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Review

Ecological and Environmental Effects of Reclaimed Water (RW) Irrigation and Recharge on Soil Environment and Groundwater Quality: a Systematic Review

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Abstract

The reuse of reclaimed water (RW) for irrigation and recharge is a promising approach to mitigate water scarcity and promote efficient water resource management. Nevertheless, there is increasing concern regarding the ecological and environmental impacts of soil and groundwater contamination resulting from the irrigation and recharge of RW. To understand the current state of research on the ecological risk of soil and groundwater during RW reuse, a bibliometric analysis of 1109 publications throughout 2002-2021 in the Web of Science Core Collection (WoSCC) database about the research topic was conducted. Through the use of HistCite Pro and Citespace, this study analyzed and visualized the number of publications, authors, citation frequency, keywords, institutions, journals, and countries where these publications have appeared. The results of this research showed an ongoing rise in the total number of publications during the 20 years prior. China was identified as the most prominent country in terms of production in this field, while the Chinese Academy of Sciences showed the highest level of productivity among institutions. *Water* has been identified as the most productive journal, while Li YK was identified as the most productive author. This current research focuses on the migration and transformation of RW contaminants in the soil-groundwater system and their ecological effects on soil and plants, whereas future research will concentrate on the risk assessment and health effects of emerging contaminants (ECs). The analysis presented in this study provides insights into research orientations, historical trends, and current research hotspots in the field of study. The aforementioned findings will offer valuable insights for formulating development strategies pertaining to RW reuse.

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Additionally, they will serve as guidance for decision-making processes within governmental management organizations.

Keywords: reclaimed water (RW), irrigation, recharge, citespace, research hotspots

Introduction

The concern of water scarcity has been identified as a substantial barrier to national economic development due to the rapid pace of economic growth and growing population [1]. In addressing the challenges of water scarcity and meeting the growing demand for water, reclaimed water (RW) has emerged as a critical alternative to conventional water sources such as surface water and groundwater [2]. The utilization of RW for agricultural irrigation, replenishment of rivers and lakes, and recharge of groundwater is an achievable solution to mitigating water scarcity in arid and semi-arid areas, offering significant social, economic, and ecological advantages [3]. Countries such as Israel, Jordan, Australia, and the USA reuse approximately 65% of treated water. By 2009, the annual use of RW in California had quadrupled since 1970, reaching 8.94 million m^3, with 47 percent of RW reused for urban green space or agricultural irrigation [4]. In Israel, 100% of domestic wastewater and 72% of municipal wastewater were properly reused [5]. In 2020, China's urban wastewater treatment volume will be approximately 75 billion m^3, while only 10 billion m^3 of RW will be used. China's RW reuse for agricultural irrigation is expected to account for 87 percent of the country's agricultural water deficit by 2030 [6]. Researchers and managers expressed concern about potential risks and ecological effects related to the increasing utilization of RW for irrigation and recharging applications.

Due to the presence of various inorganic, organic, and biological contaminants such as nutrients, organic contaminants, heavy metals, and pathogens in wastewater, the pollution treatment process employed by wastewater treatment plants may not achieve total removal of specific pollutants [7]. These pollutants not only contaminate soil-groundwater systems during the irrigation and recharge of RW, but they also pose a threat to human health through crop bioconcentration and amplification. Some pollutants, such as heavy metals, are biotoxic, environmentally persistent, and bioaccumulative. Additionally, emerging contaminants (ECs), such as alkylphenols, exhibit indirect toxicity, with their intermediate breakdown products possessing even higher biotoxicity and accumulation potential than the parent compound [8]. In particular, the ECs, including pharmaceutical and personal care products (PPCPs), endocrine disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFCs), and their intermediate breakdown products, can cause serious health risks such as brain damage, liver and lung damage, carcinogenic diseases, reproductive disorders, and endocrine duct disruptions [9]. Li et al. investigated the geographical and temporal trends of five EDCs in the RW replenishment type river, Chaobai River, and its groundwater. The highest concentrations of bisphenol A in surface water were 12.03–120.83 ng/L, followed by E1 at 1.05–25.35 ng/L. EDCs were found in 80% of the groundwater samples [10]. The RW is enriched with necessary nutrients, including nitrogen, phosphorus, and salts, which provide greater benefits for the growth of crops compared to freshwater. However, with long-term RW irrigation, even new and less concentrated contaminants present in the reclaimed water can accumulate in the soil, leading to various detrimental effects on soil microbial populations, diversity, and crops [11].

Moreover, the occurrence of ECs in the soil poses a notable risk to crop cultivation and can lead to the contamination of agricultural products, thereby potentially endangering human health. In a study conducted by Li et al., it was found that the concentration of phthalate acid esters (PAEs) in soil and vegetables increased to levels ranging from 0.73 to 9.48 mg/kg and 1.89 to 6.35 mg/kg, respectively, resulting from irrigation with RW. Increasing concern has been raised regarding various issues related to environmental pollution and the risks posed by pollutants during the irrigation and recharge of RW on soil and groundwater [12].

Multiple authors are currently contributing to the state of knowledge regarding the environmental impacts of RW. Deng et al. provided a concise overview of water reclamation technologies, identified potential contaminants present in treated RW, and described the potential dangers of water reuse to agriculture, the environment, and human health [7]. Wang et al. summarized the positive or negative effects of RW irrigation on soil, crops, the environment, and public health during agriculture and landscape irrigation [13]. These reviews summarize the progress of research into the application of contaminant risks in RW irrigation and recharge, but an overview of the overall fundamental characteristics and issues in the research is lacking.

Bibliometrics is an innovative method that encompasses data collection, analysis, compilation, and presentation. It is widely acknowledged as a highly effective approach for conducting quantitative and qualitative analyses of scientific activities [14]. The main purpose of bibliometrics is to support academics in discovering and exploring creative academic topics through the utilization of statistical and mathematical methods. These methods are employed to establish quantitative relationships within the literature as well as to analyze citation and co-citation connections among academic publications [15]. Bibliometrics, in contrast to reviews that provide an overview of the current state of research on a specific topic, focuses on analyzing future research directions in a certain field of study. It is now being widely adopted in the application of advanced oxidation processes for produced water treatment [16], water resource management [17], microplastic pollution in water ecosystems [18], and other research fields. Nevertheless, the literature lacks any research into the ecological effects of irrigation and recharge utilizing RW on soil and groundwater. This paper is based on bibliometrics by collecting literature related to the ecological effects of RW irrigation and recharge on soil and groundwater research from 2002 to 2021. The study revealed:

(1) Present the chronological distribution of the publications, most-cited papers, authors, institutions, countries/regions, and scientific journals that have made the most significant contribution to this field.

(2) Conduct analysis and identification of the current research state, hotspots, and frontiers in the topic under consideration.

(3) Provide an extensive framework for predicting future developments in the subject's field.

Material and Methods

Data Collection and Processing

The articles were obtained from the Web of Science Core Collection (WoSCC) database, a renowned literature retrieval engine administered by Thomson Reuters. The WoSCC database is widely acknowledged for curating the most significant and influential academic literature globally [19]. English documents published between 2002 and 2021 were collected on 8th November 2022. The search term is "Topic" = "reuse water" OR "reclaimed* water" OR "recycled water" OR "recycling water" OR "resurgent water" OR "gray water" OR "recreational* water" and "irrigate*" OR "recharge*". Document type = "article". The literature obtained from the search was screened out to exclude literature that was not relevant to the study; finally, 1109 articles were retrieved from the WoSCC database. Among the retrieved articles (1109 in total), 395 of the 1109 articles were related to the effects of RW irrigation and recharge on soil environments, while the remaining 714 articles were related to the effects of RW on on groundwater and surface water environments.

Combining similar keywords into one keyword, for example, "reclaimed water", "reuse water", "recycled water", "recycling water", "resurgent water", "gray water" and "recreational water" are combined to form "reclaimed water".

Data Analysis

HistCite Pro is a software tool created to perform literature indexing, enabling academics to efficiently evaluate and analyze the attributes of literature on a specific topic [20]. There presently exist two indicators, which are the Total Local Citation Score (TLCS) and the Total Global Citation Score (TGCS), which serve as indicators to evaluate the significance of individual publications. A higher TLCS value indicates greater importance of the literature in its specific field of expertise, while a higher TGCS value signifies that the literature has garnered attention from researchers worldwide and is acknowledged for its contributions [21]. Citespace (6.1.3) was a tool for building and visualizing bibliometric networks, which can be constructed based on citation, co-citation, or co-authorship relationships [22]. The retrieved publications were screened, and excluded literature that was irrelevant to the research. Bibliometric analysis is conducted to analyze these publications, including the annual number of publications, research institutions, research authors, literature published journals, highly cited publications, research contents, etc., and Origin 2018 and R4.03 were used to plot.

Results and Discussion

Distribution of Publications over the Years

The yearly number of publications represents the activity of the subject of study, the rate of its development, and the interest of scholars in adjacent topics and disciplines [23]. To better comprehend the research dynamics and advancements in this subject, a statistical analysis was conducted to analyze the number of publications in the field spanning the years 2002 to 2021 (Fig. 1). The number of publications published on the subject has been growing annually, as seen in Fig. 1. According to the growth tendency of the number of journal articles, a sluggish growth stage and a rapid growth stage may be distinguished. In the first stage (2002-2011), the number of journal articles in the field was all below 50, growing slowly, and the average annual number of journal articles was nearly 25, increasing from 7 in 2002 to 47 in 2011, with an average annual growth of nearly 4 articles. After 2012, the number of research professionals who pay close attention grows dramatically, as does the number of published publications. As a result of economic growth and social advancement, the demand for water resources is increasing in all sectors, and countries are actively seeking various means to alleviate water scarcity. The reuse of RW and its associated risks will become the center of attention in a number of fields.

Contributing Countries/Regions Analysis

According to statistical analysis performed by the Histcite Pro software, 72 countries/regions have published research publications about the subject. Table 1 displays an overview of the top countries/regions

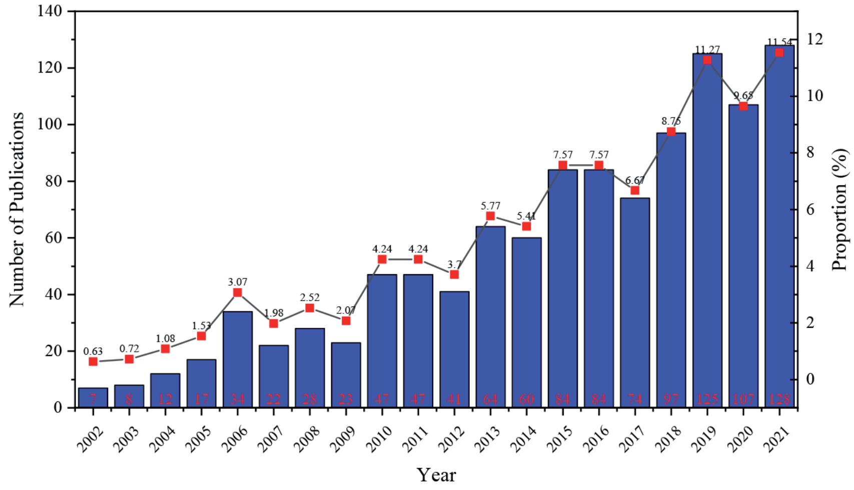

Fig. 1. Publication output performance during 2002-2021.

Table 1. Countries/regions of the top 10 publications from Jan 2002 to Dec 2021.

Rank	Country/territory	Records	% of 1109	TLCS	TGCS	Average Article Citations
1	USA	325	29.31	506	5780	17.78
2	China	225	20.29	434	4187	18.61
3	Spain	183	16.50	274	3263	17.83
4	Australia	145	13.07	409	3709	25.58
5	Italy	52	4.69	85	992	19.08
6	Greece	35	3.16	97	842	24.06
7	Germany	32	2.89	49	643	20.09
8	UK	31	2.80	100	857	27.65
9	France	30	2.71	18	376	12.53
10	Israel	29	2.61	39	662	22.83

in the field of study, wherein the USA and China contribute 29.31% and 20.29% of the total publication count, respectively. The number of publications produced by these two countries is significantly higher than that of Spain (183 articles, 16.50%) and other countries/regions. This suggests that the USA and China have a significant role in the sector. The TLCS and TGCS released by the USA and China are likewise significantly superior to those of other nations. The TLCS and TGCS issued by the USA are 9951 and 37193, whereas those published by China are 3524 and 11237, respectively. It demonstrates that the USA and China are two leading nations in the sector, considerably ahead of other countries/regions.

The network diagram of cooperation relationships in the field was drawn using Charticulator (https://charticulator.com/) (Fig. 2). The length of the circle's arc symbolizes the number of active postings in those countries/regions, and the thickness of the line connecting countries/regions shows the proximity of collaboration between them, with thicker lines representing tighter cooperation. The scientific partnership between China and the USA in this field is quite tight.

Scientific Collaboration Analysis

An analysis of the collected literature using HistCite Pro software shows that a total of 3330 research institutions have published research papers in the field. Table 2 lists the top 10 research institutes, five of which are located in China: Chinese Acad Sci, China Agr Univ, Tsinghua Univ, Beijing Water Sci & Technology Inst, and China Inst Water Resources & Hydropower. And three research institutions from the USA, including the Universities of Maryland, Florida, and California, Riverside. According to Table 2, Chinese Acad Sci was accountable for 5.68 percent of all publications over the past 20 years, followed by CSIRO Land and Water (3.79%) and China Agr Univ (3.71%).

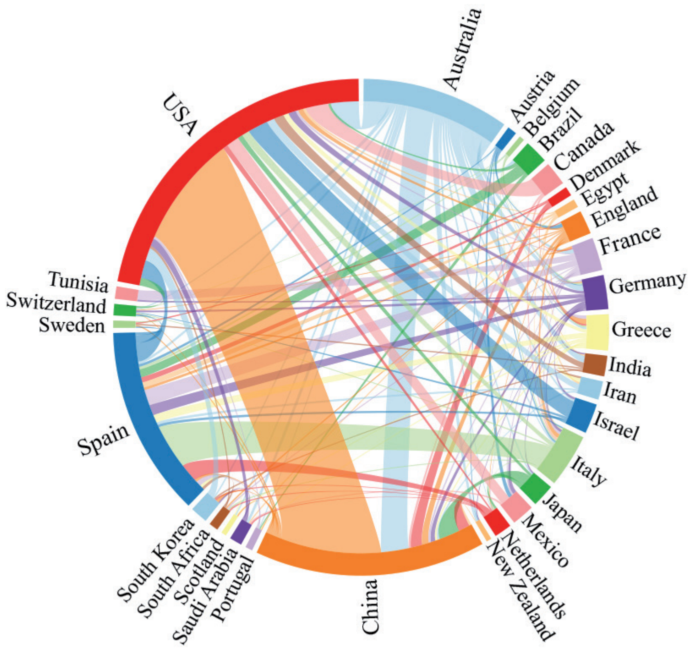

Fig. 2. Map of cooperation between the top 10 countries/regions from Jan 2002 to Dec 2021.

Table 2. Top 10 most productive institutions from Jan 2002 to Dec 2021.

Rank	Institution	Location	Records	% of 1109	TLCS	TGCS	Average Article Citations
1	Chinese Acad Sci	China	63	5.68	223	1945	30.87
2	CSIRO Land and Water	Australia	42	3.79	135	1017	24.21
3	China Agr Univ	China	41	3.70	103	524	12.78
4	CSIC	Spain	32	2.89	65	508	15.88
5	Univ Maryland	USA	32	2.89	29	337	10.53
6	Univ Florida	USA	31	2.80	68	502	16.19
7	Univ Calif Riverside	USA	27	2.43	89	838	31.04
8	Tsinghua Univ	China	26	2.34	58	463	17.81
9	Beijing Water Sci & Technology Inst	China	22	1.98	14	190	8.64
10	China Inst Water Resources & Hydropower Res	China	22	1.98	33	199	9.05

In terms of TLCS, the top three research institutions are the Chinese Acad Sci in China, the CSIRO Land and Water in Australia, and the China Agr Univ in China, with respective indices of 223, 135 and 103; the top three ranked TGCS are the Chinese Acad Sci, the CSIRO Land and Water, and the Univ Calif Riverside, with respective indices of 223, 135 and 103. This suggests that these three institutions have a substantial impact on the field. Particularly, the Univ Calif Riverside has just 27 publications, but its average citation frequency of 31.04 demonstrates the outstanding quality of the literature produced by this academic organization.

The quantification of citations received by an author's works in a specific research field provides a metric for evaluating their significance and influence in the respective field of study. According to HistCite Pro, there are 11,675 researchers on the subject. Table 3 includes the top 10 authors in the discipline, all of them have published more than 10 works. Li YK, Alarcon JJ, and Sapkota AR are the top three authors, with 26, 23, and 21 publications, respectively. The top 10 authors include three American authors, two Canadian authors, and one author each from Korea, China, Denmark, Poland, and Germany, demonstrating that the USA is a significant contributor to the subject. In terms of TLCS data, Alarcon JJ has the most TLCS with 160, followed by Toze S and Nicolas E with 135 and 103 respectively. In terms of TGCS data, Toze S

Table 3. Authors of the top 10 publications from Jan 2002 to Dec 2021.

Rank	Author	Records	% of 1109	TLCS	TGCS	Average Article Citations
1	Li YK	26	2.34	102	400	15.38
2	Alarcon JJ	23	2.07	160	586	25.48
3	Sapkota AR	21	1.89	20	217	10.33
4	Zhou B	20	1.80	82	318	15.90
5	Liu HL	18	1.62	27	218	12.11
6	Nicolas E	17	1.53	103	397	23.35
7	Romero-Triguerosos C	17	1.53	67	337	19.82
8	Toze S	15	1.35	135	968	64.53
9	Chen WP	14	1.26	98	622	44.43
10	Sharma M	14	1.26	15	150	10.71

Table 4. Journals of the top 10 publications from Jan 2002 to Dec 2021.

Rank	Journal	Records	% of 1109	TLCS	TGCS	Average Article Citations
1	Water	69	6.22	17	492	7.13
2	Agricultural Water Management	62	5.59	271	1738	28.03
3	Science of the Total Environment	62	5.59	89	1504	24.26
4	Water Research	39	3.52	99	1690	43.33
5	Water Science and Technology	35	3.16	51	443	12.66
6	Desalination and Water Treatment	24	2.16	17	125	5.21
7	Desalination	23	2.07	100	738	32.09
8	Chemosphere	20	1.80	42	579	28.95
9	Journal of Water Reuse and Desalination	19	1.71	13	104	5.47
10	Hortscience	18	1.62	72	306	17.00

had the highest number of TGCS with 968, followed by Chen WP and Alarcon JJ with 622 and 586, respectively. This indicates that these scholars are more influential in the field.

Using the HisCite Pro software, the leading journals in the field were determined. Based on the data shown in Table 4, it can be observed that the top 10 international journals publish a significant amount of publications. The research results indicate that *Water* has published the highest number of publications, amounting to 69 articles published between the years 2002 and 2021, which stands for 6.22% of the total number of publications. Following closely behind, the journals *Agricultural Water Management* and *Science of the Total Environment* have both contributed significantly, with 62 articles each. These publications account for 5.59% of the total number of publications. A total of 39 articles were published in the journal *Water Research*, representing a proportion of 3.52% of all searchable publications.

The TLCS and TGCS of *Agricultural Water Management* are the highest in all the journals, with a TLCS of 271, just ahead of *Desalination* in second place with 100 and *Water Research* in third place with 99. *Agricultural Water Management* has the highest TGCS with a TLCS of 1738, just ahead of *Water Research* in second place with 1690 and *Science of the Total Environment* in third place with 1504. The high citation frequency of *Water Research* publications, all of which have over 40 citations, demonstrates that these journals are gaining greater prominence and impact in their respective fields.

Keyword Co-Occurrence Network and Cluster Analysis

Keywords are the essence and core of the article, a very condensed and succinct representation of the article's content that represents the focus of existing research [24]. In 2002-2021, "quality", "removal",

Table 5. High frequency keywords of publications from Jan 2002 to Dec 2021.

Rank	Keywords	Occurrences	Rank	Keywords	Occurrences
1	Reclaimed water	477	11	Growth	76
2	Wastewater	344	12	Management	73
3	Irrigation	220	13	Personal care products	61
4	Soil	117	14	Fate	60
5	Quality	113	15	Effluent	55
6	Water reuse	101	16	Managed aquifer recharge	53
7	Removal	91	17	Yield	50
8	Groundwater	89	18	Drinking water	49
9	Salinity	78	19	Escherichia coli	40
10	Pharmaceuticals	77	20	Groundwater recharge	40

"salinity", "pharmaceuticals", "personal care goods", and "*Escherichia coli*" were among the top 20 most high-frequency keywords in the sector, as shown in Table 5. The assessment of risk associated with the reuse of RW is significantly affected by its quality. As the main source of RW, municipal wastewater contains a variety of inorganic, organic, and biological contaminants. In particular, ions, ECs, and biological contaminants are difficult to eliminate via conventional wastewater treatment methods. The presence of contaminants in RW poses multiple threats. It endangers human health during irrigation and recharge, degrades soil ecosystems, and causes harm to plants due to the accumulation of toxic and hazardous contaminants in the soil. Additionally, it poses a risk of groundwater contamination from the downward migration of contaminants. Numerous studies have comprehensively investigated the effects of common contaminants found in RW on various aspects such as plant growth, soil environment, groundwater quality, and public health. There are numerous potential risks involved with using RW for irrigation.

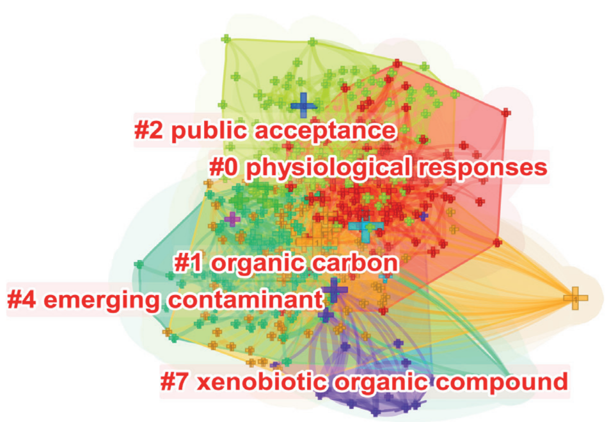

Fig. 3. Clustering analysis of research-related keywords during 2002-2021.

Human health and ecological problems associated with irrigation and recharging of RW can be efficiently avoided or mitigated via the implementation of scientific management practices.

Keywords are a simplified and generalized representation of relevant information contained in publications, which is a high degree of condensation and summary of the research content of the publications. The frequency of keyword occurrences in a particular topic is directly proportional to its representation of current and trending research in the field [25]. To explore the current research status and future development trends in this field, a comprehensive analysis was conducted on the co-occurrence of keywords in the current body of literature. Based on the results of the keyword co-occurrence analysis, it was seen that all the keywords were classified into four different clusters. Fig. 3 shows the first cluster, labeled "physiological responses," which mostly encompasses soil salinity, chemical composition, and mixed irrigation. Cluster #1, referred to as "organic carbon," is primarily concentrated on the study of organic matter. Cluster #2, labeled "public acceptance," is focused on the utilization of reclaimed water, life cycle analysis, and water scarcity. Cluster #4, designated as an "emerging contaminant," is centered around the application of liquid chromatography-tandem mass spectrometry and the investigation of personal care products. Lastly, Cluster #7, denoted as "xenobiotic organic compound," was primarily concerned with health risk assessment, organic contaminants, antibiotic resistance, and the persistence of active drugs.

The Burst keywords analysis in CiteSpace can be conducted to analyze keywords that reveal abrupt emergence and quick growth in frequency, indicating the frontiers of research in a certain topic and the development of research hotspots [26]. Through the burst keywords analysis with the strongest citation in this field (Fig. 4), it can be discernible that the research spanning the period of 2002 to 2021 could be divided into two distinct phases:

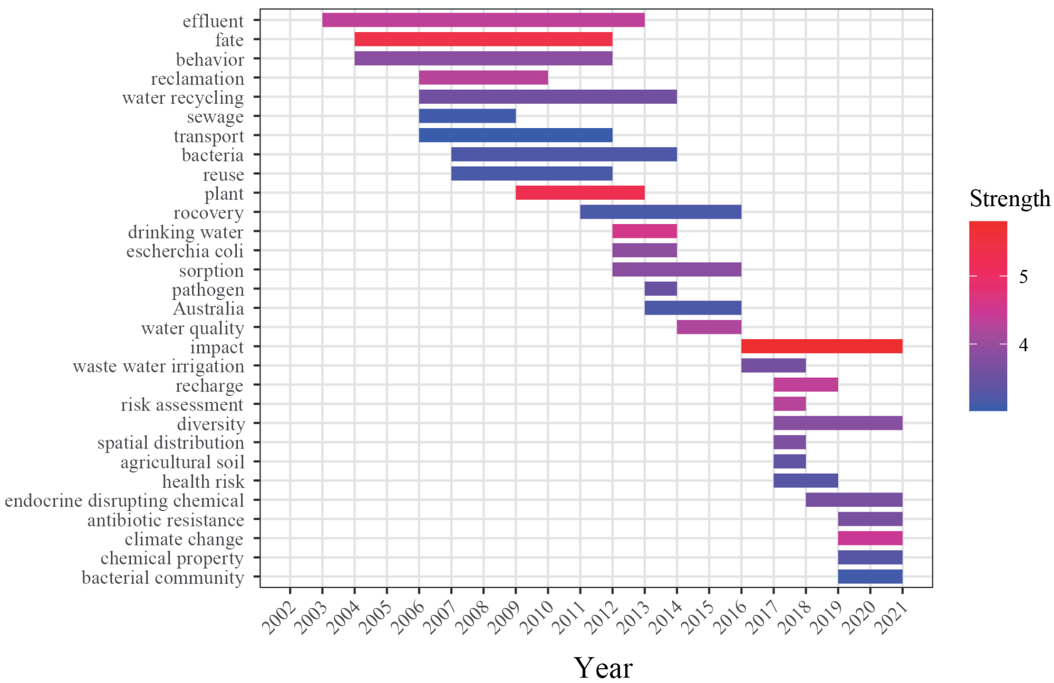

Fig. 4. The Top 30 burst keywords information for the research subject during 2002-2021.

(1) In the first stage (2003-2016), the keywords with the highest burst strength were "fate", "behaviour", "transport", "sorption", "drinking water", "bacteria", and "*Escherichia coli*". The presence of various inorganic, organic, and biological pollutants in RW, which enter the soil-groundwater system during irrigation and recharge and are transported and transformed through physicochemical and biological interactions with soil materials, is inextricably linked to their environmental behavior via sorption-desorption, degradation, and volatilization. The study of the transportation, transformation, and distribution of contaminants in RW in the soil-groundwater system has the potential to contribute to the formulation of scientifically informed management approaches aimed at averting or alleviating the human health and ecological risks related to RW utilization.

RW contains many pathogens, such as bacteria, protozoa, viruses, parasites, etc. Although RW is disinfected before reuse and the number of pathogenic bacteria is greatly reduced, pathogenic microorganisms still pose the greatest health risk when RW is reused, and the risk of contamination by pathogenic microorganisms is one of the safety indicators in the irrigation water quality standards. Pathogens often adhere to trees and lawns, and humans who come into contact with them may be infected. Most urban green areas now use sprinkler irrigation, which has a high degree of atomization and the ability to easily form aerosols. Aerosols containing pathogens can cause respiratory infections when they enter the human body via the respiratory route [27]. Pathogenic bacteria must be monitored and assessed for risk to assure the safety of RW.

(2) In the second stage (2017-2021), keywords with high burst strength were "endocrine disrupting chemical", "antibiotic resistance", "chemical property", "bacterial community" and "health risk". The main focus of this phase of research is on the environmental risks of ECs in RW. The ECs are mainly due to the daily activities of human beings, but the relevant laws, regulations, and standards have not yet been established for this category of contaminants [28]. ECs include mainly PPCPs, hormones, food additives, pesticides, plasticizers, wood preservatives, surfactants, flame retardants, and microplastics [29]. ECs are often biotoxic, environmentally persistent, and bioaccumulative, and their impact on human health and ecosystem safety is often a chronic, long-term cumulative process [30]. Therefore, the consequences of ECs on soil, flora and fauna, and human health must be systematically studied over time. Environmental pollution and ecological effects of ECs on soil and groundwater depend not only on the quality and quantity of RW and the physicochemical properties of the ECs, but also on soil properties (organic matter, clay content, and soil texture) that influence the transport and transformation of ECs in the soil. Lastly, because there is no single type of pollutant in RW, there are frequently many contaminants in addition to the unique ones, and the harmful effects on organisms must be considered when multiple pollutants coexist.

Most Highly Cited Literature

To quantitatively evaluate the academic impact of the publication, citation frequency has become recognized as an essential and distinguishing signal in current research assessment. The citation frequency of publications can

Table 6. The TOP 10 cited articles in the field during 2002-2021.

Rank	Title	Journals	Authors	TLCS	TGCS
1	Reuse of effluent water—benefits and risks	Agricultural water management	Toze S	44	407
2	The social acceptability and valuation of recycled water in Crete: A study of consumers' and farmers' attitudes	Ecological Economics	Menegaki A N	28	97
3	Long-term physiological and agronomic responses of mandarin trees to irrigation with saline reclaimed water	Agricultural Water Management	Nicolás E	27	63
4	Presence and distribution of wastewater-derived pharmaceuticals in soil irrigated with reclaimed water	Environmental Toxicology and Chemistry	Kinney C A	26	309
5	Quantitative microbial risk assessment models for consumption of raw vegetables irrigated with reclaimed water	Applied and environmental microbiology	Hamilton A J	23	173
6	Impact of reclaimed water irrigation on soil health in urban green areas	Chemosphere	Chen W	23	54
7	Transient soil salinity under the combined effect of reclaimed water and regulated deficit drip irrigation of Mandarin trees	Agricultural Water Management	Mounzer O	22	49
8	Reclaimed water as an alternative water source for crop irrigation	HortScience	Parsons L R	21	45
9	Physiological and agronomic mandarin trees performance under saline reclaimed water combined with regulated deficit irrigation	Agricultural Water Management	Pedrero F	20	41
10	Response of young 'Star Ruby' grapefruit trees to regulated deficit irrigation with saline reclaimed water	Agricultural Water Management	Pedrero F	19	30

be recognized as an indicator of the level of attention it attracts from researchers in the respective subject, as well as its application and worthiness in the field [31]. The top 10 most cited publications in this field are shown in Table 6. Most of the top 10 cited publications mainly concentrate on evaluating the impact of RW irrigation on both food security and soil quality. The top 10 cited publications are mostly about the impacts of RW irrigation on food security and soil quality. Regardless of the recognition that the nutrients and salts contained in RW are more beneficial for crop growth compared to fresh water, prolonged irrigation with RW can lead to the accumulation of low concentrations of ECs in the soil. These residual contaminants in the soil can have negative impacts on enzyme activity, soil nitrification, and soil respiration. Additionally, they can negatively impact the functional biodiversity of the soil, ultimately affecting the microbial community and diversity, and even crop production [32]. Therefore, microbial biomarkers like soil respiration, enzyme activity, and the number of indicator microorganisms can represent the ecotoxicological impacts of contaminants on soil-groundwater.

After penetration of RW into the soil, the majority of new contaminants will be absorbed by crops, which will not only hurt the growth of the plants but will also be conveyed to humans through the food chain. Low amounts of ECs will not induce acute exposure in humans in the near term, but even at extremely low concentrations, long-term exposure may be detrimental [12]. Therefore, the utilization of RW for irrigation needs should be contingent upon the assessment of local RW quality parameters, soil composition, climatic conditions, and crop types. This evaluation is crucial in establishing suitable water quality benchmarks for RW irrigation. Additionally, adopting appropriate methods for irrigation, like underground drip irrigation and sprinkler irrigation, is essential to ensure the safe application of RW and mitigate the potential negative impacts of ECs on crops and soil-groundwater systems.

Discussion

The utilization of RW is crucial for reducing water scarcity and attaining sustainable development of the world's water resources. The superiority of RW in terms of water quality, as compared to untreated wastewater, has been widely recognized owing to cost and process limitations. Nevertheless, RW continues to contain a certain level of organic pollutants, heavy metals, nutrients, salt ions, and pathogenic bacteria. The water quality characteristics of RW are further influenced by factors such as the source of the reclaimed water, the materials used in the pipe network, and the conditions during transportation [33]. The long-term irrigation and recharge of RW can potentially impact the receiving soil and groundwater environment, leading to associated ecological and environmental risks. Therefore, it is imperative to conduct research on these risks.

This study employed bibliometric analysis to analyze current research trends related to the ecological and environmental risks of RW irrigation and recharge on soil-groundwater systems. The study revealed that 3330 research institutes from a total of 72 countries and regions have been active in this field to date. Chinese research institutions, led by Chinese Acad Sci, China Agr Univ, and Tsinghua Univ, have published the most papers on this topic. China is regarded as the most prominent producer of publications on this particular subject. China's utilization of RW resources has experienced rapid growth since 2001. Numerous water quality standards have been consecutively implemented to regulate the reuse of RW, thereby establishing standards to guarantee its safe utilization. China is projected to have a total consumption of 16,105 million m^3 of RW by the year 2021 [34].

Current scientific research in the field of ecological and environmental risks related to RW irrigation and recharge on soil-groundwater systems primarily concentrates on the effects of conventional contaminants found in RW, including salt, nitrogen, phosphorus, heavy metals, and pathogenic bacteria. These research investigations are geared toward understanding the repercussions of such contaminants on soil quality, groundwater environment, and plant growth, as well as the effects on soil microcosms and potential health risks. Comprehensive investigations have been conducted by researchers in this particular field. During the period of plant growth, Lu et al. conducted a comparative analysis of the accumulation and distribution of Cd in greenhouse soils. The study specifically focused on the differences between soils watered with RW drip irrigation and those irrigated with groundwater drip irrigation. The evaluation of the transport of heavy metals in soil during drip irrigation with RW provides significant theoretical and practical significance in the study of RW irrigation and the assessment of heavy metal contamination in food [35]. Wang et al. evaluated the effects of trickle irrigation by utilizing reclaimed water on soil nitrogen dynamics. Following the implementation of drip irrigation using RW, there was a notable surge in the NH_4^+-N concentration within the uppermost layer of the soil. Subsequently, this concentration experienced a significant decline on the fifth day, ultimately reverting to its initial values before irrigation on the ninth day. The study revealed that there was an increase in the concentration of NO_3-N in the soil as the depth of the soil increased [36].

The researchers further developed and established different ecological risk assessment models to evaluate the potential risks related to the utilization of RW irrigation and recharge. Phogat et al. conducted an ecological risk assessment of utilizing RW for irrigation purposes in the period of 2018-2050 by using the HYDRUS-1D variable saturation flow and multicomponent transport module UNSATCHEM based on historical climate data, soil hydraulic properties, soil solution characteristics, and cation exchange data spanning from 1970 to 2017. The model's prediction indicates that the application of RW for irrigation will lead to an elevation in soil salinity levels, consequently diminishing the potential yield of crops that are sensitive to high salt concentrations [37]. Wu et al. developed a comprehensive quantitative assessment framework to evaluate the risk of irrigation pollution caused by RW in agricultural regions based on an improved version of the DRASTIC model. The framework presented in this study delineated the various levels of groundwater contamination risk in Beijing, categorizing them as low, medium, and high. Furthermore, it proposed a scientifically grounded methodology for implementing RW irrigation in regions with limited water resources, with the primary objective of mitigating the occurrence of groundwater pollution [38].

The utilization of RW for irrigation and recharging has a multitude of possible challenges. As the prevalence of RW utilization for irrigation and recharge its ecological and environmental effects and risks have garnered the attention of numerous scholars and managers. There remained an absence of knowledge and an urgent requirement for more investigation into the negative impacts of RW irrigation and recharge on ecosystems and human health. An extensive study has been conducted on the ecological and environmental problems related to the irrigation and recharging of RW in soil and groundwater. However, researchers must concentrate their focus on various concerns that warrant further investigation in future studies:

(1) Conduct long-term monitoring research: The potential ecological and environmental hazards related to various contaminants in soil and groundwater may only become apparent following extended periods of irrigation and recharge of RW. Consequently, effectively monitoring and evaluating these risks within a short timeframe poses significant challenges. Therefore, it is imperative to establish regular, long-term monitoring protocols for soil, vegetation, and groundwater in areas where RW is utilized for irrigation and recharge objectives. A comprehensive investigation should be conducted to evaluate the ecological and environmental risks related to the soil-groundwater-crop system during RW irrigation and recharge and to clarify the patterns of migration and transformation of different contaminants during RW irrigation and recharge, with the ultimate objective of ensuring the safety and reliability of such practices.

(2) Promote the research of soil and groundwater ecological and environmental risk assessment models: There is currently a dearth of understanding of the soil environmental reactions of normal contaminants during RW irrigation and recharge due to the complexity of RW quality and the variety of soil types, vegetation types, and irrigation systems. In addition to the physicochemical properties of ECs and the water quality and quantity of RW recharge, soil properties such as organic matter, clay content, and soil texture play a role in calculating the ecological and environmental risks of

contaminants in RW to the soil-groundwater system. Existing research is primarily limited to short-term field observations and laboratory simulation studies, and there is a dearth of research applying assessment models to couple multiple factors such as RW quality, soil, vegetation, and irrigation management practices.

(3) Strengthen the identification, monitoring, and ecological risk assessment of ECs: Over the previous decade, the increase in the prevalence of microplastics, nanomaterials, EDCs, PPCPs, and other ECs has raised notable environmental concerns. ECs refer to a category of chemical substances that possess detrimental properties and biotoxicity. The ECs do not degrade in subterranean environments. Additionally, there is a phenomenon of adsorption and desorption between ECs and aquifer media, leading to their persistence in soil and groundwater. The potential ecological and environmental risks related to ECs in soil-groundwater systems during the processes of irrigation and recharge of RW should be further strengthened.

Conclusions

This study provides a comprehensive analysis of the literature published on the subject between 2002 and 2021, utilizing the WoSCC database. It provides an extensive overview of the published literature, with an emphasis on publication trends and research hotspots. The results of this study found that the total number of publications has grown during the past two decades. The study encompassed two different stages: first, a period of slow development spanning from 2002 to 2011, followed by a subsequent phase characterized by rapid growth from 2012 to 2021. The USA of America produced the most number of publications, with a total of 325, while China followed closely with 225 publications. The Chinese Academy of Sciences was identified as the institution with the highest level of productivity. The journal that showed the highest productivity in terms of published articles was *Water*, with a total of 69 articles. Following closely after were *Agricultural Water Management* and *Science of the Total Environment*, both of which had 62 articles each. In terms of author productivity, Li YK was identified as the most prolific author, having contributed 26 papers. The following were closely followed by Alarcon JJ and Sapkota AR.

Furthermore, current research is focused on studying the migration, distribution, transformation, and accumulation patterns of normal contaminants found in RW. These contaminants include salts, heavy metals, pathogenic microorganisms, nitrogen, and phosphorus. Additionally, researchers are investigating the effect of various factors, such as the quantity and quality of RW, irrigation practices, and soil conditions, on the potential ecological risks related to reusing RW. The future study direction in the process of reusing RW may involve investigating the risk assessment, health effects, and biocumulative effects of ECs, given the increasing prevalence of these ECs. By comprehensively summarizing the current state of research on the ecological risk of soil and groundwater during RW reuse, the result of this study is to promote comprehension of current research among other researchers and to provide a helpful guide focusing on the prevalent trends.

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Conflict of Interest

The authors declare no conflict of interest.

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