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Review

A Critical Review of Recent Progress in Global Water Reuse during 2019–2021 and Perspectives to Overcome Future Water Crisis

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Abstract: The exacerbation of the global water crisis due to an increase in global population, industrialization, urbanization, and agricultural activities, along with global climate change and limited water resources, makes water reuse inevitable in all continents. By 2030, global water consumption may grow to ~160% of the currently available volume. This study reviews recently published articles (2019–2021) to explore global case studies of water reuse and discusses future perspectives by country based on a literature survey on water reuse. There are 17 obstacles reported worldwide regarding water reuse (e.g., the properties and low amounts of treated water, regulations, financial challenges, etc.) and 10 advantages of utilizing reused water in various fields (e.g., overcoming the global water crisis, improving the economy, benefiting the industrial sector, etc.). The concept of reusing water has been accepted by countries in almost every continent (e.g., Australia, Europe, Asia, Africa, South America, and North America); the technical findings from different countries are summarized in this study. The water reuse scenario is not restricted to countries with limited water supply and can be applied to those with sufficient water resources (e.g., Canada and Brazil have also implemented water reuse policies). Water reuse can be utilized by human beings via indirect and direct potable recycling, as well as in agriculture, textile, construction, hotel, groundwater recharge, and aquaculture industries. However, a standard guideline for the application of reclaimed water at a global scale is unavailable. Several perspectives have been suggested for the future utilization of reclaimed water worldwide as an effort to secure and ensure the sustainability of existing natural water resources. Lastly, water reuse may be considered a potential alternative for reducing the burden on water resources in the future.

Keywords: water reuse; water crisis; wastewater treatment; desalination; climate change

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1. Introduction

Globally, the amount of fresh water only accounts for less than 3% of the total volume of water on Earth, with the rest being seawater. However, most fresh water (3%) is not readily available for direct use, with 20% being groundwater (that requires energy for extraction and pumping) and 79% being glacial ice. Therefore, less than 1% of the globally available amount of freshwater water is suitable for direct use [1–3]. Currently, 1.5 billion people worldwide suffer from water scarcity, and this problem is even more apparent in regions located between the latitudes of 35° N and 35° S, where seven of the world's largest deserts are located. These regions experience arid and semi-arid weather, with high temperatures and low precipitation. In Australia (the driest inhabited continent on Earth), several efforts have been made towards potable water reuse, following advanced water treatment processes, subsequent recharging of aquifers, and the augmentation of surface water and reservoirs [2,4,5]. Every year, over 4 billion people experience a month of acute water scarcity [6]. At present, a quarter of the world's population suffers from acute water shortages [7], and by 2025, approximately 1.8 billion people are expected to be affected by water scarcity [8]. Approximately 40% of the world's population does not have safe water and adequate sanitation (World Health Organization; WHO, 2012) [9]. Approximately 25% of the world's population lives in 17 countries that experience high water stress throughout the year. The world's biggest groundwater systems are also in distress [6]. According to the United Nations (UN) report (2017), approximately 660 million people do not have access to potable water, 2.4 billion do not have proper access to sanitation, and 1.8 billion use contaminated water for drinking purpose. The UN Sustainable Development Goal No. 6 calls for "ensuring clean water and sanitation by 2030", by improving wastewater treatment and water reuse at the global level, while protecting water ecosystems [10].

Water reuse has been practiced for millennia. For example, from the beginning of the Bronze Age (approximately 3200–1100 BC), several civilizations, including Egypt, Mesopotamia, and Crete, used domestic wastewater (sewage) for irrigation purposes. Subsequently, from 1000 BC to 330 AD, Greek and Roman civilizations adapted water reuse in cities (e.g., in Athens and Rome) [11]. At present, almost all continents (e.g., Australia, Europe, Asia, Africa, and North America) embrace the notion of potable reuse, with a preference for membrane-based treatment [12]. Additionally, approximately 60 countries reuse water for agricultural purposes, led by Israel, which directs 86% of reclaimed water (400 million m^3) for agricultural purposes [3,13]. Crop irrigation may consume ~70% of freshwater [14], and innovations and perspectives for providing adequate water for sustainable irrigation have been introduced to overcome this big consumption [15]. The global water crisis has been discerned in several studies worldwide, and research promoting water sustainability is garnering increasing demand [10]. Climate change poses a concern by making dry regions drier and those that receive heavy rainfall increasingly humid and wet [3]. By 2030, it is expected that the global water demand will grow to ~160% of the currently available water volume [16] or 40% above the current water supplies will be required [17]. Water scarcity issues in the Middle East and North Africa (MENA) region will be more evident by 2050, causing economic losses of 6–14% [6].

Globally, the agricultural use of reclaimed water varies by continent (e.g., 32% in Asia, 44% in southern Europe), by country (e.g., 25% in Spain, 75% in Israel, 7% in Japan), and within countries, (e.g., In the USA, 46% in California, 44% in Florida). Australia uses reclaimed water only for 4% of its total water demand. Moreover, in northern Europe, 51% of environmental applications are performed using reclaimed water. Singapore fulfills its water demands by treating 30% of wastewater, which is expected to increase to 55% by 2060 [13,16]. Approximately 78% and 90–97% of wastewater is reused in Oman and Cyprus, respectively [6]. The total amount of treated wastewater (TWW) used for different purposes worldwide is ~500 Mm^3/year [6].

Five studies have recently reviewed the issues of water reuse during 2019–2021, based on a literature survey on water reuse conducted via www.sciencdirect.com [18–22]; however, these studies did not report water reuse at a global level or include future perspectives for adapting reclaimed water for safe reuse at a large scale. Therefore, in this review, we aim to illustrate case studies on global water reuse that have addressed this scenario to provide guidance for countries that will embrace this concept in the future. Based on these studies, we summarize the following: (a) fields of utilization, (b) obstacles hindering widespread water reuse, (c) advantages of water reuse, (d) global case studies, (e) future perspectives for water reuse, (f) general perspectives for water reuse, and (g) guidelines set for water reuse.

2. Summary of Fields of Utilization for Water Reuse

2.1. Water Reuse for Human Beings

As a pragmatic response to the growing water demand, the topic of water reuse has emerged in several countries, such as Singapore, Australia, South Africa, Mexico, Belgium, Namibia, the USA (specifically, California and Nevada), and the United Kingdom [23]. A summary of the fields of utilization for water reuse is shown in Figure 1. The term "reclaimed water" refers to the intentional use of highly treated urban wastewater, whereas "planned potable water reuse" refers to the intentional recycling of highly TWW for drinking water (DW) supply [23]. There are two methods for reusing wastewater as a DW source: indirect and direct potable recycling (IPR and DPR, respectively). IPR refers to the blending of reclaimed water with traditional water supplies in an environmental buffer, such as recharging aquifers, river augmentation, and lake replenishment; however, DPR directly delivers the treated water as a water supply source without blending it with other water supplies [23]. The concept of potable water reuse has emerged recently and is garnering interest as a viable method to overcome water scarcity. Australia has been considered a pioneer in this field since the mid-1990s. There are three main projects relevant to potable water reuse in Australia; some of them were suppressed owing to strident community opposition [4]. The summary of the three projects is given below:

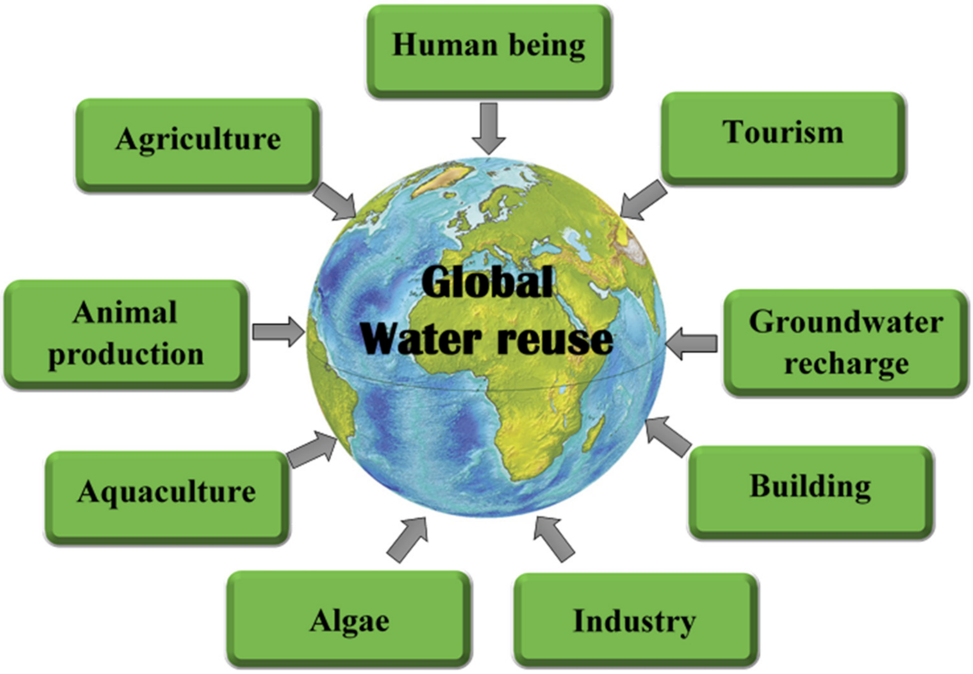

Figure 1. Fields of utilization for water reuse reported during (2019–2021).

(1) **Groundwater replenishment project**

In this project, treated municipal effluent from the Beenyup Wastewater Treatment Plant (WWTP) was processed using advanced technologies (ultrafiltration: UF, reverse osmosis: RO, and ultraviolet: UV disinfection); subsequently, the purified water was used to recharge the Yarragadee and Leederville aquifers via recharge bores [4].

(2) **Reservoir augmentation project (Western Corridor Water Recycling Project, Queensland)**

The objective of this project was to increase the amount of surface water reservoir (Lake Wivenhoe) using purified water that could be produced by treating wastewater. Notably, three advanced water treatment techniques, microfiltration, RO, and UV-advanced oxidation, were applied at Bundamba, Luggage Point, and Gibson Island. However, owing to the drought issues during that time, the treated water was not transported to Lake Wivenhoe [4].

(3) **St. Mary's Advanced Water Recycling Plant, New South Wales (A project wherein highly treated water is used to augment river flows upstream of a DW source)**

In this scenario, water was collected from three sewage treatment plants (STPs), Penrith, St. Mary's, and Quakers Hill, in western Sydney, to be treated in St. Mary's

Advanced Water Recycling Plant. The effluents were processed using UF and RO and subsequently released into the river water, which flowed downstream toward Richmond. A major obstacle faced by such projects is strident community opposition [4]. Municipalities recommended promoting IPR over DPR owing to the hypothesis that the public accepts and prefers the reintroduction of reclaimed water into natural systems. Notably, the USA (particularly in Orange County, California) is one of the few prominent countries that has successfully planned potable reuse via augmented coastal aquifers and, notably, is considered the world's largest potable water project [24].

2.2. Water Reuse for Aquaculture

In several countries in Latin America and developing countries in Asia, marine shrimp is a highly traded commodity and the second monetary group of exported aquaculture species, representing an important economic source of USD 1.51 billion/year in total [25]. The production of 1 kg of shrimp in a traditional pond requires 50 m^3 of water, and 5–20% of the total volume should be renewed daily. This kind of water usage causes severe environmental problems as the wastewater would be discharged to adjacent water bodies without any treatment. Nitrogenous compounds are generally removed from biofloc tanks via a hybrid system involving an air-lift reactor with fixed biomass in moving support and synthetic mesh for bacterial support inside the tank; this limits the proliferation of undesirable microorganisms (cyanobacteria) in the system. Integrated heterotrophic denitrification and nitrification have the advantage of maintaining the alkalinity of the water at a constant level while ensuring the removal of excessive soluble organic matter [25]. A case study was conducted in Cezarka (2.6 ha; 26,000 m^3 of water; Vodnany, Czech Republic) in which TWW produced from WWTPs was the only source of water for wastewater stabilization ponds (WSPs). The wastewater underwent primary (PT), secondary (ST), and tertiary (TT) treatment. After six months, tissue analysis of fish collected from the WSPs revealed the presence of 14 pharmaceuticals and their metabolites (at a frequency higher than 50% of samples). Moreover, remarkable differences were observed in the bioaccumulation factor of organs and species (e.g., lower levels were reported in muscle tissues), whereas several substances were elevated in other tissues in the liver, brain, and kidneys of the samples. Thus, WSPs may be considered a promising method to address the water-food nexus in aquaculture, as the residual concentrations in aquaculture products (fish fillets) are generally low [26]. Similar experiments were conducted on a nursery of shrimp (*Penaeus vananmei* postlarvae) inside a water reuse biofloc system in a low-salinity condition. The results indicated acceptable growth performance; however, a slightly higher nitrogenous load was observed [27].

2.3. Water Reuse for Agriculture

As the water crisis is a global issue, water reuse should be mandatory because it can guarantee the provision of food and feed. Therefore, we need to move toward "green chemistry" by utilizing a set of principles that reduces or eliminates hazardous substances in the design, manufacture, and application of chemical products. Moreover, it should be mandated that the discharge permitted down drains is soil-friendly, biodegradable, and non-toxic and does not lead to salt accumulation [3]. The reuse of graywater, representing 43–70% of domestic wastewater volume, for home gardening irrigation (as well as crop irrigation), particularly in arid regions, can decrease the consumption of potable water by 50%. The agriculture sector consumes a large amount of water in the country (e.g., 85–90% of withdrawal in Africa and Asia) [28]. The agricultural sector is generally considered the biggest consumer of water worldwide [15,29]. In the case of Urumqi, the capital of Xinjiang, China, the sequence order of water consumption is as follows: agriculture (58%) > secondary industry (16%) > resident life (14%) > ecology (9%) > tertiary industry (3%) [29]. After China, Mexico reuses most untreated wastewater for agricultural purposes. The capacity of the WWTP in the valley of Mexico Basin for PT is 0.5 km^3/yr; however, the actual capacity is approximately 0.2 km^3/yr. Approximately 60% of the

TWW is used for agriculture (0.1 km^3/yr), followed by public spaces (0.07 km^3/yr) and industry (0.02 km^3/yr) [10]. Wastewater without treatment is also utilized in North African countries [11] and the Uhlava River watershed in the Czech Republic at small scales [30].

2.4. Water Reuse in Industry

Water reuse in factories is a sustainable process and has the following benefits: (1) recovery of major resources for reuse, (2) reduction in the total industrial budget, and (3) safe discharge of water into the outlet streams. Wastewater discharge from factories without treatment is an environmental hazard, and it is difficult to treat the contaminates in the outlet streams after the dilution process [2,31]. The industrial sector ranks second in terms of water consumption. Several approaches have been proposed for water reuse in factories, such as fluidized-bed crystallization, used for the simultaneous recovery of copper and phosphate for safe discharge. FBC depends on the principles of chemical precipitation and crystal growth, determined by seeds added during the process (e.g., silica sand). FBC exhibits a high recovery rate (99%) and crystallization efficiency (96.07%) [32]. An integrated approach of electrodialysis and electrolysis has been proposed for water and copper recovery (82%) in its solid form [31]. This approach was further improved using an adsorption unit for Pb recovery to produce outlet discharge that can comply with international permission levels [33,34]. Ni has been recovered through electrolysis [35], and the nitrate-containing solutions can be treated using integrated electrodialysis and electrode-ionization [36].

TWW from the Wollongong WWTP, Australia, (50×10^3 m^3/day), after processing through an activated sludge unit, tertiary UV treatment, and chlorination, was used for irrigating local parks and the Wollongong Golf Club and washing coal at Port Kembla Coal Terminal. A volume of 20×10^3 m^3/d is produced via microfiltration/RO, dedicated for manufacturing at BlueScope Steel [24]. In 2012, the Gippsland Water Factory, eastern Victoria, in which wastewater from nine Gippsland towns (35×10^3 m^3 d^{-1}) is treated, was brought online, and Australian Paper's Maryvale mill used anaerobic pretreatment and a membrane bioreactor to provide high-quality water (8×10^3 m^3/d, Class A) suitable for industry reuse [24]. A study conducted by S. Lin et al. on minimizing beneficiation wastewater using flotation circuits for internal reuse highlighted that water reclamation using molybdenite and bismuthinite flotation circuits affected the performance of flotation owing to the continued increase in the saturation level that deteriorated flotation. Accordingly, dose adjustment is recommended to decrease the influence of deterioration [37].

At the industry scale, product specifications do not affect molybdenum or bismuth concentrates; for example, in the Shizhuyuan Polymetallic Dressing Plant, the amount of wastewater effluent decreased to 34.62%, which is equal to 525.60 tons of wastewater per year; freshwater supply reduced from 1898 tons to 1241 tons and the concentration of chemical reagent reduced by >10%, equaling cost savings of USD 70,260.2/year. In the textile industry, 76% of fresh water can be saved by producing four products through fourteen production stages involving thirteen tanks using a genetic algorithm to ensure an optimal production schedule; however, a 42% reduction was obtained when only two tanks were used [38].

An integrated approach of dissolved air flotation, coagulation, and flocculation was used for treating water from a tailings dam, in terms of an industrial apatite flotation unit, for water reuse purposes. The results showed that the treated water exhibited good efficiency during the flotation of apatite (80.5% recovery and 31.2% grade; P_2O_5), which is considered higher than the industry minimum acceptable levels [39]. Previous studies [40] focused on water reuse and material recovery in the textile industry that contributed to the blue economy and favored the removal of pollutants from outlet effluents before they were discharged to rivers, lakes, and the sea. Bioethanol production consumes large amounts of water, and reusing anaerobic digestion effluent (100% and 30%) of vinasse effluent does not affect *Saccharomyces cerevisiae* when sucrose or molasses are used [41]. Tetramethylammonium hydroxide (TMAH), a typical chemical compound used in the microelectronics industry, was successfully treated via a pilot plant (three aerobic bioreactors in series) for reuse purposes. The results showed a reduction of 80% and 100% of TMAH in the first and second/third bioreactors, respectively [42]. Furthermore, H_2O_2 catalyzed by UV light was proposed for treating monochromic and trichromic wastewater. The MCT/VS-based reactive dye wastewater arising from UV/H_2O_2 treatment may be used in up to two dyeing cycles without decreasing the color quality of the dyed cotton [43]. In another study [44], removing silica (reactive and colloidal) using diatom biofilms from the water generated from cooling tower blowdown of thermal power plants resulted in annual savings of 1485 megaliters/day (MLD) of fresh water, in addition to generating value-added products (biogenic silica). Chang et al. highlighted that it is feasible to increase the number of cycles for reusing the wastewater generated during the production of conventional polyvinyl alcohol sponge, but not all recycled wastewater, after blending it with fresh reactant solution. These methods overcome the difficulty of agitating the solution homogeneously while maintaining the physical properties of the contents [45].

2.5. Water Reuse for Construction

The reclaimed water produced from constructed wetland (CW) has been investigated for concrete preparation. M30-grade concrete cubes were formed using normal water and treated water (six of each) and compared with the concrete mixture stipulated by the Bureau of Indian Standards (BIS 456:2000). The results showed no difference in the compressive strengths of the concrete cubes made using treated or normal water [9]. In Ramanathapuram, India, sewage water may be considered for construction purposes [46].

2.6. Water Reuse in a Tourist-Based Community

Tourism is a major industry which contributes to the world economy. It generates approximately USD 2.22 trillion (as estimated in 2015) worldwide and employs 3.6% of the total global workforce. It is a growing industry, and it is expected that by 2026, tourism will be responsible for 11% of total employment worldwide. The tourism sector is responsible for high water consumption (0.130–1.338 m^3/guest-night); therefore, water should be reused to reduce the water consumption in tourist areas [47]. In the Spanish Mediterranean Islands, based on graywater reuse, approximately 23–80% of the total water consumption could be saved. For example, the economy of Lloret de Mar City (Costa Brava, northeastern Mediterranean) depends on the tourism industry, with 120 hotels, 29,147 beds, and an occupancy rate of 65% in 2016. Potable water is produced from the Tordera aquifer (16 km west of the city) that is treated at a conventional potable water treatment plant (40,000 m^3/day) via coagulation, flocculation, sedimentation, and filtration. The wastewater is treated at the Lloret de Mar WWTP, and the majority of treated water is discharged into the Mediterranean Sea, with only 1.4% being reused (as of 2016) (63,000 m^3) [47]. The feasibility of a vertical ecosystem (vertECO) for sustainable water treatment and reuse in Hotel Samba (a large 3-star resort in Northeast Spain) was investigated and the obtained results highlighted that the vertECO can treat graywater while ensuring the satisfactory removal of biological oxygen demand, total suspended solids, and turbidity. When vertECO and an additional disinfection stage were integrated, the outlet effluent quality complied with the general quality standards of the Urban Wastewater Directive; the treated water can be used for fulfilling hotel needs (toilet flushing) and irrigation of gardens [48].

2.7. Water Reuse for Microalgae Cultivation

Microalgae are a great source of food, animal feed, and fuel. In addition, they can be used for wastewater treatment and carbon emission reduction; however, the large amount of water required for this purpose is an obstacle [49]. Reusing water for microalgae cultivation (MC) during microalgae biodiesel production reduces the required water and nutrients by 84% and 55%, respectively. Growth inhibition in wastewater may also affect the MC. The factors that considerably affect the quality of reused water for MC are microalgae taxa, culture conditions, and harvesting methods. However, overcoming the opposing influence of reused water for MC involves pretreatment methods for inhibitory reused water and crop rotation [49]. In addition, the responses of algae growth in water reuse systems may largely rely on strain-specific factors [50].

2.8. Water Reuse for Animal Production Watering/DW

A literature survey on water reuse for animal production conducted via www.sciencdirect.com (accessed on January 2022) revealed that no studies focused on water reuse for DW for animal production, barring a recently published review article on livestock feed irrigation using reclaimed water [22]. We observed the same tendency when we searched for relevant articles on www.google.com (accessed on March 2022), finding only an article on the reuse and recycling of wastewater for livestock production in Chilean agriculture [51]. This may be due to the specific legal requirements set for livestock DW quality. Generally, DW should be clean for livestock while ensuring food safety. Animals have different capabilities to tolerate the different amounts of salts contained in DW [52]. For example, the recommended total dissolved salts (TDS) value for the Canadian livestock quality water guide for sheep is 5000, with the maximum limit being 5000–10,000 TDS and tolerance limit being 10,000–13,000 TDS; for poultry, the recommended limit is 2000 TDS, with the maximum limit being 2000–3000 TDS and tolerance limit being 3000–4000 TDS. However, beef cattle, dairy cattle, horses, and pigs have medium levels of salt tolerance compared with sheep and poultry [52]. The Canadian and United States guidelines for livestock DW and details about the water reuse innovative schemes for the agriculture sector can be found in the following literature [52].

3. Obstacles That May Hinder Widespread Reclaimed Water Reuse

Based on a survey conducted via www.sciencdirect.com (accessed on January 2022) of recent studies on water reuse during (2019–2021), the issues regarding the use of reclaimed water, as addressed by several scientists, were identified as follows (Figure 2):

- The properties of reclaimed water are not similar to tap water because of limited economic and technical conditions; therefore, reclaimed water has only been recommended for non-human contact utilization [29]. Approximately 39% of WWTPs do not follow the general standards for safe discharge with minimum constraints on ecosystems [9]. The Central Pollution Control Board (an organization belonging to the Ministry Of Environment, Forests and Climate Change, India) revealed that ~39% of WWTP production did not comply with the Environment Protection standards [9]. Notably, Lin et al. [53] highlighted that the ecological risks of reclaimed water should be urgently addressed by optimizing and updating WWTP processing, thereby ultimately decreasing the emerging contaminants present in treated effluents. The pathogen densities of gray and black water sources are comparatively different from municipal wastewater owing to the lack of wastewater dilution, as indicated by sporadic pathogen infections among small populations [54]. Several studies have reported the existence of high concentrations of bacteria and enteric viruses in TWW because of the high resistance of bacteria and viruses toward different treatment processes, even following disinfection [16];
- At present, relatively low amounts of treated water are utilized compared with groundwater and surface water. For example, in Urumqi, the capital of Xinjiang, China, treated water accounts for 3% of water use, compared to 52% and 45% for surface water and groundwater, respectively [29]. In Brazil, only 22% of wastewater is collected in semi-arid regions [55]. In France, the average daily production of treated wastewater is approximately 19,200 m^3 (2014), which is equal to 7 Mm^3/year (<0.3% of total irrigated water) [11]. In Japan, the amount of TWW consumed is 1.3% of total water consumption (210 million m^3/year, from a total of 14.7 billion m^3/year) [56]. Performing PT, ST, or TT processes using any of the available technologies may result in a reduced outlet discharge [10];

- The imbalance between the demand and supply of TWW. The distribution of TWW should be well organized across regions. This issue involves the construction of a unique pipe network and reservoir system [29]. The problem of an imbalance between supply and demand may exist if each region adapts the reclaimed water scenario that makes it mandatory to deploy the reclaimed water across regions. In general, the water resources' optimization problem for regional distribution was transformed into the transportation problem of unbalanced production and sales. The transfer costs of treated wastewater produced from WWTPs vary with the distance between regions [29];

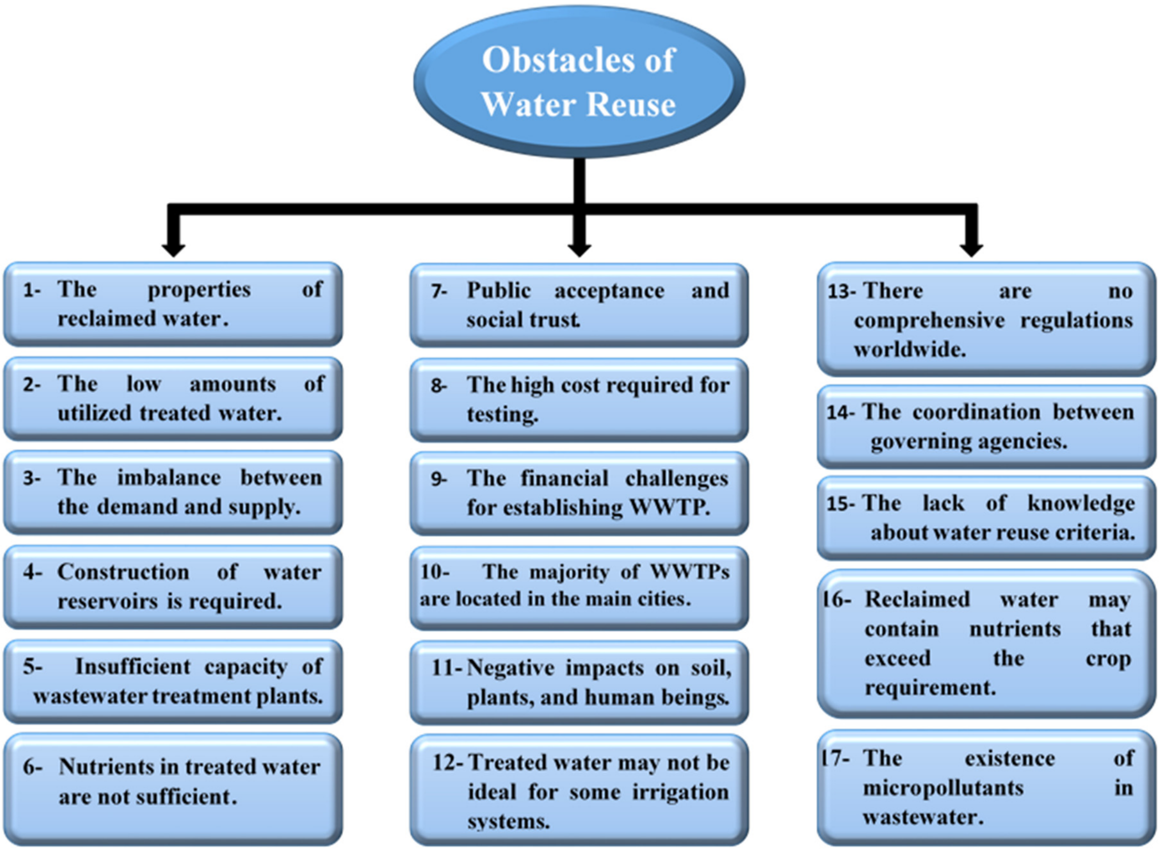

Figure 2. The obstacles that may hinder the widespread of water reuse reported during (2019–2021).

- Water reservoirs should be constructed to store reclaimed water after its discharge from WWTPs. The locations of these reservoirs should be selected carefully, for example, close to the consumption area [10,29]. Li et al. investigated the optimization of reclaimed water reuse in arid urban regions (Urumqi and Northwest China, as a case study). This study revealed three proposed scenarios that may be exploited for reclaimed water reuse. In the first scenario, reclaimed water is directly provided to the same urban area, and excess water is stored in a special reservoir or directly discharged to the river. In the second scenario, reclaimed water is immediately supplied to users in the suburban areas, and excess water is stored in special reservoirs. Finally, in the third scenario, reclaimed water is directly stored in special reservoirs and then uniformly configured to the user's transportation process. Accordingly, the construction of reservoirs to store the treated water produced from WWTPs is mandatory for sustainable practices of water reuse [29];
- The capacity of WWTPs is not sufficient to treat all wastewater. For example, in the valley of the Mexico Basin, only 10% of wastewater effluent is subjected to PT and the bulk is discharged to the nearby basins without treatment [10]. The Old Ford Water Recycling Plant, United Kingdom, is experiencing the same problem.

The daily volume of untreated wastewater is 116,000 m^3/day; however, the plant was designed to produce only 574 m^3/day of non-potable water [57]. Although the development of wastewater treatment improved from 1990–2010, the quantity of TWW is insufficient. Whereas approximately 80% of global wastewater is discharged without treatment (e.g., in India, the total wastewater amount is 61,948 MLD, and the water readily available for reuse is 23,277 MLD), indicating a huge gap between the available wastewater and the amount of treated water [9]. In high-income countries, 70% of wastewater is treated, compared to only 8% in low-income countries [58]. In Japan, 8% of WWTPs (of 176 WWTPs in total) are used as water reclamation facilities [56];

- Treated water has insufficient nutrients to provide appropriate doses of nutrients to plant growth [59]. Maeseele and Roux focused on the water reuse environmental efficiency assessment using an LCA framework (application to contrasted locations for wastewater reuse in agriculture) and mentioned that the incorporation of the denitrification process after urban wastewater treatment is not sufficient to provide significant environmental benefits (avoided fertilizer production) [59];
- Public acceptance and building social trust toward wastewater treatment strategies are important factors for sustainable water reuse development. An example is the cause of the potable water reuse project in the City of Toowoomba, Queensland, in which government politicization was precipitated by providing government funding based on public voting results [4]. Goodwin et al. reported that the stakeholders should be involved in the wastewater treatment process. This may be achieved by establishing formal and informal activities that focus on risk management to build important inter-stakeholder relationships, support the development of common understandings, and maintain trust [57]. Creating educational and outreach programs on water reuse can be challenging, considering the gaps in the scientific knowledge regarding issues related to food safety, water quality, health, inaccurate public branding of recycled water, and associated misconceptions [3]. The water governing agencies would have a difficult time without community inclination toward water reuse [60]. Public opposition in San Diego in the late 1990s and early 2000s halted proposed projects for potable water reuse in the USA and other countries owing to a range of concerns, such as public safety and social justice. Studies on public acceptance revealed that individuals prefer supporting the reuse of reclaimed water in locations that are far from human contact, such as industrial and agricultural areas, while rejecting the use of treated water for cooking and drinking [16,23]. Other findings highlighted that socio-demographic factors, such as religion, gender, age, education, income, and race/ethnicity, cannot consistently explain individual differences [23]. Public acceptance may also be affected by the "yuck factor", stemming from the opponents of potable water reuse owing to the lack of public support and psychological disgust associated with drinking treated water that was once sewage [23]. Public acceptance is influenced by concerns regarding environmental justice and exposure to risks, perceptions of trust and water scarcity, and lack of confidence in scientific assurance of safety [23]. In the USA, whether populations were located in "metro" and "non-metro" areas had a statistically significant influence on reclaimed water support, reflecting the importance of geographic areas toward public acceptance. However, in Australia, a case study on the responses from people living in rural and urban areas and two commercial buildings revealed insignificant differences in willingness to drink and use reclaimed water [23]. A recent study conducted in the Reno-Sparks area of northern Nevada (USA) on the public perceptions of potable water reuse, regional growth, and water resource management revealed concern among residents regarding the future water supply; the self-identified suburban residents were more willing to accept the perspective of reclaimed water reuse compared to rural and urban residents [23]. A study in Saudi Arabia [61] revealed a substantial reduction in the country's reliance on the total budget of water desalination, as well as the fast depletion of groundwater (non-renewable water), which necessitates embracing the perspective of reclaimed

water reuse for non-conventional purposes. Another study in the US and Australia revealed that a collaborative, local, and transparent risk-based regulation may increase the acceptance of water reuse by public and government officials [62]. A study in Qatar found an optimistic response for reusing treated industrial wastewater, particularly in low contact-level applications; however, children and females were less likely to accept this perspective for high contact-level applications [63]. In Khulna City, Bangladesh, a positive attitude was observed among major stakeholders toward the concept of water reuse in peri-urban agriculture (50% willing to pay and 66% willing to pay to obtain high-quality reclaimed water);

- High costs are associated with testing TWW. The process validation should guarantee that chemicals and pathogens that exist in the feed water are removed as per the permitted levels. Furthermore, it should be guaranteed that no acute or chronic health and environmental effects will occur owing to the reuse of TWW. The critical control point (CCP) concept has been proposed to clarify the operational boundaries of the key barriers in water treatment processes [5].
- The financial challenges and establishment of WWTPs worldwide basically depend on the national income of the country. For example, in high-income countries, ~80% of WWTPs may be constructed; however, these percentages will decrease to 35% and 8% for middle- and low-income countries, respectively [10]. Rupiper and Loge highlighted that in California, the treatment of organic solid wastes can be expensive, and it is not always a cost-effective option, thus limiting the growth of onsite non-potable water reuse systems (ONWSs) [64]. The high investment cost has been considered the major reason against the development of WWTPs [9];
- Most WWTPs are located in main cities, while smaller cities use traditional approaches for wastewater disposal. For example, India has small villages, slums, and low-population settlements or isolated towns that follow the practice of open defecation, with few sites available for onsite sanitation [9]. Wastewater treatment production and sewage systems are primarily absent in rural settings that comprise non-point agricultural runoffs; this requires decentralized installations suitable for small-scale treatment. This may lead to a scenario that primarily focuses on the agricultural sector and limits the opportunity for intentional reuse [10];
- Negative impacts on soil, plants, and human beings can be caused by chemical, physical, and microbiological contaminations in reclaimed water. These contaminants may include heavy metals, pharmaceuticals, plasticizers (e.g., phthalate esters and bisphenol A), PCPs, antibiotic-resistant bacteria, pathogens (viral, bacterial, and protozoal), chlorine, and bicarbonate sodium. The formation of organic matter pools, increased salinity, and accumulation of contaminants in soil have been reported in several studies. These contaminants may also impact soils, plants, and humans. The soil buffer capacity, pH, and cation exchange capacity of soil systems can be modified, ultimately deteriorating soil quality. A study conducted in Israel found that the damage caused by high salinity, owing to long-term usage, affected the soil and plant health of the region [3,16]. In Tufileh, Jordan, graywater has been used in urban agriculture to improve income through increased agricultural production; an increase in soil indicators, such as the salinity, sodium adsorption ratio, and organic content of the soil, was observed [28]. In South Korea, the downstream irrigation water quality may be degraded owing to WWTP effluents via informal reuse, thereby resulting in growing concerns among farmers regarding the negative impacts on crops, such as rice lodging (i.e., flattening), that may force farmers to use underground water as an alternative source and may result in groundwater depletion [65]. With long-term application, water reuse for irrigation may impact public health. Epidemiological studies conducted on farmers and irrigators exposed to pathogens, along with the subsequent gastrointestinal (GI) outcomes, revealed little to no health risks. However, emerging exposure assessment studies have revealed microbiological or chemical contaminants in reclaimed water, which may impact public health. Pharmaceutical

compounds, including carbamazepine and lamotrigine, may be translocated from the soil to the edible part of the plant and thus be consumed by people [3];

- Treated water may not be ideal for some irrigation systems. Some studies explored that using spray irrigators exposed to reclaimed water (tertiary-TWW) increased the odds of colonization and growth of bacterial pathogens, such as antibiotic-resistant coagulase-negative staphylococci [3]. Another study revealed that when irrigation water comprised 126 CFU/100 mL of *E. coli*, there was a 0.000009% risk of GI illness (diarrhea) (nine cases in 100,000,000 persons); however, a 0.0011% risk was observed for furrow irrigation (1.1 cases in 100,000 persons), along with a 0.11% risk related to sprinkler irrigation of lettuce (1.1 cases in 1000 persons) [66]. However, human health risks can be reduced by using an efficient irrigation system (e.g., sprinklers that do not require high investment, such as dripper and are more efficient than surface irrigation) owing to a reduction in the contaminants of emerging concern (CEC) load that may be translocated to crops. Notably, sulfamethoxazole and 17a-ethinylestradiol presented a high level of risk to humans [67];
- There are no comprehensive regulations worldwide that consider the contaminants that remain in reclaimed water, such as PPCPs, endocrine disruptors, and antibiotic resistance determinants. Some countries do not present regulations or guidance for "water reuse", which may ultimately lead to the continuous reuse of untreated or raw wastewater for agricultural purposes, which may be considered harmful to public health and the environment [3]. Owing to the global water crisis, the policies and regulations that embody the "One Water" approach must be embraced [3]. Wastewater reuse and wastewater treatment are radically evolving fields that typically suffer from a lack of legal and economic alignment between the regulatory and public understanding of the topic. In the San Antonio Region of Texas, 70% of agencies have policies that support increasing water reuse by 10% [60]. Although there is an advantage to ONWS, uptake has been slow. In the USA, owing to a lack of clear regulations for ONWS, local authorities may not have the necessary knowledge, resulting in the absence of active intentions required to regulate these systems [64]. The lack of knowledge and a supportive local regulatory program in California is considered an obstacle to the growth of ONWS. In the USA, there are microbial indicator standards for irrigation water and the regulations for water reuse are set based on state and local levels [66]. However, there are no federal regulations for the reuse of recycled water. Notably, several individual states and territories (e.g., Arizona, California, Colorado, Florida, Virginia, Delaware, Massachusetts, New Jersey, Hawaii, North Carolina, Idaho, Minnesota, and Washington) have established specific regulations to manage water reuse, with a focus on agricultural irrigation, animal watering, and crop production. Details about this regulation are presented in the literature [66];
- Coordination between governing agencies is crucial for the promotion of water reuse. Several studies revealed a minimal influence of governance on water reuse. In addition, governing agencies (local, regional, and state) often do not have shared water goals, particularly with respect to the objectives required to promote water reuse [60]. The study carried out by Aldaco–Manner et al., which focused on investigating the potential increase of water reuse practice in the San Antonio Region based on the analysis of four governance factors on efforts of water governing agencies showed that ~70% of agencies in the region have efforts to increase water reuse practice by as much as 10% [60];
- The lack of knowledge about the criteria for reusing reclaimed water as an alternative water resource is considered an obstacle. For example, a study on onsite non-potable water reuse system (ONWS) [64] revealed that limited public education about alternate water sources is one of the predominant reasons hindering the development of the treatment of ONWS in California. Furthermore, although farmers have years of experience in using wastewater for irrigation, they have very little knowledge about the health risks involved with reclaimed water reuse. For example, farmers do not

consume what they produce using TWW as they do not receive information about health risks to consumers [16];

- Although reclaimed water may be rich in nutrients that may be considered as fertilizer value to grow crops, in certain scenarios, the concentrations of these nutrients may exceed crop requirements, which may result in several issues, such as delayed or uneven maturity, excessive vegetative growth, and reduced crop quality. The nutrients that are considered important for plant growth, such as N and P, are associated with other elements, such as B, Zn, K, and S [16]. Although some farmers are aware of the benefits of reclaimed water for agriculture, they have inadequate information regarding the recommended dosages of fertilizers for optimal crop development [16];
- The occurrence of micro pollutants in wastewater (e.g., disrupters, pesticides, endocrine, pharmaceutical molecules, carbamazepine, diclofenac, ibuprofen, and caffeine) makes it challenging to select the ideal wastewater treatment technology. The current treatment technologies (e.g., membrane bioreactors, RO, activated carbon, and advanced oxidation) are not sufficient to produce reclaimed water that can comply with the general standards for micro pollutants in wastewater [13]. Microorganisms in urban wastewater, such as intestinal protozoa and nematodes, are difficult to remove owing to their (oo)cyst and stages of egg transmission, thereby resulting in environmental stresses and health risks [68].

4. Advantages of Reclaimed Water Reuse

The advantages of reclaimed water reuse can be classified based on whether they have market or non-market benefits for irrigation purposes [16]. Based on a literature survey via www.sciencdirect.com (accessed on January 2022), the following advantages have been reported worldwide during (2019–2021) (Figure 3):

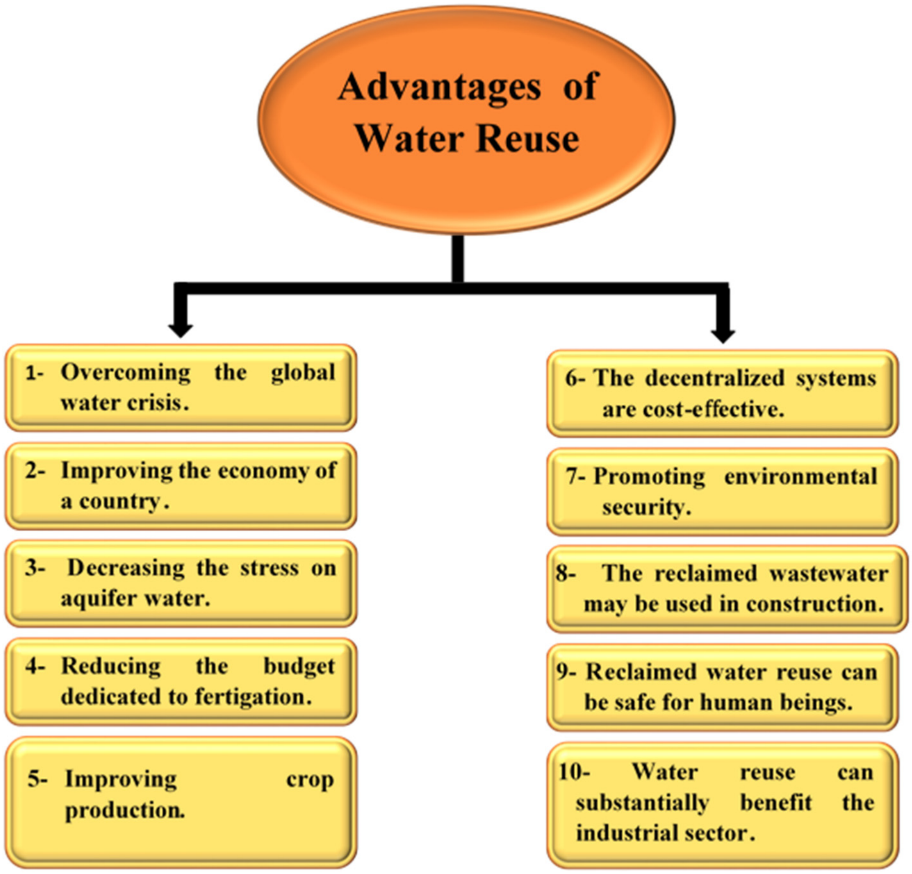

Figure 3. Summary of advantages that may prompt the widespread of water reuse reported during (2019–2021).

- Overcoming the global water crisis and avoiding the impacts of new water supply developments, such as the construction of dams, are necessary to ensure a healthy environment for future generations [16,47]. The optimal reuse of graywater may save 57% of freshwater, and this can be achieved by synthesizing and retrofitting water levels and systems at the household and community scales [69]. In the EU, the reuse of reclaimed water is considered a possible alternative water supply, with the advantages of negligible effects on food production and income of farmers [70]. In a previous study in Santiago de Chile (Chile), it was estimated that graywater reuse would ultimately decrease the consumption of fresh water by hundreds of liters per month if additional permission for graywater reuse is obtained [71]. The importance of graywater reuse has also been reported in other studies [72,73]. Using reclaimed water in industrial cooling circuits may save ~3750 m^3/y [74]. Notably, 25% of the cropland irrigation requirements in the Netherlands (Dutch) may be fulfilled via STPs during an average season and 17% during a dry season [75]. Overall potable water consumption can be reduced using an ONWS, onsite graywater reuse, and centralized blackwater systems [16,64];
- The economy of a country can be elevated by water reuse; for example, water reuse in Israel has resulted in an increase of 1600% in the economic value accumulated via agricultural production [3], and similar results were observed in other studies [60]. A study on graywater reuse in Spanish hotels explored the possibility of economic savings based on the cost of potable water [47]. The Oliva WTT in Spain and Peschiera Borromeo WTT in Italy may be considered reliable sources of water or nutrients that ultimately reflect a positive economic balance [76]. A study on brewery wastewater reuse presented increased economic value for the majority of cases (77.2%) [77];
- Decreasing the stress on aquifers and increasing the reservoir volume via an underground aquifer recharging process can help economies achieve sustainability [3,4]. For example, the case study in western Australia (the groundwater replenishment scheme), operated by the Water Corporation of Western Australia, is considered the most important potable reuse project in Australia. The groundwater replenishment scheme is considered a managed aquifer recharge project planned for drinking water aquifers recharge. The Beenyup Wastewater Treatment Plant is considered the main source of the treated municipal effluent that is subsequently purified by ultrafiltration, reverse osmosis, and UV-disinfection. To deliver the purified water to Yarragadee and Leederville aquifers, recharge bores are installed. Currently, this project has the capability of recycling around 28 × 106 m^3 (28 GL) of water per year (sufficient to supply up to 100,000 households), and it is anticipated to reach 115 × 106 m^3 per year by 2060 [4];
- The budget dedicated to fertigation can be reduced owing to the presence of nutrients in treated water [3]. Crop yields can be increased when some crops are irrigated with reclaimed water because reclaimed water can be a reliable source of nutrients, such as nitrogen, potassium, phosphorus, and organic matter, which all ultimately increase soil fertility via fertigation [3,16];
- The integration of reclaimed water with advanced water-saving (e.g., subsurface irrigation, drip irrigation technologies, sensor-based, and "irrigation on-demand" systems) has a remarkable influence on overall crop production and water conservation [3]. This was clearly seen from Israel's trials within the past six decades in which an increase in the economic value of products was achieved and reached 1600%. This was attributed to the widespread use of both drip irrigation technologies and reclaimed water, in addition to government land management policies. Whereas the prolonged and extensive application of the water reuse scenario was associated with potential risks for soils, plants, the environment, and public health that eventually require additional investigations for the expanding practices of water reuse [3];
- Decentralized systems are cost-effective and energy-efficient in certain circumstances compared to analogous centralized systems owing to the decrease in transport dis-

tances, fewer infrastructure requirements, and the convenience of treatments that are fit for all purposes [64]. Moreover, reclaimed water consumes less energy than other water use options, such as desalination and imported water [16];

- Reclaimed water can promote environmental security. Approximately half of the global water bodies are seriously contaminated. Treating and reusing wastewater will considerably decrease the possibility of freshwater resource pollution and eutrophication and promote saving nutrients [16,47]. Additionally, graywater may be exploited for green roof expansion, which has many advantages, such as reducing air pollution, promoting the mental health of habitants, reducing building cooling requirements, improving aesthetics, and reducing noise [78]. Compared with desalination, water reuse has 14–25% lower greenhouse gas emissions and 20–350% lower CO_2 emissions [47]. The anaerobic membrane bioreactor approach can contribute to a catchment-scale circular economy while reducing the carbon footprint, preserving natural water bodies, and creating business opportunities [76];
- Reclaimed wastewater may be used in construction for manufacturing concrete with compressive strength values close to those prepared using normal water [9]. Ramprasad and Rangabhashiyam mentioned that the formation of M30-grade concrete cubes uses two types of water (normal water and treated water; six of each), and the obtained results were compared with the concrete mixture stipulated by the Bureau of Indian Standards (BIS 456:2000). Moreover, there were no differences in the compressive strengths of the concrete cubes made using treated or normal water [9]. Additionally, in Ramanathapuram, India, sewage water may be considered for construction purposes [46];
- Reclaimed water reuse can be safe for humans. Based on risk assessments of different contaminants of emerging concern (CEC) in reclaimed wastewater (RWW) that may be used in agriculture irrigation, high uncertainties were observed for weakly acidic CECs, owing to the degradation in soil and pH variations inside plants [67]. Green leaf samples irrigated using reclaimed water with very low Hepatitis A Virus (HAV) concentrations (approximately 2%), mostly linked to raw sewage, did not test positive for HAV. Water samples collected from water reservoirs used by the growers near an agricultural field represented maximum reductions in norovirus, with the concentration being low in green leaves [79];
- Water reuse can substantially benefit the industrial sector. For example, bioethanol production consumes high amounts of water, and the reuse of anaerobic digestion effluent (100% and 30%) from vinasse effluent does not affect the concentrations of *Saccharomyces cerevisiae* when sucrose or molasses are used [41].

5. Global Case Studies for Reclaimed Water Reuse

Based on a survey conducted via www.sciencdirect.com (accessed on January 2022) of recent studies on water reuse during 2019–2021, the global case studies for reclaimed water reuse will be discussed in detail in the following section (Figure 4).

5.1. The Continent of Asia

5.1.1. Lessons from China

The Chinese Five-Year Plan suggested that urban sewage treatment facilities should be appropriated for the requirements of the entire urban area. A previous study suggested that the percentage rate of urban sewage treatment should be increased to 95%, and at least 20% of reused reclaimed water should be used to address water deficiency in major cities in China [29]. In Urumqi, the capital of Xinjiang, low percentages of reclaimed water (3%), representing 19–20% of other water sources, are used for crop irrigation (50%), industries (6%), and greening (1%) [29]. Results from this study showed that, except for dissolved oxygen, other parameters that determine the water quality of the effluent from the STP in Urumqi easily met the urban miscellaneous water and landscape water standards [29]. In North China, an anaerobic–anoxic–oxic membrane bioreactor in a WWTP was evaluated for reclaiming unconventional water resources; for example, a mixture of domestic wastewater and rainwater was collected from a green building residential community that could produce 1000 m^3/day of reclaimed water. This water could be used for different purposes, such as lawn irrigation, toilet flushing, and car washing [80]. The treatment sequence comprised eight steps: coarse screen (8 mm), fine screen (1 mm), adjustment tank, aerated grit basin, A^2O-MBR, chlorination system, reservoir, and sludge treatment system. The reclaimed water was used for toilet flushing and laundry (~37%), lawn irrigation and artificial lake replenishment (~19%), and road cleaning and car washing (~5%), with the remaining water being directly discharged (~39%). The results established that, from a technical and economic feasibility perspective, the A^2O-MBR-based system is an efficient and profitable technology for treating unconventional water resources in a green building residential community [80].

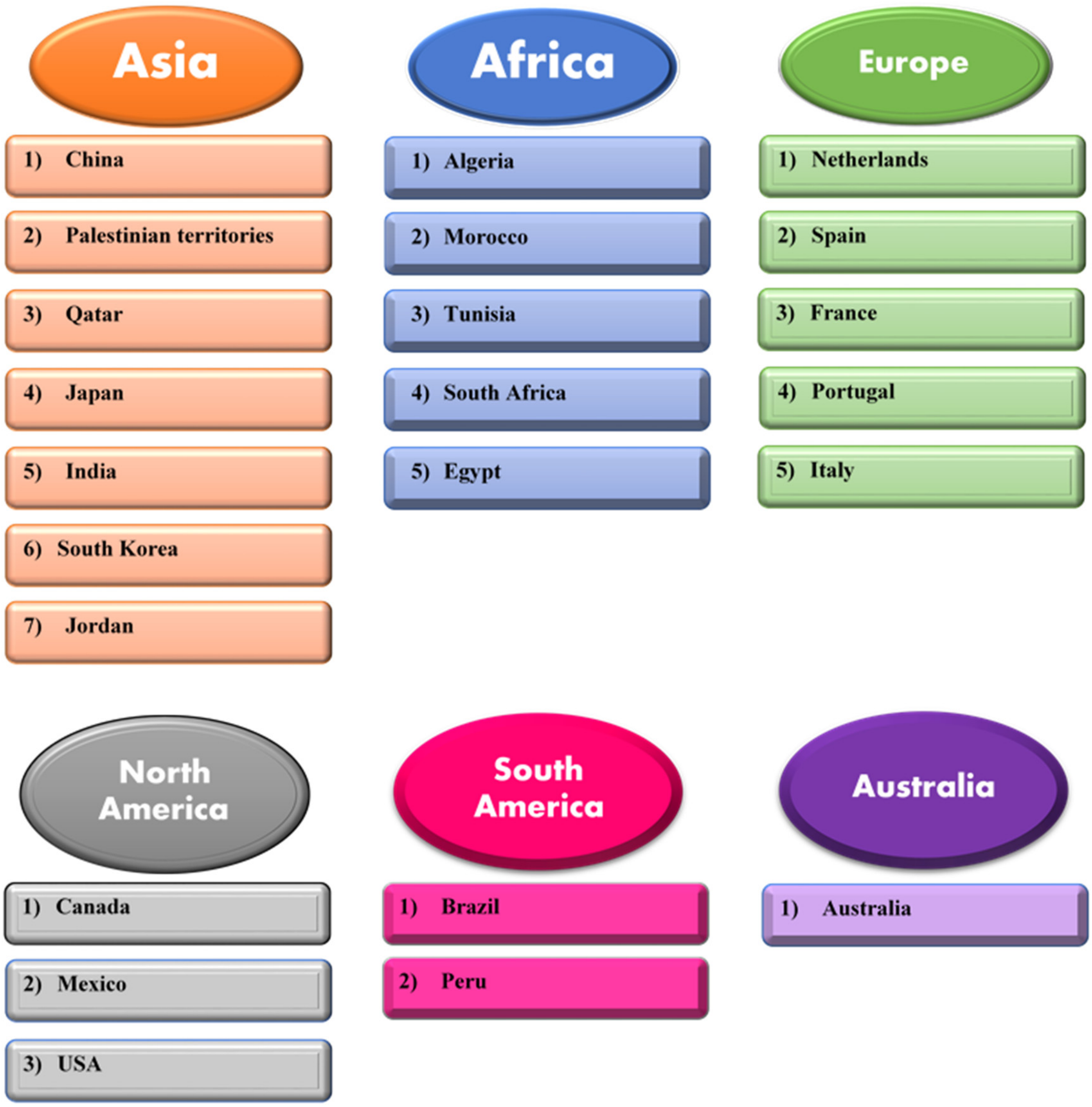

Figure 4. Summary of global case studies for water reuse reported during (2019–2021).

5.1.2. Lessons from Palestinian Territories

In the West Bank of Palestinian territories, graywater was used in four farms as an irrigation source. The farms in Hebron and Nablus governorates used CWs, and two farms in Jericho used upflow gravel filtration graywater reuse systems and surface-level ponds to hold groundwater pumped to the surface for irrigation. Graywater reuse is generally practiced via drip irrigation for several plants, such as cucumbers, tomatoes, zucchini, and citrus and date trees. Based on scientific studies, herbicides and antibiotics are widespread in the domestic graywater of the West Bank, with higher concentrations than that observed in groundwater stored in surface ponds [81]. Another study revealed that although most parameters of water quality complied with Palestinian and Israeli standards for wastewater reuse, the *E. coli* levels in the effluent exceeded them. However, the reduction in bacteria and the overall isolates from the influent and effluent, which indicate the resistance of antibiotics to the treatment, off-grid graywater treatment systems may be considered as a potential source for either antibiotic and susceptible-resistant bacteria in the agricultural environment [81,82].

5.1.3. Lessons from Qatar

A case study was conducted for planting sugar beet in Qatar using produced water (PW) generated during the extraction of oil and gas. The PW water quality may degrade soil quality owing to the high levels of sodium and salt, eventually reducing crop productivity and increasing groundwater contamination. In the case study, three types of water were investigated: PW, PW-treated sewage effluent (TSE), and reverse osmosis-treated PW. The simulation results showed that agro-environmentally sustainable irrigation may be achieved via such combinations. The lowest cost option to decrease the amounts of irrigation water requires changing the amount of PW to be the same volume as that of TSE (0.26 USD/m^3) or four times the volume of desalinated PW (0.46 USD/m^3); this is considered to be a competitive PW management strategy for oil and gas firms compared with the traditional PW disposal practices that cost 0.06–16.67 USD/m^3 [83].

5.1.4. Lessons from Japan

Since the 1980s, several cities in Japan have reused non-potable water in several urban applications, including urban stream water augmentation, toilet flushing, and landscape irrigation. Water reuse has three main applications: (a) toilet flushing (started in urban areas), (b) flow augmentation, and (c) multipurpose applications (emergency applications and heat transfer). Notably, the high energy consumption and inadequate quality standards of water reclamation facilities have limited widespread water reuse in Japan. The Core Research for Evolutional Science and Technology conducted between 2010 and 2015 analyzed the efficiency of integrated UF and UV radiation (UF-UV) processes for removing viruses from wastewater used for agricultural irrigation at a low cost [56]. Graywater reuse is practiced in Japan to address water shortages (e.g., buildings in Tokyo must reuse graywater for areas over 30,000 m^2 or have potential reuse of 100 m^3/day) [28]. In 1980, the Chubu WWTP, considered to be the first water reclamation facility near the center of the city, was constructed; the plant has a daily capacity of 400 m^3 and utilizes ST. A dual distribution system was adapted to separately distribute reclaimed and tap water. Reclaimed water reuse was also implemented in Tokyo in the Shinagawa, Shinjuku, and Tokyo Bay areas. Reclaimed water has been used for dried-up streams (Tokyo), and from 1984 to 1989, the augmentation stream flow scenario was employed for three irrigation channels by discharging effluent (ST) from the Tamagawa-Jouryu WWTP. Similarly, Ochiai WWTP effluent was discharged into three urban rivers [56].

5.1.5. Lessons from India

In India, decentralized wastewater treatment (DWT) systems have been proposed for isolated towns with low-density population areas and space-constrained urban locations. These systems can reduce the costs required for the collection, treatment, and disposal of wastewater to 60% of the current value. A summary of the performance ratings of decentralized technologies is presented in the literature [9]. CW is one of the most successful decentralized technologies for this purpose, as are rooftop wastewater treatment gardens and a zero liquid disposal (ZLD) technology. In Madhya Pradesh, India, the internal and external benefits of graywater reuse have been comprehensively analyzed for the cost-benefit analysis of graywater reuse for flushing toilets and garden irrigation [28].

5.1.6. Lessons from South Korea

In South Korea, the government encourages stakeholders to increase wastewater reuse to overcome future freshwater shortages [65]. Approximately 12% of TWW from WWTPs (>500 m^3/day) is used to irrigate paddy fields. The downstream irrigation water quality may be degraded owing to the effluents from WWTPs via informal, indirect reuse, and there are growing concerns among farmers regarding the negative impacts of the water on crops, such as rice lodging (i.e., flattening), that may force farmers to use underground water as an alternative source. This is a major concern for the government owing to potential groundwater depletion. The Osan WWTP in South Korea has a capacity of 140,000 m^3/year and augments up to 30% of the Osan River during the irrigation period (paddy irrigation) [65].

5.1.7. Lessons from Jordan

Jordan suffers from severe water scarcity, and this issue is being exacerbated owing to the increase in population (particularly due to the continuous flow of refugees from Syria since 2011) and climate change. Although the threshold of severe water scarcity for the country is 500 m^3/capita/year, the per capita supply of water in Jordan is 140 m^3/capita/year. Accordingly, reclaimed water is reused indirectly or directly for productive purposes, particularly agricultural purposes [11]. The government supports the concept of the reuse of TWW by creating policies that permit the reallocation of water across sectors to ultimately preserve sufficient fresh water for domestic use. Approximately 27 WWTPs have been constructed for this purpose, which produce 121 Mm^3/year of TWW and serve 63% of Jordan's population. Notably, 80 Mm^3/year of TWW is produced from the Al-Samra treatment plant that is used subsequently for unrestricted irrigation after "dilution" in the Jordan Valley along the Al Zarqa Wadi and ultimately stored in the King Talal Dam. Approximately 45 Mm^3/year of TWW is used in restricted irrigation for the production of fodder crops and fruit trees [11]. Additionally, the Jordan government established the Sahara Forest Project, based on the Power Plant Hyper Set, to grow essential crops and ensure food security [84]. In Tufileh, Jordan, graywater has been used in urban agriculture to improve income through increased agricultural production. Increases in soil indicators, such as salinity, SAR, and organic content of soil, have been reported in the literature [28].

5.2. The continent of Africa

5.2.1. Lessons from Algeria

In Algeria, the reuse of reclaimed water for agricultural irrigation was formalized in 2007. In 2019, more than 577 Mm^3 total volume of wastewater was produced and managed by the Algerian wastewater treatment office (the Office National de l'Assainissement; ONA). The ONA revealed that 123 Mm^3 of wastewater was treated using 148 WWTPs. Of these WWTPs, 17 were officially concerned with wastewater reuse, with a total production of 8 Mm^3 [11]. In Hennaya Tlemcen in the northwest and Guelma Bouchegouf in the northeast, there are representative cases of controlling reclaimed water reuse for irrigating 912 ha and 6980 ha, respectively. In these two cases, water produced from WWTPs (activated sludge plants) was discharged into a river and subsequently received in the plots via pumping. Two main constraints hindered the increase in reclaimed water reuse: (a) treatment was limited to ST in all plants, and (b) a limited volume was available for irrigation. Notably, only 10% of land in the high plains of Algeria is irrigated with untreated wastewater (e.g., land for growing tomatoes, cucumber, and watermelon). However, after the outbreak of cholera in the districts of Blida, unplanned water reuse was strictly prohibited [11].

5.2.2. Lessons from Morocco

Until the 21st century, in Morocco, the public investment in urban water focused on universalizing peoples' access to DW, and raw water was commonly reused informally in many cities (e.g., Settat, Meknes, and Marrakesh). In 2006, with the introduction of the National Sanitation Plan (French acronym PNA), this behavior changed, achieving a treatment rate of 8–60% and ensuring the construction and restoration of 187 and 300 WWTPs by 2020 and 2030, respectively, with the potential of achieving reclaimed water generation of 424 Mm^3 and 935 Mm^3 [11]. Additionally, in 2017, 24 different projects effectively reused 47.5 Mm^3 of water for golf resorts. Moreover, water reuse was exploited by the Cherifian Office of Phosphates for several purposes, such as rock washing and the irrigation of green spaces and green belts [11].

5.2.3. Lessons from Tunisia

In Tunisia, the wastewater reuse scenario has been planned since the 1960s. The Tunisian government launched an ambitious national program in the aftermath of its 1975 Water Act. In 1989, more specific standards were set for the quality control, treatment, and distribution of RWW reuse. The WHO guidelines are closely followed by the Tunisian government; farmers are forbidden to irrigate vegetables with wastewater treated with ST (through activated sludge). In 2016, 8415 and 1040 ha of farmland (cereals, fodder and tree crops, and industrial) and golf courses, respectively, were irrigated with 30% RWW. Moreover, over the next few years, it is predicted that reclaimed water may be used for the irrigation of 30,000 ha of land. However, there is concern among farmers in the driest part of the country, in the south, regarding the long-term effects of using reclaimed water for irrigation [11].

5.2.4. Lessons from South Africa

In South Africa, graywater is used for irrigation to a lesser extent than that for other household uses, mostly in the suburbs with middle- and higher-income areas (mostly during drought periods) and rural areas to ensure food production [28].

5.2.5. Lessons from Egypt

The Egyptian government established the El-Gabal El-Asfar WWTP, which is considered to be one of the most successful and large domestic MENA wastewater treatment facilities [2]. In 2018, a four-year project (ReWater MENA: More and safer water reuse in the Middle East and North Africa) was initiated by the International Water Management Institute (IWMI) and its partners with the aim of increasing the opportunities for safe water reuse in Egypt, Jordan, and Lebanon, as representatives for MENA countries. This project aimed to address obstacles that the countries may face during water reuse processes and encourage farmers to adopt this perspective by promoting safe reuse practices in cities and agriculture, with inclusive and participatory engagement with stakeholders, thereby improving public health, food safety, and livelihoods. Notably, the IWMI, along with its partners, creates platforms for engaging stakeholders to deliver project results in a streamlined manner. The ReWater MENA project uses a combination of participatory processes to promote promising solutions for water reuse, uptake, and scaling-up and facilitate the exchange, co-creation, and validation of innovations [85]. The Egyptian government established the El-Salam (peace) Canal by blending drainage water (representing $> 12 \times 10^9$ m^3/year) and Nile water at a constant ratio of 1:1 rather than discharging Nile Delta drainage water to the Mediterranean Sea. The El-Salam (peace) Canal water supply is planned to be delivered to the north Sinai deserts via the crossing of the Suez Canal. The aim of this project is to re-chart Egypt's population map, provide irrigation water supply (to cultivate 643,560 acres of new lands), and create new communities along the canal [86,87].

5.3. The Continent of Europe

5.3.1. Lessons from The Netherlands

In the Netherlands, the agriculture sector experiences periodic shortages in irrigation water; studies have estimated that the demand for freshwater will increase in the future, owing to the growing demand from industrial activities and climate change. Water from STP was analyzed as a possible alternative for water resources during the dry season for agricultural irrigation via subsurface irrigation (SSI) [75]. STP effluent is generally transported through groundwater flow, which may result in high water consumption via SSI; however, this may cause loss of water if the aboveground irrigation system (AIS) is used due to interception. In addition, direct contact between crops and irrigation water occurs via the AIS. The SSI systems may work as a filter and buffer zone, as the soil acts as a barrier. This perspective indicated that up to 25% of the water demand of croplands (during an average season) may be provided via the intentional reuse of STP effluents through an SSI within a 5 km transport buffer zone from the STPs; however, 17% of the water demand may be supplied during the dry season. The details of this approach are presented in the literature [75].

5.3.2. Lessons from Spain

In Cartagena and Lorca (Murcia, Spain), two WWTPs used for reclaimed water production use TT (ultraviolet-C light) and sodium hypochlorite is used for crop field production. Different types of water reservoirs are used to store reclaimed water before supplying it to end-user points. Notably, the microbiological quality at the "point of compliance" for reclaimed water complied with the minimum quality requirements (<10 CFU/100 mL); the end-user point (field irrigation) must have a threshold level established by the Commission guidance document (EC, 2017/C_163/01), which is dedicated for the primary production of fresh fruits and vegetables. During distribution, punctual cross-contamination of reclaimed water was observed, which ultimately increased the *E. coli* (>4 log CFU/100 mL) levels. In 1.3% of the samples (6/470), pathogenic bacteria were detected during the chlorination treatment and the reductions in the *E. coli* and *C. perfringens* spores in reclaimed water samples were higher than those in water samples treated using UV-C light [88]. Additionally, in the lower part of the Llobregat River, Spain, a case study was conducted to study the fate of N-nitrosodimethylamine (NDMA) and NDMA formation potential when reclaimed water is discharged to river water with and without chemical disinfection using chlorine. The results showed that at the river DW intake point, the NDMA concentrations were lower (<7.3 ng/L) than those observed at the discharge point owing to dilution and photolysis, and the NDMA formation potential decreased owing to dilution and biodegradation [89]. Biologically active carbon was more appropriate for NDMA removal at temperatures >22 °C owing to an increase in microbial activity at high temperatures [90].

5.3.3. Lessons from France

In France, deficits in water resources occur locally and seasonally; therefore, reclaimed water is restricted to certain regions. At present, approximately 40 WWTPs are used for wastewater reuse, the majority of which provide reclaimed water for turf production and golf courses and agricultural/garden irrigation. In 2014, a total volume of 19,200 m^3 was estimated to be produced as a daily average, equaling approximately 7 Mm^3/year (<0.3% of irrigation water). In Clermont-Ferrand, 0.9 Mm^3/year of reclaimed water was generated from WWTPs, which was used for the irrigation of 700 ha of farmland that cultivated wheat, seed maize, red beet, and maize. Moreover, in Noirmoutier Island, 0.38 Mm^3/year of reclaimed water was generated from WWTPs and used to irrigate 320 ha. The reclaimed water produced from WWTPs is used for the irrigation of 20 golf courses [11].

5.3.4. Lessons from Portugal

The Portuguese government recently approved a policy for reclaimed water production for exploiting different sources (e.g., domestic, urban, agriculture overflow, industrial, and surface runoff) for non-potable purposes (fire-fighting, street cleaning, recreational uses, landscape, and flushing). The lack of infrastructure, the absence of adequate legislation for wastewater treatment and distribution of treated water, and high energy and cost requirements limited water reuse projects; therefore, only a few projects are currently active. The Algarve project in Southern Portugal is dedicated to the irrigation of golf courses and citrus orchards. This small-scale project integrates horticulture and agriculture and reuses drainage water from red fruit production for crop irrigation (pomegranates or citrus) and can reduce the total amount of water dedicated for irrigation during the dry season by 15% [91].

5.3.5. Lessons from Italy

In the municipality of Peschiera Borromeo (Lombardy, Italy), a WWTP with a treatment capacity of 322,376 was constructed to serve a total catchment area of 2230 ha (for Milan and neighboring municipalities). The Peschiera Borromeo WWTP directly discharges its effluent to the Lambro River. The WWTP effluents undergo different scenarios. Different scenarios are proposed to ultimately achieve class (A) effluent quality with *E. coli* < 10 CFU/100 mL to comply with the EU regulation (minimum requirements; EU 2020/741 for reclaimed water agriculture irrigation). Life cycle assessment indicated that reclaimed water reuse offers comparatively more environmental benefits than the discharge scenario [92]. Disinfection using peracetic acid (PAA) and UV disinfection did not present any significant differences. The PAA and UV disinfection scenarios are affected by chemical transportation and energy consumption, respectively. Using the integrated anaerobic configuration, including the upflow anaerobic sludge blanket and anaerobic membrane bioreactor, previous studies analyzed the benefits of these models, with the only exception being water eutrophication [92].

5.4. The Continent of North America

5.4.1. Lessons from Canada

Although Canada has abundant water derived from the rivers sourced by glaciers, rainfall, snow, and the Great Lakes, there are regions that may experience limited water supply in the future; this is particularly true for expanding cities owing to the decreasing size of glaciers, limited sources of regular supply, and climate change [93]. Most of the university community in Canada is in favor of reusing water; however, they do not prefer using reclaimed water for personal use and drinking owing to concerns over contamination. Water reuse in London, Ontario (using cistern water from the basement sump weeping tile system) involves toilet flushing, which leads to a 25% reduction in potable water per year [93]. The Fanshawe College building square has a green roof, and storm water is reused for toilet flushing and irrigation. The Vancouver Convention Centre and the University of British Columbia Centre for Interactive Research in Sustainability have internal wastewater reuse and non-potable reuse systems. Furthermore, the ZLD system is used inside the Bowen Island Municipality's Cove Bay Water System for treating surface water from Grafton Lake to produce potable water. The Gold Bar WWTP can treat 310 million L of wastewater/day to serve 700,000 people. ZLD facilities are also present in Saskatchewan, the Co-op Refinery Complex (CRC) in Regina, etc. [93].

5.4.2. Lessons from Mexico

The majority of the population in Mexico (77%, 90 million population) has been living in urban areas for more than 50 years. Mexico ranks only behind China globally in terms of using untreated wastewater for agriculture [10]. The amount of renewable water in the valley of the Mexico Basin is approximately 1.5 km^3/yr, which can be divided into the surface water supply (50%) and aquifer recharge (50%). Notably, in this region, only PT is conducted, with a total capacity of 0.5 km^3/yr; however, the treated amount is only 0.2 km^3/yr. These relatively small amounts are divided into 60% and are used within the city, as follows: agriculture (0.1 km^3/yr), public spaces (0.07 km^3/yr), and industry

(0.02 km^3/yr). The establishment of advanced treatment does not exist in the basin. The final discharge of the bulk of wastewater produced from the valley of the Mexico Basin is transported, without treatment, to the neighboring Tula Basin (El Mezquital Valley) in Hidalgo, where it is used as the main source for crop irrigation in the region [10].

5.4.3. Lessons from the USA

The San Antonio Region of Texas is experiencing a simultaneous increase in population and drought; studies have estimated that the gap between water demand and supply will be 11% and 44% by 2020 and 2070, respectively. Studies have estimated that by 2070, water reuse will be considered as a potential source for water supply [60]. Since 1925, treated graywater has been used in the USA for irrigation and toilet flushing. In Florida, domestic graywater reuse has been adopted for more than 40 years. In the western USA, homeowners irrigate ornamental gardens using graywater owing to water shortages [28]. Wastewater dilution has been used in the USA, in which the treated or untreated wastewater may be directly discharged to the waterways for use in the downstream area [10].

5.5. The Continent of South America

5.5.1. Lessons from Brazil

The Metropolitan Region of Sao Paulo (MRSP) was selected as a case study for the water reuse scenario (a model for most urban areas worldwide). The water reuse potential (WRP) index was calculated based on a multi-criteria decision analysis approach to determine the feasibility of non-potable water reuse for the development of industrial and agricultural sectors. The model was based on several factors, including environmental and socioeconomic criteria and the analytic hierarchy process. In addition, a sensitivity analysis was conducted to accurately identify the effects of the criteria weights on the obtained results. The results showed that the WRP values were 0.813, 0.363, 0.293, 0.282, and 0.252 in Sao Paulo, Suzano, Barueri, Mogi das Cruzes, and Guarulhos, respectively. Notably, the water reuse scenario in Brazil for non-potable applications was limited and at a small scale. Brazil generally produces 0.3 m^3/s of reclaimed water (mean). In the MRSP, the Aquapolo Project was constructed with a capacity of 1.0 m^3/s; however, in practice, it produces only 0.65 m^3/s. The limited legal framework in Brazil is an obstacle. Resolution No 54/2005 of the Conselho Nacional De Recursos Hídricos (National Water Resources Council) is the only national-level regulation that refers to water reuse, with a focus on establishing allowed classes for non-potable reuse [94].

5.5.2. Lessons from Peru

In Lima, Peru, the use of graywater for vegetable production was investigated to reduce poverty and enhance the urban environment. Studies reported only a few health problems associated with using untreated graywater [28].

5.6. The Continent of Australia

Lessons from Australia

In Australia, ornamental gardens are irrigated using graywater owing to water shortages. The Australian government has dedicated up to AUD 500 as reimbursements to encourage its citizens to adopt the water reuse concept to households who establish graywater reuse systems [28]. Effluents from Canberra's Lower Molonglo WWTP undergo suitable treatment before being discharged to the River Murray, which contributes to 80% of Adelaide's DW in dry seasons [24]. The first investigation of IPR in Austria occurred in Toowoomba in Queensland in 2007. The treated water was used for IPR and for industries. For example, Foster's Brewery at Yatala, Brisbane, established its internal plant for recycling wastewater used in the brewery following a one-twentieth scale pilot trial and recycled 65% of the effluent (1.5×10^3 m^3/d water recovered). Moreover, the Kwinana Water Reclamation Plant in western Australia treats 24×10^3 m^3/d of effluent from the Woodman Point WWTP after undergoing ST to ultimately provide 17×10^3 m^3/d of industrial-grade water (40–50 mg/L TDS) of high quality. Notably, this water is diverted to five large Kwinana heavy industries in Adelaide. Finally, effluent from the Bolivar WWTP is used for agricultural production [24].

6. Future Perspectives of Global Cases for Reclaimed Water Reuse

Based on a survey conducted via www.sciencdirect.com (accessed on January 2022) of recent studies on water reuse during 2019–2021, the future perspectives of global cases for reclaimed water reuse will be discussed in detail in the following section (Figure 5).

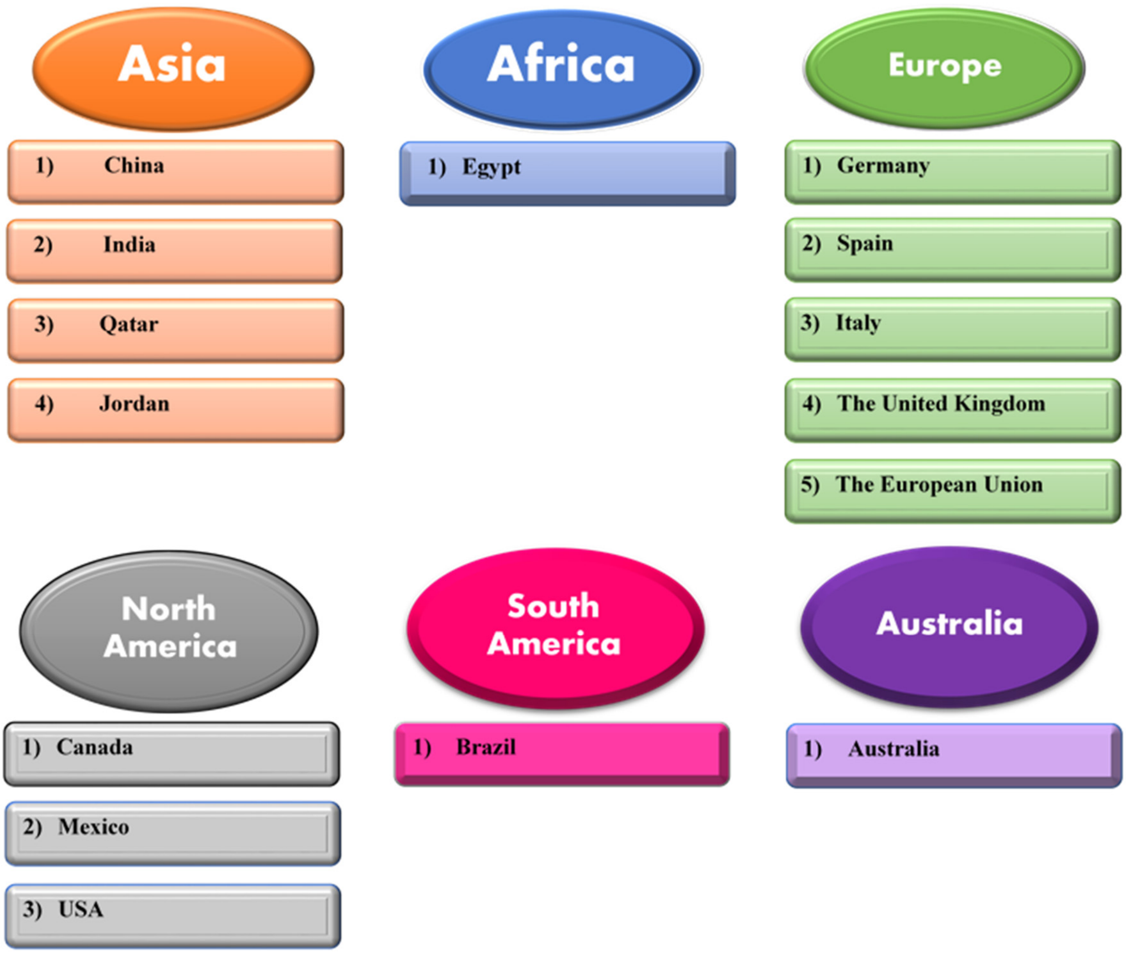

Figure 5. Summary of the future perspectives of global cases for water reuse reported during (2019–2021).

6.1. The Continent of Asia

6.1.1. China

As suggested in the literature, three proposed scenarios may be exploited for reclaimed water reuse. In the first scenario, reclaimed water is directly provided to the same urban area and excess water is stored in a special reservoir or directly discharged to the river. In the second scenario, reclaimed water is immediately supplied to users in the suburban areas and excess water is stored in special reservoirs. Finally, in the third scenario, reclaimed water is directly stored in special reservoirs and then uniformly configured to the user's transportation process [29].

6.1.2. India

In India, DWT systems have been proposed for low-density populated areas, isolated towns, and space-constrained urban locations. The DWT may involve several technologies, whereas CW, Green Rooftop Water Recycling System, and ZLD provide good operational and maintenance performances. RWW is also valid for the construction sector, particularly concrete manufacture, as long as the compressive strength values are close to those of concrete prepared using normal water [9].

6.1.3. Qatar

In Qatar, the blending of salty water that may be produced using PW with either TSE or desalinized water was investigated to form a potentially competitive PW management strategy for oil and gas firms compared with the traditional PW disposal practices that cost 0.06–16.67 USD/m^3; it was recommended that the lowest-cost option should be used to decrease the amounts of irrigation water required, which was obtained via blending PW with the same volume of TSE (0.26 USD/m^3) or four times the volume of desalinated PW (0.46 USD/m^3) [83].

6.1.4. Jordan

The Sahara Forest Project (SFP) was launched on September 7, 2017, in Jordan. The SFP was established to overcome the issues existing in low-lying desert areas worldwide to achieve a restorative growth vision. The SFP is based on the idea of running saltwater at one end of a greenhouse through honeycombed cardboard pads and simultaneously withdrawing hot desert air from them using solar-powered fans [84,95]. Accordingly, the hot air will promote the evaporation of salty water, which will become cooler and more humid than what is suitable for vegetable crop cultivation; this will minimize the water requirements of crops with a minimal carbon footprint and yield increment. The aims of the SFP are (a) efficient electricity generation via solar power, (b) production of high-value crops through the operation of energy- and water-efficient saltwater-cooled greenhouses, (c) provision of waters suitable for drinking or irrigation, (d) brine management, (e) revegetation of desert areas, and (f) energy harvest from biomass production. The details of the SFP are presented on the project website [95].

6.2. The Continent of Africa

Egypt

The Egyptian government recently directed the cooperation between different authorities to overcome all obstacles regarding the launch of the "New Delta (ND)" project, a mega national project dedicated to agricultural production that adds value to agriculture, food, and land reclamation. The project aims to increase the proportion of agricultural land to ensure food security. Additionally, the project may assist in achieving economic and development growth and create job opportunities for current and future generations [96]. The Ministry of Agriculture and Land Reclamation is generally focused on water reuse for agricultural irrigation and land reclamation and is planning land uses and investments in the ND that will reuse water as irrigation source water, in which crop structures suitable for the type of available water and land will be considered to ensure the maximum benefit from the new cultivated areas [97].

6.3. The Continent of Europe

6.3.1. Germany

The area surrounding Würzburg-Schweinfurt (Lower Franconia) is one of the driest places in Bavaria, Germany, particularly around Schweinfurt City [7]. Notably, 15–20% of crop losses reported in Gochsheim in 2018 could be attributed to insufficient irrigation. Non-potable water reuse for agricultural irrigation was implemented in Schweinfurt, Germany, based on the estimated daily and annual net irrigation requirements for 10 crops (e.g., onions, celery, lettuce, cabbage, potatoes, and others). The study revealed that the perspective for non-potable water reuse projects in Gochsheim may be based on the overall daily peak gross (14.3 mm/day); this is crucial for designing projects and promoting planned water treatment facilities, irrigation systems, pumps, and storage [7].

6.3.2. Spain

A storage for water reuse in Lloret de Mar City (northeastern Mediterranean coast) was introduced in Spain. This perspective compromised different scales based on water reuse integration in water management systems: business-as-usual, decentralized, hybrid, and centralized, in which the sources of potable water produced from the Tordera aquifer and wastewater (not reused on site) are pumped inside the sewage system and then diverted to the Lloret de Mar WWTP. The following provisions were assumed: (a) the amount of water reused (centrally or onsite) was the same as the amount of potable water extracted, treated, and distributed, and (b) some amounts of water were dedicated for irrigation at the Gardens of Santa Clotilde. The results of this study demonstrated that with increasing centralization of water management systems, carbon and water footprints will be reduced. Notably, the study highlighted the importance of indirect water usage due to the increase in water footprint associated with water reuse [47]. In an agricultural parcel (30 km south of the city of Madrid), the effect of water reuse on pharmaceutical and transformation products for grown maize was studied. The Manzanares River is augmented with Madrid City's WWTP effluents (83% of river flow), and the Henares River flows through industrialized and densely populated areas. The results showed that although only neutral and cationic pharmaceuticals are translocated from roots to maize tissues, with significantly no threats to human health derived from maize consumption, more toxicity tests are required to confirm the effects of this process [98]. A previous study explored two perspectives for water reuse systems in two different WWTPs. In the first scenario, reclaimed water is collected in one reservoir, whereas in the second scenario, reclaimed water is stored in two reservoirs before its distribution to the field [88].

6.3.3. Italy

In Fiordelisi s.r.l., Apulia (an agri-food industry area), Italy, a WWTP was constructed to treat wastewater (80,000 m^3/year) derived from growing businesses, processing, and marketing of preserved horticulture. This WWTP was dedicated to producing TWW for agricultural irrigation using its three-stage treatment technology: PTs (screening, de-oiling, and pH adjustment), STs (activated sludge process and sedimentation), and TTs (filtration and UV disinfection). Notably, ultrafiltration reduced the overall level of microbiological contamination. The decay of enteric bacteria and the concomitant growth of total prokaryotic and eukaryotic cells were observed during storage owing to the adaption of the microbial community to the new environment. Incorporating UV as TT did not actively remove microbial cells but did promote the inactivation of *E. coli* and total coliforms [99]. In the municipality of Peschiera Borromeo (Lombardy, Italy), a WWTP with a treatment capacity of 322,376 was constructed to serve a total catchment area of 2230 ha (including Milan and neighboring municipalities). The Peschiera Borromeo WWTP directly discharges its final effluent into the Lambro River. The WWTP effluents undergo different scenarios. In the first scenario (Line 1), the wastewater is collected from the municipalities of Brugherio, Pioltello, Carugate, Cologno Monzese, Cassina de'Pecchi, Peschiera Borromeo, Cernusco sul Naviglio, Segrate, and Vimodrone. Pretreatment and PT are conducted, and water is treated via a conventional activated sludge process. Subsequently, the inorganic nitrogen is also removed via biological filtration, and disinfection is conducted using PAA. In the second scenario (Line 2), wastewater is treated from the eastern district of Milan, in which wastewater undergoes pretreatment and PTs, followed by a two-stage upflow biological filtration (Biofor ®) process and two parallel lines of UV disinfection. It was suggested that CECs and the actual removal of heavy metals should be involved [92].

6.3.4. The United Kingdom

In England, the potential of pathogen infection risk to the public in either recreational or surface waters was investigated based on the quantitative microbial risk assessment approach for three conditions: de facto wastewater reuse, after augmentation using conventionally TWW, and after augmentation using RWW. The study suggested that pathogen reduction in rivers was heavily impacted by the existing de facto reuse practices via reclaimed water augmentation for IPR [100].

6.3.5. The European Union (EU) Countries

The perspective for wastewater reuse in EU countries is mentioned in the literature [8], demonstrating a multi-barrier approach for wastewater treatment for safe reuse in crop irrigation that involves typical processes (e.g., primary mechanical pretreatment, possible primary settling, and biological treatment), as well as advanced treatments and others treatment trains. A review of the best available technologies and treatment trains in the EU countries may be used to overcome the deficiency of water supply via urban wastewater reuse [8]. A review of the possibility of using CW treatment systems for agricultural irrigation within the EU framework has recently been introduced, and it was revealed that integrated CWs and supplementary approaches (e.g., UV treatment and anaerobic reactors) can more effectively remove contaminants than conventional CWs (e.g., horizontal and vertical subsurface flow), particularly when hybrid systems are utilized (based on biological oxygen demand and total suspended solids analysis) [101].

6.4. The Continent of North America

6.4.1. Canada

Edmonton, Canada, is a rapidly expanding cold urbanized region with different scenarios of graywater reuse applied through decentralized treatments, such as nature-based and engineered graywater treatment solutions (NBEGTS), CWs, and membrane bioreactors. Notably, NBEGTS and CW are typically favored owing to their good environmental performance; however, in terms of global warming, eutrophication, and human health carcinogenic potential, they do not always outperform energy-intensive systems, such as membrane bioreactors [102].

6.4.2. Mexico

A newly built treatment plant for treating the outlet discharge wastewater produced in the valley of Mexico Basin is primarily used for the agricultural sector in the Tula Basin (El Mezquital Valley), Hidalgo, Mexico. The new treatment plant is suitable for PT, with a capacity of 0.3 km^3/yr, which can be subsequently increased to 1.1 km^3/yr [10]. A study conducted by López-Morales and Rodríguez–Tapia highlighted three scenarios to investigate the response of the economic system; these scenarios were based on the capabilities of the modeling framework to ultimately guarantee sustainability constraints on groundwater extraction [10]. (1) Baseline scenario (S0) describes the current status of water resources and consumption. In this scenario, some wastewater is subject to PT, owing to the constrained capacities of the existing infrastructure, and may only be suitable for a few activities; (2) In Scenario 1 (S1), the current economic system is investigated for reducing groundwater availability; (3) In Scenario 2 (S2), the constraints on aquifer extraction of S1 are maintained; however, it permits the increased wastewater treatment capacities to produce treated water with adequate quality suitable for economic reuse; Finally, (4) Scenario 3 (S3) assumes that overcoming the domestic water leakage will ultimately reduce up to 30% of the water loss compared with the baseline conditions.

6.4.3. USA

In 2016, the Center of Excellence at the Nexus of Sustainable Water Reuse, Food and Health (CONSERVE) was established by the National Institute for Food and Agriculture (USDA-NIFA) in the University of Maryland School of Public Health using funding from the United States Department of Agriculture. The USDA-NIFA has set a long-term objective to overcome critical water resource issues across the USA, particularly in rural and agricultural watersheds, based on the CONSERVE framework shown in Figure 6 [3]. The CONSERVE framework utilizes a unique system-based approach capable of providing the following tasks:

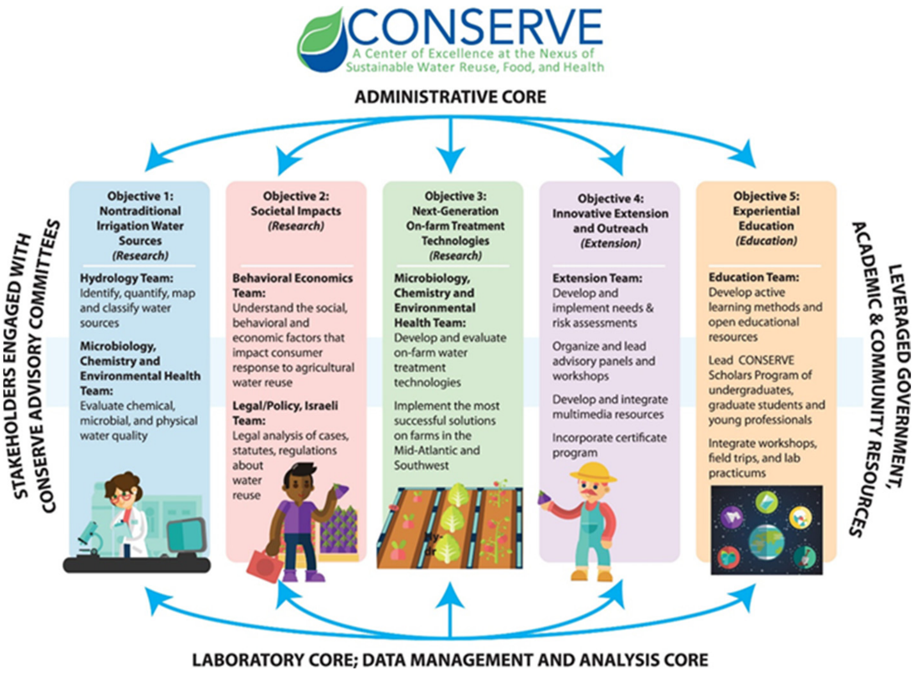

Figure 6. A schematic diagram illustrates the transdisciplinary, systems-based approach of CONSERVE: A Center of Excellence at the Nexus of Sustainable Water Reuse, Food and Health, adopted from (Sapkota) [3].

(a) Investigating the availability of nontraditional irrigation water (quantity and quality), such as reclaimed water, return flows, and brackish water, that can ultimately assist farmers in conserving groundwater;

(b) Identify the economic, socio-behavioral, and regulatory factors that influence the use of nontraditional water sources;

(c) Develop, evaluate, and implement on-farm water treatment technologies that ensure the reuse of nontraditional irrigation water that may eventually be shared with agricultural and non-agricultural communities.

In the San Antonio Region of Texas, according to the Texas Water Development Board (TWDB), the expected water requirements will increase from 573,634 acre-feet/year in 2020 to 995,247 acre-feet/year in 2070 owing to the increasing population. According to the TWDB, reclaimed water reuse will be capable of meeting approximately 24% of the water supply. In addition to water reuse, the TWDB meets the region's requirements through another four alternative ways, such as augmentation of surface water resources, demand reduction, seawater desalination, and groundwater withdrawals (the third-largest expected supply) [60].

Water quality assessment for downstream PW that is simultaneously extracted along with oil and gas originating from reservoirs was performed for reuse in the west of the 98th meridian. This fluid contained various natural chemicals (e.g., metals, hydrocarbons and their derivatives, radioactive materials, and salts), and the results determined that toxicity tests need to be conducted in detail to define any potential health impacts to downstream users. Chemical analysis alone is inadequate to assess PW for beneficial reuse [103,104]. The effect of PW on soil health and the soil microbiome was investigated by Miller et al., and the results showed that using minimally treated PW for irrigating wheat ultimately reduced field productivity [105]. Additionally, large-scale field investigations of the effects of long-term irrigation on soil health and crop productivity revealed an overall decrease in soil microbial diversity and soil health. A photocatalytic membrane reactor capable of decomposing and mineralizing organic pollutants, inactivating viruses, detoxifying heavy metals, and recovering valuable minerals has been proposed to treat PW [106].

6.5. The Continent of South America

Brazil

Brazil has the most fresh water available for use among all countries; however, 27 million people in the country live in semi-arid areas, indicating a unique scenario of disproportionate spatial distribution of water and unstable hydrography. The proposed approach for reclaimed water reuse that may be used for hydroponics, fish farming, and irrigation of crops in semi-arid regions in the northeastern and parts of the southeast, including the northern portion of the state of Minas Gerais is mentioned in the literature [55]. These regions comprise a total area of 1.03 million km^2, with 1262 municipalities and 27 million people (12% of the total population) [55].

6.6. The Continent of Australia

Australia

According to the current situation in different locations, such as California and South Africa, there is a growing discussion between academia and Australian water utilities regarding DPR projects in Australia and the future likelihood of such projects. As previously mentioned, the Australian government has exploited highly TWW effluents for aquifer recharge and augmenting the surface and lake water reservoirs. The smaller regional towns and cities may be the first places that may become early adopters of DPR in Australia. The Australian Water Association annual conference "OzWater" held in 2017 suggested that there are several factors that affect water reuse, including public acceptance, the willingness of politicians, regulatory reluctance, public health (concerns related to water quality), economic costs, lack of need/better options, industry reluctance, and environmental factors. The conference revealed that public acceptance and the willingness of politicians are the most important obstacles to determining the future of water reuse in Australia [4]. Following droughts, the Australian government adopted DPR, considering public perception and acceptance. Notably, the government commissioned a timely and technically robust update on the developments in potable recycling that involved an outline of the current status of potable reuse practice and an understanding of incentives and drivers that may support or suppress this progress [24].

7. General Perspectives for Reclaimed Water Reuse

Based on a survey conducted via www.sciencdirect.com (accessed on January 2022) of recent studies on water reuse during (2019–2021), general perspectives for reclaimed water reuse will be discussed in the following section (Figure 7).

7.1. The Critical Control Point (CCP)

During the operation of a WWTP, several tests and process validations should be conducted to guarantee that no chemicals or pathogens exist in the outlet water and ensure adherence to the standards, beyond which there may be acute or chronic health and/or environmental effects. The CCP concept was proposed to clarify the operational boundaries of the key barriers in a water treatment process [5]. The CCP approach was first developed for the beverage and food industry as a preventative approach to ensure food safety, considered a distinct approach reliable through final inspection. CCP was subsequently adapted to be valid for water quality management. CCP has recently been used by several officials to determine the risk management framework for pathogens in water treatment systems during operation. If we can monitor these critical points, we can quickly correct any deviations from the acceptable limits and risk management framework to eventually decrease the budget dedicated to chemical and pathogen analyses [5]. Previous studies [64] reported that the lack of monitoring and reporting requirements can become a significant operating burden and prevent the implementation of a system.

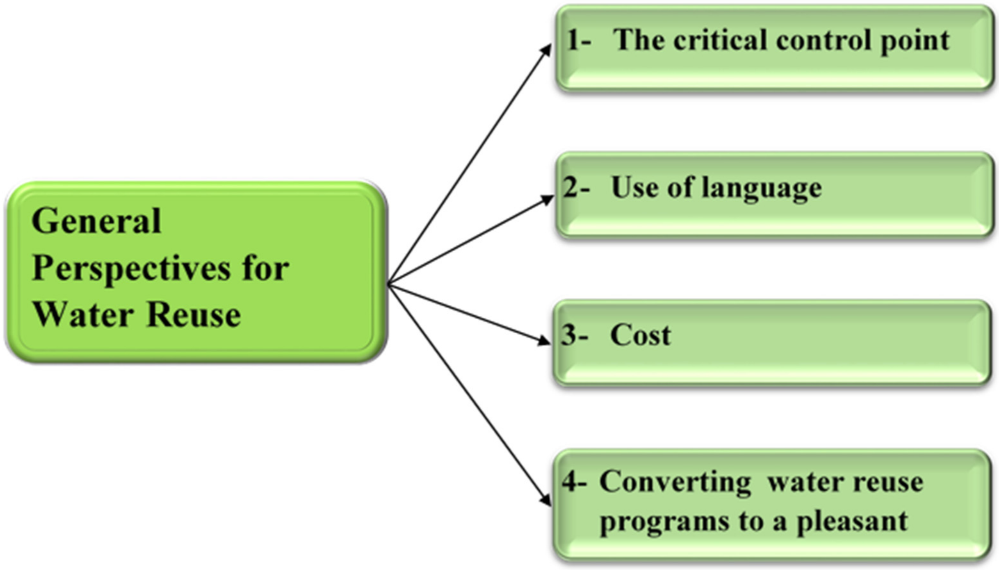

Figure 7. Summary of the general perspectives for water reuse reported during (2019–2021).

7.2. Use of Language for Promoting Reclaimed Water Reuse

The use of language was determined to be a significant factor when investigating the willingness of farmers for wastewater reuse. For example, the term "treated" refers to the fact that reclaimed water has been transformed from its previous (polluted) state, whereas the term "recycled" refers to the return toward an even earlier purer source material. Farmers who were willing to use purified effluent to irrigate crops do not pay additional money if the term "recycled" is used rather than "treated". In Singapore, the term "wastewater factory" was replaced with "NEWater factory" for the Bedok STP [16]. Another study [107] explored the influences of terminology on the perceived risk of reused water and found that public perception is based on terminology.

7.3. Costs

Reducing the costs of reclaimed water is an important factor in encouraging farmers to reuse reclaimed water as an irrigation source. The majority of reclaimed water reuse projects can be enforced with direct or indirect subsidies, in which suppliers introduce reclaimed water at concession prices. In Spain, approximately 70% of reclaimed water operation cost is covered by public administrations that convey water from treatment plants to fields and 10% of the costs of installed agricultural irrigation systems are covered [16]. The Australian government has dedicated up to AUD 500 as reimbursements to households that establish graywater reuse systems [28].

7.4. Converting Water Reuse Programs to a Pleasant Experience

By converting water reuse programs into pleasant experiences, stakeholders can easily enjoy and approve. For example, the managers of the Milano Nosedo WWTP, Italy, one of the largest plants in the region with a treating capacity of 150 million m^3/year, dedicated an open day to demonstrate the activities of the plant to farmers and the public to gain trust [16].

8. Guidelines Set for Water Reuse

In this section, recent guidelines set for water reuse during the period 2019–2021 will be discussed. Hacıfazlıoğlu et al. discussed the guidelines set by FAO, WHO, and USEPA to ensure the safe reuse of reclaimed water in agricultural irrigation [108]. These guidelines involved various parameters (e.g., total dissolved solids, electrical conductivity, total nitrogen, sodium absorption ratio, total suspended solids, NO_3-N, PO_4-P, HCO_3, potassium adsorption ratio, chloride, sodium, boron, pH, turbidity, and free chloride). According to the degree of restrictions, these parameters were classified into four categories as follows: none, slight–moderate, and severe. If the water reuse has an electrical conductivity of less than 0.7 mS/cm, it will not have any harmful effects on the ecosystem; however, the values of electrical conductivity higher than 3 mS/cm will represent severe effects. In addition, a high correlation between electrical conductivity and sodium adsorbed ratio was observed and classified as follows: none, slight–moderate, and severe [108].

Rock et al. discussed the United States regulations set by the Food and Drug Administration (FDA) as part of the Food Safety Modernization Act (FSMA). The FSMA regulations are applied to raw agricultural commodities crops that do not require commercial processing to reduce the microorganisms' growth to ultimately ensure public health. To reduce the risk of serious health consequences or biological hazards in fresh raw crops (e.g., edible leafy greens), the FSMA has set standard processes, practices, and procedures that ultimately reduce the foodborne diseases resulting from contaminated crop consumption [66]. Based on the Produce Safety Rule, a microbial water quality profile (MWQP) should be established by farmers for different sources of irrigation water, such as groundwater and untreated surfaces. In addition, annual surveys are requested to be performed that can be used in the following years. The basic parameter for the water quality profile in agricultural (pre-harvest) water is the generic *Escherichia coli* levels. The MWQP must be performed first for water samples collected as near to the harvest period as possible (not less than 20 water samples). The water samples should be collected during a period not < 2 years and not > 4 and 5 years for both groundwater and surface water. Either calculated values of the geometric mean (GM) or statistical threshold value (STV) should be performed using a minimum of five samples. The MWQP comprises both GM and STV of 126 CFU/100 mL and 410 CFU/100 mL of generic *E. coli*., respectively; details of regulations set by FDA FSMA are presented in the literature [66].

There are no established federal regulations in the USA for recycled water reuse. Whereas, to manage reclaimed water for various purposes, including agricultural irrigation, animal watering, and crop production, various individual states and territories have established specific regulations (e.g., California, Arizona, Florida, Colorado, Delaware, Virginia, New Jersey, Massachusetts, North Carolina, Hawaii, Minnesota, Idaho, and Washington) [66]. Notably, the regulations established by state standards are considered more restrictive compared to the FSMA Agricultural Water metrics for irrigation purposes to promote the use of recycled water to grow food crops. This is clearly seen from permitted concentrations of total coliform, *E. coli*, or fecal coliform bacteria that are comparatively lower than metrics set by the FSMA. State-level regulations details are discussed in the literature [66].

Otter et al. discussed a comparison of guidelines for irrigational wastewater reuse in Europe (Italy, Greece, Cyprus, and Spain) and the USA [6]. These guidelines comprise water quality uncommon parameters to represent the effectiveness of the wastewater treatment plants in removing nutrients, organic matter, and pathogens (e.g., prescribing a limit for the number of pathogen indicators). Consequently, the disinfection approach is also a mandatory step to minimize public health risks resulting from potential exposure to reclaimed water. The disinfection approaches may comprise ozonation, onsite chlorine generation system, ultraviolet (UV) radiation, and membrane filtration [6]. The European Union proposed a new regulation in May 2020 regarding the reclaimed water minimum quality requirements that should be implemented in the agriculture sector in all member states that are supposed to be implemented from June 2023 [88]. Finally, it was concluded that there are several guidelines set for water reuse worldwide; however, there is no universal standard guideline established for reclaimed water to facilitate large-scale applications [109].

9. Conclusions

The present article summarizes the recent progress in water reuse during 2019–2021 and can aid countries in overcoming the global water crisis caused by increasing global population, industrial sector, urbanization, and agricultural activities, as well as global climate change and limited water resources. These problems become more complicated day by day, and it is anticipated that by 2030, the global requirement for water resources will be approximately 160% of the currently available resources. Seventeen obstacles and ten advantages for using reclaimed water in different fields of interest were summarized, which should aid decision-makers in adapting to the water reuse scenario to decrease the stress on the available water resources. The obstacles that may hinder the widespread application of water reuse comprise the properties and low amounts of treated water, the imbalance between the demand and supply, insufficient capacity of wastewater treatment plants, public acceptance and social trust, testing costs, financial challenges, treated water may not be ideal for some irrigation systems, there are no comprehensive regulations worldwide, etc. Whereas the advantages of water reuse comprise overcoming the global water crisis, improving the economy, decreasing the stress on aquifer water, reducing the budget dedicated to fertigation, improving crop production, reusing in construction, etc.

Almost all continents (e.g., Australia, Europe, Asia, Africa, South America, and North America) have embraced the concept of water reuse. Water reuse is not restricted to countries with limited water supply but is also practiced in countries with plenty of water resources (e.g., Canada and Brazil). There are several fields of utilization for reclaimed water, such as DW supply, agriculture, industry, hotels, aquaculture, groundwater recharge, and building construction. At present, there is no standard global guideline for water reuse and several perspectives for the future reuse of reclaimed water worldwide have been suggested to maximize the benefits and ensure sustainability. Several perspectives to maximize the benefit of water reuse were discussed in this study, along with general perspectives that may be followed worldwide, such as the CCP, use of language to promote reclaimed water reuse, costs, and converting water reuse programs to pleasant experiences. Finally, water reuse may be considered a potential alternative for reducing the burden on water resources in the future.

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Acronyms and Abbreviations

DW	Drinking water	SSI	Subsurface irrigation
IPR	Indirect potable recycling	AIS	Aboveground irrigation system
DPR	Direct potable recycling	WRP	Water reuse potential
STP	Sewage treatment plant	PW	Produced water
TWW	Treated wastewater	TSE	Treated sewage effluent
WWTP	Wastewater treatment plant	NDMA	N-nitrosodimethylamine
WSP	Wastewater stabilization pond	ZLD	A zero liquid disposal
CW	Constructed wetland	DWT	Decentralized wastewater treatment
MC	Microalgae cultivation	PAA	Peracetic acid

TDS	Total dissolved salts	USDA-NIFA	United States Department of Agriculture, National Institute for Food and Agriculture
PT	Primary treatment	TWDB	Texas Water Development Board
ST	Secondary treatment	ND	New Delta
TT	Tertiary treatment	SFP	Sahara Forest Project
CCP	The critical control point	UV	Ultraviolet
ONWS	Onsite non-potable water reuse system	RO	Reverse Osmosis
CEC	Contaminants of emerging concern	UF	Ultrafiltration
RWW	Reclaimed wastewater	NBEGTS	Nature-based and engineered graywater treatment solutions
FDA	The Food and Drug Administration	FSMA	The Food Safety Modernization Act
MWQP	A microbial water quality profile	GM	The geometric mean
STV	Statistical threshold value	CFU	Colony Forming Unit
MENA	Middle East and North Africa	TMAH	Tetramethylammonium hydroxide
vertECO	Vertical ecosystem	GI	Gastrointestinal
HAV	Hepatitis A Virus	ONA	The Office National de l'Assainissement
MRSP	The Metropolitan Region of Sao Paulo	IWMI	International Water Management Institute
CONSERVE	The Center of Excellence at the Nexus of Sustainable Water Reuse, Food and Health		

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