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Reclamation of Treated Wastewater for Irrigation in Chile: Perspectives of the Current State and Challenges

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Citation: Vera-Puerto, I.; Valdés, H.; Bueno, M.; Correa, C.; Olave, J.; Carrasco-Benavides, M.; Schiappacasse, F.; Arias, C.A. Reclamation of Treated Wastewater for Irrigation in Chile: Perspectives of the Current State and Challenges. *Water* **2022**, *14*, 627. https://doi.org/10.3390/w14040627

Academic Editors: Yung-Tse Hung and Cristina Sousa Coutinho Calheiros

Received: 8 January 2022
Accepted: 10 February 2022
Published: 18 February 2022

Abstract: Reclamation of treated wastewater is considered a viable option for reducing the agricultural and national water deficit, especially in Mediterranean-type and arid climatic conditions. Given that Chile is a country around 40% of whose territory is classified as semi-arid and desert and 20% as Mediterranean, with serious water scarcity problems, and which uses a great deal of the resource in agricultural irrigation, the present paper offers perspectives on the current state of treated wastewater reuse and considers challenges to improving the development of water reclamation for irrigation in Chile as a case study. The methods followed included a systematic literature review to answer two important questions: (a) What is the state of reclamation of treated wastewater for irrigation in Chile? and (b) What criteria/parameters determine the feasibility of reclaiming treated wastewater for irrigation in Chile? The results showed that Chile has been affected by climate change in a short time: a megadrought has occurred over the last ten years, increasing the necessity for the country to secure alternative water sources for irrigation. The country has advanced greatly in wastewater treatment coverage, achieving almost 100% in urban areas, with technologies that can produce quality water as a new water source for irrigation. However, the lack of regulations and limited frameworks could explain the low direct reuse at present—below 1% of total flow. Regarding challenges, the necessity of updates to Chile's institutional and legal frameworks, besides the inclusion of rural communities and the study of emerging contaminants, will be discussed. By these means, it will be possible to more efficiently utilize recycled wastewater as a new source for irrigation in this country.

Keywords: Chilean agriculture; wastewater treatment and reuse; greywater; arid climate; Mediterranean climate; Atacama Desert

1. Introduction

Several studies have explored the reclamation and safe use of treated wastewater for irrigation [1,2]. At present, it is technologically possible to treat wastewater and remove pollutants so as to produce water that meets the standards defining drinking water quality [3–5]. In the case of irrigation, reclamation and recovery of wastewater for use as a water source is attractive and a sound alternative for reducing the agricultural water deficit, reducing the pressure of water scarcity found in Mediterranean-type and arid climatic conditions, besides being an ancient practice in numerous cities that are surrounded by agricultural fields [1,6,7].

Concerns about irrigation using treated municipal wastewater have generated several detailed studies about the risks to and effects on crops as well as human health and the environment [2,8,9]. Most of these studies have focused on the impact (or effects) of reclaimed water irrigation on the health of ecosystems and people [10–14]. Some of the studies address the technologies available for water reclamation, including best practices [15,16]. Recently, the study of emerging compounds and their effects on crops and human health have also been addressed [17,18]. In addition, development analyses of reclamation strategies for entire countries, such as China, have been published [16,19,20]. Wu et al. [16] presented the results of a risk assessment for and discussed system regulation and the efficient utilization of reclaimed water irrigation in China. The study analyzed issues such as environmental behavior and evaluated the characteristic pollutants, suggesting the use of safe and efficient irrigation systems and irrigation technology and finally recommended a model for the reclamation of treated wastewater according to different utilization types.

The World Health Organization (WHO) (Geneve, Switzerland) and the Food and Agriculture Organization (FAO) (Rome, Italy) have produced guidelines that set standards for safe use of treated wastewater for irrigation purposes [1]. Back in 1973, WHO published the first standards, with an update in 2006. The latest version is mainly focused on microbial health risks but it also contains recommended maximum organic and inorganic pollutants in soils, which are assessed by QMRA (Quantitative Microbial Risk Assessment) and epidemiological evidence [21]. In addition, several countries and organizations have adopted more detailed and rigorous standards by establishing their own regulations and guidelines to fit their needs [22–24]. The aim of these standards is to treat the raw wastewater so as to reach a quality sufficient to be considered "recycled wastewater". Even though standards are important in terms of safe wastewater recycling, other aspects must be taken into consideration if wastewater is to be reclaimed, including treatment technologies, legal frameworks, agricultural issues related to crops, economic aspects related to the promotion of this water source by governments, the distance between sources and agricultural fields, socio-cultural stands, and climate.

Voulvoulis [25] points out that reclaimed wastewater reuse has not yet been exploited in many areas and that a transition to a circular economy has the potential to create significant synergies for the broader adoption of recycled water as an alternative freshwater resource for irrigation or other purposes. This synergy is part of the goals of the circular economy, which is in line with the concept of sustainable development: economic prosperity, environmental quality, and a positive impact on social equality, also included in the United Nations Sustainable Development Goals [26–28]. However, in Chile, a country with the most arid area in the world (the Atacama Desert) and serious water scarcity problems and which uses a great deal of the resource in agricultural irrigation, faces scientific and technical challenges. Currently, reclamation of treated wastewater as part of the national circular economy strategy for managing wastewater is limited and needs to be addressed [6,7,29–34]. Therefore, the present work assesses published scientific, regulatory, institutional, and technical information, analyzing and providing an update on the current state of treated wastewater reclamation in Chile. In addition, the document describes challenges and suggestions to improve the development of recovery of treated wastewaters as "new water sources" for irrigation, as part of a circular economy strategy—a necessary vision for managing wastewater treatment for the future.

2. Methods

The systematic literature review (SLR) proposed by Tranfield et al. [35] was used to compile and analyze scientific, academic, governmental, and professional information about recycled wastewater reuse for irrigation purposes in Chile. An SLR is a review that is designed to locate, appraise, and synthesize the best available evidence relating to a specific research question in order to provide informative and evidence-based answers [36]. The SLR enables a qualitative analysis (evaluation and interpretation) and is used when the scope of a review is specific and the dataset small and manageable enough such that its content can be manually reviewed [37]. Recently, SLR has been used to evaluate the use of reclaimed water, but in very specific studies of organic compounds present in wastewater [38–40]. SLRs follow well-defined and transparent steps and always require the following: a definition of the question or problem, identification and critical appraisal of the available evidence, synthesis of the findings, and the drawing of relevant conclusions [36]. The SLR process for this research article was divided into: (1) planning, (2) execution, (3) analysis, and (4) reporting [41]. Figure 1 summarizes the SLR process for this article.

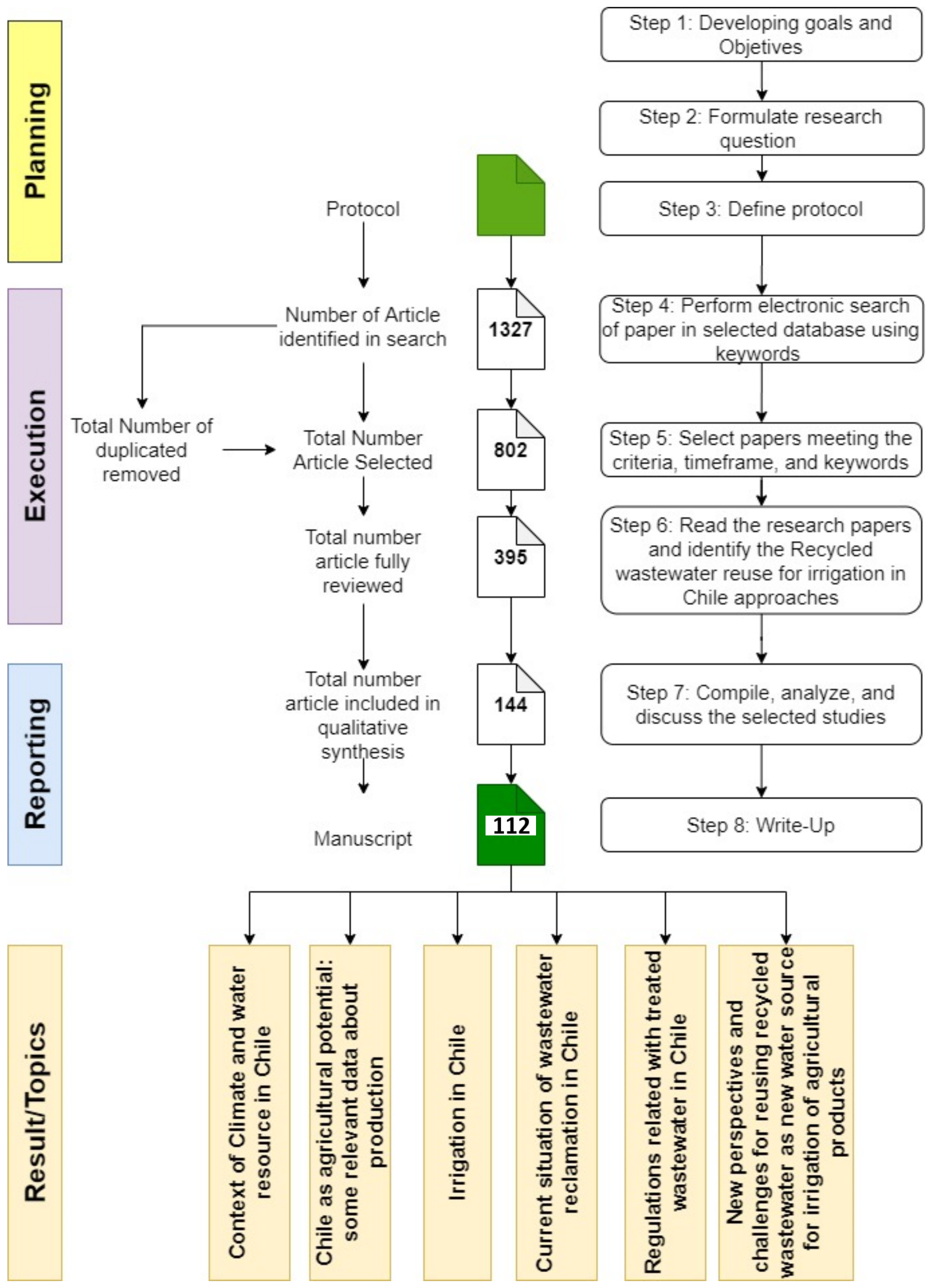

Figure 1. Information flow through the different phases of the systematic literature review (SLR). (Modified from Kim and Brown [42].).

The planning stage began with the definition of the SLR's objective: to identify the current state and the challenges faced in the reclamation of treated wastewater for irrigation in Chile. Subsequently, the research questions (RQs) were formulated in accordance with the provisions of the PICo (Population, Phenomenon of Interest, and Context) elements for qualitative reviews. The PICo elements can aid in defining the question and inclusion criteria used to select studies for the systematic review [43]. Accordingly, the following questions were formulated:

- RQ1: What is the state of the reclamation of treated wastewater for irrigation in Chile?
- RQ2: What criteria/parameters determine the state of the reclamation of treated wastewater for irrigation in Chile?

The SLR protocol establishes the process of searching for and evaluating the information to answer the search questions and achieve the research objective. To address the two questions of the article, it was decided to first include the contents of peer-reviewed journals from the Web of Science (WoS), Scopus, and Scielo. These databases were used first for obtaining scientific evidence that could apply to the Chilean context. The search continued through thesis databases of Chilean universities. Next, information about regulations and the technical reports of governmental institutions as well as technical reports in non-scientific journals, all with diffusion mainly in Chile, were examined. In this way, perspectives on the current state of affairs and challenges were obtained from scientific and technical sources so as to truly reflect the use of reclaimed wastewater in the country, making the present study more robust. The search was focused on the period 2011–2021, however, some relevant information published prior to this period was included. Table 1 shows the terms used in the search and the results.

Table 1. Keyword combinations used to obtain information about recycled wastewater reuse for irrigation as employed in the SLR process (includes only scientific databases and thesis databases of Chilean universities).

Keyword	**K1: Wastewater** **K2: Chile**	**K3: Agriculture** **K4: Irrigation**	**K5: Recycled** **K6: Reuse**	**K7: Treatment** **K8: Policy**	**K9: Regulation** **K10: Standard**
Combinations	**Results from Database**				
	WoS	**Scopus**	**Scielo**	**Thesis**	
C1: K1 and K2	68	110	25	483	
C2: K1 and K2 and K3	5	12	0	304	
C3: K1 and K2 and K4	7	16	2	38	
C4: K1 and K2 and K4 and (K5 or K6 or K7)	4	0	1	149	
C5: K1 and K2 and K3 and (K5 or K6 or K7)	0	0	0	21	
C6: K1 and K2 and (K8 or K9 or K10)	17	25	4	36	
Title/Abstract/Keywords	C1: wastewater and Chile C2: wastewater and Chile and agriculture C3: wastewater and Chile and irrigation C4: wastewater and Chile and agriculture and (recycled or reuse or Treatment) C5: wastewater and Chile and irrigation and (recycled or reuse or treatment) C6: wastewater and Chile and (Policy or regulation or Standard)				

The execution phase started with the literature search in the selected databases. Duplicate articles (present in different databases) were considered only once. Each selected article was categorized as relevant or not relevant according to the relation of its title and abstract to the research questions. Each of the authors performed the categorization independently. These articles were evaluated using an article quality checklist form. This form assessed the locality of the research, recycled wastewater reuse, and performance indicators or research outcomes.

Once the relevant articles were identified, a quality assessment took place. In the quality assessment, the authors carried out an exhaustive and complete analysis of the relevant articles to select those closely related to recycled wastewater reuse in agricultural irrigation in Chile. As in the previous stage, a cross-check of the relevant data found was performed [44].

Subsequently, the reporting stage began with data extraction, which consisted of obtaining information directly related to the objective of this research. The systematic identification and evaluation of the data/evidence in the articles was carried out according to the methodological principles of the grounded data theory (GDT). Through comparisons of the articles, evidence was collected, coded, and analyzed to generate concepts and categories in order to discover the relationships between these articles and, in this way, find decisive evidence bearing on the questions posed and construct explanations [45]. Data synthesis involved collecting and summarizing the results of the studies in tables and figures. Finally, the reporting stage concluded with the writing up of the results of the research, highlighting the methods and analysis of results. Data from the studies were integrated qualitatively by systematically describing the results included in figures and tables. The information analyzed was separated into two main subjects that cover several topics. First, perspectives on the current state encompass: (1) the context of climate and water resources in Chile, (2) Chile as an agricultural country, (3) irrigation in Chile, (4) the current status of wastewater reclamation in Chile, and (5) regulations related to treated wastewater in Chile. Second, challenges for reclamation of recycled wastewater as a new source for irrigation of agricultural products include: (1) institutional and (2) regulatory challenges, as well as challenges for (3) rural communities and those presented by (4) emerging compounds.

3. Results and Discussion

3.1. Perspectives on the Current State

3.1.1. The Context of Climate in Chile

Continental Chile is located in South America between latitudes 17°30′ S and 56°30′ S, with a vast length of more than 4000 km, bounded on the east by the Andes Mountain Range and on the west by the Pacific Ocean [33]. The country covers an area of 756,102 km^2 [46]. The climate in Chile is highly varied and can be categorized into four regional macrozones: semi-arid and desert (north), Mediterranean (central), temperate (south), and tundra and glacial (extreme south) (Figure 2). According to Vera-Puerto et al. [33] and depicted in Figure 2, approximately 40% of Chilean territory can be categorized as semi-arid and desert (north). This area is known as the Atacama Desert. Chile is organized into 16 administrative regions, occupying each climatic macrozone: (a) semi-arid and desert, which covers Arica and Parinacota, Tarapacá, Antofagasta, Atacama, and Coquimbo; (b) Meditarrenean, including Valparaíso (excluding Easter Island), Metropolitana, O'Higgins, Maule, Biobio, and Araucania; (c) temperate, including Los Ríos and Los Lagos; and (d) tundra and glacial, represented by Aysén and Magallanes (excluding Antarctic territory).

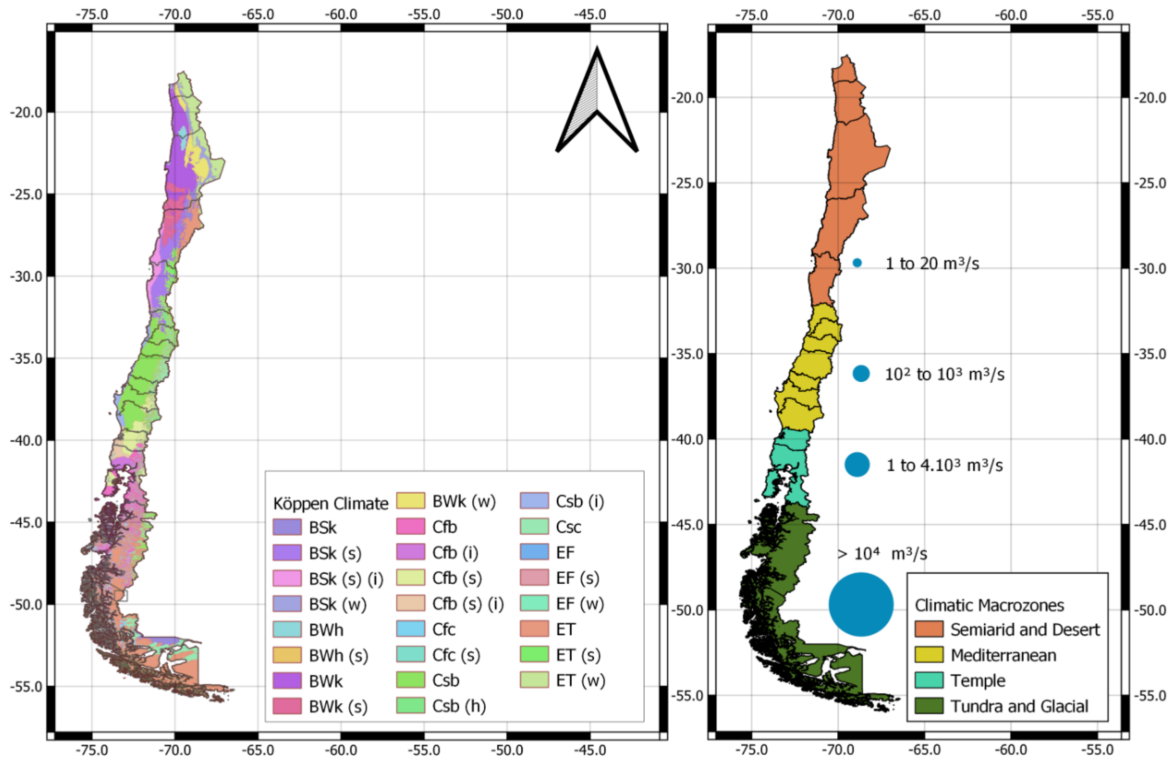

Figure 2. Geopolitical maps of Chile, with Köppen climatic classification (see Beck et al. [47] for details), on the left side, and climatic macrozones, on the right side. Water supply information (blue circles) based on Villamar et al. [34].

The extent of the country presents a large variety of geographical and geological characteristics which can translate into a high vulnerability to climate change effects. One of the most evident effects is drought. Historically, the country has always suffered from drought events, with a maximum duration of two years. However, since 2010, Chile has been suffering megadrought events which have impacted the central zone where more than 13 million inhabitants live (79% of the country's population) [48]. Garreaud et al. [48] showed that the longevity of the megadrought is associated with anthropogenic forces, showing the influence of climate change on Chile's climate. For the near future, climate change, also, will play an important role in the hydrological components, causing an increase of evapotranspiration and a decrease of precipitation, percolation, surface flow, and groundwater recharge [49]. Therefore, climate change impacts agricultural production, influencing the quality and quantity of water available for irrigation [50].

Given the water scarcity scenario in the country, amplified by climate change, there is a need to find new water sources in order to maintain agricultural production and ensure potable water supplies for the whole country [51]. In the last two decades, several authors have discussed the use of recycled wastewater as a new water source mainly to be used for the irrigation of agricultural products [7,30,33,52,53].

3.1.2. Chile as an Agricultural Country

In the last part of the 20th century, the Chilean agricultural sector turned its production paradigm from a traditional model to a globalized one, mainly focused on producing and exporting fresh fruits [54,55]. As one would expect, water has been vital for Chile, irrigation being required for nearly 70% of the country's agricultural surface [56]. Currently, Chile is the largest southern hemisphere fruit exporter and ranks second worldwide [56–59]. This is because the country has unique comparative advantages in terms of agroclimatic and soil conditions for fruit production. Due to its geography, the country has an enormous climate heterogeneity from its northern to its southern extremities (Figure 2) [60,61].

Agriculture contributes around 3% to the Chilean gross national product, and its fresh fruit export industry is crucial to this contribution [56,58,59,62]. The top five fruit species planted and exported by Chile are table grapes, apples, avocados, cherries, and citrus fruits (Table 2) [57,59]. Table 2 resumes Chilean fruit production between 2013 and 2018.

Table 2. Ranking of the main fresh fruits produced and exported by Chile between the years 2013 and 2018.

Region	Fruit Species	Planted Surface (ha)	Total Volume Exported (t) per Agricultural Season				
			2013–2014	2014–2015	2015–2016	2016–2017	2017–2018
Antofagasta–O'Higgins	Table grapes	48,593	729,754	759,855	700,799	732,663	731,775
O'Higgins–Los Lagos	Apples	36,205	811,894	683,485	730,615	709,528	774,710
O'Higgins–Los Lagos	Avocado	36,205	134,586	68,050	119,928	1,263,657	1,431,257
O'Higgins–Maule	Cherry	29,908	68,544	103,081	83,763	95,289	186,504
Coquimbo–O'Higgins	Citrus	17,385	169,815	191,860	246,609	279,103	295,620
RM–Maule	Plums	17,340	46,982	97,092	116,279	99,452	120,658
O'Higgins–Los Lagos	Blueberries	14,573	74,387	92,210	91,431	103,687	110,206
Valparaiso–O'Higgins	Peaches	11,540	18,391	27,927	29,054	26,045	31,191
O'Higgins–Maule	Kiwifruit	9717	116,123	166,507	185,986	181,162	176,556
RM–Maule	Pears	8537	119,381	133,799	126,561	150,842	129,541
RM–O'Higgins	Nectarines	5340	25,123	56,782	57,124	62,107	66,634
Coquimbo–Los Lagos	Others	≤800	6533	7672	7855	7750	7094

The statistics for fruit production indicate that the northern (the regions of Arica and Parinacota to Coquimbo), central (the regions of Valparaíso to Bío-Bío), and southern macrozones (the regions of La Araucanía to Aysén) accounted for 11%, 84%, and 5% of the almost 348,000 planted hectares (ha) [54,60]. This fact shows that more agricultural development is located in the central macrozone where Mediterranean climatic conditions are prevalent.

3.1.3. Irrigation in Chile

It is well known that irrigated agriculture consumes more than 70–80% of world freshwater resources, implying a high vulnerability to climate change [63,64]. In the northern Chilean macrozone, water for irrigation is predominantly taken from the Andes Mountains from the melting glaciers and the rainfall-induced highland floods in summer. The water balance in this area is negative due to the high aridity and lack of rainfall, limiting water availability for agriculture [6,65]. The central macrozone (Mediterranean), where the greater part of Chilean agriculture is concentrated, obtains water for irrigation from water reservoirs, products of the rain and snow accumulated in the Andes Mountains in the fall–winter season. Most annual precipitations occur during this period, with almost negligible events in the spring and summer seasons [48]. The southern climate macrozone is mainly temperate (Figure 2), with rainfall spread over the whole year, and the region is focused on agriculture and livestock [60,65].

Since the 1980s, several state economic incentives for increased irrigation efficiency have been provided, including changing traditional gravitational methods, e.g., flood and furrow methods, to technical methods, such as sprinkler, drip, or similar technologies. Unfortunately, irrigation policies have only focused on technological development and have not dealt with the use of alternative water sources, including reclamation of treated wastewater.

According to the Comision Nacional del Riego (CNR, by its initials in Spanish) (National Commission for Irrigation (Santiago, Chile) [66], the water balance projected for Chile between 2005 and 2025 will result in a reduction of water available for irrigation. The northern climatic macrozone will linearly increase its overall water deficit at rates of 24 million m^3 every 15 years. The projected reductions in water availability will average 1481 million m^3 by the year 2025. The projections of water availability for the central and southern macrozones in 2025 also showed reductions of 346 and 37 million m^3 every 15 years, respectively. This situation forces the Chilean agriculture industry, if it wishes going to maintain current production levels and expand to other products and open new markets, to take measures to deal with the altered scenario. Among the different measures that might be taken, including investment in modern irrigation technologies, better irrigation to cover water demand, exploration of new crops and new cultivation techniques, it is clear that new water sources and the reclamation of treated wastewater will be important components of this adaptation.

3.1.4. Current Status of Wastewater Reclamation in Chile

According to INE [67], the Chilean population is around 17.5 million, of which 88% is urban and 12% rural. In urban areas, private concession companies provide water supply, sewage, and treatment. Potable water supply has reached 99.9% [68]. In the case of sewage, 97.2% is already covered, and in the case of wastewater treatment, the coverage was 99.8% (including only the population connected to the sewage system) [68]. This treatment coverage suggests the possibility of producing treated wastewater to be recycled in productive activities. Chile has better wastewater treatment conditions than other Latin-American countries, for example, Colombia, Brazil, or Argentina, where coverage of treatment is below 50% [69]. In Chile, wastewater treatment plants (WWTPs) established in urban areas have been designed mainly to provide secondary treatment (organic matter removal) plus disinfection. Figure 3 shows the percentage of the main treatment technologies (primary and/or secondary treatment) used by each macrozone of the country. It is important to mention that marine outfall with only solids removal is considered a treatment alternative according to Chilean regulations.

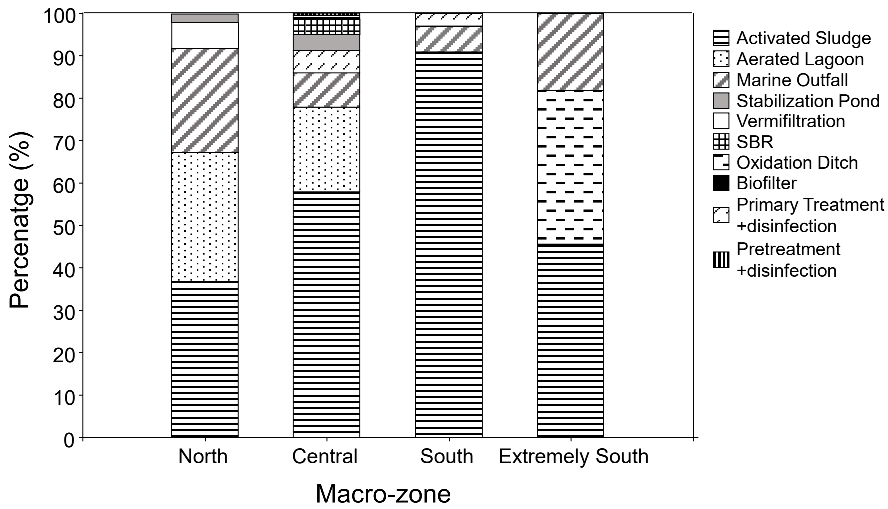

Figure 3. Municipal wastewater treatment technologies applied by macrozone in Chile. North: 49 WWTP; Central: 209 WWTP; South: 33 WWTP; Extremely South: 11 WWTP; Total: 302 WWTP.

Figure 3 shows three important issues: first, marine outfalls are a more common treatment in the north of the country with a usage rate of around 25%; second, activated sludge represents the most employed technology with a usage rate above 35% in each of the four macrozones of the country; and three, aerobic technologies, including activated sludge, aerated lagoons and oxidation ditches, represent more than 60% in each of the four macrozones of the country. For aerobic technologies, Vera et al. [70] reported for WWTPs based in the central macrozone a solid (TSS) and organic matter (BOD_5, COD) removal higher than 80% and reclaimed wastewater with concentrations below 20 mg/L for BOD_5 and TSS and below 60 mg/L for COD. Nitrogen and phosphorus removal varied between 20% and 60%, with concentrations in recycled wastewater below 25 mg/L and 8 mg/L, respectively. With these effluent concentrations, a good portion (above 60%) of Chilean WWTPs generate reclaimed wastewater with the potential to be reused in the irrigation of agricultural products [34]. However, another part of the WWTPs' production, including marine outfalls and primary treatments, does not have the possibility to be reused.

Regarding flows, Superintendencia de Servicios Sanitarios (SISS) [68] reports for 2019 a countrywide production of 1.26 million m^3 of treated wastewater, which represents a production level of around 40 m^3/s. The distribution of this reclaimed wastewater is correlated with the distribution of the Chilean population concentrated in the central macrozone (with a Mediterranean climate), where 79% live [67]. In addition, 22% of the reclaimed wastewater is discharged through marine outfalls [68]. Villamar et al. [34] and SISS [68] established that only 0.8% of the total reclaimed wastewater (in terms of flow) is directly reused in agricultural activities. In terms of quantity of WWTPs, less than 4% of their effluents is reused in irrigation [68]. All these data show that in the country, at the urban level, reclaimed wastewater has a high potential to be reused for irrigation.

In rural areas, water supply, sewage, and treatment are provided by cooperatives and rural drinking water committees, most of them (around 1900) part of the Rural Drinking program of the Ministry of Public Works [68,71]. This organization, with support from the Ministry of Public Works, opposes organization at the urban level, which is based on private companies. Fifty percent of the rural sanitation systems are located in the central macrozone (with a Mediterranean climate). In the case of water supply, these systems provide up to 99% coverage to concentrated rural communities (this includes communities with between 150 and 3000 inhabitants and at least 15 houses by kilometer of network) and 53% coverage to semi-concentrated rural communities (this includes communities with at least 80 inhabitants and eight houses by kilometer of network). In the case of dispersed rural areas (this includes communities with below 80 inhabitants and fewer than eight houses by kilometer of network) no official data are available [71]. Regarding sewerage, a coverage around 25% has been estimated by governmental institutions, while wastewater treatment coverage has been calculated as less than 10% [72,73].

Subdere [74] published a report that includes information related to wastewater treatment technologies in decentralized WWTPs (this includes rural areas). More than 500 WWTPs were identified as being in operation in Chile. Figure 4 shows different wastewater treatment technologies employed in decentralized areas divided by each macrozone. Just like in urban areas, the most commonly employed wastewater treatment technology is activated sludge. However, the performance of and information on recycled wastewater from these WWTPs has not been reported and the possibilities for reusing its effluents cannot be established at this point in time. In addition, no data about reuse of recycled wastewater is available at the rural level.

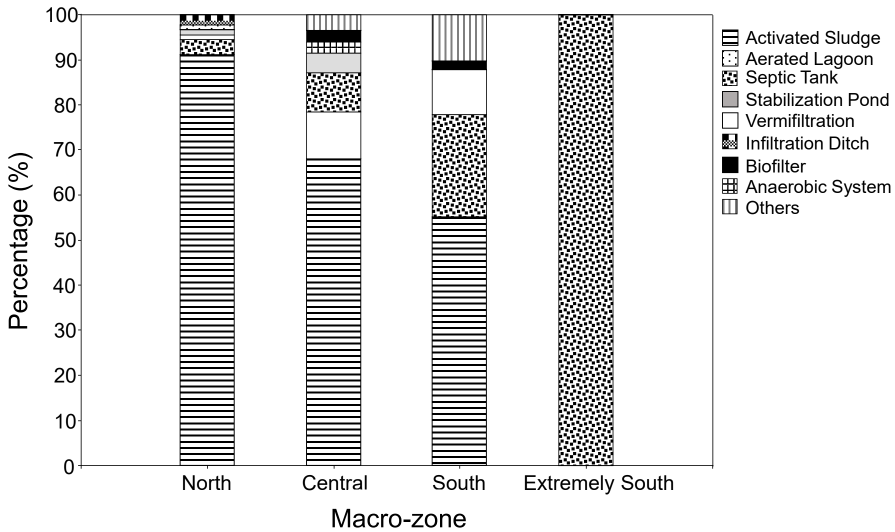

Figure 4. Rural wastewater treatment technologies applied by macrozone in Chile. North: 90 WWTP; Central: 375 WWTP; South: 49 WWTP; Extremely South: 17 WWTP. Total: 531 WWTP.

3.1.5. Regulations Related to Treated Wastewater and Its Reclamation

In both areas (urban or rural), Chile has two main regulations regarding effluents (treated wastewater) coming from WWTPs: Supreme Decree 90 [65] and Supreme Decree 46 [75]. Table 3 shows some important parameters of water quality included in Chilean discharge regulations. According to SISS [68], 71% of Chilean WWTPs have to accomplish the discharge into Streamflow 3 (no dilution capacity) (Table 2). In April 2021, discharge limits by WWTPs in Chile achieved 94%, which means that 283 WWTPs had effluents that fulfilled the discharge regulation [76]. This data confirms the potential to use treated wastewater as a new water source for irrigation.

Table 3. Selected water quality standards include in Chilean regulations for discharge (DS 90 [77] and DS 46 [75]. (Modified from Vera et al. [32].).

Water Quality Parameter	Units	Discharge Place					
		Stream-Flow 2	Stream-Flow 3	Lakes	Sea 1	Sea 2	Aquifer
pH	Uni.	6.0–8.5	6.0–8.5	6.0–8.5	6.0–9.0	5.5–9.0	6.0–8.5
Total Suspended Solids (TSS)	mg/L	300	80	80	100	300	
Total Nitrogen (TN) [a]	mg/L	75	50	10 [b]	50		10 [d]–15 [e]
Total Phosphorus (TP)	mg/L	15	10	2	5		
Fecal Coliforms (FC)	NMP/100 mL	1000	1000	1000–70 [c]	1000–70 [c]		
5-day Biological Oxygen Demand (BOD_5)	mg/L	300	35	35	60		

Streamflow 2: streams with dilution capacity; Streamflow 3: streams without dilution capacity. Sea 1: within the coastal protection zone; Sea 2: outside the coastal protection zone. [a] Total Kjeldahl Nitrogen (TKN) in the regulation. [b] TKN plus nitrite and nitrate. [c] The value of 70 must be applied only in areas suitable for aquaculture and exploitation of benthic resources. [d] Aquifer with high vulnerability. [e] Aquifer with low vulnerability.

For water reuse, the practice in Chile has been to follow the guideline NCh 1333/87 [78]. However, NCh 1333/87 is a guideline focused on different water uses, including irrigation regardless of the source. This guideline is not specific to the reclamation of wastewater and, at present, despite around 40% of the territory being classified as semi-arid and desert (Figure 1), Chile has not produced a specific regulation focused on this new water source. This lack of specific regulations for reusing recycled wastewater could partially explain the low development (below 0.8% in terms of flow [34,68]) of this practice in the country. Only in the last five years have several guidelines and various regulations been enacted. These will be discussed in the section on challenges.

3.2. Challenges for Improving Reclamation of Wastewater in Chile

3.2.1. Institutional

Chile faces several challenges related specifically to institutions and regulations which must be solved soon due to the necessity to improve the management of water resources, including the management of recycled wastewater, especially in the central macrozone where agricultural activities are mainly developed. It is important to mention that when the regulatory framework was implemented for the sanitary system, only wastewater at the urban level was included and recycling of wastewater was not the focus. The main objective of the Chilean legal framework, and therefore its associated institutions during the first decade of the 21st century was to extend the coverage of water supply and treatment, reduce health risk, and protect water resources. Now, the country has to move to a second step and search for a way to safely reuse treated wastewater as a new source for irrigation as part of the concept of the circular economy. Recently, MOP [79] and Segura et al. [31] established that reclamation of treated wastewater is an important issue for the Chilean population.

Related to recycled wastewater, SISS is the governmental institution assigned to the inspection of treated wastewater at the urban level. Furthermore, during the next few years, SISS will also be the institution responsible at the rural level (Law 20,998 [80]). With respect to recycled wastewater reuse, SISS has explained that, in Chile, the action of disposal for a WWTP is defined as "action to leave," meaning for example, in a natural or artificial water body (Table 2). Therefore, following this concept, the reuse of recycling wastewater would be possible after this "action to leave." However, at the present time, in urban areas, water supply, sewage, and treatment are provided by private concession companies, who are responsible for fulfilling the Decree of Sanitary Concession. The decree applies to the discharge point (related to action to leave) and the quality of the water, and any modification of that, for example, as carried out by a new agricultural project for recycling wastewater, must receive governmental authorizations and permissions. According to SISS, the responsibility for authorizations and permissions is relegated entirely to these companies, who at the time have no economic incentives to promote the reuse of treated wastewater nor even the support of a governmental institution that by law is dedicated to promoting the reuse of treated wastewater. The previously explained situation shows the necessity for an institutional framework to support and encourage the development of reclamation of recycled wastewater in reuse projects. Alongside this framework, it is necessary to develop national studies to be undertaken by universities, research centers, and stakeholders, to provide a safe alternative using recycled wastewater, and for the government to develop economic incentives to encourage water reclamation.

According to MOP [79], in Chile, water, including recycling wastewater reuse, is a complex issue. There are more than forty governmental institutions involved in its management and the multiplicity of agencies and a lack of intersectoral coordination and collaboration is evident. Thus, in the next few years it will be essential to create a unique governmental institution at the national level with the capacity to articulate all the activities and questions related to water (including recycled wastewater) if the situation is to improve. In this institution, one part would be dedicated to promoting the use of new water sources with a defined program and strategy that should include different alternatives for the reuse of treated wastewater. The national goal for 2030 is that 30% of wastewater discharge into the sea and 20% of the recycled wastewater discharged into surface waters bodies will be available for reuse [81]. In addition, one important task for the new institution would be to guarantee autonomy and the decision-making capacity to manage the watershed level, since Chile's geography and length mean that water issues in the north of the country are very different from those in the extreme south (Figure 1). At present, the Mesa Nacional del Agua (an intersectoral space for discussion of the future of water in the country) has made several recommendations along these lines for this new institutional framework for water management [61,72,79].

3.2.2. The Necessity of Regulations

For all the importance of an institutional framework, an institution related to water management needs guidelines and laws to promote and regulate the reuse of recycled wastewater. The challenge for the country is enacting these regulations. Recently, one important step was the law 21,075 [82] which regulates collection, reuse, and disposal of greywater. This law has an important aspect related to the economic possibility of negotiating the prices charged by water companies relating to sewerage and treatment. In addition, the law established five uses for recycled greywater: (a) urban, including use for the irrigation of gardens or recycling water for toilets; (b) recreation, including irrigation of green spaces, sports fields, and other places with free access to the public; (c) ornamental, including green areas with no access to the public; (d) industrial, including restriction for use in food products or for non-evaporative cooling purposes; and (e) environmental, including irrigation of forestry species, wetland maintenance, and other uses relating to environmental conservation and sustainability. However, the law does not include water quality standards. These water quality standards will be defined by the Ministry of Health when a specific regulation is passed. Still, today, after almost four years of work, this has not been promulgated, but a proposal (Resolution 404 Exempt) was published in 2021 for public consultation [83]. Table 4 shows the five water quality parameters with the limits proposed for each category by Resolution 404 Exempt in comparison with standards for greywater reuse in Israel and the United Kingdom.

Table 4. Water quality standards proposed for greywater reuse, Resolution 404 Exempt, and comparison with Israel and United Kingdom [83].

Climate Condition		**Arid–Mediterranean–Temperate**				**Arid**				**Temperate**			
Guideline or Regulation		**Chile (Resolution 404 Exempt; 2021)**				**Israel (SI 6147; 2012)**				**United Kingdom (BS 8525; 2011)**			
Classification		**1**	**2**	**3**	**4**	**A**	**B**	**C**	**D**	**1**	**2**	**3**	**4**
Parameter	**Units**												
pH	Unit									5.0–9.5			
Total Suspended Solids (TSS)	mg/L	10	140 (SSI) 30 (SI)	70			30						
5-day Biological Oxygen Demand (BOD_5)	mg/L	10	240 (SSI) 30 (SI)	70			20						
Turbidity	UNT	5	- (SSI) 10 (SI)	30				10	5	10	10		10
Fecal Coliforms (FC)	Log UFC/100 ml	1	3 (SSI) 2.3 (SI)	3				2	1				
E. coli	Log MPN/100 ml									N.D.	2.4	2.4	N.D.
Residual Chlorine	mg/L	$0.5 < \times < 2.0$	- (SSI) $0.5 < \times < 2.0$ (SI)							2.0	2.0	0.5	2.0

For Chile: 1, urban uses; 2, recreational uses, SSI: subsurface irrigation, SI: surface irrigation; 3, ornamental uses; 4, industrial uses. Industrial uses do not include standards because these will be defined by local authorities. Data extracted from BCN [83] and INN [84]. For Israel: Up to 1 m^3 per day; A, subsurface drip irrigation for irrigation of ornamental plants and fruit trees; B, irrigation of ornamental plants and fruit trees; C, toilet flushing; above 1 m^3 per day, C, irrigation of ornamental areas, waterfalls, green wetlands, green grass and ornamental ponds, toilet flushing; D, Irrigation of ornamental areas, waterfalls, green wetlands, green grass, lawn, and ornamental ponds. Data extracted from Oron et al. [85] considering only annual mean. For UK: 1, spray application, pressure washing, garden sprinkler use, and car. N.D.: not detected; 2, non-spray application, WC flushing; 3, non-spray application, garden watering; 4, non-spray application, washing machine use. Data extracted from Albalawneh and Chang [86].

Table 4 shows the similarity between the regulations proposed in Chile and international standards. However, it is clear that only one list of standards was defined for the whole country and that it does not consider the climatic particularities shown in Figure 2. This information would be useful for controlling future greywater treatment systems in the country but other water quality parameters should be followed (for example, electrical conductivity in arid conditions), especially when treated greywater will be employed for irrigation, considering the climatic variations along the length of Chile (Figure 2). The selection of these water quality parameters should be locally defined, considering the kind of plants that are to be irrigated. Recent interest in this new water source in Chile has motivated several research articles and the implementation of small projects in the country [87–91]. In addition, recently, the obligation to include greywater reuse systems in edifices of more than 5000 m^2 has been included in Chilean regulations [92], showing the interest of the country in employing this new water source and the challenge in implementing it.

In the case of municipal wastewater, the National Institute of Standardization (initials in Spanish INN, Instituto Nacional de Normalización) between 2020 and 2021 has been working on a new guideline package focused on recycled wastewater reuse as irrigation water for agricultural activities: NCh 3456, Parts 1, 2, 3 and 4 [84] (approved on May 2021). This guideline package includes aspects related to agricultural practices, water quality standards, monitoring, and sampling. In the case of water quality standards, the package includes four categories in Part 2. The four categories were defined taking into account the Chilean discharge regulations described previously (Table 3), and the package is similar to the recent EU 2020/741 regulation on minimum requirements for water reuse in Europe [93]. Table 5 shows the water quality limits included in NCh 3456, Part 2 in comparison with the recent EU 2020/74 regulation setting out the minimum requirements for water reuse in Europe [93], two Latin-American countries, and two countries with arid and Mediterranean climatic conditions.

Table 5. Comparison of some water quality parameters relevant to the reclamation of wastewater including parameters for Chile, two Latin-America countries and countries with arid and Mediterranean climates.

Climatic Conditions		Arid–Mediterranean–Temperate					Mediterranean–Temperate				Tropical		Arid	Mediterranean
Guideline or Regulation		Chile (NCh 1333 [78])	Chile (NCh 3456, Part 2 [84])				Europe (EU 2020/741 [93])				Mexico (NOM-003-ECOL-1997 [94])	Costa Rica (Decree 33601/2007 [95])	Israel (National Standards for Water Reuse [21,96])	Italy (GAB/DEC/93/06 [23,97])
Classification		Water for Irrigation	I	II	III	IV	A	B	C	D	Reclaimed Wastewater	Reclaimed Wastewater	Reclaimed Wastewater	Reclaimed Wastewater
Parameter	**Units**													
Electrical Conductivity (EC)	µS/cm	<750 [1]												
pH	Unit	5.5–9.0										6.0–9.0	7.0–8.5	6.0–9.5
Total Suspended Solids (TSS)	mg/L		10	25	50	80	10	35	35	35	20	50	10	10
5-day Biological Oxygen Demand (BOD_5)	mg/L		10	20	35	35	10	25	25	25	20	50	10	20
Chemical Oxygen Demand (COD)	mg/L												100	100
Total Nitrogen (TN)	mg/L											50	10	15
Total Phosphorus (TP)	mg/L											25	1	2
Fecal Coliforms (FC)	Log MPN/100 mL	3	1 [2]	2 [2,3]	3 [2]	3 [2]					2.4	3	1	
E. coli	Log MPN/100 mL						1	2	3	4				2 [4]
Helmints	Eggs/L					5	1 [3]	1 [3]	1 [3]	1 [3]	1	1		

[1] EC value is the limit for no effects on crops. [2] Limits for FC in 95% of the samples. [3] Irrigation of grasses and forage. [4] Eighty percent of the samples, employing unit measure UFC/100mL. For Chile, I: treated wastewater with very high quality; II: treated wastewater with high quality; III: treated wastewater with good quality; IV: treated wastewater with medium quality [84]. For Europe, A: all food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw; B: food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops, and non-food crops, including crops used to feed milk- or meat-producing animals; C: food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops, and non-food crops, including crops used to feed milk- or meat-producing animals; D: industrial, energy, and seeded crops [93]. For Mexico were included water quality parameters for direct contact, which includes reuse for irrigation of parks and gardens. For Costa Rica were included water quality criteria for reuse type 3, which includes irrigation for crops which are not processed previous to commercialization, and wastewater from different sources than domestic.

The values of treated wastewater for discharge in streamflow 3, shown in Table 3, have similar values to Category C included in the recent EU 2020/741 regulation [93] and NCh 3456, Category D (Table 5). This is important because it suggests that effluents to Chilean WWTPs have great potential to be reused (as previously discussed). In addition, the water quality standards included in NCh 3456, Part 2 and shown in Table 5 have higher values in comparison to Israel and Italy. In this way, the country can start with the values proposed in the guideline but with intention to review in the next few years. However, despite the advance of having a Chilean guideline set out, at present, no specific mandatory regulation concerning the reclamation of wastewater has been enacted. One challenge for the future will be precisely the discussion of a new regulation. The first step will be to discuss the list of standards to guarantee the safe reclamation of treated wastewater. In addition, what option would be better, one unique list of standards for the whole country or specific standards for each macrozone, as proposed in this work? This discussion has to consider the climatic variation along the length of the country (Figure 2) because the water necessities among populations are different when you compare conditions in the northern, central or southern parts. In Table 5, water quality standards for reclamation of treated wastewater in arid and Mediterranean countries are very similar, suggesting similar water quality standards for the whole country as in the proposed regulation for greywater [83].

3.2.3. Rural Communities

The previous discussion about the institutional and regulatory framework challenges for the reclamation of treated wastewater will be important for the future of sanitation in the country, especially for rural populations. At present, for rural communities, the specific regulatory framework for this sector has been updated in Law 20,998 and Decree 50/2020 [80,98], which of course, is a general framework, not specific to treatment and reuse. Thus, the implementation of treatment and reuse projects and the necessity to innovate treatment technologies with a focus on the circular economy, of which reclamation of treated wastewater is a part, will be an important challenge for the country. The previous consideration must be included in discussion of the new WWTPs for this part of the population. This will be crucial to modify the present focus of treatment in rural sectors, as more than 70% of decentralized WWTPs (including rural sectors) are based on activated sludge systems [32], without focus on resource recovery. Under this new scenario, moving toward the use of technologies that are easier to build and operate in the rural sector, nature-based solutions, e.g., treatment wetlands, would be sanitary solutions to be considered. Treatment wetlands have been recommended for this part of the population, this a technology in which natural processes are optimized to improve water quality and which has the possibility to produce treated wastewater of high enough quality to be reused as irrigation water in agricultural activities, following the circular economy concept [99–103]. However, at a national level, it has the lowest usage rate—below 2% in the rural sector [32]—despite several studies based on local experiences showing the potential for its use across the country [104–108].

3.2.4. Emerging Compounds

The term emerging compounds (ECs) includes a wide range of compounds with relevant biological activities, such as pharmaceutical and personal care products (PPCPs), endocrine disrupting compounds (EDs), and their transformation products and/or metabolites [109]. In nature, wastewater is the most common source of these compounds, and therefore generates concerns among scientists and policy makers in the context of water use or reuse [17]. On account of their toxicity and potential adverse effects on the environment and humans, their release into effluents must be minimized, particularly when wastewater reuse for crops irrigation is expected [110]. In the case of PPCPs, irrigation with treated wastewater can contribute to the dissemination of antibiotic resistance due to the low effectiveness of conventional and non-conventional WWTPs for removing antibiotics [109]. Antibiotics have been detected in treated wastewater in concentrations ranging from 55 to 22,000 ng/L [18]. Therefore, irrigation with treated wastewater can affect soil and plant microbial communities and can contribute to this global concern endangering human health and the environment [109].

ECs, such as diclofenac, ibuprofen, naproxen, carbamazepine, fluoxetine, caffeine, sulfamethoxazole, bisphenol A, atenolol, triclosan, tonalide, among others, have been reported in effluents to WWTPs in Chile [111,112]. Thus, ECs in Chilean treated wastewater present a challenge to universities and research centers looking to understand, under local conditions, the effects of ECs on crops and the potential human and animal health risks when treated wastewater is employed as water for irrigation. Crops irrigated with treated wastewater can bear ECs accumulated in roots and aerial organs, which can affect plant physiology [17]. In this way, further specific studies in the country must be established. In addition, supplementary local research on ECs can provide insights into the need for improvements to current wastewater treatment systems to ensure the quality and safety of new water sources.

4. Conclusions

Chile is a country with a length that provides different climates along its territory. This variety of climates is an important advantage for agricultural production, but it also introduces complexity when it comes to water sources for irrigation. Forty percent of Chile's territory has been classified as semiarid and desert, while twenty percent has been classified as Mediterranean. The Mediterranean part was identified as the place where more agricultural production is developed, mainly focused on fruit production, and it is where 79% of the country's population lives, putting a strain on water resources, further aggravated by a megadrought extending over the last ten years.

The previously described situation has imposed the necessity to find new water sources. In this regard, the country has made an important advance in wastewater treatment coverage, achieving almost 100% in urban areas. This important achievement included the establishment of technologies with the possibility of producing recycled wastewater as a new water source for irrigation. However, due to a lack of regulations (specific guidelines and laws for reclamation) and inadequate institutional frameworks (more than forty governmental institutions interfere in water issues), management of this resource has not developed at the same pace as the water necessities of the country, which can partially explain the fact that direct reuse of treated wastewater across the country is still below 1% of the total national flow.

During the last twenty years, reuse has emerged in the country's discourse and only during the last five years has the regulatory framework been partially updated to match the new reality. The challenges to increase the use of recycled wastewater in the 21st century will require the development of adequate institutional and regulatory frameworks which must include or solve the particularities for each macrozone and confront the realities of Chilean rural populations. In this way, the implementation of treatment and reuse projects and innovation in treatment technologies will be needed at the rural level. Additionally, more research into recycled wastewater reuse has to be carried out across the country by universities, research centers, and stakeholders, studying traditional compounds but especially focusing on emerging compounds and their effect on the irrigation of crops, especially the crops needed to feed the growing national population and supply international markets. Based on the challenges discussed and the national water scarcity situation presented in this manuscript, it is expected that the reuse of safe, treated wastewater will increase in the coming years in the country, making a new water source available for irrigation to cover the agricultural necessities and mitigate the new climate challenge (megadrought) imposed by climate change.

Author Contributions: Conceptualization, I.V.-P., C.C. and H.V.; methodology, C.C. and H.V.; software, C.C. and H.V.; validation, H.V. and C.A.A.; formal analysis, I.V.-P., M.B. and M.C.-B.; investigation, I.V.-P., M.B., M.C.-B., J.O. and F.S.; resources, I.V.-P.; data curation, I.V.-P., M.B. and M.C.-B.; writing—original draft preparation, I.V.-P., M.B., M.C.-B., J.O. and F.S.; writing—review and editing, H.V., F.S. and C.A.A.; visualization, I.V.-P., M.B., C.C. and M.C.-B.; supervision, I.V.-P.; project administration, I.V.-P.; funding acquisition, I.V.-P., J.O. and C.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Agencia Nacional de Investigación y Desarrollo (ANID) (CHILE), grant number ANID/FONDECYT/11180672. The APC was funded by ANID/FONDECYT/11180672.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors wish to express their gratitude to Aguas del Altiplano (a water company) for their interest in and contributions to developing the reuse of treated wastewater in the country. In addition, the authors would like to thank the Agencia Nacional de Investigación y Desarrollo (ANID) (Chile) through Grant ANID/FSEQ210015 and Universidad Católica del Maule for supporting the research into wastewater treatment and reclamation.

Conflicts of Interest: The authors declare no conflict of interest.

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