social	Wastewater/adsorption method	Wastewater treatment with adsorption methods presents quality results concerning other methods (reverse osmosis) for ammonium capture, sustaining the current social demand for water.	Zhang et al. [132]

Table 2. *Cont.*

Clusters	Aspect	Author/Secondary Keywords	Description of Results	References
C 6 [6]	Environmental	Desalination/renewable resources	Geothermal presents benefit that could meet current demand, as it is not dependent on weather conditions and the heat flow is constant relative to other renewable sources.	Prajapat et al. [195]
		Desalination/ecological desalination	The technological advances and renewable energies allow implementing green desalination methods, replacing conventional desalination and reducing environmental problems.	Ihsanullah et al. [151]
	Economic	Environmental impact/shale gas	The analysis showed that shale gas is not an option for development, as it presents polluting factors, such as methane gas, groundwater contamination and increased seismicity.	Melikoglu [197]
		Environmental impacts/economic development	The water harvesting alternatives demonstrated that ultrafiltration plants have a reduced added value than the conventional system, demonstrating new urban development.	Faragò et al. [128]
	Social	Desalination, water resource/retarded osmosis	Dual-purpose pressure retarded osmosis desalination plants offer a potential solution, as they provide water security at a lower cost and incentivise renewable energy, meeting the social tdemand.	Sahin et al. [201]
		Water resources/water infrastructure	Through a strategic planning methodology, it is possible to expand urban water infrastructure to balance temporary water supply and demand.	Hao et al. [200]
C 7 [7]	Environmental	Life cycle assessment/water-energy nexus	Analysis in 20 regions and four countries demonstrated the importance of understanding the water-energy nexus and water supply-quality systems, and a policy formulation.	Lee et al. [59]
		Life cycle assessment/concrete	Concrete has some benefits over conventional cement in terms of reducing environmental impact.	Dandautiya & Singh [203]
	Economic	Life cycle assessment/non-potable reuse	Mixed wastewater bioreactor systems showed a lower cost of potable water reuse for drinking water consumption in urban buildings.	Arden et al. [204]
		Life cycle assessment/solar photovoltaic energy	Solar photovoltaic energy in agriculture has economic and environmental benefits, as it reduces the cost and consumption of electricity and the emission of greenhouse gases.	Lago et al. [205]
	Social	Life cycle assessment/urban management	Renewable energy impacts meeting energy demand in countries with large urban water distribution areas and are important in urban planning and management.	Wakeel & Chen [206]

[1] Cluster 1; [2] Cluster 2; [3] Cluster 3; [4] Cluster 4; [5] Cluster 5; [6] Cluster 6; [7] Cluster 7.

4. Interpretation of Results and Discussion

The Scopus and WoS databases made it possible to obtain information on this field of study based on the following search keywords. However, these databases present certain inconsistencies in the downloaded documents, necessitating a detailed cleaning of each format. Some studies have implemented cleaning mechanisms to obtain reliable data removing inconsistencies in the records, like duplicated and missing records (e.g., authors, titles) [78,210]. Our work generated a reliable analysis of the results. The information had a rigorous cleaning process, obtaining records of relation more proximity with the groundwater life cycle for quality literature use.

This study analyses the scientific production that deals with groundwater's LCA through bibliometric methods, broadening knowledge in an environmental, economic and social framework. Several studies have used bibliometric models in LCA of water ecosystems to understand the basic concepts and theories related to water supply sources. For example, Vander Wilder & Newell [211], developed a robust bibliometric review, integrating deep and broad content on ecosystem services. This bibliometric analysis shows the intellectual interaction, thematic strengths and evolving interest of various focus groups integrating scientific methods to solve groundwater and related ecosystem problems.

In the fields linked to groundwater, there is research showing the global status of sustainable water use, finding that agriculture is the main consumer of water resources with trends starting from 2000 [212,213]. Our study determines that from 2012 onwards, there is a greater influence of LCA studies, mainly in agricultural consumption and urban water supply, in a framework of groundwater resources' treatment and distribution/consumption and related ecosystems (e.g., [59,126,188]). Determining that it is fundamental to apply this tool (i.e., LCA) in the assessment processes of contaminated sites, allowing the generation of study strategies that strengthen LCA processes and decision making [51].

In general, the bibliometric results indicate the participation of 2672 authors, where Christensen T., Hauschild, Hellweg S., Pfister S. and Bayer P. show a predominance of production in the scientific field, affiliated with countries with an exceptional number of documents and citations. The literature indicates that 60% of publications belong to the areas of "Environmental Science", "Engineering" and "Chemistry", most frequently published by the Journal of Cleaner Production, International Journal of Life Cycle Assessment, and Science of the Total Environment.

On the other hand, the literature review of the Author Keywords allowed us to analyse various works related to the life cycle of groundwater based on an environmental, economic and social framework:

- Environmental. Groundwater ecosystems and related environments have shown depletion of water resources, mainly caused by conventional energy consumption, such as hydropower and traditional pumping methods (agricultural and urban) [172,206]. Zhang [214] indicates the great interest in remediating pollution in groundwater ecosystems, finding 5486 papers with significant growth in the last 15 years. The present study proves that, since 2003, several scientists have valued the importance of implementing sustainable methods for water management, benefiting the environment and energy profile, like water supply mix [160], solar water heating systems [173], algal feedstock [177], water treatment adsorbents [190,191] and simulators [194]; as well as a variety of physical-chemical processes that ensure water quality through ultrafiltration techniques [178] and wastewater treatment [56]. In general, LCA methods have allowed strengthening the knowledge of water resources decision-making in various activities, like agricultural production [164], industrial production of raw materials [181], urban settlements in new natural areas [146], desalination processes [195] and water supply-quality analyses [59].
- Economic. Over the last decades, economic growth has increased the demand for groundwater sources [18,19]. This market development leads to new sustainable strategies that maintain the balance between economic progress and water availability, like decision-making for growers and agricultural producers [167], food system monitoring in countries around the world [154], technology assessment method [185] and food production cost reduction through Multiple Inlet Rice Irrigation [193]. On the other hand, water harvesting and treatment techniques have been implemented to reduce value-added costs in industrial and urban consumption [128]. Renewable energy systems (e.g., photovoltaic and wind energy) have an essential role in the energy supply for water pumping, as they have lower investment costs than conventional systems (e.g., diesel and petrol engines) [171,205]. These renewable sources provide a favourable energy supply in areas with financial problems requiring wastewater treatment processes (e.g., mixed wastewater membrane bioreactors and integrated anaerobic) [132,204].
- Social. Population growth conducts to new social development objectives that certify water and food quality. In the last decade, the LCA has played a considerable role in the quality analysis of urban drinking water sources [145]. This scientific interest determines methods of solving urban problems (e.g., health damage and water scarcity) caused by agricultural and mining pollution [45,58,126]. In detail,

cause-effect modelling methods [161], multi-objective mixed integer linear programming [175], nano-technology in agricultural products [186], adsorption methods [132] and dual-purpose pressure retarded osmosis desalination plants [201].

In general terms, the work aims to maintain a balance between socio-economic development and the protection of groundwater ecosystems [103,117,215], through various sustainable strategies or methods that encourage the development of a future with available natural resources for industrial, agricultural and urban consumption [48,49,216]. Another important aspect is the future challenges of the LCA technique. According to Goglio et al. [217], a better determination of the boundary conditions would favour a better estimation of life cycle analysis. In addition, Finkbeiner et al. [218], highlight the low frequency of challenges such as allocation, uncertainty and biodiversity in inventory studies, impact assessment, generic aspects and evolution related to LCA.

5. Conclusions

The analysis of groundwater life cycle scientific production in the Scopus and WoS databases shows a 38-year evolution of the scientific field with a linear production in the first 27 years (1983–2010) and exponential growth since 2011. This scientific development deduces a boom in the last 16 years (2006–2021), grouping 86.5% of the scientific production. We also note the collaboration of 2672 authors and 450 journals from various subject areas. On the other hand, the academic structure indicates an intellectual focus of 2109 keywords and a scientific contribution from 72 countries, led by the USA and Denmark.

The LCA of groundwater is an important factor in environmental, economic and social development, linked to ecosystems that present the relationship with water resources used in industrial and municipal mechanisms for agricultural irrigation systems and urban supply. LCA is central to decision-making processes and water resources quality analyses, defining water use controls, like urban water security, water treatment-reuse, irrigation, reduction of conventional systems, calculation of water footprint and carbon footprint in the context of an environmental system. These strategies would strengthen the modern economy and meet the global demand for water in both developed and developing countries. Promoting new sustainable methods in industrial, agricultural and urban activities is crucial for groundwater life cycle and linked water environments (rivers, lakes, lagoons).

The field's intellectual structure also provided insight into various research topics to strengthen scientific interest:

- Applying LCA assessment methods benefits socio-economic systems.
- LCA strengthens decision-making according to savings and financial gains during agricultural and industrial activities with water requirements for energy and food supply.
- Renewable energies presented favourable results in energy supply, substituting the water need and balancing the water sources available for distribution to sectors with high demands.
- Agricultural nanotechnology contributes to the environmental and social profile, reducing chemical substance emissions and improving the quality of food products.
- Environmental remediation through LCA integrates sustainable methods for water reuse, like adsorbents, geothermal processing and biomass.

This study contributes to the academic literature in terms of: (i) the possibility of knowing different subject areas and relationships with the keywords through the link between nodes; (ii) to know the scientific approaches that various authors and countries contribute to environmental problems solution currently faced by groundwater ecosystems; (iii) the study used as a guide for researchers that wish to understand the general outline of the scientific field in an environmental, economic and social framework; (iv) review the techniques and technologies used and tested as reference knowledge applicable in similar cases. It may also allow the creation of a new process to preserve groundwater and its relationship with LCA.

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