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Analysis of reclaimed water irrigation research based on China National Knowledge Infrastructure

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ABSTRACT

Reclaimed water irrigation has become an important way to alleviate the shortage of water resources in the world. This study analyzed reclaimed water irrigation research in the China National Knowledge Infrastructure database from 2000–2021 using Excel and SPSS, as well as literature metrology. A qualitative and quantitative analysis of Chinese reclaimed water irrigation research in the past 20 y from the aspects of the number of publications, topics, experimental factors, survey region, and irrigation duration was carried out. The results indicated that there exists a wide discrepancy in the development of reclaimed water reuse among the provinces of China. Furthermore, the effects of reclaimed water on soil environments are highly dependent on water quality, while the appropriate irrigation practices still require further study under drought stress. This research will help facilitate understanding of reclaimed water irrigation in China and promote the practice of reclaimed water utilization in the future.

Keywords: Treated sewage effluent; Water quality; Soil environment; Bibliometric analysis

1. Introduction

Rapid urbanization and population growth have intensified the mismatch between the supply and demand of global water utilization. The shortfall between the forecast demand and available water supply in the world in 2030 has been estimated to be 40% [1]. More than 60% of the global population could suffer from water scarcity by 2030 [2]. Thus, the reuse of reclaimed water as an alternative water source for farmland and landscape irrigation can effectively address water shortages [3]. More than 80% of Israeli sewage effluent was treated and reused to provide 50% of agricultural water consumption in 2020 [4]. In the United States, the total amount of municipal sewage is approximately 44.2 billion m^3/a, of which the renewable utilization is approximately 16.4 billion m^3/a [5]. However, reclaimed water is currently used to irrigate only 10% of the world's agricultural land [6]. Therefore, a synthetic analysis of reclaimed water irrigation practices should be conducted to identify limiting conditions for its development.

As the most populous and largest developing country, China suffers from severe water scarcity. The amount of water resources per capita in China is approximately 2,237 m^3 [7], which is only approximately 25% of the world's average. To encourage the utilization of reclaimed water, guidelines on promoting the utilization of recycled water as a resource were passed by the National Development and Reform Commission of China in 2021 [8]. The guidelines explicitly indicate that the utilization rate of reclaimed water in water-deficient cities of China should be over 25%

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by 2025, while in the Beijing–Tianjin–Hebei region it should be over 35%. Although China has made efforts to develop reclaimed water reclamation for several decades, the current developments in wastewater recycling still greatly fall behind those of the European and American developed countries. A survey in 2021 showed that approximately 20% of the total reclaimed water was used for agricultural irrigation, while 80% of the treated water was reused for recreational/environmental enhancement, miscellaneous urban use, industry, and groundwater recharge [7]. Furthermore, the consumption of treated sewage effluent in China was 10.89 billion m^3, and approximately 22.5% of wastewater was disposed of, accounting for only 3% of agricultural water in 2020 (Fig. 1) [7]. Consequently, there is great potential for reclaimed water irrigation to partially fulfill the agricultural water demand in China in the future.

To promote the utilization of treated sewage effluent in China, it is important to summarize and analyze the current situation and development trends of reclaimed water irrigation. The article applies a statistical approach to outline, analyze, and discuss the topics, contents, institutions, and journal distribution of domestic reclaimed water irrigation research from 2000 to 2021. In addition, it proposes suggestions and raises issues to provide a better understanding of the status of recycled water irrigation to promote the sustainable use of water resources.

2. Methods

2.1. Research approach

Based on a large number of studies about reclaimed water irrigation, the study proceeds with an in-depth look at three aspects: research themes and contents, research scale and duration, and research region distribution. Then, the status of reclaimed water irrigation, difference of reclaimed water irrigation impact, and irrigation method are outlined, analyzed, and discussed.

2.2. Data search and collection

We comprehensively searched the peer-reviewed literature by using China National Knowledge Infrastructure

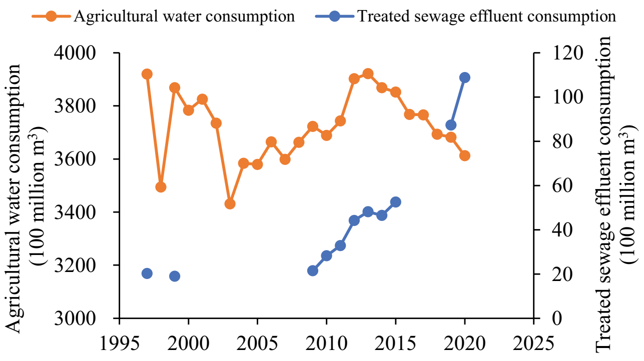

Fig. 1. The variation in treated sewage effluent consumption and agricultural water consumption in China from 1997 to 2020. Data source: Ministry of Water Resources (2021).

(CNKI), with search topics related to reclaimed water irrigation. Irrigation referred to drip irrigation, sprinkling irrigation, and traditional irrigation by furrow or flood or watering. The search terms included "reclaimed water", "treated sewage", "irrigation", "drip irrigation", "furrow irrigation", and "sprinkling irrigation" in the article title, abstract, or keywords. Articles from Science Citation Index (SCI), Engineering Index (EI), Chinese Science Citation Database (CSCD) and Peking University core periodical catalogue published in Chinese from January 2000 to May 2021 were collected. This search returned a total of 236 publications, which were screened on the basis of the following criteria: (1) experimental studies were included, while reviews were excluded; (2) and articles were included, while proceedings papers, meeting abstracts, editorial material, and corrections were excluded. Finally, 198 published studies were selected.

2.3. Data analysis

The basic characteristics of the variables such as the article themes, experimental factors, survey regions, research scales, irrigation methods, and irrigation durations were analyzed statistically in Microsoft Excel 2016 (Microsoft, Redmond, USA). The linear regression was used to verify the trends of accumulative publications with years. Pearson's linear correlation was conducted to establish the relationship between the number of citations and the number of publication downloads. These statistical tests were conducted using SPSS 19.0 software (IBM, New York, USA).

3. Results

3.1. Overview of publications

The trends of publications on reclaimed water irrigation in China from 2000 to 2021 are illustrated in Fig. 2. The first article on this topic was published in 2004, and the highest number of articles were published in 2012 (29 papers, 15%). During the research period, the accumulated number of publications increased linearly, with a coefficient of determination of R^2 = 0.98. Pearson's linear correlation was used to establish the relationship between the number of citations and the number of publication downloads. The results showed that the number of

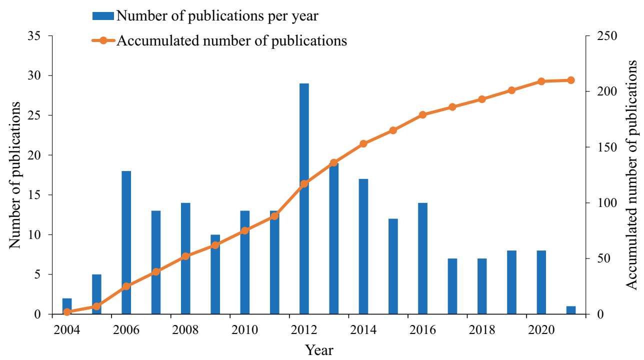

Fig. 2. Literature statistics of reclaimed water irrigation in China from 1991 to 2021.

citations and the number of publication downloads were significantly correlated, with correlation coefficient values of up to 0.825 (P < 0.001), which suggested that more downloads represent more remarkable topics and contents.

3.2. Research themes and contents

The statistical results on reclaimed water irrigation research themes and contents are summarized in Table 1. There were 188 experimental studies, accounting for 95% of the publications, while only 10 publications referred to numerical simulation which may have been due to the complex composition of reclaimed water and its unclear transformation in the soil. In the experimental studies, most scientists focused on the different effects of reclaimed water and conventional water irrigation, and a total of 140 articles were published. Compared to irrigation water quality, only 37 and 30 publications gave attention to irrigation patterns and parameters for the distribution and migration of reclaimed water in the soil. Irrigation was found to substantially influence the effects of reclaimed water on soil and crops. It may be reasonably expected that more effort will be made to study the influence of irrigation technology on reclaimed water transportation in the soil.

As illustrated in Table 1, more attention has been given to the effects of treated sewage effluent on soil physico-chemical properties (103 publications) and crop growth (83 publications) in reclaimed water irrigation studies. Furthermore, the influence of reclaimed water irrigation on the migration and accumulation of heavy metals in soil and crops was the focus of 34 and 21 publications, respectively. However, the effects of reclaimed water irrigation on soil and crop bioactivity were examined by 20 and 13 studies, respectively, and few studies have been conducted on the effects of reclaimed water irrigation on groundwater quality (2 publications) and air quality (4 publications).

A total of 137 articles examined irrigation methods, including watering, surface drip irrigation, and surface irrigation, which corresponded to 48, 44, and 24 papers, respectively, accounting for 85% of the publications. These results indicated that reclaimed water irrigation has been mainly conducted by watering, surface drip irrigation, and surface irrigation in China. In addition, there was a lack of research on subsurface drip irrigation and sprinkler irrigation when using reclaimed water.

3.3. Research region distribution

The regional distributions of reclaimed water irrigation in China are shown in Table 2. Reclaimed water irrigation practices were carried out in 19 provinces and cities of China, accounting for 61% of the 31 provincial administrative regions (excluding Hong Kong, Macao and Taiwan). The results indicated that reclaimed water irrigation research covered a wide area in China. However, these studies (167 publications, accounting for 84% of the total articles) were mainly conducted in Northern China (Fig. 5). This may imply a wide discrepancy in the development of reclaimed water reuse among the provinces of China. According to rainfall amount, dry and wet regions were identified. Chinese reclaimed water irrigation was primarily conducted in sub-humid areas (151 publications, accounting for 76% of the total articles). In arid, semiarid and humid regions, 3, 12 and 31 reclaimed water irrigation studies were carried out, accounting for 2%, 6% and 16% of the articles, respectively. In addition, Beijing and Henan were the provinces with the most published articles on reclaimed water irrigation.

Table 1
Summary of reclaimed water irrigation article themes and research contents

Irrigation method	Papers	Experimental factor	Papers	Research object	Papers	Type	Papers
Surface irrigation	24	Water quality	140	Physico-chemical properties and nutrients of soil	103	Experimental study	188
Watering	48	Irrigation patterns (mixed irrigation, alternate irrigation, Irrigation method)	37	Heavy metal in soil	34	Numerical simulation	10
Surface drip irrigation	44	Irrigation parameters (irrigation level, irrigation frequency, lateral depth, emitter types)	30	Soil biological activity	20		
Subsurface drip irrigation	6	Fertilizer (fertilizing amount, fertilizer types)	16	Crop growth and quality	83		
Sprinkling irrigation	10			Heavy metal in crops	21		
Else	10			Crops biological activity	13		
Irrigation method unknown	61			Groundwater quality	2		
				Air quality	4		
				Else	10		

Table 2
Summary of regional distributions of reclaimed water irrigation research

Northern China	Papers	South China	Papers
Beijing (semi-humid region)	90	Hubei (humid region)	12
Henan (semi-humid region)	32	Jiangsu (humid region)	5
Tianjing (semi-humid region)	12	Hunan (humid region)	4
Hebei (semi-humid region)	10	Guangdong (humid region)	4
Neimenggu (semi-arid region)	7	Guangxi (humid region)	2
Shandong (sub-humid region)	5	Sichuan (humid region)	2
Xinjiang (arid region)	3	Yunnan (humid region)	2
Ningxia (semi-arid region)	3		
Gansu (semi-arid region)	2		
Heilongjiang (sub-humid region)	1		
Jilin (sub-humid region)	1		
Shanxi (sub-humid region)	1		

3.4. Research scale and duration

The experimental scale and irrigation duration are two fundamental aspects for promoting the development of reclaimed water irrigation. A summary of the research duration and scale is shown in Table 3. Ninety and 86 publications reported reclaimed water irrigation studies that were carried out at the field and laboratory scales, respectively. Moreover, plot and pot experiments were most commonly conducted. Furthermore, in 29 studies, soil samples were collected from reclaimed water irrigated areas.

As illustrated in Table 3, the irrigation durations using reclaimed water in China were mostly less than 2a, and 112 of them were less than 1a. 42 studies reported irrigation durations between 2a and 5a, accounting for 20% of the total articles, while 24 studies reported irrigation durations equal to or greater than 5a, which accounted for 12%.

Table 3
Summary of reclaimed water irrigation research duration and scale

Scale and experimental method		Papers	Irrigation duration	Papers
Field	Plot experiment	55	≤1a	112
	Field sampling	29	1a~2a	27
	Lysimeter	6	2a~5a	42
Laboratory	Pot experiment	50	5a~10a	12
	Soil column	16	≥10a	12
	Plot experiment	20		
Else		14		

4. Discussion

4.1. Current status of reclaimed water irrigation in China

Since the1960s, China has made efforts to develop sewage reuse in irrigation. As illustrated in Fig. 3, the amount of land irrigated by sewage in China was 11,500 ha at the beginning of sewage irrigation [9]. With the rapid growth of the national economy, the scales of cities and industries expanded, and the area of sewage irrigation in China increased from 0.333 million ha to 3.33 million ha from the 1970s to the 1990s. During this period, an increasingly serious environmental problem resulting from irrigation with raw or primary-treated sewage effluent appeared in some farmland, which slowed the increase in the area irrigated by sewage. Therefore, the Chinese government issued the document “Arrangement for Soil Environmental Protection and Comprehensive Treatment” in 2013, which banned the use of sewage and sludge in agricultural production [10]. This is also one of the reasons for the rapid development of sewage disposal in China after 2006 (Fig. 4).

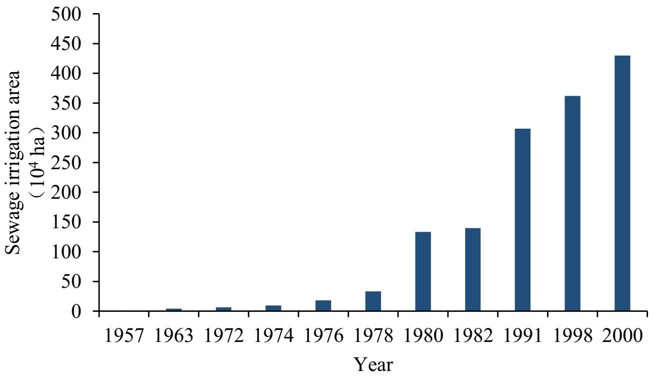

Fig. 3. The variation in sewage irrigated area in China. Data source: Shi et al. 2014 [9].

According to the statistics, more than 90% of reclaimed water irrigation acreage in China is in the North China plain (Fig. 5). Generally, reclaimed water irrigation practices are mainly carried out in the outskirts of large and medium cities, which form the Beijing, Tianjin–Wubaoning

(Wuqing, Baodi, Ninghe), Liaoning–Shenfu (Shenyang, Fushun), Shanxi–Huiming, and Xinjiang–Shihezi irrigated areas [11]. This is an important reason why reclaimed water irrigation has been mainly investigated in Northern China.

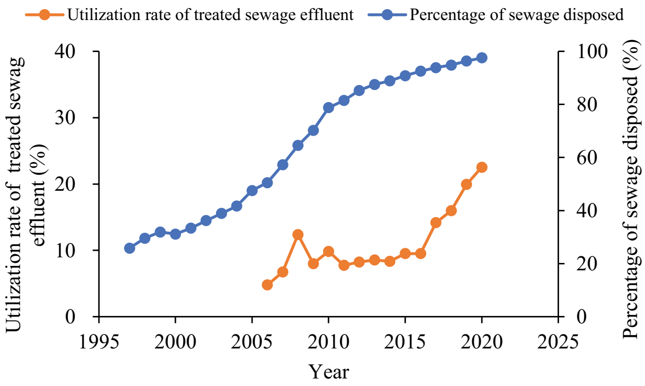

Fig. 4. The variation in utilization rate of treated sewage effluent and percentage of sewage disposed in China from 1997 to 2020. Data source: Ministry of Housing and Urban-Rural Development (2021).

For the last 20 y, there were more than 40 reclaimed water irrigation research institutions in China. The top five institutions sorted through the published articles were Chinese Agricultural University (Beijing), Farmland Irrigation Research Institute (Henan), Beijing Forestry University (Beijing), Beijing Hydraulic Research Institute (Beijing), and Agro-Environmental Protection Institute (Tianjing), respectively. Furthermore, there were 16 reclaimed water irrigation research institutions in Beijing, accounting for 40% of all irrigation research institutions in China. This may be attributed to the large number of universities and research institutes in Beijing and the great concern for reclaimed water utilization by the Beijing municipal government under the background of urban water shortages. A survey conducted by the Chinese Ministry of Construction in 2021 reported that the utilization of reclaimed water resources by Beijing accounted for 65% of its total sewage treatment and that Beijing ranked first in the country in terms of utilization, far ahead of the second-ranked Shandong provinces (44%) [12]. Compared to Beijing, where the total agricultural water consumption accounted for merely 0.1% of the

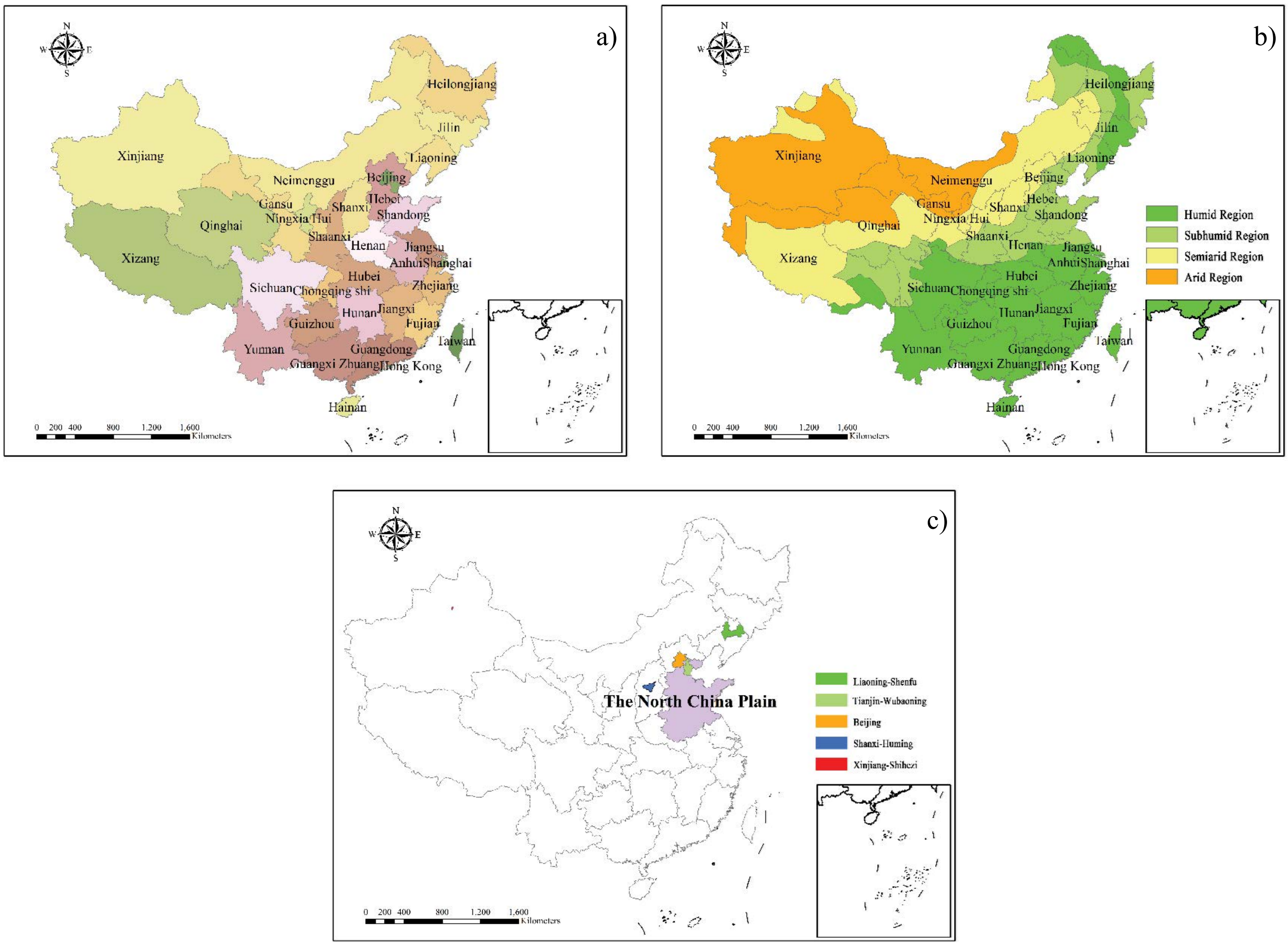

Fig. 5. (a) Province-scale distribution in China, (b) dry and wet region distribution in China and (c) distribution of reclaimed water irrigation acreage in China.

national total agricultural water consumption, the combined utilization of reclaimed water resources in Xinjiang, Gansu, Ningxia and other arid and semiarid areas accounted for less than 36% of the total sewage treatment, while the agricultural water consumption in these regions accounted for 18% of the total agricultural water consumption in China [7]. Therefore, the research and popularization of reclaimed water irrigation in arid and semiarid areas is of urgent necessity.

The abundant water resources in the southern area are unevenly distributed in time and space. Han et al. [13] analyzed the spatial-temporal characteristics of drought severity, frequency, duration, and regional differences in China. They reported that six large-scale agricultural droughts that occurred in the south resulted in huge losses to grain and other farming industries from 2000 to 2010. Moreover, with the acceleration of climate change and urbanization, the south, which is an economically developed region in China, is confronted with increasingly severe agricultural water challenges. The investigation and popularization of reclaimed water irrigation will be essential for addressing the insufficiency of natural endowment for agricultural water resource distribution in time and space in southern China.

4.2. Why is the effect of reclaimed water irrigation different?

4.2.1. Water quality

Compared to conventional water, reclaimed water is more complex. For instance, reclaimed water may contain high concentrations of toxic organic matter, heavy metals, pathogens, suspended solids, residual chlorine and salts, which can reduce soil fertility and induce the risk of soil salinization and groundwater contamination, as well as increase the exposure risk of crops, animals, and human beings to pathogens. In addition, reclaimed water can provide nitrogen, phosphorus, and organic matter to soil and plants, which improves crop growth and production and reduces fertilizer use. Therefore, a comprehensive comparison between reclaimed water and conventional water irrigation in the environment is needed to determine the feasibility of using reclaimed water as irrigation water and ensure the safety of food production, which is the focus of society and scientists in addressing for the increasing water resource shortage.

Extensive research has revealed that the different effects of reclaimed water and conventional water irrigation on soil and crops are related to the components contained in reclaimed water. Pot experiments were conducted using the ^{15}N isotope tracer method to evaluate the effluent N availability [14]. The results showed that reclaimed water drip irrigation could promote the assimilation of effluent N for maize, while higher fertilizer N application rates hampered the uptake of N derived from the effluent. After 2 y of reclaimed water irrigation, Qiu [15] reported that the concentrations of soil nitrate and total phosphorus with reclaimed water irrigation were significantly higher than those with groundwater irrigation for a given lateral depth. Furthermore, reclaimed water quality (content of suspended inorganic solids in reclaimed water) played a vital role in the impacts of reclaimed water irrigation on the soil infiltration rate, hydraulic conductivity and soil properties [16]. Compared to the reclaimed water quality guidelines recommended by the US Environmental Protection Agency (EPA), the upper limits of pollutant indices in the Chinese national standard of water quality for urban sewage reclamation and irrigation (GB20922-2007) are relatively high. For instance, the upper limits of suspended solids for vegetable, paddy grain, dryland grain and fiber crops are 60, 80, 90, and 100 mg/L, respectively, which are substantially higher than the 30 mg/L in the American EPA guidelines. Additionally, the components contained in reclaimed water fluctuate with time due to the interactions between the components. The great difference in water quality components is an important reason for the differential experimental results when using reclaimed water. For irrigation water collected from the Beijing GaoBeiDian sewage treatment plant, Huang et al. [17] found that reclaimed water irrigation significantly promoted the growth and yield of corn and soybean through pot experiments, while Huang et al. [18] found that there was no significant difference in cereal crop yield between reclaimed water irrigation and conventional water irrigation; in contrast, reclaimed water irrigation had negative effects on crop growth due to soil salinity accumulation. Coincidentally, Zheng et al. [19] summarized the differences in the influence of reclaimed water irrigation on soil aggregate and air permeability and believed that they were highly related to the different organic matter content in reclaimed water. Further studies on the impacts of components contained in reclaimed water on environmental media will be essential for improving the application of reclaimed water for irrigation.

4.2.2. Experiment scale and irrigation duration

Compared to pot, greenhouse and other agricultural experiments, field experiments best approximate the actual production conditions. Generally, research results confirmed through field experiments can be promoted and applied to production practice. However, environmental factors, such as precipitation and air temperature, have a great influence on field experiments. In a field study conducted by Van Donk et al. [20] in Nebraska, the effect of subsurface drip irrigation on corn yield was evaluated. The results showed that there were no significant yield differences between the irrigation practices due to more precipitation and cooler weather. Similarly, a 2-y field experiment conducted in Beijing also revealed that uniform rainfall could partially compensate for the experimental differences resulting from water application and fertilization [21]. Furthermore, field experiments are periodic with the planting of crops, and usually take more than 2 y to confirm data stability. For instance, Li et al. [22] investigated the influence of water quality on the rhizosphere soil properties and leaf physiology of different landscape plants and conducted a 3-y field experiment. These could be the major reasons for the insufficient studies on reclaimed water irrigation using field experiments. Additionally, the influences of reclaimed water irrigation on soil, groundwater, and air, as well as the responses of crops and creatures to reclaimed water, are short-term behaviors with uncertainty since the research period of reclaimed water irrigation in

China is fairly short. In a study conducted by Guan et al. [23] in Beijing, the characteristics and heterogeneity of soil pore distribution after reclaimed water irrigation for various years were analyzed by applying a KYKY-2800B scanning electron microscope. Their results indicated that the pore distribution was more heterogeneous after 30 y of reclaimed water irrigation than after 50 y of reclaimed water irrigation. Zheng et al. [24] investigated the effect of the reclaimed water irrigation period (2, 3, 5, 8, 10, and 12 y) on heavy metal enrichment in purple paddy soil. The results showed that the heavy metal enrichment in the soil generally decreased with increasing duration of reclaimed water irrigation. All of these results suggest that attention should be given to the long-term effects of reclaimed water irrigation on variations in soils, groundwater, air, and crops.

4.3. Reclaimed water irrigation methods

Since treated sewage effluent represents an alternative source of agricultural and landscape irrigation water in water-scarce areas, the contamination of crops, human beings and animals with pathogens originating from reclaimed water can occur when irrigation methods such as watering, surface irrigation, and sprinkler irrigation are used, due to their direct exposure to the reclaimed water. Surface drip irrigation applies water to the surface soil and is less likely to contaminate above the topsoil, while subsurface drip irrigation applies water directly to the roots, with minimal transfer of pathogens to the soil surface [25]. Additionally, drip irrigation can reduce the spread of reclaimed water aerosols into the air and decrease odors. In a field experiment conducted by Fonseca et al. [26], sprinkler, furrow and subsurface drip irrigation of lettuce were compared. The results showed that almost all lettuce samples from subsurface drip irrigation were free of *E. coli*, while spray and furrow irrigation resulted in significantly higher concentrations of *E. coli* contamination. These results were confirmed by Li and Wen [27], who found a substantial weak association between drip irrigation management practices and *E.coli* contamination of leaves. Drip irrigation is the application of water through point or line sources on or below the soil surface at a small operating pressure and at a low discharge rate, resulting in partial wetting of the soil surface, which substantially different from surface irrigation and sprinkling [28]. Moreover, the technical parameters of drip irrigation (emitter flowrate, irrigation frequency, irrigation amount, lateral depth, etc.) are important factors affecting soil water distribution and nutrient migration and transformation under drip irrigation. The various technical parameters of drip irrigation differentially impact the soil, crops and groundwater. A solar-heat field experiment was conducted by Li et al. [29] in Beijing to evaluate the influence of water quality, irrigation interval and lateral depth on tomato yield and fruit quality. Their results showed that a shorter irrigation interval and greater lateral depth increased tomato production and had no adverse effect on fruit quality. Cao et al. [30] used the orthogonal test to compare surface drip irrigation, subsurface drip irrigation, and microspray irrigation of alfalfa, and found that subsurface drip irrigation applying reclaimed water resulted in higher plant height, stem thickness, first-level branch number, and hay yield when 2,280 m^3/hm^2 water was irrigated nine times with an irrigation time of 240 m^3/hm^2. In addition, the fate of undesirable constituents contained in reclaimed water in the soil was greatly influenced by irrigation practices. A 2-y field experiment was conducted in Beijing to investigate the effects of lateral depth, irrigation level, and water quality on deep percolation, nitrate leaching, and *E. coli* distribution in soil while applying treated sewage effluent [31]. The results indicated that a high irrigation level usually produced more deep percolation and nitrate leaching and that the cumulative nitrate leaching beyond the root zone increased as the lateral depth increased. Additionally, the lateral depth distinctly influenced the distribution of *E. coli* in the soil, and subsurface drip irrigation usually induced *E. coli* contamination deeper in the soil. Nevertheless, the influences of drip irrigation parameters, as well as water and fertilizer management, on the behavior of reclaimed water in soil-crop-groundwater systems are still not well documented. Further studies on the effects of reclaimed water irrigation practices on soils and crops will be essential for improving the application of treated sewage effluent for agriculture.

Landscape irrigation is another important application of reclaimed water. A survey conducted by the Chinese Ministry of Construction reported that treated sewage effluent was mainly applied for recreational/environmental enhancement (34% of the total reclaimed water) and miscellaneous urban use (12%) [32]. Different from field crop irrigation, greenbelt landscape gardens are much closer to residential areas and are generally irrigated by sprinkler or microspray irrigation; hence, they pose a higher risk of exposure to reclaimed water. The spray for green area reclaimed water irrigation has a high degree of atomization, which renders it susceptible to the formation of pathogen aerosols resulting in human respiratory system infection. Hao et al. [33] used gas chromatography and mass spectrometry to investigate the volatile organic compounds in golf courses and assess the health risk. The results showed that the maximum risk value of volatile organic compounds was 2.3 times larger than that of the control after 2 h of irrigation. In a study conducted by Manios et al. [34] in the Mediterranean, the effect of chlorinated reclaimed water on the survival of *E. coli* after irrigation was evaluated. Their results showed that chlorination, high temperature, and solar radiation could merely temporarily inhibit *E. coli*, while the growth of *E. coli* recovered after 4 h of irrigation. The results implied that the influence of soil type, depth, irrigation method, and water quality on the fate of pathogens should be further investigated. Furthermore, the management system of park opening and irrigation should be optimized based on risk control and health protection. He et al. [35] assessed the exposure risk of green-area reclaimed water irrigation. The results demonstrated that the total daily ingestion dose of reclaimed water was 0.07 L/d for occupational workers (gardener). The lifetime average daily intake dose of disinfection by-products via the respiratory route ranged from 1.1 e^{-7} to 6.8 e^{-6} mg/kg·d [36]. Moreover, sprinkler irrigation may induce surface runoff, and residual reclaimed water will enter lakes or groundwater through the drainage system, resulting in environmental problems such as eutrophication [37]. Additional information concerning the influence of irrigation parameters on pollutants in reclaimed water migration and the interactions between pollutants in reclaimed water and environmental media (grass, soil, air, and groundwater) is still needed in China.

5. Conclusions and suggestions

The shortage of water resources has become the main bottleneck restricting the sustainable development of the social economy in China. The reuse of urban treated sewage as an alternative water source for farmland and landscape irrigation can effectively relieve the shortage of agricultural water. Strengthening the research on reclaimed water irrigation and determining the influence of reclaimed water quality, irrigation regime, irrigation parameters and water and fertilizer management on human health, soil, crops, groundwater, and air will be essential for promoting the application of reclaimed water irrigation in agriculture and in urban and rural water ecological environments. At present, there are various issues of great concern that should be further studied for the sustainable use of reclaimed water irrigation in China.

- Strengthening the investigation of reclaimed water irrigation in arid and semiarid areas. Due to the larger production scales and total volumes of maize and wheat in arid and semiarid areas, the application of reclaimed water irrigation has great prospects. However, no accurate information is available on the effects of reclaimed water irrigation practices on soils, crops, air, and groundwater under drought stress.
- Improving wastewater treatment equipment and the standards of treated sewage effluent for irrigation. Since the influences of reclaimed water irrigation on soil health and crop growth are highly dependent on the quality of the irrigation water, reasonably limiting the constituents of reclaimed water is essential for ensuring environmental health when using reclaimed water.
- Configuration of irrigation parameters and water and fertilizer management based on risk control and health protection. Effectively reducing the exposure of human beings and crop to reclaimed water is an important way to control irrigation risk. Moreover, the technical parameters and water and fertilizer irrigation management strategies should be reasonably determined to enhance the safety and efficiency of irrigation.
- Continuous monitoring and evaluation of reclaimed water irrigation. The impact of reclaimed water irrigation on the environment is a continuous and cumulative process, strengthening long-term persistent monitoring and research to ensure the safety of crops, the quality of soils and groundwater, and finally the health of human beings.

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Data availability statement

All relevant data are included in the paper or derived from public domain resources.

Conflict of interest statement

The authors declare that there is no conflict of interests. We do not have any possible conflicts of interest.

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