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Perspective

Water Availability and Status of Wastewater Treatment and Agriculture Reuse in China: A Review

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Abstract: Due to climate change, 2/3 of the world's population will face water shortage problems by 2025, while a 50% increase in food production is required in 2050 to feed nine billion people. In addition, the intensified anthropogenic activities have significantly increased water resource pollution. In this condition, wastewater reuse for crop irrigation to reduce water scarcity is currently becoming global, while it often causes soil pollution and heavy metal accumulation in agricultural areas. This situation has increased public concern over its environmental impact. Thus, an integrated framework was conducted to discuss the status of water availability in China, wastewater treatment and reuse in irrigation systems, and the potential health risks. Avenues for new research toward sustainable agriculture were discussed. We emphasize that wastewater reuse reduces the freshwater deficit and increases food productivity. However, adequate treatment should be applied before use to reduce its adverse impacts on human health risks and environmental pollution. Facilities and policies should support more accessible access to reclaimed water used in industries and urban facilities from secondary municipal wastewater treatment plants. This could be a long-term solution to eradicate water scarcity and inefficient water resources in agricultural systems.

Keywords: water scarcity; water resources; wastewater treatment; wastewater reuse; agricultural reuse

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1. Introduction

Achieving food security for 9.3 billion people by 2050 with healthy and nutritious food and improving living conditions for rural populations while reducing environmental pollution are the major challenges of the 21st century [1]. As the global food system faces wide-ranging issues such as water scarcity, soil pollution, and the lack of cultivable land [2–4], farmers and agricultural experts need to develop alternatives to obtain abundant resources to improve agricultural productivity without depriving future generations. Water is the most precious natural resource on planet Earth, yet freshwater supplies around the world are under 3% of total water [5,6], and the strain on these resources has been growing as population density continues to rise [7–9]. Water shortage has been and remains a major issue for global agricultural output, particularly in arid and semi-arid regions [9–13]. However, setting up suitable water management strategies, such as using treated wastewater as an alternative, can guarantee the survival and sustainability of water-related activities.

According to the United Nations Department of Social and Economic Affairs (UNDSEA), the survival and development of human society depend on water, and the global demand has been and still is increasing due to population growth, which expanded irrigated croplands and economic development. Increasing water demands, in combination with their geographic and temporal mismatch with freshwater availability, have rendered water scarcity a widespread problem in many parts of the world, giving stakeholders few other options than wastewater treatment and reuse [14]. Treated wastewater is currently considered a crucial alternative to freshwater scarcity in the agricultural, environmental, and industrial sectors [15–17]. Wastewater reuse gives a great opportunity to reduce freshwater stress in some regions due to the continuous increase in excessive freshwater demand [18,19]. For instance, it has been shown that the city of Ait Melloul (Morocco) saved 4 Mm^3 of freshwater with wastewater reuse to irrigate 400 hectares of arable land [18]. Additionally, a field trial carried out in Saudi Arabia showed that wastewater reuse for irrigation purposes decreased groundwater use by 60% [20]. Furthermore, a significant quantity of reclaimed wastewater is currently used in arid and semi-arid regions [18]. For example, treated wastewater is mainly used for irrigation in Israel [18], and a similar situation is observed in Australia, where treated wastewater is the main water source for irrigation in the agricultural systems [18,21]. This treated wastewater reuse in agricultural systems plays a crucial role in reducing freshwater scarcity.

Appropriate wastewater reuse is currently indispensable because of its increasing volume of discharge, which depends on multiple factors, including agriculture and industrial development levels as well as population size. Previous studies showed that wastewater is very suitable for irrigation [22]. It boosts soil fertility and crop growth, which in turn improves soil health and lowers soil alkalinization [23]. In addition, compared with groundwater, wastewater irrigation increases soil fertility and crop yield by 15% and 90%, respectively [22,24]. However, it should be treated to meet certain requirements enhancing or maintaining soil fertility, and regularly monitored to reduce the risk of pollution [22].

Besides the positive effects, it is also important to mention the negative effects related to wastewater reuse. For instance, studies conducted on maize and alfalfa showed that wastewater irrigation had no significant effects on alfalfa or maize yield but increased the salt accumulation in soil with chlorides and sulfates [23]. In addition, high concentrations of heavy metals were found in animal feed derived from such crops [25]. The impact of wastewater irrigation on soil quality and crop productivity still needs further investigation. These negative effects of wastewater reuse have obligated farmers to employ water-settling and filtering techniques to remove large debris and coarse materials before using wastewater for irrigation. However, more information on wastewater treatment methods and efficiency, as well as their impacts on agricultural products used for human and soil quality, are still needed.

China has significant water resources consisting of surface water, groundwater, and others. This huge water resource is approximately 71.7% of rivers, 60.7% of reservoirs and lakes, and 37.3% of groundwater, which reportedly meet the water quality standards for water source supply [26], according to the national environmental report [27]. However, its yearly freshwater availability per person is about 2300 m^3, which represents 1/4 of the world average [28]. Thus, wastewater reuse, which is currently a popular option, could be an alternative to reduce water stress [29]. Furthermore, recent regulatory and policy adjustments have created opportunities for expanding municipal wastewater recovery projects and their capacity [22]. Though a complete analysis of wastewater regulations and standards for agricultural reuse is currently in place, there is still a highly uneven situation due to continuous environmental changes [30]. Targeted criteria and threshold limits are subject to varied regulations. For instance, coliforms may be regulated under different names in different nations, such as total coliforms, *E. coli*, or thermal coliforms. Additionally, limits may vary depending on the type of crop or soil [30]. Despite numerous studies conducted on wastewater status and water management, many uncertainties still exist regarding the current water availability as well as wastewater treatment technologies and reuse in China (Figure 1) [22,23,27].

The main objectives of this review are to (i) elaborate on the water status and availability in China, (ii) assess wastewater treatment and reuse, (iii) explore the impacts of treated wastewater irrigation in agricultural systems and the food chain, (iv) underline the potential health risk related to wastewater reuse in agricultural systems, and, lastly, (v) provide some solutions to reduce those risks.

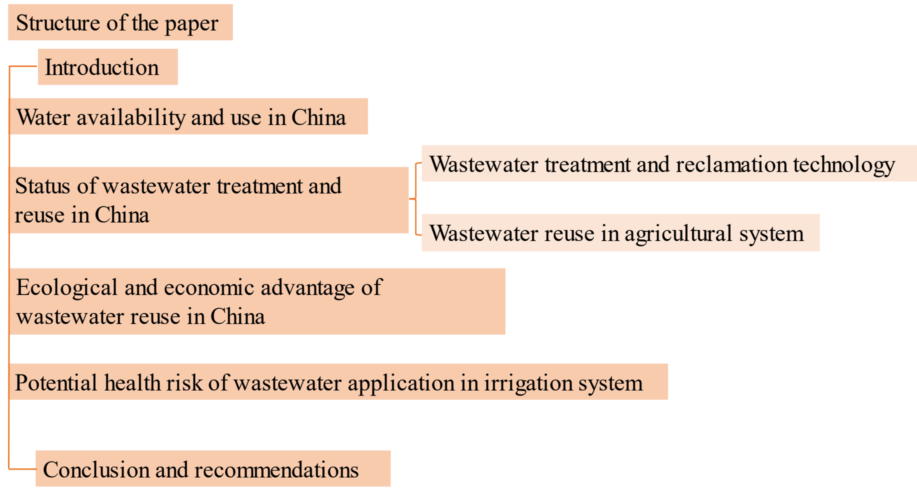

Figure 1. Schematic structure of the paper.

2. Water Availability and Use in China

Water availability is continuously decreasing in many countries in the world. This situation can be explained by the increasing population relative to the available water across the globe. The global population has increased from 2 billion in 1950 to the current population of 7.4 billion for the same water availability, which causes an inverse relationship of the global per capita water availability, decreasing by a factor greater than 3 [31]. Efficient water resource use is indispensable for maintaining ecological balance, sustainable agriculture, and increasing crop productivity. China has one of the world's 13 lowest water resources per capita [28]. The distribution of precipitation in China is also unbalanced, with the eastern and southern regions receiving considerable rainfall contrastingly to the northern and western parts [32], which explains the regular floods and droughts observed in China. To effectively utilize both surface and groundwater, efforts have been made to address this disparity between water resources supply and demand. The main steps taken to address this disparity in water resources were to implement a strict water management system that requires water efficiency, then modify the primary, secondary, and tertiary industry structures for water-saving purposes, and implement the trans-basin South-to-North Water Diversion Project across the country [28,33,34]. Recent research on China's wastewater condition revealed that the country's biggest issues are endangering crop productivity and the sustainability of agriculture [22,27]. The population and activities involving water resources continue to increase even though there have not been any notable increases in the physical volume of water over the past three decades [22].

Water scarcity is a crucial and recurrent problem in China (Figure 2) (BWS-China: WRI's New Water Stress Map. Available online: https://www.chinawaterrisk.org/opinions/wris-new-china-water-stress-map/, 14 December 2022) and in almost all other countries in the world. For instance, water scarcity has been, and still is, a crucial problem in Europe for decades due to water quality deterioration and the lack of adequate wastewater treatment [35]. Thus, the concept of sustainable wastewater management implying ecological and economic sustainability has been strongly articulated. Concerning China, Beijing, for instance, with a population of more than 20 million people, has only 10% of the world's average water resources per capita [34]. Beijing has suffered droughts almost every year for the last decade; significant decreases were observed in its supply of surface water from reservoirs, rivers, and lakes [2,22,34]. This situation caused a crucial decrease in its groundwater resources, with water being pumped much faster than it can ever be recharged. The severe water scarcity in Beijing is emblematic of the broader challenge facing China as well as many developing countries such as India, South Africa, and Brazil [2]. This situation has been intensified by climate change and water pollution. Based on the national statistical data published in the yearbook of 2021 by the Chinese National Bureau of Statistics (China Statistical Yearbook 2021. Available online: http://www.stats.gov.cn/tjsj/ndsj/2021/indexeh.htm, 25

December 2022), water resource in China has been decreasing for the last 10 years (Figure 3). For instance, a decreasing trend of total water resources (TWR) and surface water resources (SWR) was observed from 2010 to 2020, except for the slight increase noted in 2016 [36]. A stable situation was noted concerning groundwater resources (GWR) and per capita water resources (PCWR). However, this situation may change in the near future with the increasing population demand.

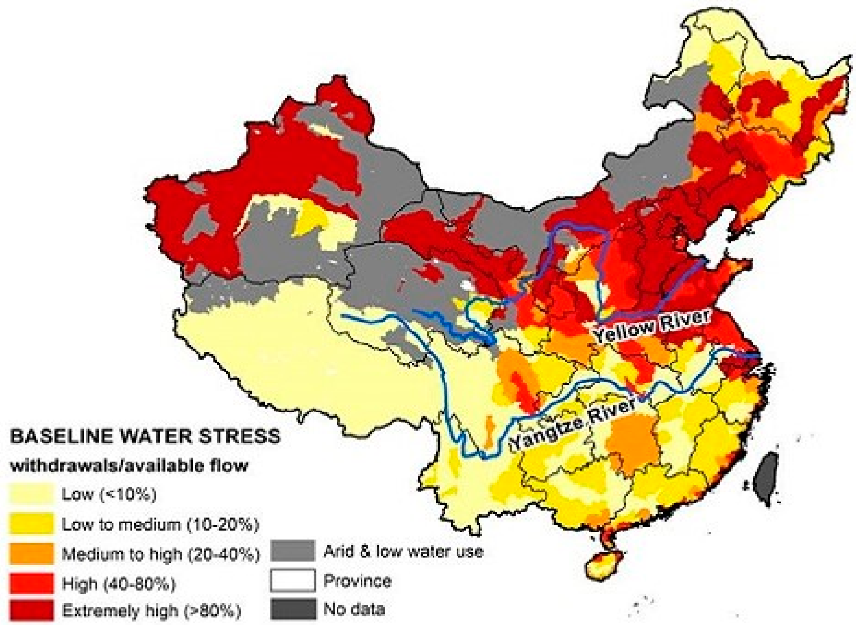

Figure 2. Spatial distribution of water stress in China (CRW).

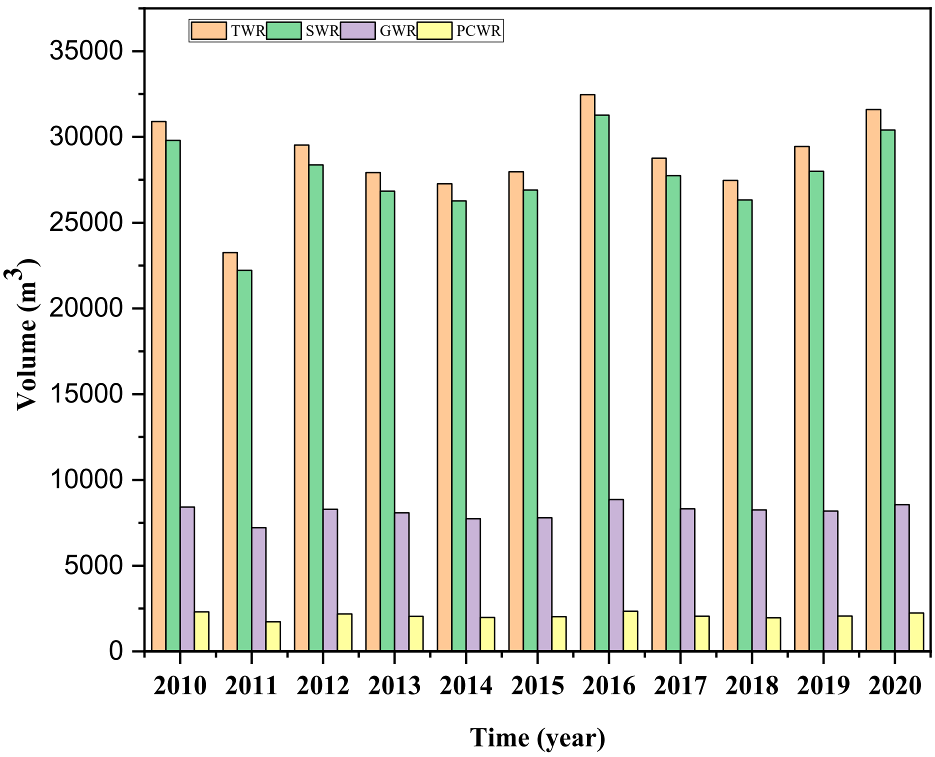

Figure 3. Water resources per year (China Statistical Yearbook 2021). Note: TWR: total water resources (100 million m^3); SWR: surface water resources (100 million m^3); GWR: groundwater resources (100 million m^3); and PCWR: per capita water resources (m^3/person).

Wastewater reuse has become crucial in almost every country with increasing freshwater scarcity. For instance, wastewater reuse programs have been launched in some areas, such as the United States, Australia, Belgium, Italy, and South Africa [24,37,38]. In addition, wastewater reuse has become indispensable in China, due to the uneven water resources repartition in the country, with serious water scarcity observed in many cities, including Beijing. According to the 2021 yearbook, more water is needed than what is available (Table 1) (China Statistical Yearbook 2021. Available online: http://www.stats.gov.cn/tjsj/ndsj/2021/indexeh.htm, 2 January 2023). Previous studies showed that almost 1/2 of all provinces are facing water scarcity, which affects their economy because of the dependence on water in power generation to manufacturing [34]. Table 1 shows the unbalanced regional distribution of water resources in China. For instance, the Yangtze River basin and its southern region have an area that accounts for 36.5% of the country and 81% of the country's water resources [39]. The region north of the Yangtze River basin has an area of 63.5% of the country [39]. Water resources are important to support and guarantee national economic and social development. With the increasing impact of global climate change and China's industrialization and urbanization process accelerating, the contradiction between socioeconomic development and insufficient capacity of water resources has become more prominent. We believe that improving water resource use efficiency would solve the water resource problem. In addition, promoting the implementation and execution of works to build a water-efficient society, implementing a scientific development approach, and coordinating regional development while maintaining the stable and long-term development of society would help.

Table 1. Water resources distribution in 2020 (China Statistical Yearbook 2021).

Province/City	Total Water Resources (100 million m^3)	Surface Water Resources (100 million m^3)	Groundwater Resources (100 million m^3)	Overlapped Measurement between Surface Water Resources and Groundwater Resources (100 million m^3)	Per Capita Water Resources (m^3/Person)
Beijing	25.8	8.2	22.3	4.7	117.8
Tianjin	13.3	8.6	5.8	1.1	96.0
Hebei	146.3	55.7	130.3	39.7	196.2
Shanxi	115.2	72.2	85.9	42.9	329.8
Inner Mongolia	503.9	354.2	243.9	94.2	2091.7
Liaoning	397.1	357.7	115.2	75.8	930.8
Jilin	586.2	504.8	169.4	88.0	2418.8
Heilongjiang	1419.9	1221.5	406.5	208.1	4419.2
Shanghai	58.6	49.9	11.6	2.9	235.9
Jiangsu	543.4	486.6	137.8	81.0	641.3
Zhejiang	1026.6	1008.8	224.4	206.6	1598.7
Anhui	1280.4	1193.7	228.6	141.9	2099.5
Fujian	760.3	759.0	243.5	242.2	1832.5
Jiangxi	1685.6	1666.7	386.0	367.1	3731.3
Shandong	375.3	259.8	201.8	86.3	370.3
Henan	408.6	294.8	185.8	72.0	411.9
Hubei	1754.7	1735.0	381.6	361.9	3006.7
Hunan	2118.9	2111.2	466.1	458.4	3189.9
Guangdong	1626.0	1616.3	399.0	389.4	1294.9
Guangxi	2114.8	2113.7	445.4	444.3	4229.2
Hainan	263.6	260.6	74.6	71.6	2626.8
Chongqing	766.9	766.9	128.7	128.7	2397.7
Sichuan	2337.3	3236.2	649.1	648.0	3871.9

Table 1. *Cont.*

Province/City	Total Water Resources (100 million m³)	Surface Water Resources (100 million m³)	Groundwater Resources (100 million m³)	Overlapped Measurement between Surface Water Resources and Groundwater Resources (100 million m³)	Per Capita Water Resources (m³/Person)
Guizhou	1329.6	1328.6	281.0	281.0	3448.2
Yunnan	1799.2	1799.2	619.8	619.8	3813.5
Tibet	4597.3	4597.3	1045.7	1045.7	126,473.2
Shaanxi	419.6	385.6	146.7	112.7	1062.4
Gansu	408.0	396.0	158.2	146.2	1628.7
Qinghai	1011.9	989.5	437.3	414.9	17,107.4
Ningxia	11.0	9.0	17.8	15.8	153.0
Xinjiang	801.0	759.6	503.5	462.1	3111.3

Figure 4 shows the water resource use in China from 2010 to 2020, which is significantly impacted by rapid socioeconomic transitions. Based on the data published on 10 January 2022 by the Stata Research Department (Statista 2022. Available online: https://www.statista.com/statistics/279679/average-per-capita-water-consumption-in-china/, 18 January 2023) the amount of water used in China in 2020 amounted to nearly 581 billion cubic meters (Figure 4). Water use efficiency and economic structural improvements effectively balance the increase in water use, underlined by the growing population. New policies in inter-sectoral transactions of water-intensive sectors would significantly impact the effects of production structure changes on water use. Thus, close attention should be paid to the changes in the production structures of these sectors.

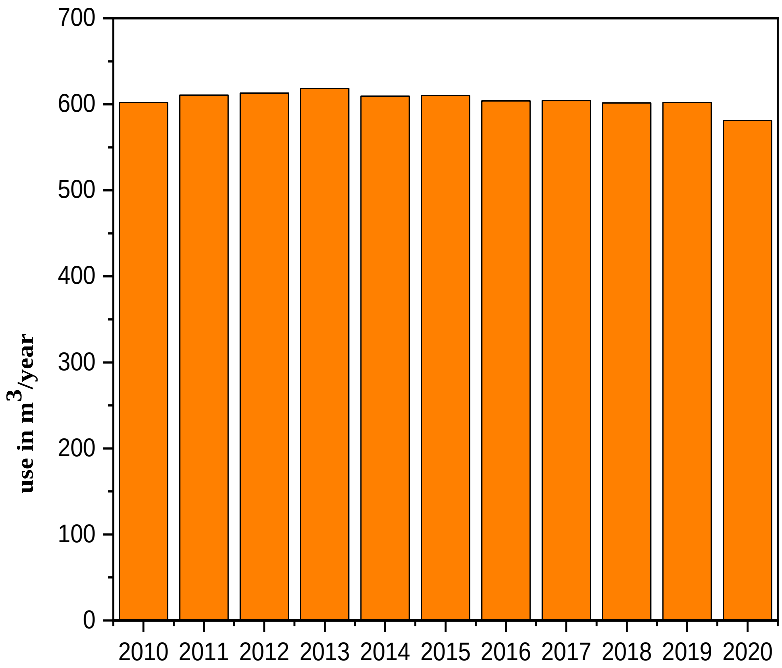

Figure 4. China's water uses from 2010 to 2020 in billion cubic meters (Statista 2022).

China is currently the second-most populous country, with 21% of the world population behind India, but it has only 6% of its freshwater [5]. Overall, China's water availability per person is roughly 25% below the global average, and water shortages have been noted in more than 400 Chinese cities [22]. This water scarcity is more common in the northern part, characterized by less rainfall compared to the South. Therefore, it is crucial to find alternatives to solve this water shortage in the North. Moreover, this water shortage is further aggravated by pollution. Based on the repartition of water demand per activity sector, the agricultural sector occupies the first position in which wastewater irrigation is recommended with proper treatment [22]. Therefore, improving wastewater treatment and reuse in the agricultural sector (Figure 5), which is the most demanding in terms of water resources, could be a significant step toward eradicating water scarcity.

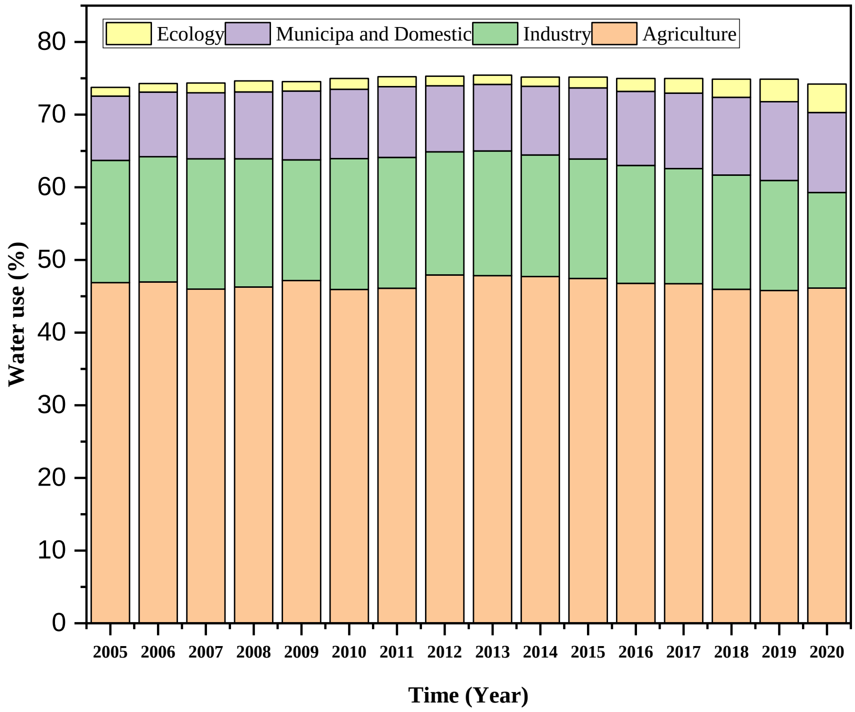

Figure 5. Projected water demand by different sectors (China Statistical Yearbook 2021).

3. Status of Wastewater Treatment and Reuse in China

The continuous population growth and increase in food demand affect the daily life of communities with a low freshwater supply. Water scarcity and water pollution are two major problems that almost every country in the world is facing [40,41]. Global water scarcity is expected to reach 40% by 2030 [42], threatening food security as agriculture accounts for about 69% of global water use. In addition, the demand for food is increasing due to continuous population growth. Therefore, improving agricultural water use efficiency and finding alternative irrigation water resources is the only way to alleviate these challenges. The world's wastewater volume is about 380 km^3 annually, equivalent to 15% of agricultural water use [43]. With the advancement of urbanization, the amount of wastewater will continue to increase. Thus, treated wastewater could be an alternative water source for irrigation. As China has the second largest economy in the world, water scarcity and water pollution are still part of the biggest challenges, with estimated water resources per capita of 2239.8 m^3 in 2020 (Figure 3). Several other alternatives have been taken to reduce the insufficiency of water resources, including water recycling and regeneration, and seawater desalination [28,33]. In addition, some countries, such as the USA, are at advanced levels in wastewater treatment. For example, wastewater reclamation and reuse have been adopted in the USA since long ago, with the development of the first regulations which address the use of recycled water for agricultural irrigation in 1918 in the state of California [44]. California can be used as a great example concerning water reclamation, recycling, and water resource planning and management. Wastewater treatment usually requires advanced technology with high costs and large energy consumption [23,28]. For instance, wastewater treatment and reuse provide only limited additional water resources due to the lack of technology and funds in some areas. However, significant progress have been made in reclaimed wastewater with advanced technology to meet the increasing water demand (Table 2) [28]. With the recent accelerated economic development and public and governmental consciousness concerning environmental protection, China's capacity to treat sewage has rapidly increased [45,46]. This capacity was established in a relatively short period, within which the treatment efficiencies were also significantly improved [47,48].

Table 2. Public acceptance of wastewater reuse [27].

Reuse Category	Managers (%)	Producers (%)	Researchers (%)	Public (%)
Potentially potable reuse	3.5	2.27	2.32	2.87
Body contact	3.9	3.32	2.64	-
Non-body contact and non-potable reuses	4.6	4.95	4.86	3.37
Average	4	3.51	3.27	3.12

Concerning wastewater treatment in rural Chinese areas, there are several wastewater treatment technologies. The most common is septic tanks [49]. A national effort to build rural biogas reactors supporting anaerobic treatment is still needed. In addition, less than 30% of regions used an oxidation tank, a biofilm reactor, a built wetland, or engineered soil treatment, indicating that secondary treatment techniques were limited [50]. Standard-activated sludge is rarely used in rich villages with a high population.

Reusing treated wastewater will complement the limited supply of freshwater. However, proper treatment is required for efficient health risk assessment. Several treatment technologies have been adopted with advantages and disadvantages (Tables 3 and 4). In addition, these technologies are mostly applied based on the available facilities and financial support. Significant improvements have been made, with more than 3508 wastewater treatment plants recorded in 31 provinces, though the distribution is not balanced throughout the country (Figure 6), with more wastewater treatments located in Guangdong and Jiangsu provinces [46].

Table 3. Representative wastewater treatment plants in China.

Province/City	Name	Treatment Process	Daily Treatment Capacity (10^4 Tons/Day)
Beijing	Gaobeidian sewage treatment plant	Activated sludge process	100.00
Tianjin	Jizhuangzi sewage treatment plant	A^2/O	45.00
Tianjin	Xianyang Road sewage treatment plant	A/O	45.00
Hebei	Qiaodong sewage treatment plant (Shijiazhuang City)	A^2/O	50.00
Liaoning	Xiannvhe sewage treatment plant (Shenyang City)	Biological aerated filter	40.00
Shanghai	Bailonggang sewage treatment plant	Chemical precipitation	200.00
Jiangsu	Jingxinzhou sewage treatment plant (Nanjing City)	A^2/O	64.00
Zhejiang	Shaoxing Water Treatment Development Co., Ltd.	A/O	90.00
Jiangxi	Qingshan lake sewage treatment plant	Phase 1: Oxidation Ditch Process: phase 2: CASS	46.00
Henan	Wangxinzhuang sewage treatment plant	A^2/O	40.00
Hubei	Hanxi sewage treatment plant (Wuhan City)	A/O	40.00
Guangdong	Liede sewage treatment plant	A^2/O	120.00
Guangxi	Greentown Water Co., Ltd.	Improved SBR	48.00
Chongqing	Jiguanshi sewage treatment plant	A^2/O	80.00
Sichuan	The First sewage treatment plant of Chengdu Drainage Co., Ltd.	A/O	40.00
Xinjiang	Hedongweiliya Water Corporation of Urumchi City	AB	40.00

Table 4. Standard for irrigation water quality in China (GB5084-2021).

	Crop Type		
Indexes	**Paddy Crops**	**Dryland Crops**	**Vegetables**
pH	5.5–8.5		
TDS (mg/L)	≤1000, ≤2000 [c]	≤1000, ≤2000 [c]	≤1000
Temperature (°C)	35		
Suspended solids (mg/L)	80	100	60 [a], 15 [b]
DO (mg/L)	-	≥0.5	≥0.5
BOD_5 (mg/L)	60	100	40 [a], 15 [b]
COD_{Cr} (mg/L)	150	200	100 [a], 60 [b]
Anionic surfactant (mg/L)	5	8	5
Chloride (mg/L)	350		
Sulfide (mg/L)	1		
Total salt content (mg/L)	1000 (non-saline-alkali land area), 2000 (saline-alkali land area)		
Pb (mg/L)	0.2		
Fe (mg/L)	≤1.5		
Mn (mg/L)	≤0.3		
Cd (mg/L)	0.01		
Chromium (hexavalent) (mg/L)	0.1		
Total mercury (mg/L)	0.001		
Total arsenic (mg/L)	0.05	0.1	0.05
Cr (mg/L)	≤0.1		
Fecal coliform (MPN/L)	40,000	40,000	20,000 [a], 10,000 [b]
Ascaris lumbricoides eggs (pcs/10 L)	20		20 [a], 10 [b]

Note: TDS: total dissolved solids; DO: dissolved oxygen; BOD_5: biochemical oxygen demand; and COD_{Cr}: chemical oxygen demand. [a] Processed, cooked, and peeled vegetables. [b] Raw vegetables, melons, and herbs. [c] Boron high tolerant crops, such as rice, radish, rapeseed, cabbage, etc.

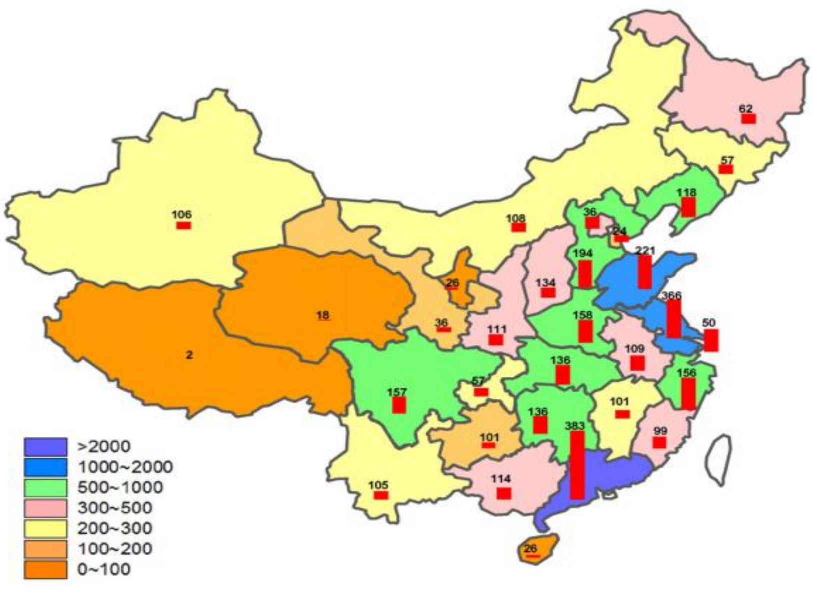

Figure 6. Distribution of wastewater treatment plants in China [46].

The development of wastewater treatment technology is the primary determinant of treated wastewater quality. Moreover, successful wastewater reuse is closely linked to the quality of the treatment. Several wastewater treatment technologies have been implemented, including physical, chemical, and biological treatments. The installations differ from one to another based on the type of technology employed, its intensity, and the potential combinations of technologies. Table 3 shows the representative wastewater treatment plants in China in which nearly 1/2 of wastewater treatment processes are treated by oxidation and anaerobic–anoxic–oxic process (AAO), which treat 46% of the total volume of wastewater generated, 1/4 by traditional activated sludge and Sequencing Batch Reactor Activated Sludge Process (SBR), and 28% by other processes (anaerobic–oxic, biological film, chemical and physicochemical, among others) [46]. AAO and oxidation ditch are the most used technologies in China because they are relatively stable and easy to manage in daily operations [46]. According to the statistic, 467 urban domestic wastewater treatment plants (WWTPs) were surveyed in China, and about 63.17% of the WWTPs' hydraulic loading rates (HLRs) are greater than 80% [45]. According to the Stata Research Department publication in 2022, more than 14,000 wastewater treatment plants were recorded across the United States, serving approximately 240 million Americans, which is comparable with China. These facilities treat domestic sewage from sources such as toilets. For instance, in 800,000 miles of public sewage pipes, an estimated 25,000 to 75,000 sewer overflows occur yearly. Approximately 1% of the national electricity consumption is related to WWTP, with an annual chemical consumption of 100,000 tons. These numbers show how vital wastewater reuse has become crucial in China [45].

Figure 7 shows the investment in industrial wastewater treatment from 2010 to 2020, published by the Stata Research Department on 25 January 2022. According to the Stata Research Department, the investment in industrial wastewater treatment in China from 2010 to 2020 was approximately USD 5.7 billion. Though the investment is decreasing, the massive investment from 2010 to 2016 (Figure 7) shows how important and indispensable wastewater reuse has become in many economic sectors.

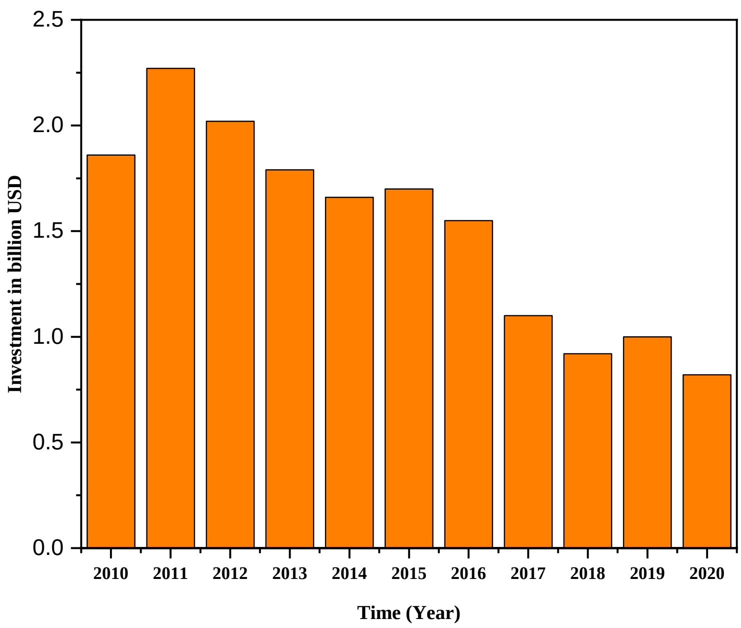

Figure 7. Investment in the treatment of industrial wastewater in China from 2010 to 2020 (Statista 2022).

The major part of wastewater utilization is for non-potable uses such as industrial processes, agricultural irrigation, and ornamental and recreational uses. The government has implemented several initiatives to motivate industries to use recycled water from nearby sources. Additionally, industrial parks' internal water reuse has substantially improved, as well as the use for car washing, landscape irrigation, toilet and urinal flushing, and firefighting. However, compared to the intended volume of water reclamation plants, the reclaimed volume still needs to be significant. Although the facility's capacity utilization rate increased from 33% in 2009 to 56% in 2013 (Figure 8), it still remains low. In urban regions, the rate of wastewater reuse was 19.9%. With an annual volume of 65.7 billion m^3 in 2019, a substantial volume of wastewater was discharged in urban areas, of which roughly 96.3% (63.3 billion m^3) was treated.

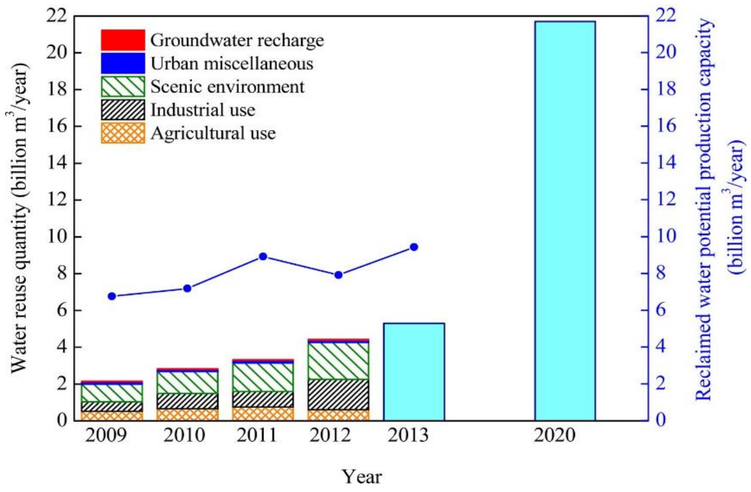

Figure 8. Water reuse quantity by different applications in urban areas of China [51]. Notes: (1) the bars represent the water reuse quantity annually; (2) the bars in 2013 and 2020 represent the total and estimated water reuse quantity respectively; (3) the blue dots indicate the reclaimed water production capacity.

One of the main objectives of the National Development and Reform Commission's (NDRC) 14th five-year plan was to explicitly promote wastewater treatment and reuse before 2016 (Figure 8) [18]. The primary objectives were to increase water reuse across the country by 15%, the amount of recycled water to 3.9×10^8 m^3/d, and the investment in water reuse facility planning and building by USD 62.15 billion [18]. It was estimated that the amount of reclaimed water used in China would reach 2.2×10^{10} m^3/year in 2020 with the advance and exploitation of current and new applications (Figure 8) [18]. Significant advancements have been noted in wastewater reuse, especially in the agricultural and industrial sectors. China is in advance in terms of wastewater reuse compared with some countries, such as Spain, where the volume of reclaimed water is about 368.2 Hm^3 per year [52]. However, improvements are still required for quality, effectiveness, and refined operation.

3.1. Wastewater Reuse in Agricultural System

Water scarcity has been a major problem in agricultural systems, especially in arid and semi-arid regions, due to the continuous augmentation of the world population and food demand [53–55]. This situation has attracted policymakers' attention to the adoption of sustainable and effective wastewater reuse in agricultural systems (Figure 9). For instance, it has been indicated that more than 4.0 billion people globally experience severe water shortages for at least one month every year [2,15,29]. In some places, it is predicted that water consumption will double, the same as the human population [56]. Numerous studies showed that municipal and industrial wastewater play a crucial role in filling the gap of water shortage in agricultural systems and promoting sustainable agriculture [57–59]. The agricultural sector, where more water is used, plays an important role in the integrated water management plan. In regions where there is frequent water shortage, wastewater reuse is the leading solution for crop irrigation [23]. These advantages of wastewater reuse include the reduction in water bills, freshwater conservation, and, more importantly, it is widely used for irrigation in agricultural systems. However, wastewater reuse also has some disadvantages which need to be considered, such as soil pollution [60].

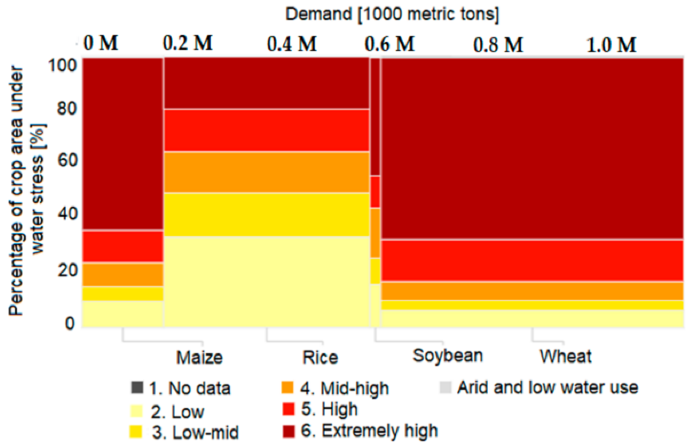

Figure 9. Projected percentage of the world's irrigated cropland by water stress level and demand in 2040 [61].

3.2. Farmland Irrigation Water Quality Standards

Treated wastewater irrigation in agricultural systems has become a common practice in many places in China [62]; however, the wastewater should undertake proper treatment before application. The wastewater regulation standard in China has been significantly improved over the past decades. However, there are still many imperfections and limitations. Nonetheless, unprecedented great efforts are underway to address all these challenges. It has been suggested that reclaimed water use for irrigation sometimes causes risks of salt, nitrogen, and heavy metal accumulation and disease transmission [61,63]. Although heavy metal soil pollution is sometimes uncertain, the potential problems of soil salinization, nitrogen excess, and salt and nitrate groundwater pollution should be addressed. The risks of emerging pollutants and pathogens related to reclaimed water irrigation require further assessments [64]. Among the many factors that affect the risk are reclaimed water quality, plant and soil types, irrigation methods, cultivation and harvesting techniques, and environmental factors. Risk management strategies for the irrigation of agricultural and urban green space with reclaimed water should be assessed for the safe utilization of reclaimed water in the irrigation system. The standard for irrigation water quality in China (GB 5084-2021) specifies the water quality for farmland irrigation, monitoring, analysis, and supervision methods. The quality of urban sewage and untreated livestock wastewater, agricultural processing wastewater, and rural domestic sewage, which are used for farmland irrigation, is also upheld with this standard. Table 4 summarizes the latest version of the standard for irrigation water quality in China GB5084-2021. However, it is important to mention that no significant change was observed in these indexes in GB5084-2021, published in 2021, compared with GB5084-2005, which was published in 2005. These standards are similar to the quality criteria for the reuse of treated effluent in Spain in terms of agricultural uses [52]. However, more stringent standards and, subsequently, a cleaner water environment in China can be expected in the near future with more details on urban, industrial, recreational, and environmental uses as in Spain [52].

In addition, the emerging contaminants, defined as chemicals that are not currently regulated, should be assessed in that there exist concerns regarding their impacts on human or ecological health, such as disinfection by-products, pharmaceutical and personal care products, persistent organic chemicals, as well as their degradation products [65]. These emerging pollutants endanger the reuse of treated wastewater for irrigation in agricultural systems which has become a common practice for farmers to overcome water scarcity in arid and semi-arid areas [64,66]. Though, the removal of emerging pollutants cannot be completely performed with conventional water treatment [64]. Reusing wastewater benefits agricultural systems in several ways, but it poses health risks when it is not properly treated before use [57]. In addition, China is a big producer and consumer of food, so food safety is directly related to public health. The National Health Commission of the

People's Republic of China has established and improved the national standard system of food safety to meet the requirements of health protection, centering on establishing the "most stringent standards". However, there is a crucial need of implementing more advanced treatment technologies including ozonation, adsorption, or membrane filtration to support the existing WWTPs.

4. Ecological and Economic Advantages of Treated Wastewater Reuse in China

It is well known that there is a water reclamation problem worldwide, with 30% to 92% of the total wastewater being directly discharged into the environment [67]. With the recurrence of water scarcity in the agricultural system, suitable reclamation would be of significant help for farmers to obtain enough water for irrigation and increase their production. Thus, encouraging ecological and environmental management has become crucial with the increasing environmental pollution, but also the fact that this discharged wastewater can be used for irrigation after undergoing proper treatments. China has taken actions that showed significant positive results in terms of ecological and environmental management. In addition, agricultural soils have been exploited with treated wastewater, allowing farmers to produce diversified crops for the whole year. This situation is expected to bring new species and increase the overall crop diversity in China. In addition, the Beijing Olympic Park project and Summer Palace, with a daily reclamation of 3200 m^3, have turned that area into one of the most outstanding sceneries in the city. Furthermore, the high concentrations of multiple elements have provided new alternatives, and selecting the target area for water reuse is advantageous at different levels. Macronutrients such as nitrogen and phosphorus concentrations at the secondary effluent are around the requirements for grasses; therefore, it reduces the need for freshwater and additional nutrient input. With adjustments to the contents of relevant elements in the soil, soil enzyme activities with reclaimed water irrigation can also be improved. Over the years, new technologies have been introduced, improving the overall effectiveness and reducing the costs of recycling [22]. Currently, the cost of reclamation and reuse for agricultural and industrial applications might be as low as USD0.32/m^3 and USD0.45/m^3 for potable water [27]. It has been shown that agricultural systems can benefit from nutrient reclamation, reducing the cost of crop production and increasing the options for sustainable and greener agriculture. In addition, energy savings, carbon footprint, and pollution control are more significant when reclaimed water is used by different people within an area, yet with different water quality requirements (Table 5).

Table 5. Cost and benefit of wastewater reuse [27].

Cost Category	Value (Million USD)	Benefit Category	Value (Million USD)
Remunerated investment	7.77	Wastewater reuse revenue	97.84
Power consumption	24.03	Water resources saving	138.15
Chemical components	12.99	Water replacement savings	3.29
Upkeep	3.37	Wastewater discharge reduction	4.88
Workforce	7.22	Environmental perfection	29.5
Pipeline construction	87.91	Public health effects	−48.78
Empty Cell		Groundwater pollution	−0.08
Empty Cell		Groundwater recharge	28.78
Total cost	143.31	Total benefit	245.75

5. Potential Health Risk of Wastewater Application in Irrigation System

Wastewater irrigation and reducing freshwater demand decrease the deterioration of aquatic ecosystems caused by sewage discharge [68]. Moreover, this wastewater can be transformed into valuable resources and supply minerals, organic matter, and nutrients for crop growth and productivity. Contrastingly, considerations must be made for the effects of treated wastewater irrigation on crop quality, soil physicochemical and biological qualities, and public health. Specific strategies should be applied, such as applying the right amount of treatment and regularly monitoring plant and soil characteristics for the sustainable adoption of treated wastewater in agricultural systems. To reduce risks to human health and the environment and ensure the safe, sustainable, and profitable reuse of wastewater, adequate irrigation, cultivation, and harvesting practices are fundamental. Nevertheless, it has been noted that wastewater is used for irrigation in both treated and untreated forms, depending on the geographical and economical situation. This situation has made health risk assessment related to wastewater reuse complex. For instance, it has been shown that wastewater reuse in urban or peri-urban agriculture comprises approximately 11% of the global irrigated croplands [69]. Significant amounts of pollutants from industrial, agricultural, and municipal sources are found in untreated wastewater. Many diseases have been associated with wastewater exposure, including cholera, giardiasis, amoebiasis, and hepatitis [70]. Table 6 summarizes water-borne diseases related to wastewater.

Table 6. Some water-borne diseases related to wastewater [71].

Disease	Cause
Typhoid fever	*Salmonella typhi*
Paratyphoid fever [2]	*Salmonella paratyphi*
Gastroenteritis [1]	*Salmonella typhimurium*
Cholera [2]	*Vibrio cholerae*
Bacillary dysentery [2]	*Shigella dysenteriae*
Amebiasis [2]	*Entamoeba histolytica*
Giardiasis [1]	*Giardia duodenalis*
Cryptosporidiosis [1]	*Cryptosporidium*
Cyclosporiasis [2]	*Cyclospora cayetanensis*
Infectious hepatitis [1]	Hepatitis A
Gastroenteritis [2]	Enterovirus, parvovirus, rotavirus
Infantile paralysis	Poliovirus
Leptospirosis [1]	*Leptospira icterohaemorrhagiae*
Ear infections	*Pseudomonas aeruginosa*
Scabies	*Sarcoptes scabiei*
Trachoma	*Chlamydia trachomatis*
Schistosomiasis [2]	*Schistosoma*
Malaria	*Plasmodium*
Yellow fever	Flavivirus
Dengue	Flavivirus

[1] Human and/or animal excrement, [2] Human excrement.

Additionally, the population which is in constant contact with wastewater suffers from rashes and dermatitis. Consuming food contaminated with heavy metals through poorly treated wastewater irrigation has long-term health consequences. For example, cadmium accumulation damages the kidney and causes osteoporosis [72]. Many international organizations working on water resource utilization and the WHO have developed guidelines to make sure wastewater pollutant levels are maintained below levels that are detrimental to human health [70]. However, these guidelines were progressively applied with different targets based on the wastewater situation since proper treatment cannot be achieved in some areas due to the lack of technology and funds. In addition, despite serious health risks related to untreated wastewater reuse, it is still indispensable for smallholders, particularly in water stress and economically disadvantaged areas. Therefore, these guidelines should be applied based on the available resources and the treatment technology. Farmers in urban and peri-urban areas of many developing countries rely on wastewater to irrigate their crops despite being exposed to water-related infections [73]. The various factors influencing wastewater reuse demonstrate the need to balance actions to lower health risks and improve food security, nutrition, and livelihoods. The scope of wastewater pollutant exposure has to be investigated in light of these health issues. The objective of this review was to critically evaluate recent research on water availability, wastewater treatment and reuse, and health concerns and exposure pathways related to wastewater reuse in agricultural systems (Figure 10).

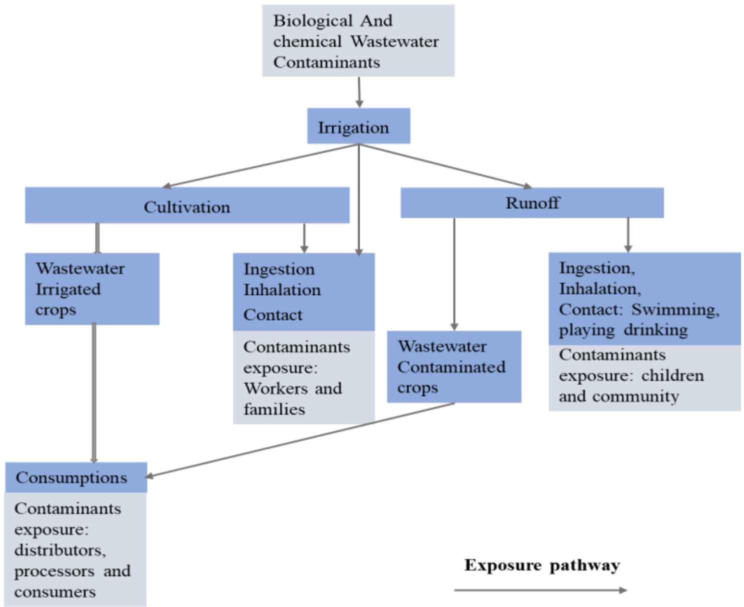

Figure 10. Exposure pathway associated with wastewater reuse in irrigation system.

We believe that a long-term solution to China's water shortage (BWS-China: WRI's New Water Stress Map. Available online: https://www.chinawaterrisk.org/opinions/wris-new-china-water-stress-map/, 14 December 2022) and inefficient water resources (China Statistical Yearbook 2021. Available online: http://www.stats.gov.cn/tjsj/ndsj/2021/indexeh.htm, 25 December 2022) could be found in lowering the cost of recovered wastewater and encouraging its usage in businesses and municipal infrastructure (Statista 2022. Available online: https://www.statista.com/statistics/279679/average-per-capita-water-consumption-in-china/, 18 January 2023). Additionally, advocating regulations for treated wastewater reuse, as well as taking into account the use of secondary effluent from municipal wastewater treatment plants in farm irrigation, can improve the efficiency of water resource development.

6. Conclusion and Recommendations

Water scarcity is one of the main factors affecting the agricultural system in China. China has made great efforts to reduce water scarcity with novel and effective strategies for enhancing water security in water-stressed areas. The Chinese government has established extensive rules that offer specific technical standards and guidance. The enforcement of capacity building might enhance the current outcomes. As treated wastewater reuse in agriculture reduces groundwater scarcity, assessing the associated health risks is critical. Thus, elaborating wastewater reuse guidelines that balance health promotion and protect other benefits, including farmer livelihoods and a secured food supply, is challenging and depends on adequate health data.

Although there are several studies on water resources and the status of wastewater treatment and reuse in China, we believe that efforts to compile the most recent findings are limited. In addition, the current circumstances of global climate change are extremely unusual, and water scarcity, pollution, and other resource crises are severe, causing an urgent use of unconventional water resources. Given One World with One Health, this summary of wastewater treatment status and reuse in China is very practical for farmers and agricultural experts both in China and in the world. To support the decision-making and context-specific guidelines, more resources are still required. Thus, there is a crucial need to evaluate and reduce the ongoing occupational or food-based exposure risk to low contamination levels in long-term exposure. To prioritize risk reduction, particularly for vulnerable groups, it is also necessary to thoroughly investigate the environmental exposures affecting communities in wastewater reuse areas.

Though treated wastewater reuse is indispensable in the agricultural system, developing planting patterns that could attenuate potential wastewater diseases and environmental pollution and provide a safe utilization of treated wastewater should be encouraged for sustainable agriculture. Providing more details on the framework for managing water resources, which includes the control of water supply, stormwater, wastewater, non-point source pollution, and water reuse, would increase wastewater reuse efficiency. The following suggestions could also be considered in wastewater management plants:

Modifying the standards, regulations, and guidelines based on the financial situation and available technology for wastewater reuse to reflect local conditions within the context of the national framework;

Educating stakeholders on the environmental and economic benefits of wastewater reuse; and involving the general public in the creation of wastewater reuse standards and policies. Supporting scientific investigation of the utilization of resources and energy during the production of reclaimed water as well as the impacts of reclaimed water reuse on the land and water ecology.

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