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Review

Reuse and Recycling of Livestock and Municipal Wastewater in Chilean Agriculture: A Preliminary Assessment

Cristina-Alejandra Villamar [1,*], Ismael Vera-Puerto [2], Diego Rivera [3] and Felipe De la Hoz [4]

[1] Departamento de Ingeniería en Obras Civiles, Facultad de Ingeniería, Universidad de Santiago de Chile, Av. Ecuador 3659, Estación Central, Santiago 9170124, Chile
[2] Centro de Innovación en Ingeniería Aplicada, Departamento de Obras Civiles, Facultad de Ciencias de la Ingeniería, Universidad Católica del Maule, Av. San Miguel 3605, Talca 3480112, Chile; ivera@ucm.cl
[3] Centro de Recursos Hídricos para la Agricultura y Minería CRHIAM, Laboratorio de Políticas Comparadas en Gestión de Recursos Hídricos, Universidad de Concepción, Av. Méndez 595, Chillán 3812120, Chile; dirivera@udec.cl
[4] Centro del Agua para la Agricultura, Universidad de Concepción, Av. Méndez 595, Chillán 3812120, Chile; felipedelahoz@udec.cl
* Correspondence: cristina.villamar@usach.cl; Tel.: +56-022-718-2810

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Abstract: Chile is an agricultural power, but also one of the most vulnerable countries to climate change and water shortage. About 50% of the irrigated agriculture land in Chile is in the central zone, thanks to its agricultural-climatic characteristics that provide an adequate water supply (100–4000 m^3/s). However, the vulnerability scenario in this zone is high due to the seasonal availability of water resources. Therefore, opportunities to use non-conventional alternative sources (e.g., wastewater) become an appealing and feasible option due to the high population and animal density (>76%) in this part of the country. Moreover, the physicochemical characteristics of the municipal and livestock wastewater suggest that there are potential opportunities to recycle nutrients for agricultural production. In Chile, wastewater reuse opportunities are noted by the wide coverage of wastewater treatment programs, with municipal and intensified livestock production taking up most of the percentage (>99%). Nevertheless, more than 70% of wastewater treatment systems reach biological secondary treatment, which suggests reuse possibilities only for non-food crops. Therefore, this paper is focused on a preliminary analysis of the potential of reusing and recycling municipal and livestock wastewater for Chilean agriculture. There is some reuse work occurring in Chile, specifically in the use of municipal and livestock wastewater for cereal crops (animal feed), forests, and grasslands. However, aspects related to the long-term effects of these practices have not yet been evaluated. Therefore, municipal and livestock wastewater in Chile could be re-valued in agriculture, but the current quality and condition of treated wastewater do not ensure its safe use in food crops. In addition, state policies are needed to provide sustainability (circular and ethic economy) to water reusing/recycling in agriculture.

Keywords: Chilean irrigated agriculture; livestock wastewater; municipal wastewater; recycle; reuse; treatment

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1. Introduction

Irrigated agriculture contributes to 33% of world agricultural production, using 25% of the agricultural land, and consuming 65% (ca. 2989 km^3/year) of available freshwater [1–3]. Irrigated agriculture provides stability and global food security. It is favored because of its increased productivity of both seasonal (e.g., corn) and permanent crops (e.g., fruit and berry plantations), and has optimized land use [3,4]. However, global water consumption from irrigated agriculture represents about 2/3 of water withdrawals, threatening future sustainability [1]. The water consumption for agricultural irrigation has problems in regards to availability, water use rights, competing uses, and water resources management. Some alternatives concern water governance with inclusive resource co-management policies, which avoid conflicts, but these are vulnerable to globalized trade [5]. Other water resource governance models are related to contemporary economic planning, where the management focuses on "water markets" using the "water rights" concept [6]. However, this model type leads to conflicts due to water shortages and competition with other productive activities [7].

Chile is considered to the world as a "forestry-agricultural power", as forestry-agriculture exports generate around 800 USD/per capita [8]. Chile's agricultural potential has a main limiting factor to its climatic diversity from north to south (arid and semi-arid, Mediterranean, and temperate-wet climates) [9]. Geopolitically, continental Chile is divided into three zones. The northern zone (18–33° S) includes regions from Arica and Parinacota to Coquimbo, it is characterized by a low water supply (1–20 m^3/s) and agricultural production conformed by fruit trees and emergent hydroponic crops. Both types of irrigated cultivation support the domestic market during winter. The central zone (33–42° S) includes from Valparaiso to Los Lagos Regions, where there exists a medium-sized water supply (100–4000 m^3/s) and most of the country's irrigated agriculture is located. Chile maintains its irrigated agricultural production in the central zone for internal consumption and exportation, which is based on fruit trees and cereal crops. This area presents a strong seasonality, as precipitation occurs during wet-cold winters (May to August), while during the agricultural season precipitation is less than 15% of mean annual values. Thus, irrigation is key for producing high quality crops and orchards. Finally, the southern zone (42–55° S) comprises between the Aysén and Magallanes Regions, which contain a high-water supply (>10,000 m^3/s) but only subsistent agriculture because the temperature constrains plant growth. Therefore, Chilean irrigated agriculture for export and internal consumption is mainly located in the northern and central part of the country. Figure 1 details the geopolitical, climatic and water supply characteristics of Continental Chile.

Thus, access and availability of water resources are the key factors to the current Chilean agriculture condition. Despite that, the water cost per hectare does not exceed 4% of the total average production cost [10]. However, the Chilean agriculture critical scenario may be observed by current climate variability and future climate change. Some global projections consider a temperature increase between 3 and 4 °C, which would mainly affect irrigated agriculture in the Mediterranean areas [11]. In Chile, this situation would increase agricultural water requirements in the central zone (Mediterranean climate) between 4% and 18% [12,13]. Some studies suggest that mitigating climate change for irrigated agriculture is achieved with better water management. A worldwide decrease in water for agricultural consumption by 40% (125–160 trillion m^3) would reduce irrigation costs by 10 billion USD [14].

Revaluating wastewater in agriculture is a viable and sustainable alternative for decreasing fresh water consumption [15]. In addition, wastewater reuse/recycling is an important part of the concept of the circular economy and for the management of wastewater treatment plants [16]. However, wastewater use without prior treatment (non-reclaimed wastewater) is a common strategy in developing countries, in which 2/3 of the world's irrigated agricultural production is concentrated [17]. This is associated to the treatment costs (0.15–0.18 USD/m^3 reclaimed wastewater from secondary treatment) and the "advantage" that it offers as an alternative nutrient source (fertilizers) [15,17]. The safe use of wastewater (health risk) in agriculture is influenced by its microbiological quality (Fecal Coliforms <103 CFU/100 mL and helminth eggs <1 units), which can only be achieved with treatment [18,19]. Municipal and livestock (slurries) wastewater are the most widely used treatment types in agriculture, even though they do not comply to the microbiological requirements for use [15,20].

Therefore, wastewater treatment appears as a viable and safe alternative for recovering these types of non-conventional water sources for agriculture.

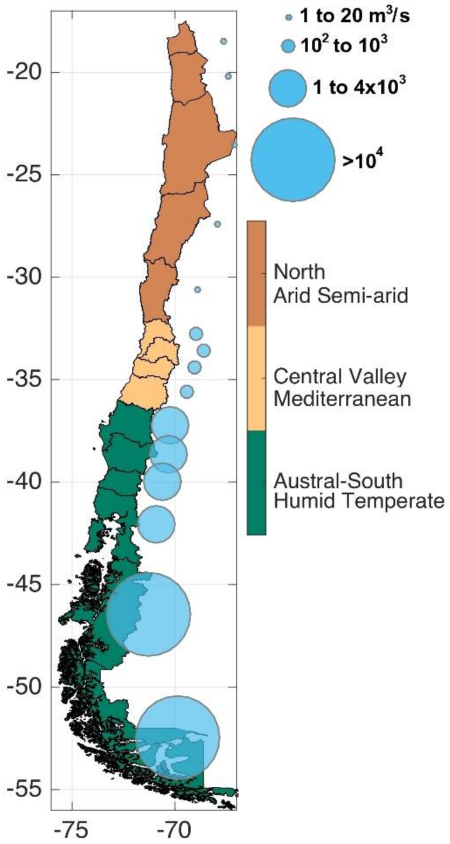

Figure 1. Maps geopolitical, climatic and water supply of Continental Chile.

The geographical concentration of Chilean productive activities, the unequal temporal and spatial distribution of water resources, as well as the coverage of municipal and industrial wastewater treatment are key factors for revaluating their potential in irrigation. Hence, assessing reuse and recycling schemes requires integrating information regarding the location of demand hotspots and potential supply points, as there is a large seasonal need for water by agriculture and a relatively small volume from municipal use, which is nonetheless constant in time. On the other hand, wastewater treatment plants treat 99.9% of municipal wastewater, and environmental regulations obligate livestock operations to treat and control wastewater prior to discharge. Both measures have increased the volume and quality of wastewater for reclamation. However, country-wide water budgets have failed to address the local context in terms of the volumes of wastewater as a new source of irrigation water and nutrients in order to match water quality requirements. Thus, this work aims to provide a perspective on the recycling potential of municipal and livestock wastewater for Chilean agriculture and the role of the treatment as an efficient tool for improving the sustainability of these kinds of practices. In doing so, we collated spatial and temporal information related to water demand from agriculture and wastewater production. First, we analyze current practices of wastewater management—livestock and municipal—and its potential for reuse in agriculture and the requirements of the treatment phases to fulfill water quality regulation. Then, we discuss opportunities and issues for recycling municipal and livestock wastewater into irrigation water.

2. Water Resources for Chilean Irrigation

The availability of water resources for irrigation in Chile varies highly due to geography and seasonal factors. The Chilean climate is highly variable on an annual and inter-decadal scale, which increases the uncertainty of resource availability within the different productive activities [6]. Currently, there is an imbalance between the surface water and groundwater supply in terms of the increasing water resource demand from different productive sectors (agriculture, mining, and drinking water) [12]. Agriculture is the main water consumer with values between 80% and 85% of the volume of granted water rights [1]. Therefore, this is the most vulnerable productive activity in the context of water resource scarcity [12]. To understand agriculture vulnerability, in terms of water resources, variables such as agricultural land, existing water infrastructure for irrigation and exposure areas must be considered. Exposure is defined as irrigation areas with a higher efficiency of water consumption and an area under irrigation regarding soil conditions and productive potential. Therefore, exposure defines the GDP (Gross Domestic Product) percentages per capita and per territorial unit, which considers the potential agricultural losses due to water scarcity [21]. Figure 2 shows the agricultural vulnerability map and the related non-conventional water sources (wastewater) from the human and livestock population zones in the country (18–40° S).

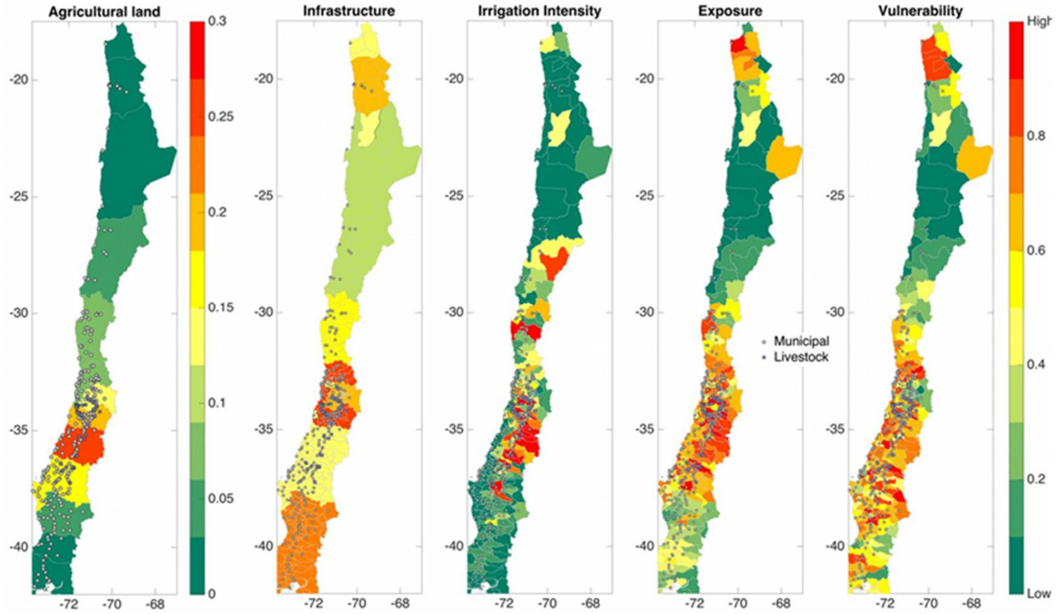

Figure 2. Chilean vulnerability maps of water resources availability and accessibility. Information based on Vulnerability Atlas from MA [21].

In the northern area, between 18 and 20° S (Arica and Parinacota, and Tarapacá), the Chilean agricultural sector vulnerability is high (0.6 to 1), due mainly to exposure to water scarcity. From 20 to 25° S latitude (Antofagasta), the averaged vulnerability is low (0–0.7) and it is related to the presence of irrigation infrastructure, which solves the low and intermediate zone requirements. On the other hand, different conditions in the altiplanic zones occur. Between 25 and 33° S (Atacama and Coquimbo), the sector vulnerability is low (0–0.1) because it is not a highly exposed zone, even though it has low water irrigation infrastructure (<0.5).

In the central zone, the vulnerability is higher (0.5 to 1), mainly due to exposure factors such as irrigation infrastructure and crop density. Although irrigation water infrastructure is higher (0.5 to 1) in this zone, the irrigation pressure is high too. About 50% of irrigated agriculture is concentrated in the central zone (Bernardo O'Higgins and Bío-Bío, 34–38° S), where around 550,000 ha of surface irrigation sustain 25% of the total country agriculture (ca. 2,000,000 ha). The central zone situation could be contradictory at the climatic level, because the agricultural activities begin between September and March and annual precipitation arrives in May and lasts until August [6]. Indeed, agricultural census data (1997 and 2007) show stagnation of both the under irrigation area and water consumption in agriculture [9]. The increase in agricultural productivity in recent years has been due to the research/conversion of conventional irrigation systems (gravitational and superficial) by pressurized irrigation (sprinkler and micro-irrigation), as well as the increased efficiency of furrow irrigation [22,23]. However, the dynamic growth of this activity requires looking for sustainable alternatives for the future. Under this scenario, non-conventional water sources are opening, considering that in this zone is also a concentrated human population and the livestock of the country. Therefore, this zone becomes a "*hot spot*" for using non-conventional water sources from wastewater. Specifically, coastal areas within the central zone show higher vulnerability to hydro-geological conditions and a reduced availability of agricultural land, but they have agro-climatic advantages (Valparaiso Region, 33° S).

Due to the above, there is a growing interest and demand for non-conventional water sources to sustain Chilean agriculture. Preliminary studies (national level) highlight the agriculture sector's interest to reuse wastewater. However, requirements of quantity and quality (physiochemical and agronomic characteristics) from wastewater must be established, thus complying with irrigation regulations and access availability [24]. Reclaiming wastewater from municipal and livestock wastewater treatment plants (WWTP) are presented as an interesting opportunity for water irrigation security and as an alternative to the sector resistance to climate change. However, to make it sustainable, several operational aspects must be improved [24].

- The location, design, and operation of reuse schemes, which consider the distance between the wastewater supply point and irrigation distribution sites.
- The implementation of quality standards based on an institutional framework and State policies, which determine the specific use of reclaimed wastewater in agriculture.
- Training for users (irrigation) of treated wastewater about the correct use of water from these sources.
- The control and monitoring systems implementation, due to the potential (direct and indirect) impact on the soil, air, surface and groundwater, crops, and human health risk.

3. Livestock Wastewater Management and Recycling, and Its Potential for Agricultural Irrigation in Chile

Human economic and demographic growth is the main-driver of current production and consumption of animal-based food [25]. In the last decades, the livestock revolution has intensified this activity mainly in developing countries, where 50% of world's meat production and consumption is concentrated [26]. The Chilean livestock sector generates about 46.8 million heads/year, of which more than 50% are cattle and swine [27]. Intensifying factors over the last three decades have facilitated the cattle and swine growth by 6.3% and 55%, respectively [26]. However, the animal population density in this country is heterogeneous, with more than 76% of cattle and almost 100% of swine in the central zone (32–42° S) [27]. The diversity of the Chilean livestock population determines the farm-based production type, which is differentiated according to the stage of animal growth (swine) or production type (cattle) [28]. The waste generation (livestock wastewater) is an important factor to animal husbandry (growth/production type). Figure 3 summarizes the livestock wastewater generation, according to the animal/production type.

In Chile, intensive farms with more than 300 animals generate an average swine wastewater between 10.7 (breeding-fattening) and 71.3 (maternity) L/animal-day. Cattle production reports average values of between 25.6 (beef) to 41.1 (dairy) L/animal-day [29]. The average reported values are like the ones reported (10–60 L/animal-day) in the literature [30–32]. The Chilean cattle and swine population could potentially generate around 2.5 million m^3/day of wastewater [27,32]. Table 1 describes the Chilean livestock population (cattle and swine) and its potential wastewater generation.

Wastewater physicochemical characteristics from livestock farms vary depending on the animal/production type and growth stage. In general, the low food-digestibility (<30% protein) of monogastrics (swine) and polygastrics (cattle) generates wastewater (slurries) with high organic content (2.6–24.9 g COD/L) [32–34]. The organic matter, upon reaching the soil during irrigation, is partially degraded (the first 5 days under incomplete anaerobic digestion), generating volatile fatty acids, which are odor precursors [35]. In addition, it favors the accumulation (A-horizon from soil) of more than 99% of pathogens and nutrients (10^7 CFU/100 mL and 2.5 g NH_4^+/L), which increases the health risk in irrigated crops [36,37]. The sensitive species (*Raphanus sativus*) germination/growth that is irrigated with livestock wastewater is inhibited to concentrations higher than 25% [38]. There is also evidence of microbiological pollution persistence (*Escherichia coli*, *Salmonella*) on fertilized crops (vegetables and fruit) with livestock wastewater after 8 to 200 days [39,40].

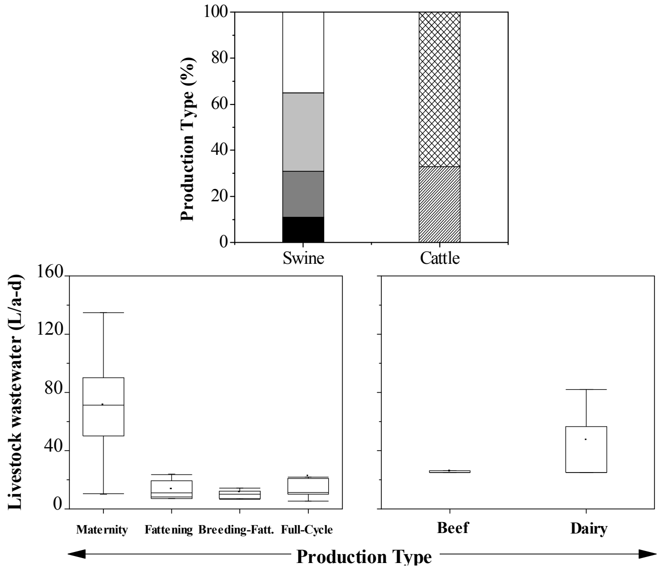

Figure 3. Production type and per capita wastewater generated within Chilean livestock intensified farms. The information is based on the Environmental Impact Statements of farms with more than 300 heads SEA [29]. Swine: (□) Fattening, (▫) Breeding-Fattening, (▣) Full-Cycle, (■) Maternity. Cattle: (⊠) Dairy, (▧) Beef.

Micro-pollutants (metals and antibiotics) from livestock wastewater are assimilated by some edible plant species (*Zea mays* L., *Allium cepa* L., *Brassica oleracea* L.) [41]. However, the acute eco-toxic effect from metals/antibiotics in plants has not been reported, because metal (Cu, Zn) and antibiotic (tetracycline, penicillin, and sulfamides) concentrations do not exceed 500 and 0.008 mg/L, respectively [42,43]. The presence of organic matter from non-reclaimed livestock wastewater facilitates the retention of metals/antibiotics in the productive soil layer, which will generate long-term crop toxic effects (oxidative stress and antibiotic resistance) [44,45].

Despite the disadvantages of livestock wastewater irrigation (non-reclaimed wastewater), it is a by-product rich in essential plant nutrients. Livestock wastewater has N:P:K relationships ranging from 0.1:0.1:1.0 to 4.0:2.0:1.0, which could facilitate its use in agriculture [46–50]. Preliminary studies report that the N:P:K nutritional requirements for cereals vary between 1.2:0.2:1.0 and 1.6:0.3:1.0 [51]. Meanwhile, recent studies show the hormetic effect in some cereals (*Triticum aestivum*) irrigated with livestock wastewater [38]. Other advantages are related to soil physicochemical property improvements such as the structure and moisture-holding capacity, which would motivate their reuse [37]. Table 2 summarizes the main physicochemical and agronomic characteristics from swine and cattle non-reclaimed wastewater.

Table 1. Livestock population and potential non-reclaimed wastewater generation within Chilean farms. Data based on last agricultural census ODEPA [26]. Wastewater values were calculated with mean values of per capita generation by livestock type.

Zone	Region	Livestock				Potential Livestock Wastewater			
		Cattle		Swine		Cattle		Swine	
		Number (10^3 Heads)	Percentage (%)	Number (10^3 Heads)	Percentage (%)	Flow (10^3 m^3/d)	Percentage (%)	Flow (10^3 m^3/d)	Percentage (%)
North	Arica y Parinacota	66.81	16.4	1.89	0.4	0.02	1.4	0.02	0.3
	Tarapacá	0.12		1.45		0.01		0.01	
	Antofagasta	0.28		1.89		0.02		0.02	
	Atacama	7.15		1.39		0.43		0.01	
	Coquimbo	41.28		3.78		2.48		0.04	
Central	Valparaíso	102.70	76.0	173.79	99.5	6.16	89.6	1.74	99.5
	O'higgins	83.35		860.02		5.00		8.60	
	Maule	2582.23		93.45		15.49		0.93	
	Biobio	449.40		179.81		26.96		1.80	
	Araucanía	668.14		199.63		40.09		2.00	
	Metropolitana	101.28		1292.66		6.08		12.93	
	Los Ríos	621.60		34.30		37.30		0.34	
	Los Lagos	1047.19		79.76		62.83		0.80	
South	Aysén	193.80	7.7	2.86	0.2	11.63	9.0	0.03	0.2
	Magallanes	141.76		1.90		8.51		0.02	
Total		4384.40		2928.98		223.11		29.29	

Table 2. Physicochemical and agronomic characteristics of non-reclaimed livestock wastewater.

Parameter	Unit	Swine			Cattle		
		Maternity-Weaning	Breeding-Fattening	References	Dairy	Calves-Beef	References
pH		6.9–7.5	7.2–8.4	3,4,5,6,9,10,12	6.9–7.8	6.3–7.9	2,7,10
EC	mS/cm	12.8–15.5	15.3–25.3	4,4,8,9,10	2.3–3.1	7.1–24.7	2,7,10
BOD_5	g/L	9.0–25.0	16.6–21.6	3,4,8,9,10,12	0.6–2.9	-	10
COD	g/L	24.0–65.2	45.3–57.7	3,4,5,8,9,10,12	2.6–4.8	3.1–41.0	2,10
NH_4^+-N	g/L	1.4–1.8	2.0–3.1	1,3,4,5,6,7,8,9,10,12	0.1–0.2	0.2–2.4	2,10
TP	g/L	0.6–1.4	0.8–2.8	1,3,4,5,6,7,8,9,10,12	0.01–0.07	0.3–1.2	2,7,10
K	g/L	1.8–2.2	1.9–3.8	4,8	0.4–5.2	0.6–3.6	2,7
FC	NPM/100 mL	10^3–10^8		11	10^5–10^7		10
C/N		5.0–6.4 [a]	5.4–10.8 [a]		6.0–14.5 [a]	2.6–205 [a,*]	
N:P:K		0.6–0.8:0.3–0.6:1.0 [a]	0.5–1.6:0.2–1.5:1.0 [a]		0.1–0.5:0.1–0.5:1.0 [a]	0.1–4.0: 0.1–2.0: 1.0 [a]	

Notes: [1] Scotford et al. [52]; [2] Sweeten et al. [46]; [3] Portejoie et al. [31]; [4] Boursier et al. [53]; [5] Moral et al. [42]; [6] Provolo and Martinez-Suller [48]; [7] Martinez-Suller et al. [49]; [8] Moral et al. [54]; [9] Suresh and Choi [50]; [10] Villamar et al. [28]; [11] Chartier et al. [36]; [12] Villamar [55]. EC = Electric Conductivity, BOD_5: Biochemical Oxygen Demand, COD: Chemical Oxygen Demand, TP: Total Phosphorous, K: Potassium; FC: Fecal Coliforms. * Considered as COD/NH_4^+-N. [a] Values calculated from published research.

From the perspective of recycling, livestock wastewater treatment is an effective wastewater reclamation mechanism for agricultural use. According to water reuse guidelines [19], reclaimed wastewater from secondary treatment (solids and organic matter removal) is “safe” under certain categories (restricted or unrestricted) for agricultural recycling. Meanwhile, most adequate treatments according to their physicochemical characteristics ($BOD_5/COD > 0.5$ and $C/N > 5$) are biological wastewater processes (secondary/tertiary) [32].

Figure 4 describes the treatment types used by 62 intensive farms, where more than 300 heads are confined. These intensive farms are located in the central zone between the Coquimbo and Bio Bio Regions (33–38° S). The data was extracted from the Chilean Environmental Assessment Service. The Chilean intensive livestock sector represents nearly 95% and 33% of the swine and cattle population, respectively [27,28]. Clean Production Agreements (1999, 2005)—government-supported initiatives through implementing treatment technologies programs—and the legal requirements of the Environmental Impact Studies on farms have favored current technological coverage [28,29].

In Chile, wastewater from all intensive farms gets a primary treatment. This process type is mainly based on equalization stages (homogenizer tank) and separation/filtration (parabolic filter, press filter, rotary drum, sieve, and settler, among others). At this stage, Chilean livestock wastewater reported efficiencies in the removal of total suspended solids between 53% and 90%. A secondary treatment was applied to 79% of intensified farms, both swine and cattle. Treatment technologies applied at the swine sector range from anaerobic lagoons (55%), biodigesters (14%), activated sludge (11%), and vermifilters (7%), while cattle farms apply storage tanks (83%) and aerated lagoons (17%). Organic matter removal efficiencies under these typologies varied between 60% and 90%. From the application of secondary processes, reuse can be “safe” for non-food crops and the restricted irrigation of landscapes (grassland, forest) [19]. Finally, Chilean cattle farms did not apply tertiary treatment, while the swine sector only applied tertiary treatment in 30% of farms. The reported tertiary technologies are maturation lagoons (14%), constructed wetlands (11%), chlorination (3%), and UV radiation systems (2%). Nutrients (nitrogen and phosphorous) and pathogen removal efficiency under this technology type is reported to be 19%, 70%, and 90%, respectively. Disinfection technologies give agricultural value to livestock wastewater, so its recycle could be extended to gardens and golf courses [19].

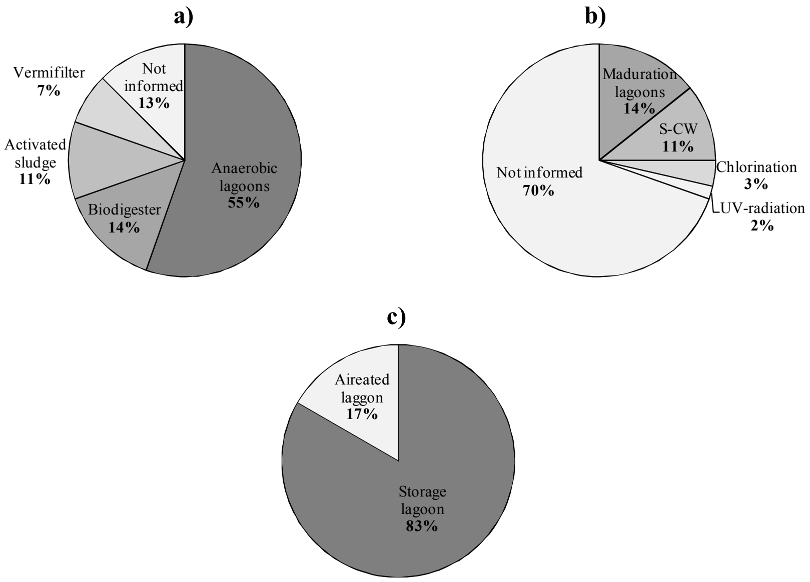

Figure 4. Livestock treatment technology applied on Chilean intensified farms. Swine: (**a**) secondary and (**b**) tertiary, Cattle: (**c**) secondary treatments. The information is based on Environmental Impact Statements of farms with more than 300 heads SEA [29].

4. Municipal Wastewater Management and Its Agricultural Irrigation Recycling Potential in Chile

The world population is reaching 7 billion habitants, and more than 70% live in developing countries [56]. In Chile, the projected population for 2017 is around 18 million habitants, of which 87% of the population is urban and 13% is rural [57,58]. In the last 27 years, Chilean demographic growth has slowed down (1.1% in 2014) at a greater pace than other OECD countries (−0.2 to 0.9%) [59]. In addition, population density is low at the national level (8.7 hab/km^2) due to the country's length (more than 4000 km) and demographic concentration is mainly in the central zone (86.3%), where 87% of the population is urban [58]. With this background, Chilean municipal wastewater generation potential would attain 3.2 million m^3/d with unit production of 0.205 m^3/inhab-day [60]. This value is within the range reported by the literature (50–400 L/inhab-day; urban population >150 L/inhab-day) [61–64]. Table 3 summarizes the Chilean population and its municipal wastewater generation.

Table 3. Chilean municipal wastewater production by zone and by each Chilean region.

Zone	**Region**	**Population**				**Municipal Wastewater (m^3/s)**
		Rural		**Urban**		
		10^3 People	**Percentage (%)**	**10^3 People**	**Percentage (%)**	
North	Arica y Parinacota	18.58	9.9	162.82	12.5	1.110
	Tarapacá	22.67		306.25		
	Antofagasta	15.04		573.09		1.154
	Atacama	26.63		257.98		0.596
	Coquimbo	141.61		597.54		1.091
Central	Valparaíso	152.31	88.9	1643.45	85.9	3.878
	O'higgins	260.91		639.26		1.386
	Maule	334.84		688.84		2.559
	Biobio	335.45		1726.10		4.008
	Araucanía	316.06		670.34		2.077
	Metropolitana	235.66		6771.96		16.774
	Los Ríos	119.82		261.90		2.121
	Los Lagos	251.54		605.43		
South	Aysén	16.10	1.2	90.77	1.6	0.206
	Magallanes	11.10		148.57		0.425
	Total	**2258.35**		**15,144.28**		**37.385**

Physicochemical characteristics from municipal wastewater depend on the population behavior and socio-economic level. Urban wastewater is between 20% and 50% more concentrated than in rural areas [65]. In general, municipal wastewater is a source of organic matter (110–800 mg BOD$_5$/L, 250–1600 mg COD/L), nutrients (12–120 mg NH$_4$$^+$-N/L, 2–23 mg TP/L) and pathogens (>10^3 NPM/100 mL) [64,66]. However, the municipal wastewater organic loading (g BOD$_5$/d) is between 5 and 12 times lower than livestock wastewater organic loading. The main problem of its use in agriculture is related to the microbiological loading, which exceeds recommended values (<10^3 MPN/100 mL as Fecal Coliforms) by the international reuse guidelines [18,19]. These studies describe the entero-pathogens (*E. coli*) presence from municipal wastewater, which form biofilms on lettuce crop foliar surfaces, increasing their survival [39]. Municipal wastewater treatment in developing countries is incomplete (removal of suspended solids and organic matter). Therefore, it could not be used for recycling with human consumption agriculture because of its microbiological content [67]. Furthermore, recent studies have reported the presence of Emergent Organic Compounds (EOCs) from pharmaceutical personal care products within soil irrigated with municipal wastewater [68]. The EOCs risk to agriculture level ranges from potential toxicity to terrestrial organisms (worms, bacteria and plants) to accumulation in consumed vegetal species by humans [69,70]. Therefore, municipal wastewater treatment arises as a necessity for agricultural reclamation wastewater, according to their agricultural quality. Some studies mention that conventional secondary (activated sludge) and tertiary (filtration with activated carbon) treatment processes can remove much of the EOCs (antibiotics) [68,71]. Recently, Roccaro et al. [72] showed there are water reclamation plants (WRPs) in the US that employ the Microfiltration + Reverse Osmosis + Oxidation with UV/H_2O_2, as an advanced oxidation process, for the removal of EOCs. These WRPs have produced water of high to exceptionally high quality, making it suitable for practically any purpose, including indirect potable reuse.

From the agronomic point of view, the N:P:K relationship (2.85–4.7:0.6–0.8:1) from municipal wastewater is sustainable for agriculture [73]. Other studies have shown that the use of municipal wastewater maintains the production of some grasses and their nutrient contents without the need for additional nutrients (e.g., Castro et al. [74]). Table 4 describes the physicochemical and agronomic characteristics from reclaimed from secondary/tertiary treatment and non-reclaimed municipal wastewater (principally Chilean information and in a complementary way bibliographic information).

Table 4. Physicochemical and agronomic characteristics of non-reclaimed and reclaimed municipal wastewater.

Parameter	Units	Non-Reclaimed	Reclaimed [a]
pH	unit	6.5–8.5	6.0–8.0
BOD_5	mg/L	110–800	5–45
COD	mg/L	250–1600	5–120
NH_4^+-N	mg/L	12–120	-
TN	mg/L	20–120	5–75 [b]
TP	mg/L	2–23	2–20
K	mg/L	7–15	
FC	MPN/100 mL	10^3–10^8	$<10^3$ [c]
C/N	-	66.7–1.0 [b]	-
N:P:K	-	2.9–4.7:0.6–0.8 [d]:1.0	

Notes: Vera et al. [64], Vera et al. [66]. [a] Effluent from the aerobic treatment process with final disinfection. In general, the Chilean WWTP has secondary treatment with disinfection [b] Corresponding to Total Kjeldahl Nitrogen. [c] Limit in DS 90 Table 1 [74]. [d] Values calculated with bibliography information [71].

With the enactment of Supreme Decree 90 in 2000 [74], Chile increased its municipal wastewater treatment coverage from 20.9% at the beginning of the century to almost 100% (99.93%) in 2014 [60]. This growth mainly occurred between the years 2000 and 2010, and reached a total of 289 municipal Wastewater Treatment Plants (WWTPs) in 2016 [75,76]. Figure 5 shows the main technologies originating from the Chilean municipal WWTPs. Three aspects stand out. First, the highest submarine emissaries' presence is located in the north, corresponding to 25% of the WWTPs. Second, a higher presence of aerobic systems (activated sludge, aerated lagoons, oxidation trenches) corresponds to 70% of the WWTPs in the central and southern zones. Third, only 5% of the primary disinfection systems are present in the central zone. The reclaimed municipal wastewater coming from these WWTP's without secondary treatment restricts their recycling [19].

According to treatment coverage in Chile, there are 289 WWTPs that treat about 1,179,000,000 m^3/year (37.4 m^3/s) from by approximately 15,929,157 inhabitants (0.205 m^3/inhab-day) [60]. The reclaimed wastewaters from the WWTPs are discharged: 78.5% (29.4 m^3/s) to rivers, 20.4% (7.6 m^3/s) to the sea, 0.3% (0.1 m^3/s) to other surface water bodies, and 0.8% (0.3 m^3/s) for agricultural recycling [59]. It is important to emphasize that Chilean WWTPs have been designed to remove organic matter (COD, BOD_5), solids (TSS), and to disinfect. In this regard, Vera et al. [64] reported solid (TSS) and organic matter (BOD_5, COD) removal higher than 80% from aerobic processes with reclaimed wastewater 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 below 25 mg/L and

8 mg/L, respectively. With these removal efficiencies and concentrations, Chilean reclaimed municipal wastewater has the potential to be reused in the irrigation of agricultural products.

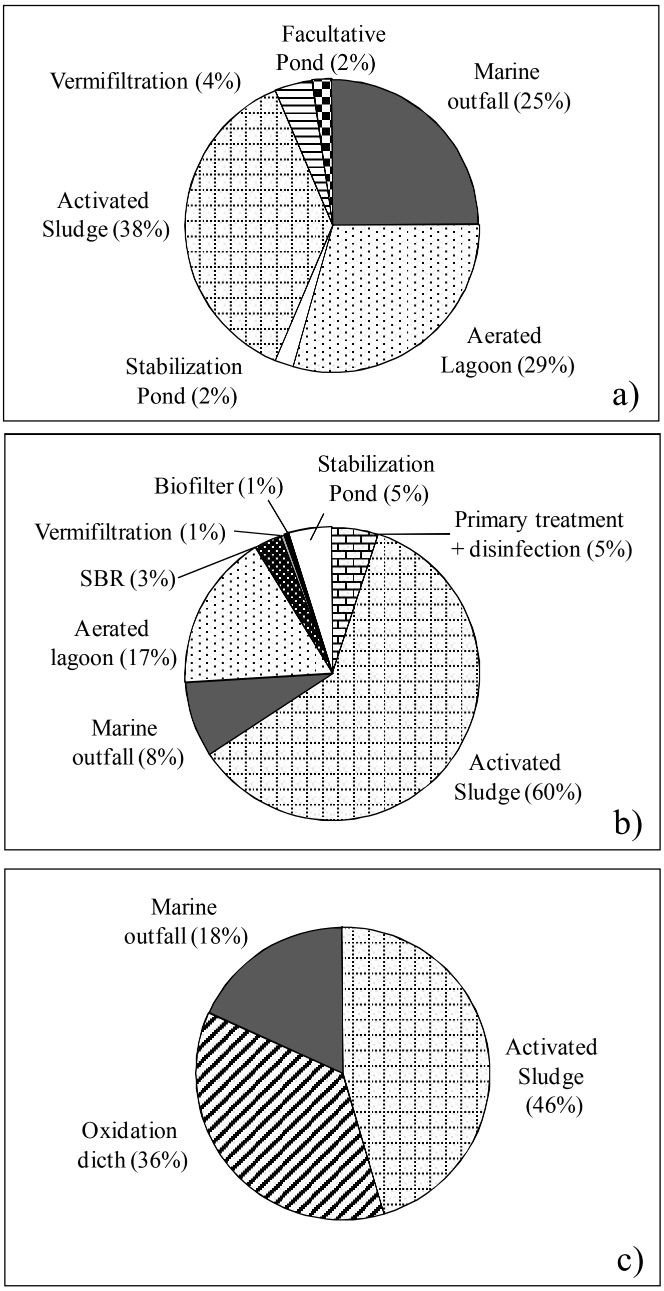

Figure 5. Municipal wastewater treatment technology applied in Chile. (**a**) North area, 48 WWTP; (**b**) Central area, 230 WWTP; (**c**) South area, 11 WWTP.

5. Opportunities for Recycling Municipal and Livestock Wastewater in Chilean Agriculture

According to the previous data, Chile has matured regarding its coverage of municipal and livestock WWPTs. However, there are no government policies (only general guidelines) that adequately strengthen wastewater recycling [23,66]. These new policies must be based on the circular-economy concept to establish a more sustainable model in wastewater management [16]. Furthermore, these new policies should be addressed in the short- and medium-term, as water scarcity is a current problem in the north and a future problem in the central zone. Fader et al. [13] project a water resource deficit for

Mediterranean agriculture and similar climatic conditions for the central Chilean zone. Therefore, the reclaimed municipal and livestock wastewater recycling should be considered as a non-conventional alternative source [77].

Figure 6 summarizes the potential availability/accessibility of municipal and livestock wastewater to agricultural areas. It also describes the quality (reclamation level) in regard to the achieved treatment stage (primary, secondary and tertiary), which is compared with international guidelines [19]. At the zonal scale, about 80% and 98% of municipal and intensive livestock wastewater is concentrated in the central zone, where 75% of Chilean irrigated agriculture is located. This condition opens up opportunities for municipal and livestock wastewater reuse in agriculture.

At the quality level and according to the achieved treatment stage, wastewater in this work was classified as "A" for surface irrigation for non-food crops and grasslands and "B" for gardens and golf courses. "NA" and "Dry" are categories regarding the wastewater with primary treatment (not suitable for agriculture) or wastewater (slurries) and manure treatment technologies (Deep Bedding) [19]. At the national level, 84% of reclaimed municipal wastewater shows quality A and only 12% shows quality NA. Meanwhile, 61% of reclaimed livestock wastewater shows quality A and only 3% shows quality NA. The central zone offers better quality reclaimed wastewater thanks to technological investment and regulation. Therefore, the central zone offers the best opportunities for wastewater recycling in agriculture.

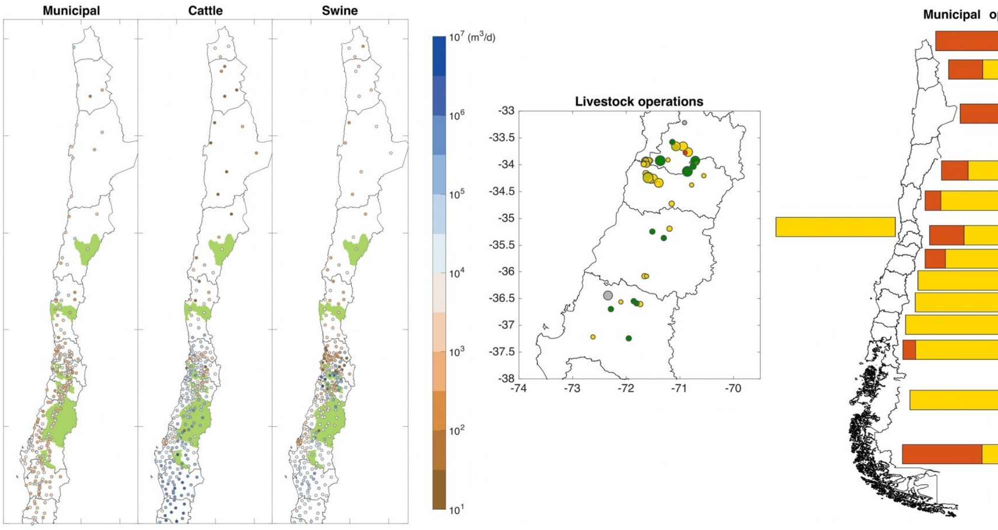

Figure 6. Availability/quality maps of non-reclaimed and reclaimed wastewater from municipalities and livestock farms with respect to irrigated areas. (🟥) NR: Not suitable for reuse, (🟨) A Class: Surface irrigation of orchards and vineyards, irrigation of non-food crops and landscape Restrictions (🟩) B Class: Irrigation of gardens and golf courses and (▣) Dry: Dry treatment. Restrictions used are described by Bastian and Murray [19].

Table 5 describes the impact of reclaimed wastewater recycling (municipal and livestock) on Chilean agricultural purposes. At a national level, the potential reclaimed municipal wastewater reaches 37.4 m^3/s, of which approximately 88% is concentrated in the central zone. However, the agricultural contribution level does not exceed 20%. As there are large differences in agricultural patterns—area and crops—among regions, there exist regions where the potential is significantly higher, such as Antofagasta, Metropolitana, Los Ríos, Los Lagos, Aysen, and the Magallanes regions. In a complementary way, due the proportion of agricultural water use versus total water uses in economic activities (Table 5), the region with the greatest reuse potential is in the Araucanía Region (37–39° S). In this region, the agricultural water use represents more than 70% of the productive activities using water resources, so that any reuse activities will be very important for this region.

On the other hand, reclaimed livestock wastewater from intensive facilities up to 0.34 m^3/s concentrated mainly in the central zone could be an alternative source of water recycling in agriculture. Currently, its agricultural contribution level reaches values between 50% and 100% (Table 5).

Table 5. Contribution of wastewater reuse on agricultural activities by zone and by each Chilean region. Data are based from MISP [78], SISS [60] and SEA [29].

Zone	**Region**	**Water Used for Agricultural Activities**		**Reclaimed Wastewater (m^3/s)**		**Reclaimed Wastewater Recycling in Agricultural Activities (%)**	
		m^3/s	**% [a]**	**Municipal**	**Livestock**	**Municipal [b]**	**Livestock [c]**
North	Arica y Parinacota, Tarapacá;	8.926	56.7	1.154	-	12.9	-
	Antofagasta	3.308	14.8	1.110	-	33.6	-
	Atacama	12.033	79.6	0.596	-	5.0	-
	Coquimbo	27.194	84.9	1.091	0.003	4.0	100
Central	Valparaíso	42.438	30.0	3.878	-	9.1	-
	O'higgins	97.964	12.8	1.386	0.147	1.4	89.5
	Maule	166.489	11.0	2.559	0.012	1.5	50.0
	Biobio	69.436	4.6	4.008	0.031	5.8	77.8
	Araucanía	11.512	78.5	2.077	-	18.0	-
	Metropolitana	82.361	34.2	16.774	0.153	20.4	69.0
	Los Ríos; Los Lagos	3.308	0.8	2.121	-	64.1	-
South	Aysén	0.644	0.2	0.206	-	32.0	-
	Magallanes	1.119	1.3	0.425	-	38.0	-
	Total	**526.732**	**-**	**37.385**	**0.343**		

Notes: [a] Percentage of agricultural water use regarding total water use in different economic activities (including power generation by hydropower dams). [b] In the case of municipally reclaimed water, the percentage is potential, and is calculated taking into account 100% of recycling. [c] The Percentage is based on reported information in SEA [29].

Currently, for the explained reasons, regional initiatives exist to address issues of reusing municipal wastewater. The Valparaíso Region (central zone, 33–34° S) has proposed the reconversion of its submarine emissaries as a "treatment" system. For this, its discharges would be transported to new WWTPs located in the central area of this region. The aim of this proposal was to start a discussion on the topic of reuse at the national level. The study carried out by Fundación Chile [77], located in Santiago, proposes transporting to the interior of the Valparaiso Region by more than 40 km, a municipal wastewater flow of 2.6 m^3/s towards three WWTPs (Quillota = 1.1 m^3/s; Casablanca = 0.4 m^3/s; Petorca = 1.1 m^3/s). The new WWTPs are based on activated sludge and disinfection. The estimated total investment costs range from 0.9 USD/m^3 to 1.93 USD/m^3 of reclaimed wastewater, while operating costs are estimated to be from 0.42 USD/m^3 to 0.68 USD/m^3. Three scenarios are proposed for water recycling: (a) scenario 1, 94% only for agriculture; (b) scenario 2, 15% for mining, 10% for industry, and 59% for agriculture; (c) scenario 3, 16% for industry and 72% for agriculture. However, the scenario analysis is limited to an economic approach. This proposal is interesting, since it is the first of its kind in Chile. Aspects such as an evaluation of the proposed treatment system, the lack of regulation and institutionalism, and the scope of scenario analysis according to environmental and socio-cultural factors will be interesting points to address in the second and third phases of this study.

This same topic, the reconversion of submarine emissaries, could be discussed for the North zone, which is within the Atacama Desert. Indeed, the WWTPs participation based on marine emissaries (25%, Figure 5) indicates that this zone has the potential to improve the wastewater quality of 2.6 m^3/s, corresponding to 65% of the total generated municipal wastewater in this zone [79]. This higher wastewater flow is given by cities such as Arica, Iquique, Antofagasta, La Serena, and Coquimbo, located on the coast.

Conversely, the wastewater and soil from the North zone have higher salinity and Electrical Conductivity (EC), above 2 dS/m and 26.8 dS/m, respectively, under regular or natural conditions [80–83]. Four strategies are feasible in solving the geological soil conditions in the Chilean northern zone to promote municipal and livestock wastewater reuse in agriculture. These strategies could be extended to other developing countries with arid climatic conditions. First, desalination systems could be built within the WWTPs. Drinking water in the north of Chile has electrical conductivities of 1.5 dS/m. In fact, regulations indicate that electrical conductivities less than 0.7 dS/m would not have a significant effect on agricultural production [66]. However, according to Jiménez [17] salinity control mechanisms on wastewater would be more expensive than a mitigation on the origin. In this sense, the second strategy is precisely to regulate salts (sodium, boron, chlorides, and fluorides) from products such as detergents, which contribute to municipal wastewater salinity. This strategy would decrease the wastewater salinity up to 1 dS/m. As an example, Israel recycle 70% of its reclaimed wastewater, due the control it has on the salt content from detergents. This mechanism resulted in chloride decreasing from 120 mg/L to 60 mg/L in 10 years (1992–2002), as well as boron decreasing from 0.6 mg/L to 0.3 mg/L in 4 years (1999–2002) [17]. The Chilean northern zone has chloride levels above 200 mg/L and boron levels over 2 mg/L within the reclaimed wastewater [82]. These chloride and boron levels produce adverse effects, such as dehydration and plant wilt, within most crops [84]. However, this strategy requires public policies, which in the short term of this review can be used as a preliminary discussion tool in the country.

The third strategy is focused on the soil salinity problems. In this regard, agricultural systems without soil, such as hydroponics and aeroponics, would be alternatives to evaluate. Hydroponics is a soil-free cropping system, where the belowground plant part (root) is in contact with nutrients, water, and an inert medium (this part is optional) [85]. Aeroponics is a soil-free cropping system where the belowground plant part is placed in air and adheres to an inert medium below a dark controlled environment saturated with moisture and nutrients [84]. Vegetables such as lettuce, tomatoes, cucumbers, zucchini, carrots, and ornamental species such as chrysanthemum and poinsettia have been grown below soil-free cropping systems [84,86]. In the case of lettuce, aeroponic crops use only 10% of the water normally consumed in this traditional soil crop [85]. This efficient use of water is important in desert conditions like northern Chile. The operational conditions from these new agricultural techniques are still being researched [86]; therefore, they are the most viable alternatives for northern Chilean agricultural development [85].

The fourth strategy is to select the crop type. In this regard, cultivation of barley, jojoba, sugar beet, asparagus, date palms, artichokes, among other crops that are tolerant to salinity, are what could be recommendable for the Northern zone [87]. Even flowers such as *Lisianthus*, *Trachelium* and *Limonium* have been shown not to be affected in their commercial quality when irrigated with water with electrical conductivity above 3 dS/m [88].

On the other hand, the aerobic treatment systems from the central zone treat approximately 50% of reclaimed wastewater in this zone, which is equivalent to a constant flow of 15 m^3/s [89]. The physicochemical characteristics from this reclaimed wastewater according to organic matter, solids, and nutrients are suitable for agricultural proposes [64]. In this regard, the country's highest agricultural production is concentrated in the central zone [6]. However, there are legal (especially property) challenges that have hindered the further development of non-conventional water recourses in agriculture [66]. Moreover, it is necessary to evaluate the potential environmental impacts associated with reclaimed wastewater irrigation.

In the case of livestock wastewater reuse in Chile, it is most frequently used within intensified facilities, owing to Clean Production Agreements, discharge restrictions on superficial water bodies, and their closeness with the agriculture. There are about 62 intensified livestock farms located from Bio Bio to Coquimbo Regions. Their Environmental Impact Statements report reusing/recycling practices of reclaimed/non-reclaimed livestock wastewater on animal consumption crops (corn, oats, wheat), fruit trees (plums, peaches), forestry (foreign: eucalyptus and native: molle, huigán, mayo, pepper, quillay, and maitén), prairies (rumpus, clover) and gardens. This practice type (42%) is focused on the irrigation of cereals and forest trees. The first case is commonly used because these farms provide the agricultural production of animal feed. Meanwhile, the second is related with the proximate of foreign species plantations (*Eucalyptus* spp.) used by the pulp and paper mills, which are located mainly between Maule and Los Ríos regions (35–39° S).

Thus, approximately 27,000 m^3/d of livestock wastewater are available in agricultural areas adjacent to intensified livestock facilities. However, there are problems regarding proper management during irrigation; 94% of reclaimed livestock wastewater has quality levels allowed for agricultural recycling (secondary treatment process). Approximately 56% of livestock wastewater reaches only a secondary treatment, which removes pathogenic microorganisms at concentrations higher than those required for reuse/recycle (>1000 NPM/100 mL) [66]. The bio-aerosols risk during the wastewater spraying of livestock can cause cross-pollution, indirect pollution in edible crops (50 to 150 m distance), and direct pollution to workers (1.50 m height) [90]. Risk factors are climatic, and others relate to the biological material transported. Increases in temperature and solar radiation with decreases in humidity would favor microbiological inactivation of these aerosols [91]. Therefore, it is necessary to regulate the wastewater application, considering the achieved level of wastewater treatment (reclaimed wastewater quality), type of irrigation system management, soil characteristics, and meteorological conditions of the zone [52].

Reclaimed wastewater from tertiary processes can be used by spraying water under favorable temperatures and radiation (noontime or afternoon during the summer) conditions for microbiological inactivation [91]. Other irrigation problems are related to micro-pollutant (metals, antibiotics, hormones) accumulation. Physicochemical characteristics from these micro-pollutants suggest soil availability/affinity (octanol-carbon partition coefficient or log Kow > 2) [43]. In soil, these micro-pollutants are adsorbed by terrestrial organisms (plants), generating direct toxicity (metals) or bioaccumulations (antibiotics) with unpredictable effects on other trophic scales [41,45]. Therefore, if there is a desire to recycle livestock wastewater, ensuring that these practices are sustainable, it is necessary to start evaluating how to eliminate them under current optimized technologies or new technological alternatives. Now, advanced processes such as ultrafiltration, microfiltration, reverse osmosis, oxidation with UV/H_2O_2, and ozonization have been used for improving reclaimed wastewater quality [72].

Chilean non-intensive livestock production is located in the north, south-central, and south parts of the country, and it potentially generates 150 m^3/d of non-reclaimed wastewater. The contribution of livestock wastewater reuse is uncertain, although it would be expected that, in the northern zone (arid climate), for every 1 m^3/s of non-reclaimed wastewater generated irrigation surface is increased by almost 1500 ha [12].

Currently in Chile, there is reuse legislation (Law No. 21075) [92], which regulates the grey water reuse only for use in watering gardens. Wastewater recycling legislation does not exist, only recycling practices in agriculture, based on water quality requirements (DS.1333) [93] as mentioned above, exist. Moreover, the current water offer in Chile has operated based on a market model (water rights market) since 1981. Therefore, the water resource is sold, bought, and granted. Thus, the water cost for irrigation is regulated by the market, considering aspects such as: construction/maintaining of infrastructure, and use and damage to third parties by assignment. This model has advantages (efficiency in the resource use) and disadvantages (resource privatized and not regulated cost), which together with the potential impacts of climate change could be affecting Chilean agriculture. On the other hand, the treated wastewater cost (collection + treatment) reaches values up to 0.8 USD/m^3, being part of the water consumption cost rate of the population. If circular economy concepts are adopted into the use of reclaimed wastewater in Chilean irrigation, would it be possible to reduce the wastewater treatment costs rate for the population and fixing the costs of this alternative water resource to irrigators. However, it would be possible under an additional concept of ethical economy, where human and environmental development rest above the economic. Therefore, the public policies in reclaimed wastewater recycling should not only establish quality criteria, but also a sustainable model based on circular and ethical economy.

6. Conclusions

The Chilean central zone holds 50% of the country's irrigated agricultural production, but it also shows the highest vulnerability (0.5 to 1) to water scarcity due to agricultural requirements exceeding 470 m^3/s and has a water supply from 100 to 4000 m^3/s, which is not fully available at planting time. Therefore, among non-conventional water sources, municipal and livestock wastewater is an alternative source for agricultural irrigation, thus reducing pressure over water resources.

In terms of constant flow, municipal and livestock wastewater in Chile reaches values of 37 and 0.3 m^3/s, against 526 m^3/s demand for agricultural use. However, this country-wide budget hides large differences among regions due to the demand to wastewater ratio. Reuse opportunities due to resource availability (municipal and livestock wastewater) in the central zone are related to the concentration of the human population (88%) and livestock population (76–100%) in this sector. The Chilean treatment coverage of municipal and intensified livestock wastewater exceeds 99%. However, the achieved treatment levels allow for restricted recycling of forest and non-food crops. Therefore, quality would still be a determining factor and a condition of reuse in agricultural irrigation. Moreover, the reusing/recycling experiences of municipal and livestock wastewater are conditioned on their evaluation of future effects, as well as the need for policies that favor the sustainability of this practice type.

Therefore, there is potential for the recycling of municipal and livestock wastewater in Chile, due to resource's spatial availability and the quality achieved by the treatment level. However, water-recycling opportunities are not harnessed because there are no water recycling governmental policies and some strategies are limited to specific kinds of wastewater resource management. The current Chilean irrigation regulations (quality standards, water code) are not focused on recycle concepts. New policies focused on the circular and ethic economy concepts are necessary to improve the management of WWTPs and water resources. Furthermore, new research studies need to be developed that focus on reclaimed wastewater. It is important to move away from technology that allows compliance with a standard technology that closes the water cycle. In addition, the possibility of research level studies might allow for the indirect agricultural use of this reclaimed wastewater from recharging the aquifers.

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