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Trends in global greywater reuse: a bibliometric analysis

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ABSTRACT

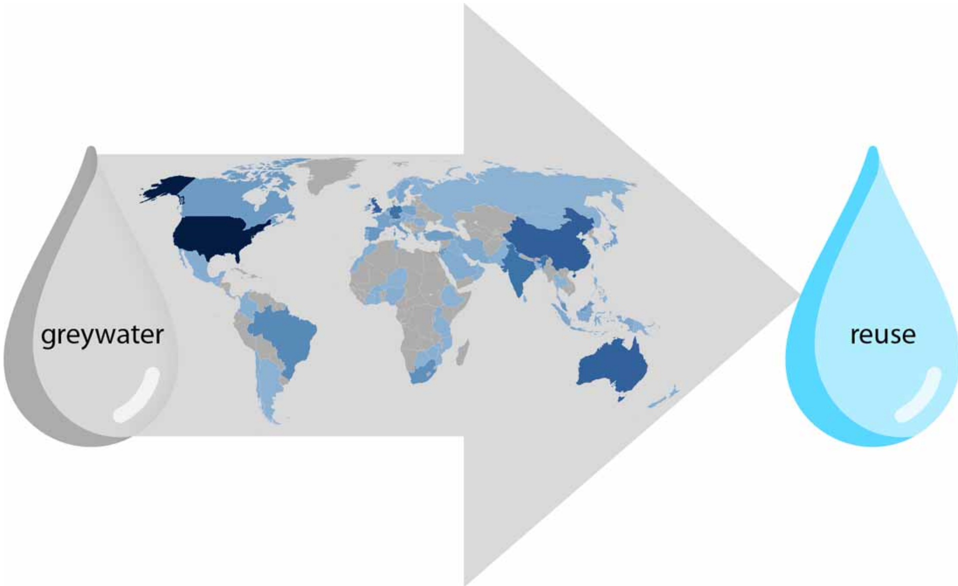
The increase in water demand in recent years led to the expansion of research and public policies on the reuse of water, especially greywater (GW). Given the diversity of research in the area, this paper proposes an analysis of the evolution of the area through an objectivity metric. Metadata of 1,524 publications indexed in the Scopus database between 1974 and 2021 were analyzed using the VOSviewer tool, and showed exponential growth in publications from 2013. Six different spelling variations were found for GW in the database. Despite the highly geographical scattering of academic production, developed countries, who began researching greywater earlier, had more connections and published more papers; except for Israel, which had the highest average of citations per article. While developed countries lead the research area, developing countries are emerging in GW reuse research. These aspects reveal both the dispersion of the research structure development and a trend of intellectual production in GW from developed to developing countries. Also, we noted that countries suffering from water scarcity stood out with the highest activity in paper publishing. Thus, we expect that future research on GW reuse will take place in developing countries that face water scarcity.

Key words: bibliometrix, developing countries, greywater reuse, sustainable development goals, water resources management, water scarcity

HIGHLIGHTS

- The evolution of the greywater scientific field was mapped from 1,524 indexed publications.
- While developed countries lead the research area, developing countries are emerging in greywater reuse research.
- There is a trend that countries under water scarcity conditions are more active in greywater publishing.
- The research structure development in greywater is scattered and presents low international cooperation.

GRAPHICAL ABSTRACT



INTRODUCTION

The 2030 Agenda for Sustainable Development of the United Nations (UN) presents several sustainable development goals (SDGs) to be achieved by 2030, of which the 6th SDG aims to ensure the availability and sustainable management of water and sanitation for all (United Nations 2015b). The UN's concern highlights the magnitude of the problem of water scarcity and access to treated and quality water. This problem is one of the greatest challenges for human development. As affirmed by Haak *et al.* (2018), effluent reuse is a water resource management tool that optimizes water use, increases drought resistance, and can nearly double the water availability of the region analyzed.

In this sense, greywaters (GW) reuse is considered an important factor in reducing the demand for drinking water towards sustainable water management, and its usage can be applied in activities that demand potable and non-potable water, such as flushing toilets, agriculture (Oteng-Peprah *et al.* 2018), watering gardens, washing cars, and extinguishing fires (Boyjoo *et al.* 2013). However, there are risks associated with GW reuse (Goodwin *et al.* 2019; Vuppaladadiyam *et al.* 2019) that must be considered. Thus, it is important to understand the whole process of GW reuse, from its production, characteristics, treatment, risks, uses, legal aspects, user acceptance, among other fields.

To help to keep track of the evolution of the field of study of GW reuse, some researchers have centered their analyses on literature reviews. These are presented in two main central axes: characteristics, as presented in Boyjoo *et al.* (2013), Eriksson *et al.* (2002), Etchepare & van der Hoek (2015), Leong *et al.* (2017) and Wu (2019); and treatment systems, the object of study by Baideme *et al.* (2013), Boyjoo *et al.* (2013), Gassie & Englehardt (2017), Leong *et al.* (2017), Li *et al.* (2009), Pellegrin *et al.* (2017), Pradhan *et al.* (2019) and Wu (2019). In addition to presenting reviews on characterization and treatment systems, some more comprehensive studies propose to also review aspects related to perceptions of reuse, as shown in Oteng-Peprah *et al.* (2018); and risks, dangers, and barriers to the reuse of GW, as pointed out in Vuppaladadiyam *et al.* (2019), both in global scenarios.

Thus, qualitative and quantitative reviews of structured literature are important to express state of the art of a research field (Miranda & Garcia-Carpintero 2018). In this sense, bibliometric analysis is a relevant tool that can be used that can be used to measure objectivity in the scientific literature evaluation. It has the potential to increase rigor and mitigate research bias, through a systematic, transparent, and reproducible review process (Zupic & Čater 2015). The authors add that bibliometrics assists literature reviews, even in the initial moments of reading, providing the researcher with a guide to the most influential works and mapping the research field. This scientific mapping can also help revisions to become more comprehensive, adding a more in-depth discussion (Jin *et al.* 2019).

At a time when the emphasis on empirical contributions is producing massive, fragmented, and controversial research flows, it is important to evaluate the qualitative criteria involved in the research through a bibliographic survey on the researched topic. Based on this theoretical construction, the use of bibliometrics is particularly suitable for scientific mapping and subsequent analysis (Aria & Cuccurullo 2017). As previously stated, many reviews on related topics were published, but, to date, no bibliometric analysis was performed for the greywater reuse scientific field. In this context, this paper aimed to contextualize, map, and analyze the evolution and trends of GW around the world using this objective metric tool. Thus, we performed a bibliometric analysis on GW reuse to quantitatively assess the information on the publications found. In this study, several metadata of publications dealing with GW reuse were identified and evaluated, such as articles, authors, journals, keywords, author affiliations, countries, and languages to provide the necessary data to analyze the changes in the past and predict future trends of the GW reuse scientific field.

METHODOLOGY

To map and evaluate the evolution of the scientific field, the analysis was classified by authors publications, periodicals, keywords, and countries. The present bibliometric study processed data from the search for keywords related to the theme to select documents from a database. The most widespread and used databases for literature search are the Web of Science and Scopus, which are complementary and non-exclusive information systems. However, despite its similarities, Scopus has better coverage in the specific area of Sustainable Management of Water Resources, and has a greater number of articles, in addition to a higher average of citations per article (Durán-Sánchez *et al.* 2018). Thus, this database was selected to conduct this study.

Then, from the selected database, we searched for papers in which both the terms 'greywater' and 'reuse', in English, were present in either titles, abstracts, and keywords. This search was performed in August 2021, and the timeframe analyzed had no time restrictions. From the analysis of this preliminary result, we observed variations in the spellings of the words searched and that authors use some other terms with similar meanings to reuse. Thus, a new search was performed on the titles, abstracts, and keywords of the terms ((graywater OR greywater OR 'gray water' OR 'gray-water' OR 'grey water' OR 'grey-water') AND (reuse* OR re-use* OR recycl* OR reclamation OR reclaimed OR conservation)). The database from this search contains 39 variables (metadata) among which we highlighted authors, title, type of document, language of publication, year, source, DOI (digital object identifier), citations, summary, author's affiliation, source of funding, keywords and references cited in the documents.

From this sample, data such as the evolution of publications over the years, types of documents, language of the publication, list of the most productive authors, most cited documents, and journals that published the most were examined. In addition, the keywords of the authors and those indexed by the database were investigated. Finally, observations were made about the countries of publications, such as frequency and number of citations per country.

The publications found were used as input data for the bibliometric analysis. Prior to that, the data was analyzed using the bibliometrix package, developed to perform scientific mapping analysis (Aria & Cuccurullo 2017). The package was developed in R (version 4.0.2), a free statistical programming language that provides a wide variety of statistical and graphical techniques (Oliveira *et al.* 2018). Due to the limitations of bibliometrix and because of some flaws observed in the data extracted from Scopus, the countrycode, tidyverse, varhandle, and googleVis packages were also used to carry out the complementary analyses presented in this article.

To offer better visualization of the processed data, VOSviewer was used, a tool that allows the creation and visualization of bibliometric maps. This program aims to provide researchers with auxiliary tools in conducting bibliometric studies (van Eck & Waltman 2010). The maps in VOSviewer were elaborated from bibliometric methods for the analysis of citations, bibliographic coupling, co-authorship, co-occurrence. Such methods are intended to complement traditional review methodologies, such as meta-analysis and qualitative reviews of structured literature, through the investigation of how disciplines, fields, specialties, and individual works are related to each other (Zupic & Čater 2015).

Bibliometric methods

Bibliometrics has two main procedures: performance analysis, which aims to evaluate authors, universities, departments, and researchers concerning the impact of their activities; and scientific mapping, used to represent the cognitive structure of a research field (Cobo *et al.* 2011). Quantitative information derived from bibliographic databases, such as the number of citations, for example, are becoming standard tools for evaluating the productivity and impact of research (Radicchi & Castellano

2013). Storopoli *et al.* (2019) highlight that the objective of bibliometrics is to catalog, classify and quantify the knowledge of a certain area.

Authors, publication title, document type, source, authors' affiliation, country, and keywords are some of the main metadata analyzed by bibliometrics. Therefore, they can support a fair assessment of researchers being used as a tool for quality control in science (Gagolewski 2011). Unlike other techniques, bibliometrics provides more objective and reliable analyses using tools that describe the current state of various domains of human activity related to science, which is important not only for research but also for the formulation of policies and practices (Aria & Cuccurullo 2017).

To help objectively analyze their scientific fields, Abejón & Garea (2015), Taddeo *et al.* (2019), Tang *et al.* (2018), Velasco-Muñoz *et al.* (2019), and Zhang *et al.* (2017) applied the following bibliometric methods: analysis of citations, bibliographic coupling, co-authorship, and co-occurrence. These methods are important to introduce quantitative rigor into the subjective evaluation of literature (Zupic & Čater 2015).

The citation is one of the indicators with objective and quantitative features that have been used to assess the performance of the research (Kamdem *et al.* 2016) and is a measure that correlates with the influence of the authors in the scientific field (Ji *et al.* 2018). Bibliographic coupling uses the number of shared references as a measure of similarity between them (Zupic & Čater 2015). Jarneving (2007) highlights that this method can provide information on the structure of the research fronts, such as the initial stages of the evolution of a specialty, the representation of works from the same research specialty, and the identification of research topics, through the association of documents with a similar research focus.

The number of publications in co-authorship helps to investigate the relationship of authors, institutes, and countries (Türkeli *et al.* 2018), with the country's international co-authorship being one of the most important (Tang *et al.* 2018). Co-authoring networks make it possible to increase a determined field of science through the collaboration of its members and the dissemination of academic production (Acedo *et al.* 2006). The co-occurrence method uses words in documents to establish relationships so that when words often co-occur in documents it is an indication that the concepts behind those words are related (Zupic & Čater 2015). This analysis helps to identify research topics (Ji *et al.* 2018) and to understand the evolution of themes, their origins, and interrelations (Cobo *et al.* 2011).

The bibliometric maps presented in this research were generated in VOSviewer and used four bibliometric methods: analysis of citations, bibliographic coupling, co-authorship, and co-occurrence. These maps are classified as distance-based maps, in which the distance between two items reflects the strength of the relationship between them, which facilitates the identification of groupings of related items, usually known as clusters (Zupic & Čater 2015).

RESULTS OF BIBLIOMETRIC ANALYSIS

Sample general statistical

The search result in the database provided 1,524 papers associated with the searched terms, available in the Supplementary Material. The chronological distribution of publications, along with a trend line with exponential adjustment ($R^2=0.9729$ and p-value<0.01), is shown in Figure 1, with documents from 1974 to 2021. From 2007 onwards, the average number of published documents increased considerably, with fluctuations between 2007 and 2012 and showing growth from 2013. Between 2013 and 2021, 941 (61.7%) of the works from the entire period were published, with an average of 104.5 articles per year. Eriksson *et al.* (2002) concluded in their research that few studies focused on the characterization of different types of greywater and on the different methods of reusing this type of wastewater. The result of this analysis suggests that the scientific field has been dedicated to filling this gap highlighted at the time.

The analysis of publications in the area of GW reuse shows that the distribution of publications is more concentrated in the decade of 2010. From 2010 onwards, 1,141 (74.9%) works were published. In addition, the distribution (Figure 1) shows an exponential growth trend, indicating that it is an area in full development.

From the 1,524 documents in the sample, 1,087 (71.3%) are articles published in journals, 290 (19.0%) published in congresses, 81 (5.3%) are review articles published in journals, 39 are book chapters, nine are reviews published in congresses, six are books, five are notes, four are classified as short surveys, three publications are errata, and one publication was retracted. As for the languages of the documents: 1,459 (95.7%) are in English; 24 (1.6%) are written in Chinese; 13 (0.8%) in German; six in Portuguese; four in Spanish; four in French; three in Czech; three in Japanese; one in Italian; one in Persian; one in Polish; and five other documents did not have their written language registered according to the available metadata.

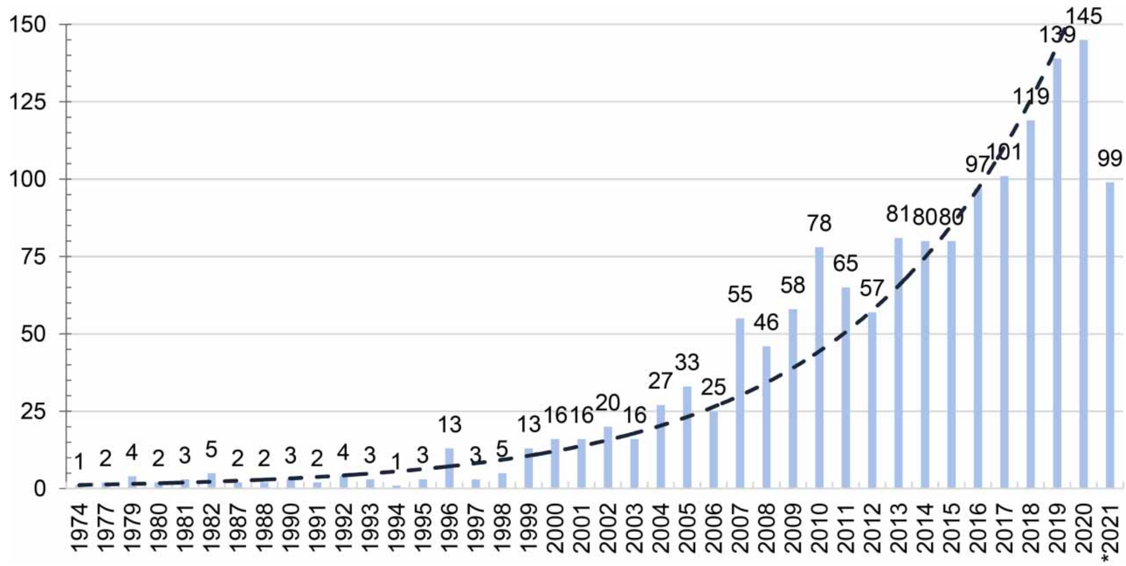


Figure 1 | Number of publications distributed per year. *Source*: Scopus. Processed by authors (2021). Observation: * the year 2021 only considers works published until August 2021.

Analysis of periodicals

In Table 1, the 10 periodicals with more publications within the sample were ordered, as well as the total number of citations and some impact metrics of the periodicals were listed. We list the newest available metrics: impact factor Journal Citation Reports (JCR) 2020, which is based on the Web of Science and counts citations in the previous two years, 2018 and 2019; CiteScore 2020, which is based on Scopus and counts citations received in 2017, 2018, 2019, and 2020 from documents published in the same years; and the h index of journals according to the relationship between the number of articles and citations indexed in Scopus, published in 2020, as proposed by Hirsch (2005).

Thus, in addition to the difference in the database adopted in each of the indicators, the difference in the analyzed period also stands out. Due to the time window, the JCR indicator presents the most current trends in journal citations in the two previous years; while CiteScore considers a larger temporal sample of metadata for analysis over four years, thus having a more comprehensive observation.

The journal *Water Science and Technology* stands out as the one that publishes most articles on the subject and for having the highest number of citations in the sample. Although the *Urban Water* journal published some of the most cited papers in

Table 1 | Publications by periodicals

Journal	Publications	Total citations	JCR 2020	CiteScore 2020	h Index 2020
Water Science and Technology	107	3,066	1.915	3.3	9
Journal of Cleaner Production	60	1,576	9.297	13.1	51
Science of the Total Environment	53	1,856	7.963	10.5	80
Desalination	45	2,114	9.501	14.3	25
Water (Switzerland)	42	336	3.103	3.7	20
Desalination and Water Treatment	41	189	1.254	1.6	9
Water Research	32	1,182	11.236	15.6	36
Resources Conservation and Recycling	28	732	10.204	14.7	30
Journal of Environmental Management	26	612	6.789	9.8	33
Water Supply	20	230	1.033	1.6	6

Source: Scopus. Processed by authors (2021).

the area, such as Eriksson *et al.* (2002) and Nolde (2000), it was discontinued in 2003 and, therefore, does not appear in Table 1.

Analysis of authors with more publications

Table 2 presents the list of authors with the largest number of publications, the current affiliation institution, the country of affiliation, the number of articles and citations, and the h index of these authors. The number of articles and citations are indexed by Scopus.

Table 2 contains the 12 authors with more than 12 published works, with emphasis on E. Friedler, affiliated with the Technion – Israel Institute of Technology, with 33 publications. B. Jefferson has the highest h index, so 59 of his articles indexed in Scopus received at least 59 citations, according to the information available in that database. It is noteworthy that of the total sample, 17 (1.1%) publications do not have authors associated with them. In this list all nine reviews are published in congresses, according to the data indexed by Scopus.

Analysis of the relationship between researchers

Figure 2 shows the mapping of the citation network of the same authors listed in Table 2. In the network presented in Figure 2 network, the size of the nodes represents the number of citations for each author. The relationship between them is determined based on the number of times they cite themselves. In this way, the thickness of the line represents the intensity of these citations, whilst the colors of each node represent the annual average of publications by each author.

Thus, it can be inferred that R. Otterpohl and Jefferson, with annual averages close to 2006 and with large numbers of citations, were precursor authors. Their papers published until the middle of the first decade of the century had great relevance in the evolution of knowledge and publications about GW, represented in Figure 1, and these papers served as a basis for the publications of the following years. Friedler has the largest number of publications and citations, and is connected to all other authors, as highlighted in the center of the map, with an annual average of approximately 2013. E. Ghisi and N. J. Ashbolt are the authors with the newest research, with annual averages of approximately 2015.

The co-authorship network of the authors present in Table 2 is represented in Figure 3 to investigate the collaboration between these authors. The network consists of seven clusters identified by different colors. The size of the nodes represents the number of documents, and the connection line between them represents the number of documents in which these authors are co-authors. The thickness of this line is associated with the intensity of this connection; therefore, the thicker this line, the greater the number of publications that these authors share co-authoring.

Friedler co-authored six documents with A. Gross, both of whom are associated with institutions in Israel, five of these documents assessed the risks and impacts associated with the GW reuse in irrigation. J. L. Garland is the central link in the green cluster. He co-authored two articles with S. E. Sharvelle on the analysis of microorganisms and substances present

Table 2 | Authors with more publications

Author	Affiliation	Country	Publications	Citations	h Index
Friedler E.	Technion – Israel Institute of Technology	Israel	33	1,363	31
Garland J. L.	United States Environmental Protection Agency	United States	26	328	34
Gross A.	Ben-Gurion University of the Negev	Israel	21	921	29
Jefferson B.	Cranfield University	United Kingdom	21	1,264	59
Otterpohl R.	Hamburg University of Technology	Germany	20	911	23
Sharvelle S. E.	Colorado State University	United States	18	96	10
Butler D.	University of Exeter	United Kingdom	16	526	46
Sharma A. K.	Victoria University	Australia	14	296	24
Ashbolt N. J.	Southern Cross University	Australia	13	196	50
Ghisi E.	Universidade Federal de Santa Catarina	Brazil	13	403	28
Makropoulos C.	National Technical University of Athens	Greece	13	292	28
Zeeman G.	Wageningen University & Research	Netherlands	13	561	50

Source: Scopus. Processed by authors (2021).

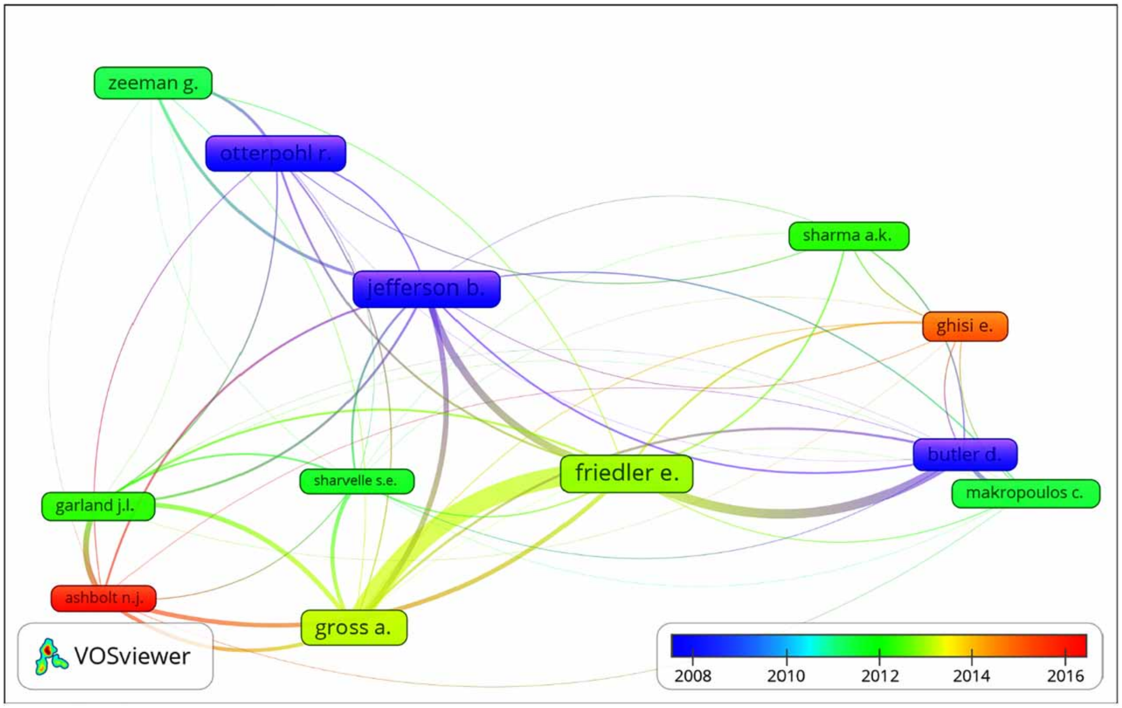


Figure 2 | Citations network of authors with more publications. *Source*: Scopus. Processed by authors (2021).

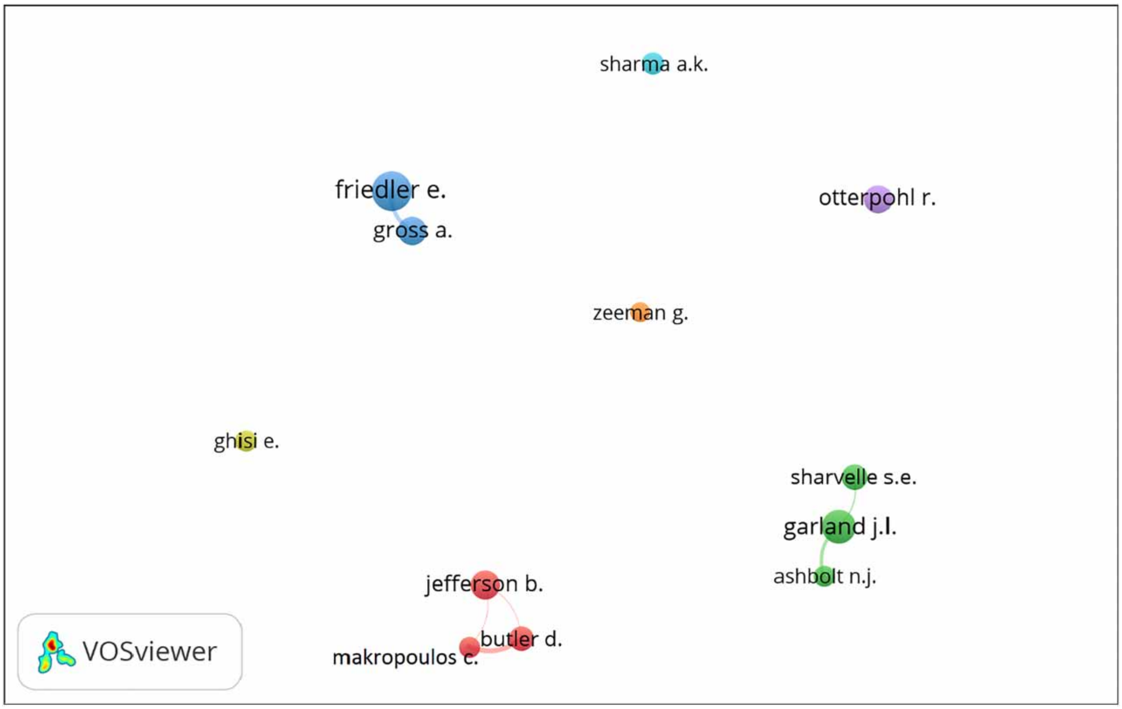


Figure 3 | Co-authorship network of authors with more publications. *Source*: Scopus. Processed by authors (2021).

in wastewater. Another five articles were published in co-authorship with Ashbolt, of which two address the biological risks associated with the GW reuse, while two compare water sources technologically and one assesses the cost-benefit of nitrogen mitigation in wastewater.

The red cluster is formed by the researchers Jefferson, D. Butler, and C. Makropoulos. The last two are co-authors of seven documents dealing with impacts, costs, and dimensioning of reuse systems for GW and water infrastructure planning. The other four authors – Otterpohl, A. K. Sharma, Ghisi, and G. Zeeman – are identified as clusters of a single element, which indicates that, according to the data and criteria applied in this analysis, they do not have a co-authoring relationship with the others.

Analysis of the most cited publications

The discussions were divided between most cited publications, spelling, and keywords. Table 3 shows the list of the 10 most cited works, listing their authors, the title and the respective year of publication, the journal in which the article was published, the number of citations, and citations per year. This last data is a reason why the number of citations is different in the date of publication until 2021.

Table 3 shows that the most cited document, 'Characteristics of grey wastewater', was published 20 years ago, and had, on average, 26.75 citations per year. Eriksson *et al.* (2002) conducted a wide review of the literature on GW characteristics and stands out in this representation. Li *et al.* (2009) present a review of the literature on the treatment for GW reuse and it is the third most cited article. Rowe (2011), the second most cited document, addresses the reduction of different types of pollution through the use of green roofs. Although it does not have GW as an axis of discussion, the author suggests the use of GW for the irrigation of this vegetation. The other articles present in Table 3 bring different contributions to different aspects of GW.

Figure 4 shows the time evolution of the citations of the articles present in Table 3. The increase in the number of academic publications (Aria & Cuccurullo 2017) associated with the expansion of the Internet and globalization of communication are possible justifications for the increase in the number of citations over the years. In this sense, Persson *et al.* (2004) point out that it has become easier to search and access relevant literature, particularly the good coverage offered by the databases.

The bibliographic coupling network can help to understand the structure of the evolution of a research field through the analysis of documents that share references. This network is shown in Figure 5, using the same most cited publications present in Table 3. The size of the nodes represents the number of citations for each document, information is also presented in a

Table 3 | Most cited publications

Publication	Title	Journal	Citations	Citations per year
Eriksson *et al.* (2002)	Characteristics of grey wastewater	*Urban Water*	535	26.75
Rowe (2011)	Green roofs as a means of pollution abatement	*Environmental Pollution*	340	30.91
Li *et al.* (2009)	Review of the technological approaches for grey water treatment and reuses	*Science of the Total Environment*	328	25.23
Al-Jayyousi (2003)	Greywater reuse: towards sustainable water management	*Desalination*	244	12.84
Nolde (2000)	Greywater reuse systems for toilet flushing in multi-storey buildings – over ten years experience in Berlin	*Urban Water*	240	10.91
Christova-Boal *et al.* (1996)	An investigation into greywater reuse for urban residential properties	*Desalination*	223	8.58
Friedler & Hadari (2006)	Economic feasibility of on-site greywater reuse in multi-storey buildings	*Desalination*	186	11.63
Gross *et al.* (2007)	Recycled vertical flow constructed wetland (RVFCW)—a novel method of recycling greywater for irrigation in small communities and households	*Chemosphere*	176	11.73
Jefferson *et al.* (2004)	Grey water characterisation and its impact on the selection and operation of technologies for urban reuse	*Water Science and Technology*	175	9.72
Friedler (2004)	Quality of individual domestic greywater streams and its implication for on-site treatment and reuse possibilities	*Environmental Technology*	172	9.56

Source: Scopus. Processed by authors (2021).

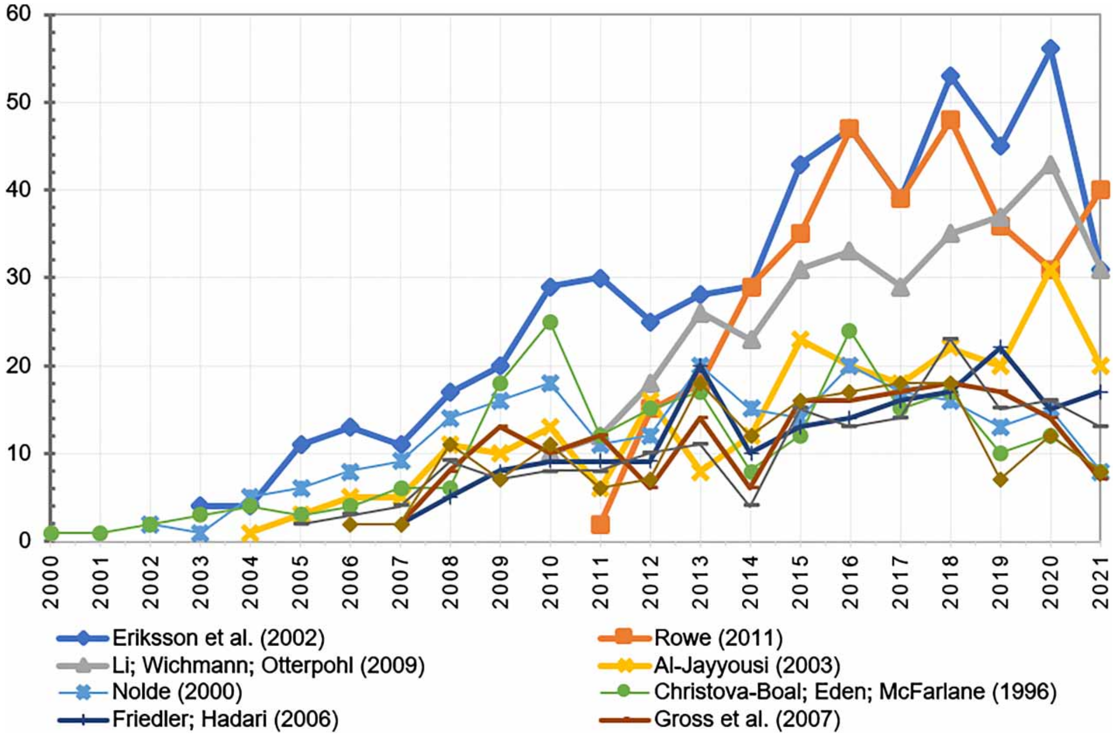


Figure 4 | Number of citations distributed per year. *Source*: Scopus. Processed by authors (2021).

color scale. The connecting line between each publication represents the references shared by each document, and the thickness of that line is the intensity. Thus, the thicker the line, the greater the number of shared references.

The network consists of eight documents. Despite Christova-Boal *et al.* (1996) being among the ten most cited works, it is not represented in this network because the document has no references. This also happens with Rowe (2011), who does not share any reference with the other publications listed in Table 3, since the object of this study differs from the others.

Eriksson *et al.* (2002), the most cited document, stands out in this representation because it shares references with six publications from the network, except for Nolde (2000). In addition, studies published after Eriksson *et al.* (2002) started to

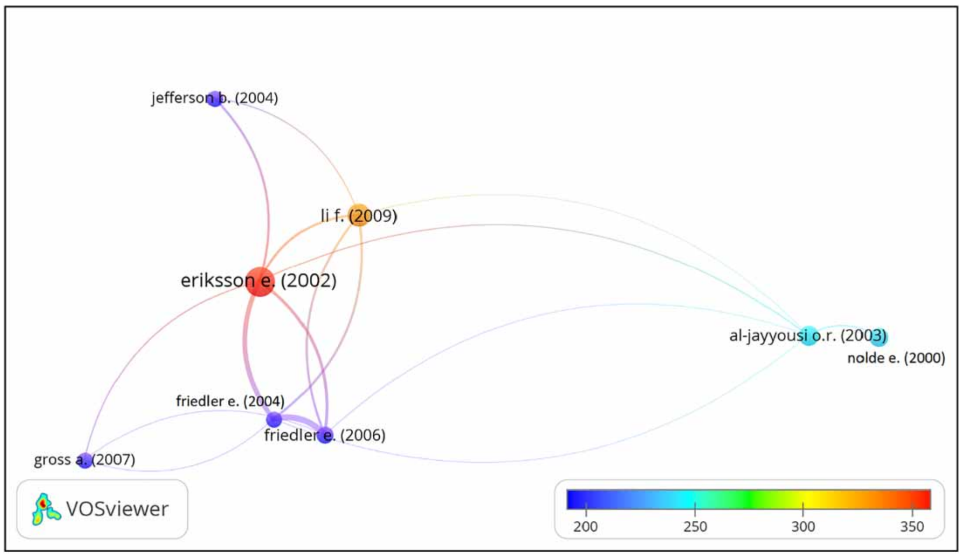


Figure 5 | Bibliographic coupling network of the most cited publications. *Source*: Scopus. Processed by authors (2021).

consult it and, in this way, share their references. Therefore, the relevance and importance of this publication for the evolution of GW are highlighted.

Spelling analysis

Different spellings of the terms *greywater* were observed, with -e, -a, space, or hyphen between grey and water (Figure 6). The difference between greywater and graywater comes from the orthographic difference between the British and American English variants, respectively. This difference is observed in official American documents that use graywater (United States Environmental Protection Agency 2011; ASTM International 2012); and greywater in documents from countries that adopt British English (Queensland Government 2008; BSI British Standards 2010). The use of space between the terms grey/gray and water is optional due to the rule for the formation of compound nouns in the adjective+noun configuration. As for the use of the hyphen, due to the lack of well-defined rules on the use of hyphens (The Economist 2015), its use is arbitrary and has fallen into disuse over the years. This effect is reflected in the low incidence of hyphenated spellings in the database. Taking into account the definitions for the formation of compound words, the dictionaries (Cambridge Dictionary 2021; Collins English Dictionary 2021; Merriam-Webster 2021) catalog only the nouns 'grey water' (British) and 'gray water' (American) separated by space and do not present results for the other spellings.

After analyzing the temporal evolution of the distribution of articles segregated by the spelling of the term, it is observed that the variant 'gray water' was the first spelling recorded in the database, in 1974. Although the spellings 'grey water' and 'gray water' are the most grammatically correct, they are not the most used. The spelling with the largest number of publications is 'greywater', with 52.0% of the total, followed by 'grey water', with 25.4%, totaling more than three-quarters of all published studies.

The most plausible explanation for this trend is the fact that six of the ten most cited studies in the area use the 'greywater' spelling, including the two oldest articles (Christova-Boal *et al.* 1996; Nolde 2000). The adoption of this spelling influenced the other authors to maintain the spelling, possibly due to the credibility deposited in articles reviewed and published in influential journals in the area.

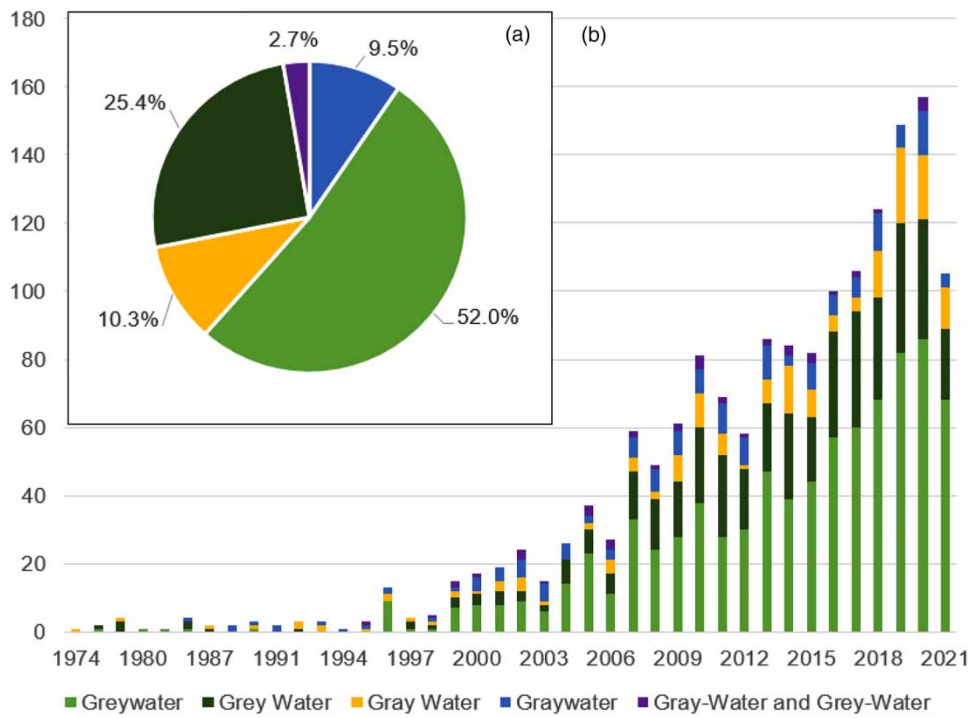


Figure 6 | (a) Percentage distribution of the spellings of articles published since 1974 and (b) temporal distribution of the variants. *Source*: Scopus. Processed by authors (2021).

In addition to the fragmentation of the scientific field, observed in the co-authorship networks (Figure 3), these variations in the spelling reinforce the segregation thesis previously observed. A possible explanation for this is due to the low international cooperation, which leads each group to use its spelling, highlighting the phenomenon of clustering.

Keyword analysis

Table 4 shows ten of the most frequent keywords in the sample. This includes the authors' keywords and keywords indexed by the database used in the collection of documents. It is noteworthy that the words searched in Scopus, 'greywater' and 'reuse', and their variations, are the keywords most used by the authors. To analyze the research topics and their interrelations, the co-occurrence network of 22 authors' keywords with a frequency greater than or equal to 25 is shown in Figure 7. In this network, the size of each node is associated with the quantity of the occurrences of those keywords. The links between the nodes represent the number of times that two keywords were together in the same document. The line's thickness is a measure of intensity.

This network denotes four clusters divided into four colors. The variation of the greywater spelling is evident in Figure 7. Regarding the green cluster, it can be inferred that they are more comprehensive and generic research on GW, where the term 'greywater' is the most relevant to the main associated terms, such as 'reuse', 'wastewater', 'recycling', 'rainwater', and 'treatment'. The red cluster, with emphasis on 'grey water' and 'water reuse', indicates research that centers on water reuse, including 'greywater treatment', 'wastewater reuse', 'membrane bioreactor', and 'sustainability'. Similar searches are grouped in the blue cluster, but centered on the 'graywater' spelling and with associations to the terms 'water quality', 'water conservation', 'water supply', and 'irrigation'. The yellow cluster gives evidence of research showing developments in the others, using the terms 'graywater reuse', 'greywater recycling', and 'rainwater harvesting'.

Analysis of most active countries

The 20 countries with the highest number of publications, responsible for about 73.8% of the 1,524 documents in the sample, are listed in Table 5 under two different perspectives. In the first columns, the classification considered the address of the institution that the first author is affiliated with. In the last columns, the analysis took place on all the authors of the document. If a publication has more than one author affiliated with institutions in the same country, in this investigation, the country was counted only once. Both analyses included the total number of citations and the average number of citations per document.

Moreover, Table 5 also presents the international cooperation of the listed countries. This table contains the frequencies of publications made by only one country. For the attribution of the publication to a country, the affiliation of the first author is considered.

The top ten countries on this list have a high concentration of publications without international cooperation with other institutions. Among these, China is the one that, proportionally, has the the greatest international cooperation because it

Table 4 | Most frequent keywords

Authors' keywords	Publications	Indexed keywords	Publications
Greywater	307	Water supply	657
Grey water	118	Wastewater reclamation	606
Water reuse	107	Water conservation	520
Reuse	106	Recycling	460
Wastewater	72	Wastewater	429
Greywater reuse	62	Water treatment	426
Sustainability	57	Wastewater treatment	424
Graywater	54	Water quality	395
Irrigation	48	Water management	391
Rainwater harvesting	48	Article	331

Source: Scopus. Processed by authors (2021).

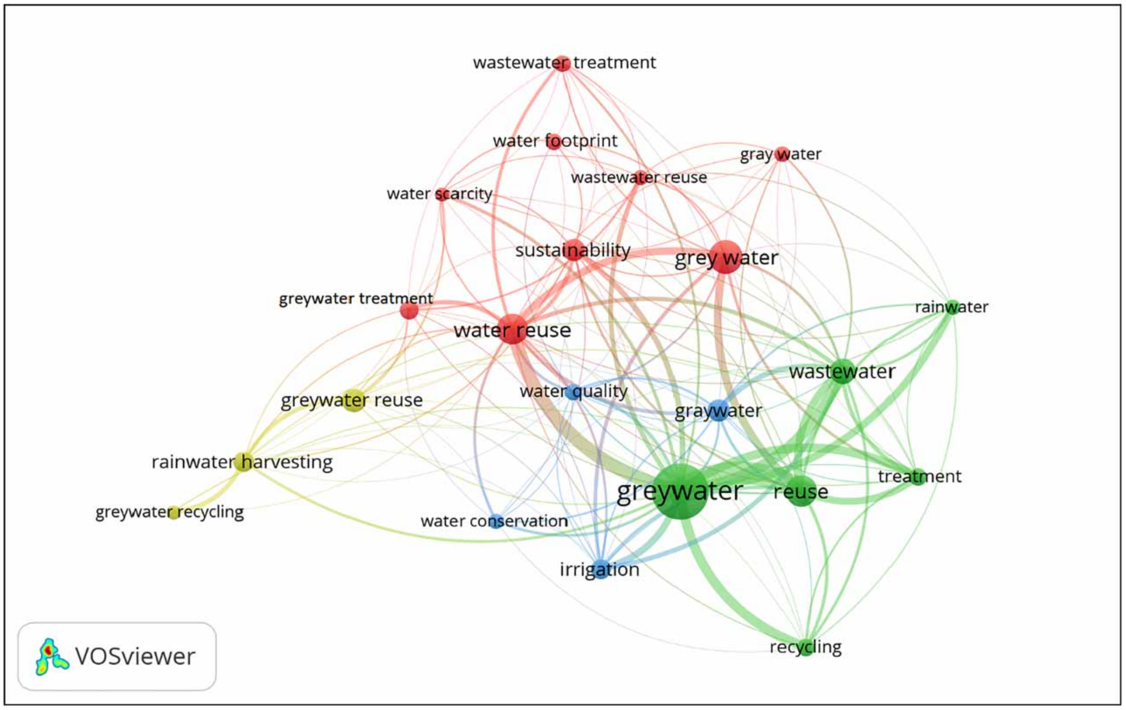


Figure 7 | Co-occurrence network of the keywords of the most frequent authors. *Source*: Scopus. Processed by authors (2021).

Table 5 | Publications and citations by country (first author and all authors); and international cooperation

	First author				**All authors**		
Country	**Total publications**	**Total citations**	**Average citations by publication**	**Publications attributed to a single country**	**Total publications**	**Total citations**	**Average citations by publication**
United States	235	2,531	10.77	86.8%	277	3,222	11.63
China	111	1,363	12.28	68.5%	122	1,470	12.05
India	93	726	7.81	92.5%	99	846	8.55
Australia	91	1,903	20.91	86.8%	118	2,548	21.59
United Kingdom	89	2,441	27.43	79.8%	123	3,051	24.80
Germany	67	1,694	25.28	76.1%	91	2,156	23.69
Israel	56	2,257	40.30	83.9%	58	2,268	39.10
Brazil	50	911	18.22	84.0%	53	966	18.23
South Africa	41	264	6.44	92.7%	47	280	5.96
Jordan	35	928	26.51	71.4%	38	1,076	28.32
Malaysia	33	453	13.73	81.8%	36	491	13.64
Netherlands	32	935	29.22	62.5%	49	1,437	29.33
Spain	32	833	26.03	78.1%	43	952	22.14
Canada	29	290	10.00	86.2%	48	603	12.56
Turkey	27	269	9.96	88.9%	30	372	12.40
Italy	25	607	24.28	72.0%	31	712	22.97
Poland	23	121	5.26	95.7%	26	153	5.88
Iran	22	183	8.32	72.7%	24	196	8.17
France	17	322	18.94	88.2%	23	465	20.22
Greece	17	368	21.65	82.4%	22	453	20.59

Source: Scopus. Processed by authors (2021).

presents a smaller percentage of publications attributed to a single country. The other nine first countries have a proportion greater than 71%.

Besides China, the Netherlands has the lowest proportion of publication from a single country. This indicates that authors associated with institutions in these countries publish in collaboration with authors affiliated with institutions in other nations, thus being able to infer a strong internationalization. Others already concentrate most of the publishing partnerships at a national level, with emphasis on India, South Africa, and Poland.

Despite not being in the list presented in Table 5, Denmark occupies the 23rd position, with 14 published documents and 883 citations, thus having an average of citations per article of 63.01. This is because the authors of the most cited article, 'Characteristics of grey wastewater', are affiliated with the Technical University of Denmark, located in Kongens Lyngby, Denmark.

In the analyzed data, which were exported from Scopus, 75 (4.9%) publications did not have the address of their authors' affiliation registered, thus not allowing the counting of those countries that had 197 citations. The missing authors' affiliation in these 75 documents corroborates the study presented by Schmidt *et al.* (2016), who identified that approximately 7% of the publications in the sample analyzed by the researchers did not have identifiers for author affiliation.

The countries identified in the sample, considering the affiliation of all authors, are geographically illustrated in Figure 8. In this presentation, the intensity of the color scale represents the number of documents associated with each country. The United States, China, Australia, and the United Kingdom are the most influential countries in terms of the number of publications in the area. While the former has the largest number of articles, in both analyses present in Table 5, the UK institutions are responsible for the highest number of citations. Israel stands out for having the highest average of citations per document, which indicates a high impact of its publications. Authors affiliated with Israeli institutions are the first author in 96.5% of the documents in which they are present.

The data presented in Table 5 and Figure 8 differ from those presented by bibliometrix. The function present in this package counts the addresses of the affiliations of all authors, thus allowing a document to have the same country counted more than once. According to this analysis, the United States, China, Australia, and the United Kingdom would have 438, 263, 196, and 190 articles, respectively. The sum of these first four countries would correspond to 38.5% of the total sample. While According to the data presented in Table 5, these same four countries have a total of 640 (34.9%) documents.

The dispersion of the 20 most productive countries across the continents of Oceania, Asia, the Americas, Europe, and Africa is an indication that different institutions around the world have been dedicated to researching the reuse of GW. This promotes the hypothesis that factors such as geographic location, availability, and water consumption are determining variables for the existence of research on reuse.

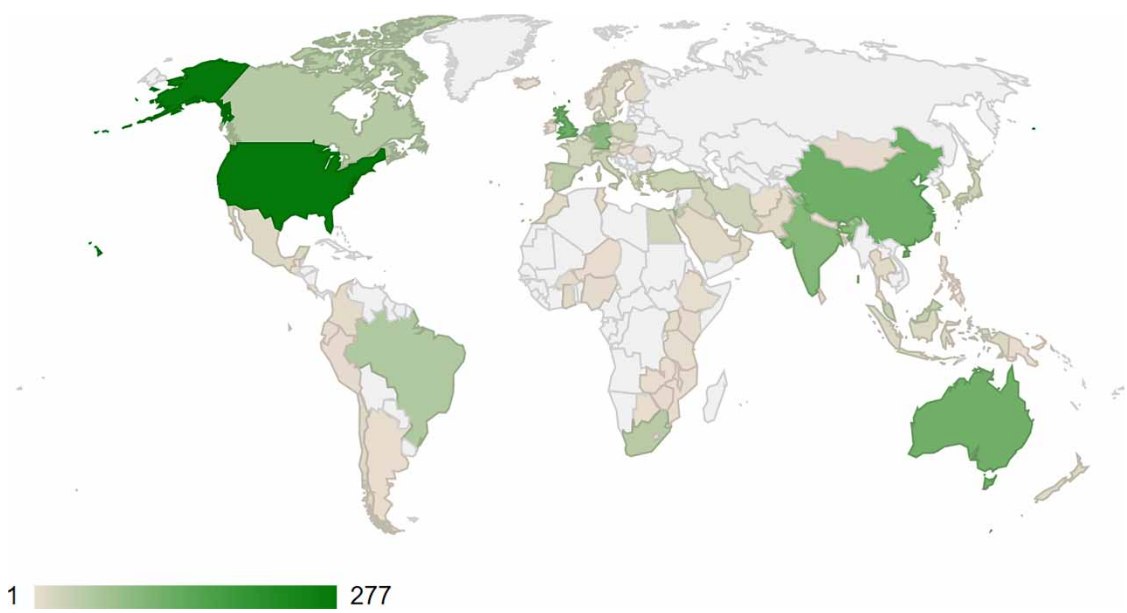


Figure 8 | Publications by country (all authors). *Source*: Scopus. Processed by authors (2021).

The co-authorship network of the countries listed in Table 5, considering all the authors of each document, is presented in Figure 9 to examine the relationship between the authors associated with institutions in those countries. The size of the nodes represents the number of publications associated with each country, and the connection line between the nodes represents the documents in which authors from these countries are co-authors. The thicker that line, the greater the number of documents. Figure 9 also shows a color scale representing the annual average of publications from each country.

Among the countries that published the most, the United States, Australia, United Kingdom, and Germany, in blue, stand out for having the lowest annual average of papers published, approximately 2011. This result of a low annual average indicates that these countries, called pioneers, were precursors in publications about GW in the world. This avant-garde made them the countries with the most citations on the subject and their prominence to GW research led to the search for co-authorship relationships in other countries. Yet authors from countries whose averages are higher and, therefore, have more recent research in GW, tended to associate themselves with institutions in countries with lower averages. This phenomenon possibly occurred due to the interest of these emerging countries in participating in research with pioneers in the field.

When analyzing network connectivity, the countries with the largest number of network connections were the United Kingdom who connected with 15 countries; the United States with 14 countries; China and Germany with 12 countries each; and Australia who co-authored documents with ten countries. Except for the others, Jordan, which also has an annual average of publications close to that of 2012, has a connection with only five countries and, consequently, 38 published articles, fewer articles than other countries in the same annual average. Thus, we found that the pioneer countries are more connected and tend to publish more articles, corroborating the analysis by Tang *et al.* (2018).

At a later point in the evolution of publications, there are countries such as Israel, France, and the Netherlands with annual averages around 2013, but they have not established themselves as countries that have built strong connections with the rest of the network. Among these, it is remarkable that Israel has a connection with only four countries: United States, Germany, Canada, and the United Kingdom. This corroborates the analysis of the low international cooperation of Israeli institutions.

With annual averages in 2016, countries like China, India, Brazil, South Africa, and the rest are at another stage in the evolution of knowledge, and due to the high average of the year of publications, we consider such countries as emerging in the area. However, these countries form connections with the countries previously mentioned and precursors in publications. In this way, a liaison hub is established between the countries that publish the most, thus occupying a central position in the country's co-authorship network.

DISCUSSION

Bibliometric analysis

From Figure 1, we observed there has been an increase in the number of publications in the area over the years, which indicates an evolution in the field of studies. Until the end of the last century the average number of publications per year was not

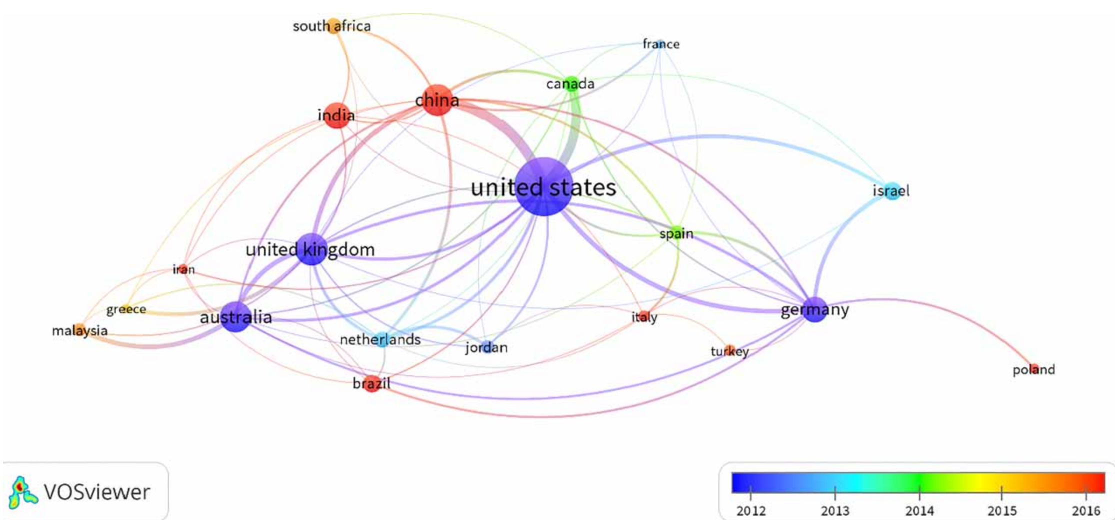


Figure 9 | Co-authorship network of the most productive countries. *Source*: Scopus. Processed by authors (2021).

very significant, but there has been great growth in the last 20 years, a trend observed in studies in the environmental area (Abejón & Garea 2015; Durán-Sánchez *et al.* 2018; Ji *et al.* 2018; Taddeo *et al.* 2019; Velasco-Muñoz *et al.* 2019).

Mubako (2018) produced a bibliometric analysis on blue, green, and greywater quantification approaches and his results present a correlation between the number of articles published by the journal. However, specifically in greywater, *Water Science and Technology*, which is not well ranked in Mubako (2018) analysis, stands out as the top publisher and as the one that receives more citations among the sample.

As for the most active authors in GW reuse, there is a positive correlation between the number of publications and the number of citations ($R^2=0.6564$ and p-value$=0.020$). From the list of authors with most citations, Garland is the only one who is not affiliated to a university, but rather to the United States Environmental Protection Agency. Despite not being on the list of authors with the largest number of publications, E. Eriksson is the sixth most cited author with 823 citations in eight documents.

Despite the degree of complementarity between the subjects analyzed in the database, there is big segregation between the clusters, segregated by colors, from the research groups in Figure 3. This distance is a variable that reflects the strength of the relationship between these groups (Zupic & Čater 2015), which is little in the greywater reuse research field. This is illustrated by the fact that Friedler co-authors five papers with Gross about risks associated with GW reuse in irrigation, one specifically in microbial risk analysis for various bacterial exposure involving greywater reuse for irrigation (Busgang *et al.* 2018). Concurrently, Garland and Ashbolt also worked on this theme in their paper about bacterial risk assessment of graywater reuse (Zimmerman *et al.* 2014). Although both groups work on related themes, neither have ever worked together; anecdotally, the papers cited use different spellings 'greywater', by Friedler and Gross, and 'graywater', by Garland and Ashbolt. This fragmentation indicates strong evidence of the dispersion in GW research field development structure.

Results from the most cited publications, Table 3, comply with Abejón & Garea (2015) and reveal that review papers received lots of citations, notedly, the first (Eriksson *et al.* 2002) and third (Li *et al.* 2009) most cited papers. This finding also corroborates that review articles from journals classified as environmental sciences are cited almost three times more than research papers (Miranda & Garcia-Carpintero 2018). These authors claim that good reviews are valuable for researchers because they provide critical analysis of other studies results, thus summarizing the state of the art of research and pointing out future research needs.

Regarding the variance of GW spelling throughout the papers published in the area, we observed that 'greywater' is the most frequent spelling. The most plausible explanation for this trend is the fact that six of the ten most cited studies in the area use the 'greywater' spelling, including the two oldest articles (Christova-Boal *et al.* 1996; Nolde 2000). The adoption of this spelling influenced other authors to maintain the spelling, possibly due to the credibility deposited in articles reviewed and published in influential journals in the area.

From the keyword analysis, it is clear in Table 4 that the top indexed keywords, which represent the key terms available from the journal, do not represent greywater. This is highlighted by the fact that no author keyword is repeated in indexed keywords, apart from 'wastewater', which is a broader term to define GW. However, wastewater is mainly related to sewage and may mislead the readers from the actual meaning. Moreover, 'water scarcity', 'sustainability', and 'water conservation', which are the main purpose of greywater reuse, show prominence on most used author keywords.

Lastly, developed countries stand out as the most active in GW reuse publications and citations. The United States is the country that publishes the most papers in GW reuse, twice as many as the second country, China. The list goes on with European countries, Australia, and Brazil, Russia, India, China, and South Africa (BRICS), who are becoming highly productive countries. This trend is also observed in Velasco-Muñoz *et al.* (2019), Zhang *et al.* (2017), and Abejón & Garea (2015). It is noteworthy that this country analysis reflects the affiliated institutions' nationality rather than the authors' nationality, and thus, national research fundings play an important factor in the country's publication activity. The reasons why these countries stand out, the context in which the research is developed, and future trends are discussed further in the next section.

Contextualization, evolution, and trends of greywater reuse

In an international context, Goal 7 of the UN's eight Millenium Development Goals ensures environmental sustainability by 2015 (United Nations 2015a). This is a generic objective that has four specific objectives, in which access to drinking water and basic sanitation was one of the sub-indicators. However, at the end of the Millennium Development Goals deadline, the UN recognized the importance of the scheme and proposed Agenda 2030 (United Nations 2015b), with 17 SDGs, of which it dedicated four to themes that permeate the reuse of greywaters: drinking water and sanitation; sustainable cities and communities; action against global climate change; and life in the water.

Most of the analyzed countries that stand out in the analysis are countries that live, totally or partially, with water vulnerability problems (Li *et al.* 2015). The authors correlate the water-related challenges in the world's megacities with various aspects, such as population growth and resulting climate changes. Finally, the study states that population growth in megacities directly influences the exhaustion of the capacity of water sources and urban infrastructure. Thus, it can also be inferred that the countries that live with these problems tend to do more research on the subject. This phenomenon can be explained due to the governments' influence on financing national research, and thus orienting the needs of the economy (Marginson 1997; Hicks 2012).

In the United States, although with continental dimensions and regions with an abundance of water, there are regions that are in a situation of high-water stress (Heim 2002). This problem has been worsening with the growth of metropolitan regions (Fuller & Harhay 2010). To solve water crisis problems, the state of California was the first to develop regulations regarding reuse in 1918 and currently has the largest reuse systems in the United States (California State Board of Health 1918; Angelakis *et al.* 2018).

In the United Kingdom, de Vries & Weatherhead (2005) state that there are conflicts in England over water that will be amplified by climate change. Conflicts in the southeastern region of England, more specifically in Essex, led to the first planned indirect drinking water reuse project in Europe in 1997 (Lazarova *et al.* 2001). Goodwin *et al.* (2019) identified that population growth would lead to water stress problems in London. The authors concluded that the reuse of effluents is a viable water-oriented tool to mitigate water use conflicts in megacities.

Australia was the first countries to develop national quality guidelines for the reuse of drinking water (Khan & Anderson 2018). The use of treated greywater for non-drinking activities is common practice in the country, in addition to its application in industrial activities and irrigation (Vuppaladadiyam *et al.* 2019).

Supplying 250 m^3 of water per inhabitant per year, Israel has very low water availability. This amount corresponds to half of what is considered 'absolute scarcity' according to the Falkenmark indicator (Tal 2006). Due to the need for new sources of water, in 1953 the country developed the first regulations for the reuse of sewage, which contributed to the reuse of effluents as the main water resources management tool (Shuval 1980). With the increase in water demand, as well as the increase in disputes over its use, desalination has become the main policy for increasing water availability (Kartin 2001). However, such technologies for removing salt from water have high costs, which directly impact the tariff charged to users. In addition to promoting conscientious use, citizens began to install GW reuse systems in their homes to save on their water bills. Such reuse without regulation or standardization has led water resource management committees to discuss and raise guidelines for the practice of reusing GW (Oron *et al.* 2014).

It is also observed that the pioneer countries are economically developed and highly productive in the world research scenario, while, as in Figure 9, the other countries are mostly developing countries, of which four of the five BRICS stand out: Brazil, India, China, and South Africa. Thus, we understand that the research about the reuse of greywaters follows the trend of diffusion from countries that invest more in research to countries that are in less advanced stages of development.

CONCLUSION

Research into the reuse of GW has been, is, and probably will be linked to the situation of regional water vulnerability. In this context of increased water demand, reuse is already inserted in the planning of water resources in countries such as the United States, Australia, United Kingdom, and Israel, which were pioneers in the studies of GW reuse and stand out academically in the area. In this article, the trends, evolution, and contextualization of the reuse of GW, as a water-oriented solution, around the world were analyzed. We observed that the area's growth in recent years is aligned with national and international water conservation policies. There was also an increase in the number of publications on the reuse of GW in recent years, with more than half of them published since 2013. The most frequent themes in the articles analyze the variability of the characteristics, quantity, and quality of GW, and also the variables depending on the quality and consumption of water, country, regions, customs, and habits.

From the bibliometric analysis, we concluded that countries with more connections have a tendency to publish more articles. However, there is dispersion and clustering in the structure of the research field on GW reuse. The main factors that corroborate these statements were the spatio-temporal distribution of publications; the sparse co-authorship networks found; the variety of authors from different institutions with high numbers of published works, but with few co-authorships in institutions from different countries (low rate of international cooperation); as well as the variation of the greywater spelling (graywater, graywater, gray water, gray water, gray-water, and gray-water). These factors show the disconnection between researchers and the absence of collaboration networks that integrate knowledge networks.

It should be noted that although Scopus is the most suitable database for work in the area of water resources, the analysis in this article was based only on this source. Therefore, it is suggested that future works replicate the analysis in other databases, such as Google Scholar, Web of Science, and PubMed. In addition, gaps in the metadata of some publications were identified that hindered data analysis, such as the absence of a variety of spelling of the name of some institutions. Due to inconsistencies observed in the metadata, it may be appropriate to identify institutions with a universal code, just as ORCID iD (Open Researcher and Contributor ID) identifies authors.

Finally, this observed dispersion of research on the topic follows the trend of diffusion of intellectual production originated in developed countries, such as the United States, Germany, United Kingdom, and Australia, which strongly invest in research and have a knowledge gradient that goes toward less developed countries, and with less investment in academic research. Currently, interest in the subject is on the rise, mostly in developing countries, such as Brazil, India, China, and South Africa, which seek interactions with pioneer countries. Therefore, we estimate that the future of research on GW reuse will occur in other developing countries that face water scarcity. Through the growing international cooperation between the institutions, we anticipate that the advances in the area of knowledge will be more solid and significant to promote the sustainable use of water resources.

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CREDIT AUTHOR STATEMENT

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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