

Research article

Tertiary treatment of domestic wastewater for reuse: Implementation and evaluation in a rural context in Chile

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ABSTRACT

Water scarcity in arid and semi-arid regions of Chile is intensifying demand for safe irrigation water sources. This study assesses a modular tertiary treatment train for rural wastewater reuse based on fixed-bed polishing with natural zeolite and activated carbon, followed by UV-C disinfection. Pilot-scale implementation at the La Higuera wastewater treatment plant confirmed robust field performance, reducing TSS by $\approx 70\%$, BOD₅ by $\approx 56\%$, and fecal coliforms by 99.9%, enabling compliance with Chilean irrigation reuse criteria (NCh 1333; DS 90/2001). Average salinity indicators during monitoring were EC = 1774 $\mu\text{S}/\text{cm}$ and TDS = 964 mg/L, suggesting moderate irrigation restrictions and practical suitability mainly for moderately salt-tolerant crops under appropriate management (e.g., leaching and drainage). Because the pilot evaluation covered only $\sim 3\text{--}4$ months, long-term performance claims remain preliminary, and seasonal variability and fixed-bed media breakthrough/saturation should be validated through extended multi-season monitoring. Persisting limitations include dissolved solids control and maintaining nitrogen removal during extended operation. Overall, the proposed low-energy, locally adaptable train provides a pragmatic and transferable pathway for decentralized water reuse in arid rural settings, with site-specific adaptation mainly required for influent nitrogen loading/speciation, background salinity/TDS, and local reuse regulations, supporting circular water management aligned with SDG 6 and SDG 12.

1. Introduction

Water availability is one of the environmental variables most sensitive to the impacts of climate change (Trenberth, 2008). Currently, more than 60% of the global population lives under increasing water stress (Huang et al., 2021). In South America, the magnitude of these impacts varies according to regional climatic conditions (Hagen et al., 2022). In Chile, projections indicate a 10–20% decline in rainfall and temperature increases of up to 6 °C, particularly in northern and central regions (Salazar et al., 2024; Vicuña et al., 2020). These environmental pressures, combined with growing anthropogenic demands, have intensified

conflicts between competing water uses, including domestic supply, agriculture, and industry (Flörke et al., 2018; Gerland et al., 2014; Howden et al., 2007). In some areas, increasing consumption has exacerbated scarcity even where water availability has risen, while in regions with pre-existing deficits, the expansion of irrigated agriculture remains the primary driver of water stress (Huang et al., 2021). This local issue is situated within a global challenge, where a significant proportion of the population, even in Europe, lacks access to secondary treatment. Furthermore, the aging of centralized infrastructure is fostering a paradigm shift toward alternative water management systems (Ribarova et al., 2024).

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Agriculture is the most water-demanding activity worldwide, accounting for approximately 60% of global freshwater withdrawals (Adeyemi et al., 2017; Velasco-Muñoz et al., 2018). In developing countries, this proportion is even higher and is expected to increase by nearly 50% in the coming decades due to rising food demands (Fischer et al., 2007). In Chile, about 80% of available freshwater is allocated to irrigation, while significant volumes are also diverted to support mining operations (Fernández and Gironás, 2021). The northern region (18°–33°S), which includes the commune of La Higuera, is characterized by an arid to semi-arid climate, with an annual average precipitation of only 87 mm and surface runoff accounting for just 0.13% of the national total—the lowest per capita water availability in the country (Fernández and Gironás, 2021; Villamar et al., 2018). Despite these limitations, small-scale farmers in the region maintain horticultural production, underscoring the need for reliable alternative water sources.

Wastewater reuse has emerged as a sustainable strategy to mitigate water scarcity in arid and semi-arid regions, particularly for agricultural irrigation (Jaramillo and Restrepo, 2017; Vera-Puerto et al., 2022). In Chile, wastewater treatment coverage increased from 10% in 1990 to nearly 100% by 2016. However, only 0.8% of treated effluents are currently reused for agriculture, with most being discharged into rivers or the sea (Villamar et al., 2018). This conventional “treat-and-discharge” approach has been widely criticized for its energy-intensive nature and for functioning merely as a transfer station for pollutants, thereby contradicting the principles of a circular economy (Zhao et al., 2023). Consequently, a paradigm shift toward resource recovery is imperative, redefining wastewater treatment plants (WWTPs) as facilities for the recovery of water, energy, and nutrients (Zhao et al., 2023). The main barriers to reuse are microbial contamination and the presence of emerging organic contaminants, which require tertiary treatment to meet international and national safety standards (Khasawneh and Palaniandy, 2021; MINSAL: Ministerio de Salud de Chile, 2022). Disinfection technologies such as ultraviolet (UV) irradiation are widely recognized as effective for pathogen inactivation without generating harmful by products when the water does not show a high organic charge (Collivignarelli et al., 2021; Zhang et al., 2023). For this reason, it is necessary that UV irradiation will be applied in combination with another pre-treatment such as adsorption.

Fixed-bed filtration and adsorption have emerged as pragmatic tertiary-treatment options because they combine operational simplicity with the ability to target specific contaminant groups. Natural and synthetic zeolites have demonstrated high adsorption capacities for metals, ammonium, and organic compounds from wastewater because of their unique physicochemical properties and cost-effectiveness (Bahmanzadegan and Ghaemi, 2025; de Magalhães et al., 2022; Halalshah et al., 2022; Kumari et al., 2024; Onyutha et al., 2024). Evidence from pilot implementations indicates that mineral media can markedly improve effluent quality under continuous flow; for instance, gravity-driven fixed-bed reactors packed with zeolite or bentonite have delivered substantial decolorization and chemical oxygen demand (COD) abatement in real textile wastewater, with bentonite generally providing superior polishing and underscoring the importance of sufficient contact time to approach adsorption equilibrium (Zulti et al., 2025). In municipal reuse settings, more selective fixed-bed concepts have been developed to address trace contaminants. Engineered high-silica zeolites (Beta and Mordenite) have demonstrated high removal of diverse organic micropollutants (OMPs) with limited concomitant dissolved organic carbon (DOC) uptake, while in situ regeneration using gaseous ozone can restore adsorption capacity over repeated adsorption–regeneration cycles and reduce oxidant demand through optimized backwash and operational sequences (Fu et al., 2022). In parallel, zeolite columns have been explored within circular-economy frameworks for nitrogen valorization, where NH_4^+ uptake and subsequent desorption are strongly governed by particle size and hydraulic loading; smaller grains and higher adsorption flows typically enhance adsorption capacity, whereas controlled, lower

desorption flows can improve nutrient recovery efficiency (Muscarella et al., 2024).

Despite these advances, a clear knowledge gap persists for rural and water-scarce contexts, where tertiary treatment must be resilient to variable influent quality, rely on locally accessible materials, and address nitrogen species that frequently constrain reuse in irrigation. Prior fixed-bed studies have largely focused on (i) industrial COD/color polishing, (ii) OMP-selective adsorption using engineered media coupled to regeneration, or (iii) single-nutrient recovery strategies, and comparatively fewer investigations have systematically evaluated how low-cost filter media and operating conditions jointly control nitrate related pollutants and bulk water quality parameters in real secondary-treated domestic effluents. To address this gap, we investigate a modular, field-relevant tertiary treatment train for a rural WWTP in northern Chile, quantifying the influence of filter medium (natural zeolite, expanded clay, and manganese dioxide), particle-size fraction, and flow rate on the removal of nitrate and total nitrogen alongside COD, total suspended solids (TSS), and total dissolved solids (TDS). Importantly, the fixed-bed stage is integrated in series with activated carbon adsorption and UV irradiation, enabling an integrated assessment of solids/organic polishing, nitrogen attenuation, and downstream disinfection readiness within a scalable configuration tailored to decentralized wastewater reuse.

The results indicate that the configuration consisting of fixed-bed column filtration packed with natural zeolite (1.5–3 mm) operated in series with activated carbon at a flow rate of 2 m³/h, followed by UV disinfection at a power of 64 mJ/cm², achieved efficient removal of nitrate, total nitrogen, TSS, and fecal coliforms. Nevertheless, persistent challenges remained, particularly elevated electrical conductivity and TDS, which may constrain the suitability of the reclaimed water for irrigation of salt-sensitive crops.

2. Experimental section

2.1. Study design and experimental approach

The study was conducted in two sequential stages, laboratory-scale testing and pilot-scale validation, to design, optimize, and evaluate a sustainable tertiary treatment system for wastewater reuse in rural Chile. In the first stage, secondary effluents from the La Higuera wastewater treatment plant were characterized. Elevated levels of suspended solids (TSS), biochemical oxygen demand ($\text{BOD}_5 > 25 \text{ mg/L}$), fecal coliforms ($> 1.6 \times 10^4 \text{ MPN/100 mL}$), and variable total nitrogen (40–93 mg/L) and electrical conductivity (640–2209 $\mu\text{S/cm}$) highlighted the need for robust tertiary treatment. Two treatment configurations were evaluated:

Configuration A: zeolite column + activated carbon column + UV-C disinfection.

Configuration B: zeolite column + activated carbon column + ultrafiltration membrane + UV-C disinfection.

Operational parameters including flow rate (4–6 L/h), retention time (12–18 min), and membrane operating pressure (60 psi) were optimized at the laboratory scale. In the second stage, the optimized system was implemented at the La Higuera municipal treatment plant, where monthly monitoring (July–October 2024) was performed to evaluate performance under real operating conditions.

2.2. Study site and sampling

Secondary effluent samples were obtained from the La Higuera wastewater treatment plant, located in the Coquimbo Region of northern Chile (−29.512516°S, −71.208425°W). The facility employs primary and secondary treatment based on a biological activated sludge process. The implemented tertiary treatment plant is entirely powered by Non-Conventional Renewable Energy (NCRE) through photovoltaic panels, which reduces operational costs and results in lower costs for the

community. Three sampling campaigns were conducted in February 2024, each collecting 40 L of secondary effluent. Samples were preserved and transported under appropriate conditions to prevent degradation prior to analysis and treatment.

2.3. Physicochemical and microbiological characterization

Physicochemical and bacteriological analyzes were performed on all real wastewater samples using standardized methods. pH and electrical conductivity (EC) were measured using a multiparameter meter (Orion VersaStar) equipped with pH (Thermo Scientific) and conductivity (Orion 013005MD) probes. Total dissolved solids (TDS) and total suspended solids (TSS) were determined using standard gravimetric methods in accordance with Chilean Standard NCh 411, harmonized with the Standard Methods for the Examination of Water and Wastewater (APHA 2540 C and D). Major anions, including chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), and sulfate (SO_4^{2-}), were analyzed by ion chromatography (DIONEX™ ICS-3000) using an ion-exchange column (IONPAC™ AS11-HC) and a conductivity detector. Total phosphorus (tP) and total nitrogen (tN) were determined using HACH standard methods 8190 and 10,072, respectively. Chemical oxygen demand (COD) was measured using the cell test method (range: 0–1500 mg/L) at 147 °C, with absorbance at 600 nm measured using a HACH (DR2800) spectrophotometer, while biochemical oxygen demand (BOD₅) was determined by the dilution method using optical oxygen sensors after 5 days of incubation. Fecal and total coliforms were measured in DICTUC laboratory (Dirección de Investigaciones Científicas y Tecnológicas, Universidad Católica de Chile) under the Chilean standard ISO 9001 (www.dictuc.cl/; 2024). Regulatory limits were established based on Decree No. 90/2001 (DS 90/2001) for discharges to surface waters and Chilean Standard NCh 1333.Of 1978 for agricultural irrigation (Table 1).

2.4. Selection of adsorbent materials

Four different inorganic filter medias and activated carbon were selected based on their availability and reported performance in

Table 1
Maximum physicochemical and bacteriological parameters in Chilean standards.

Parameter	Unit	DS 90/2001	NCh 1333
Acidity	pH	6.0 - 8.5*	5.5 - 9.0
Electrical conductivity	EC	μS/cm	≤750*
Total dissolved solids	TDS	mg/L	≤500*
Total suspended solids	TSS	mg/L	80*
Chloride	Cl^-	mg/L	400*
Fluoride	F^-	mg/L	1.5*
Nitrate	NO_3^-	mg/L	
Sulfate	SO_4^{2-}	mg/L	1000*
Total phosphorus	tP	mg/L	10*
Total nitrogen	tN	mg/L	50*
Chemical oxygen demand	COD	mg/L	
Biochemical oxygen demand	BOD ₅	mg/L	35*
Fecal coliforms	(MPN/100 mL)		<1000/100 mL*
Total coliforms	(MPN/100 mL)		

Decree No. 90/2001, Emission Standard for Discharging Liquid Waste into Marine and Continental Surface Waters, which establishes limits for treated water discharged into rivers without dilution of the receiving body (DS 90/2001). Chilean Standard NCh 1333.Of78 (modified in 1987), which specifies water quality requirements for various uses (Norma Chilena Oficial NCh 1333.Of.78 modified in 1987). MPN: Most Probable Number; *: parameter used in this study, NR: not reported.

wastewater treatment. Two natural zeolite with different size particles (Zeo1 and Zeo2), one expanded clay (Zeo3) and one manganese dioxide (Zeo4) were compared to assess efficiency (Table 2, Fig. S1). Granular activated carbon was used as the secondary adsorbent. Key properties included granulometry, zeolite content, BET surface area, and bulk density.

2.5. Treatment performance evaluation

The experimental study was conducted in two main stages, aiming to address the physicochemical and bacteriological characteristics of the effluent from the La Higuera treatment plant after secondary treatment. In Stage 1, the performance of different zeolites and activated carbon was evaluated to determine the effectiveness of fixed-bed filtration (filtration columns) in removing TSS and organic compounds in the effluent. In Stage 2, two treatment sequences were assessed. In Stage 2A, the effluent previously filtered in Stage 1 was directly subjected to UV-C light radiation disinfection at varying flow rates. In Stage 2B, the effluent obtained from Stage 1 was first treated by an ultrafiltration (UF) membrane, followed by UV-C light radiation disinfection, to evaluate the potential synergistic effect of the combined processes (Table S1 and Fig. 1).

2.5.1. Stage 1: Column filtration

Column filtration experiments were performed using two laboratory-scale columns (Fig. S2) under the following conditions: Zeolite column (60 cm bed height, 1.08 kg) followed by activated carbon column (0.648 kg). PVC columns (90 cm × 5 cm i.d.) with stainless steel mesh at the base. Flow rates: 4 and 6 L/h, operated at room temperature in downward flow. Each experiment used ≈8 L of effluent and was run in duplicate.

A backwashing process was performed on the zeolites prior to their use. No regeneration studies of the zeolites after treatment were conducted.

The performance of the filtration columns was evaluated using three key parameters: flow rate (Eq. (1)) (Herrmann et al., 2013), retention time (R_t ; Eq. (2)) (Ladu and Lü, 2014), and removal efficiency ($Re\%$; Eq. (3)) (Ahmad et al., 2020).

$$\text{Flow rate} = \frac{Q}{A}, \text{ where } A = \frac{D^2 \times \pi}{4} \quad \text{Eq. 1}$$

Where Q is the volumetric flow rate (L/h or m^3/d), A is the cross-sectional area of the column (m^2), D is the internal diameter of the column (m), and π is 3.1416. This equation was used to estimate the velocity at which water flows through the filter bed.

$$\text{Retention time } (R_t) = \frac{V}{Q}; \text{ where } V = A \times h \quad \text{Eq. 2}$$

Where V is the effective volume of the column (m^3), Q is the flow rate (m^3/d), A is the cross-sectional area (m^2), and h is the filter bed height (m). Retention time indicates the duration that wastewater remains in contact with the filter medium, a key factor in contaminant removal.

$$\text{Removal performance } (Re\%) = \frac{C_0 - C_e}{C_0} \times 100 \quad \text{Eq. 3}$$

Table 2
Zeolites (Zeo) and activated carbon (AC) properties.

Parameter	Zeo1	Zeo2	Zeo3	Zeo4	AC
Granulometry (mm)	1.5-3.5	3.0-5.0	1.0-2.5	0.8-1.6	0.6-2.4
Zeolite content (%)	50-80	50-80	>80	63	–
Specific surface area (BET Method m^2/g)	446-480	446-480	–	22.4	1050
Bulk density (g/ml)	–	–	0.9	0.515	0.54

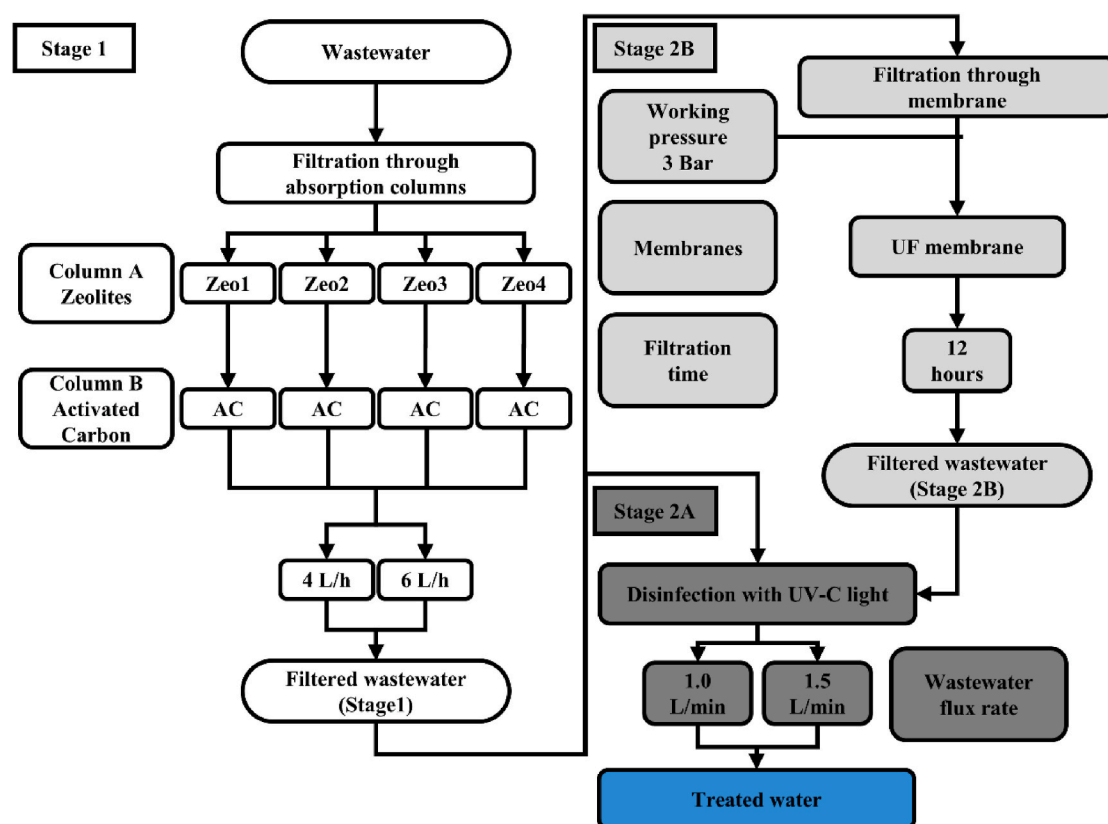


Fig. 1. Experimental design for wastewater treatments. Inorganic filtrate materials (Zeo1, Zeo2, Zeo3, Zeo4), activated carbon (AC), UV-C light radiation (UV-C), ultrafiltration membrane (UF), liters per hour (L/h), and liters per minute (L/min).

Where C_0 is the initial concentration of a specific contaminant (mg/L), and C_e is the final concentration of the same contaminant (mg/L). This metric was used to quantify the effectiveness of each filtration setup under controlled conditions.

2.5.2. Stage 2A: UV-C disinfection

Effluent from Stage 1 was treated with a UV Oji Reuse disinfection system under two different flow rates (1.0 and 1.5 L/min). The UV-C LED reactor (OJIMICRO UV 02) was installed inline and operated in continuous-flow mode at a flow rate, under ambient temperature conditions, allowing direct irradiation of the effluent. UV dose was 96 mJ/cm² and 64 mJ/cm² at 98% UV transmittance, to the operating flow rate 1.0 and 1.5 L/min, respectively.

Bacteriological and physicochemical parameters were measured before and after UV-C exposure.

2.5.3. Stage 2B: Ultrafiltration + UV-C disinfection

Effluent from Stage 1 was further treated using a flat-sheet ultrafiltration (UF) membrane (Synder BX-UB70, PVDF, nominal pore size 0.03 µm, effective membrane area 20.6 cm²). The UF system was operated in cross-flow mode at an operating pressure of 40–60 psi and at ambient temperature, processing approximately 8 L per experimental run. Subsequently, the UF permeate was disinfected using the UV-C disinfection system described in section 2.5.2 at flow rate of 1.5 L/min.

3. Results and discussion

Recurrent droughts in Chile have underscored the urgency of implementing sustainable water policies that balance anthropogenic demand and climatic constraints (Segura et al., 2018). The commune of La Higuera, located in the northern Coquimbo Region (4158 km²; 4335 inhabitants), represents a critical case of water stress, driven primarily

by agricultural demand (82% of total water use) and exacerbated by limited technical efficiency (Broschek and Díaz, 2018). This study evaluated tertiary treatment strategies for domestic wastewater reuse, with potential application in agricultural and urban irrigation.

3.1. Physicochemical and bacteriological characteristics of secondary effluent

The secondary effluent exhibited substantial temporal variability (Fig. 2), with several parameters exceeding Chilean standards (Broschek and Díaz, 2018; MINSAL: Ministerio de Salud de Chile, 2022). The pH remained stable within permissible limits (6.8–7.2), but EC (1252–1854 µS/cm) and TDS (1015–1276 mg/L) often surpassed regulatory reflecting the high ionic background typical of northern Chile (Table S2).

Suspended solids generally complied (<8.6 mg/L), except for the final measurement (86.7 mg/L), which emphasizes their episodic role in reducing water quality and facilitating pathogen transport (Adjovu et al., 2023a, 2023b). Organic load indicators also varied: BOD₅ (9–33 mg/L) consistently complied with Chilean standards (<35 mg/L), whereas COD (46–185 mg/L) occasionally exceeded international thresholds (100 mg/L).

Bacteriological quality was the most critical issue: both fecal and total coliforms consistently exceeded standards (Table S2), highlighting health risks for direct agricultural reuse (Faour-Klingbeil and Todd, 2018). Nutrients showed dual behavior: phosphorus remained <10 mg/L, while tN (45–56 mg/L) frequently exceeded the 50 mg/L limit. Although nutrients may enhance crop productivity, continuous application risks soil accumulation and eutrophication (El Lateef et al., 2020; Jaramillo and Restrepo, 2017). Overall, the data confirmed the need for tertiary treatment to ensure safe reuse.

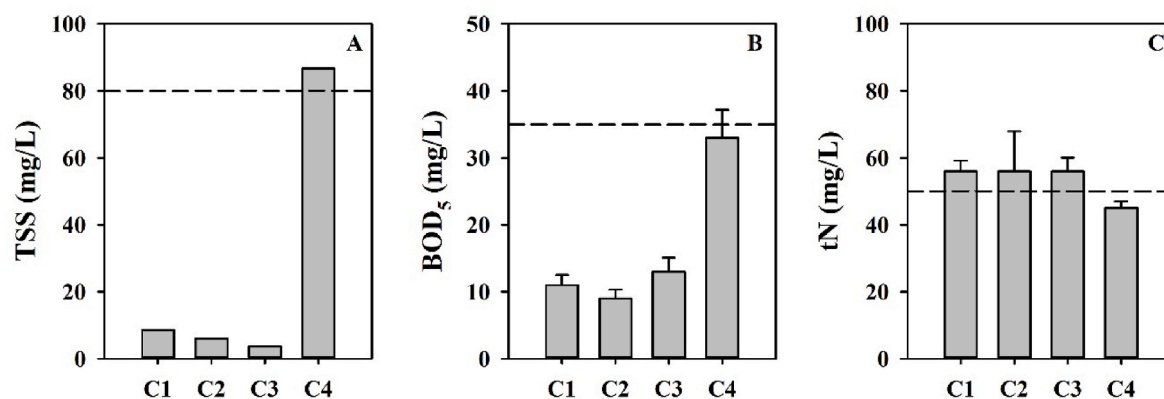


Fig. 2. Wastewater characteristics from La Higuera treatment plant. A) Total suspended solids (TSS; mg/L), B) Biochemical oxygen demand (BOD₅; mg/L), and C) Total nitrogen (tN; mg/L) in effluent after secondary treatment. Parameters were monitored from February to April 2024. C1, C2, C3, C4 correspond to sampling campaigns. Bars represent parameter concentrations; error bars indicate standard deviation when replicate measurements were available. For parameters determined from a single measurement following standardized methods, no error bars are shown. The dotted horizontal line indicates the maximum limit established by the Chilean standard (TSS: 80 mg/L, BOD₅: 35 mg/L and tN: 50 mg/L).

3.2. Laboratory-scale tertiary treatment

Considering the different physicochemical parameters measured in the water obtained from secondary treatment, we carried out a systematic study to develop a tertiary treatment at the laboratory scale. This study involved the selection of robust processes such as column filtration, membrane filtration, and UV disinfection, using different filter materials like zeolites, activated carbon, and membranes (Fig. 1).

3.2.1. Stage 1 – Column filtration – Zeo + CA: Zeolite selection and flow rate

Four filter materials (Zeo1–Zeo4) were tested at two flow rates (4 and 6 L/h). All systems improved effluent quality, but performance varied by zeolite origin and hydraulic conditions (Table 3). The pH increased to 8.1–9.5, sometimes exceeding limits (6.0–8.5). This alkalization is linked to NH₄⁺ exchange and proton retention on zeolite surfaces (Guida et al., 2020). The TSS removal was highly effective, with complete elimination in most cases. Zeo4+AC showed the lowest

Table 3

Physicochemical and bacteriological characteristics of wastewater after filtration with four zeolites (Zeo1 to Zeo4, national and imported) and activated carbon (AC) under two flow rates (4 and 6 L/h).

				National						Imported			Water quality regulations	
				Zeo1+CA		Zeo2+CA			Zeo3+CA		Zeo4+CA		NCh1333 ^a	DS90/2001 ^{**}
Parameter		Unit	Control	4.0 L/h	6.0 L/h	4.0 L/h	6.0 L/h	Control	4.0 L/h	6.0 L/h	4.0 L/h	6.0 L/h		
Acidity	pH		7.1	8.7	8.9	8.5	9.2	7.2	8.1	8.1	9.5	9.3	5.5-9.0	6.0-8.5
Electrical conductivity	EC	μS/cm	1748	1191	1323	1297	1253	1854	1459	1295	1245	1577	≤750	NA
Total dissolved solids	TDS	mg/L	1098	829	891	845	847	1092	750	737	743	1005	≤500	NA
Total suspended solids	TSS	mg/L	8.6	ND	ND	ND	ND	6.0	ND	ND	2.0	2.0	NA	80
Chloride	Cl ⁻	mg/L	275 ± 23	260 ± 16	158 ± 8	323 ± 20	136 ± 12	283 ± 22	202 ± 16	201 ± 12	125 ± 10	185 ± 21	200	400
Fluoride	F ⁻	mg/L	0.26 ± 0.01	ND	ND	ND	ND	0.26 ± 0.05	ND	ND	ND	ND	NA	1.5
Nitrate	NO ₃ ⁻	mg/L	3.29 ± 0.5	ND	ND	ND	ND	27.30 ± 16	ND	ND	ND	ND	NA	NA
Sulfate	SO ₄ ²⁻	mg/L	290 ± 7	206 ± 11	230 ± 11	222 ± 9	203 ± 10	289 ± 22	256 ± 18	256 ± 16	187 ± 21	243 ± 16	250	1000
Total phosphorus	tP	mg/L	5.4 ± 1.0	ND	ND	ND	ND	5.0 ± 1.1	ND	ND	ND	ND	NA	10
Total nitrogen	tN	mg/L	56 ± 3.2	4 ± 0.4	10 ± 1.6	9 ± 1.4	11 ± 0.9	56 ± 12	14 ± 1.2	4 ± 0.8	23 ± 1.1	27 ± 1.0	NA	50
Chemical oxygen demand	COD	mg/L	79.0 ± 6.1	ND	10.5 ± 1	22.6 ± 3.1	17.5 ± 1.1	46.0 ± 3.4	11.0 ± 1	25.0 ± 1.2	ND	ND	NA	NA
Biochemical oxygen demand	BOD ₅	mg/L	11.0 ± 1.5	1.5 ± 0.07	6.0 ± 0.9	15.5 ± 1.3	3.5 ± 0.03	9.0 ± 1.3	ND	2.0 ± 0.05	ND	ND	NA	35

^a Chilean Standard NCh 1333.Of.78, amended in 1987, which specifies water quality requirements for different uses. ^{**}Supreme Decree No. 90/2001, Emission Standard for Discharges of Liquid Waste into Marine and Continental Surface Waters, which establishes limit values for treated effluents discharged to receiving water bodies without dilution (DS 90/2001). MPN: Most Probable Number; ND: Not detected (considered as regulatory compliance); NA: Not applicable, corresponding to parameters that are not included in the evaluated standard or regulation.

performance (67% removal), attributed to lower bulk density and larger interstitial voids (Shaikh and Ahammed, 2022). Organic load removal was substantial: COD decreased by up to 100% in Zeo1 and Zeo4, while BOD₅ dropped to 1.5–6.0 mg/L, consistent with the reported synergy between zeolite filtration and activated carbon polishing (Titah and Nasir, 2024).

Nitrogen removal was highest with zeolites (Zeo1 and Zeo2) which is primarily attributed to the inherent cation exchange capacity of natural aluminosilicates. The crystalline framework of zeolites, characterized by the isomorphic substitution of Si⁴⁺ by Al³⁺, generates a net negative charge balanced by exchangeable cations such as Ca²⁺, K⁺, and Na⁺ (Paliaga et al., 2025). This structure facilitates the selective adsorption of ammonium ions (NH₄⁺) through ion exchange and electrostatic interactions, enabling effective nitrogen recovery from treated effluents (Nibe and Gaikwad, 2025). However, since NH₄⁺ was not measured in this study, NH₄⁺ exchange cannot be directly confirmed from the available dataset. Accordingly, we interpret the improved tN performance of zeolite-based configurations primarily as an observed net decrease in tN, and we discuss NH₄⁺ exchange as a plausible contributing mechanism supported by literature. Mechanistically, clinoptilolite-type zeolites exhibit enhanced selectivity toward NH₄⁺ due to pore-size compatibility (≈0.4 nm) and relatively low hydration energy compared with competing cations (Bulacio Fischer et al., 2025a), which would be consistent with the higher tN attenuation observed here.

For the Zeo1+AC configuration at 4.0 L/min, nitrate-N (NO₃⁻-N) and tN decreased simultaneously under a high COD/NO₃⁻-N ratio (≈24). This co-decline is an observed outcome, while the underlying pathway cannot be resolved with certainty because NH₄⁺ and NO₂⁻ were not monitored. Nevertheless, the high COD/NO₃⁻-N ratio and the likelihood of anoxic microenvironments within a flooded packed bed are conditions that may be consistent with heterotrophic denitrification as a contributing process (Forbis-Stokes et al., 2018). In addition, at identical flow, the higher tN removal of Zeo1-AC relative to Zeo4-AC (≤59%, Table 3) suggests an additional removal contribution associated with the zeolite stage. Because nitrogen speciation was not fully characterized, we conservatively interpret this difference as retention/removal of non-nitrate nitrogen fractions, potentially including particulate/colloidal N and/or NH₄⁺ via cation exchange, which could remain effective even at short empty bed contact time. Importantly, the measured tN decrease indicates net removal from the aqueous phase, but it does not by itself distinguish between adsorption/filtration versus biological conversion pathways. Future monitoring of NH₄⁺-N, NO₂⁻-N, and TKN/DON (or a complete nitrogen mass balance) would close the speciation gap and enable a clearer separation of exchange/filtration-driven tN removal from biological transformations.

A persistent challenge identified in our system was the limited reduction of EC and TDS parameters that frequently exceeded the limits established by the Chilean standard NCh 1333 (≤750 µS/cm, ≤500 mg/L). This limitation is inherent to the nature of fixed-bed adsorption processes with zeolite and activated carbon. While these media are highly effective for the removal of specific ions (e.g., NH₄⁺), particulate matter, and organic compounds, they possess an intrinsically limited capacity to reduce the total ionic load responsible for salinity (Lin et al., 2009). The removal of dissolved ions such as Cl⁻ and SO₄²⁻ was minimal, which is consistent with the ion-exchange and physical adsorption mechanisms that characterize these materials. In the context of agricultural reuse in arid zones, soil salinity accumulation is a critical risk (De Sanctis et al., 2016; Rahimi et al., 2000). Therefore, although our system produced a microbiologically safe effluent with low levels of nutrients and organic matter, its application should prioritize salt-tolerant crops or consider a complementary post-treatment stage (e.g., dilution with another water source) if the effluent is intended for salt-sensitive crops. High salinity remains a long-term challenge due to risks of soil degradation (De Sanctis et al., 2016; Rahimi et al., 2000).

3.2.2. Reuse standards and compliance assessment

Supreme Decree No. 90/2001 sets Chile's emission standards for liquid waste discharges into marine waters and continental surface waters, establishing maximum permissible limits for 35 regulated parameters grouped into physical, organic, nutrients, inorganic salts/anions, heavy metals, and microbiological categories (Ministerio Secretaría General de la Presidencia, 2001). In this study, compliance was evaluated for nine parameters: pH, TSS, BOD₅, tN, phosphorus, chlorides, sulfates, fluorides, and fecal coliforms were selected as the most representative indicators of effluent quality for surface-water discharge, particularly regarding organic load, nutrient enrichment potential, salinity-related constraints, and sanitary condition. Heavy metals were not included, consistent with the domestic origin of the influent and the absence of identifiable industrial inputs, for which trace or negligible concentrations are typically expected. The compliance of selected parameter is showed in Table 4.

Across configurations, pH exhibited the greatest operational sensitivity: full compliance (100%) was achieved only by Zeo2+CA (4 L/h) and Zeo3+CA (4 and 6 L/h), whereas the remaining configurations fell outside the regulatory range, highlighting pH control as a potential limiting factor for discharge under certain operating conditions. The TSS performance was consistently strong; most configurations returned concentrations below the detection limit and were thus classified as fully compliant under the adopted criterion, while Zeo4+CA (4 and 6 L/h) yielded quantifiable values yet still maintained high compliance (97.5%), confirming effective solids polishing through the treatment train. Salinity-related ions showed more heterogeneous behavior: chloride compliance remained intermediate and seldom reached optimal levels, with the highest compliance observed for Zeo4+CA (4 L/h) (68.8%), followed by Zeo1+CA (6 L/h) (60.5%) and Zeo4+CA (6 L/h) (53.8%), while Zeo3+CA (4 and 6 L/h) approached ≈50% and Zeo1+CA (4 L/h) and Zeo2+CA (4 and 6 L/h) remained below 50%, indicating limited chloride attenuation across most configurations. In contrast, sulfate showed consistently higher compliance (>70%) in all cases, peaking for Zeo4+CA (4 L/h) (81.3%), suggesting a comparatively uniform system response for this anion under the tested conditions. Nitrogen outcomes were configuration-dependent, with the strongest tN compliance obtained for Zeo1+CA (4 L/h) and Zeo3+CA (6 L/h) (both ≈92%), whereas Zeo4+CA (4 and 6 L/h) exhibited the lowest compliance (54% and 46%), implying reduced effectiveness for nitrogen compound removal in that configuration. The BOD₅, reflecting biodegradable organic load, further differentiated performance: Zeo3+CA (6 L/h) achieved 100% compliance, while Zeo1+CA and Zeo2+CA showed partial compliance; for configurations with non-quantifiable BOD₅ results (ND), compliance was conservatively assumed under the adopted criterion, overall supporting efficient biodegradable organic matter removal across the evaluated treatment train. Taken together, Zeo3+CA (6 L/h) emerged as the most robust configuration with respect to DS 90/2001-regulated parameters, combining full compliance for pH and BOD₅ with consistently strong solids removal, thereby reducing oxygen-demanding discharges that may impair ecological quality in receiving waters (Jaramillo and Restrepo, 2017). Its high tN compliance further underscores a meaningful capacity to mitigate nitrogen-related eutrophication risks when discharge concentrations are not adequately controlled (De Sanctis et al., 2016; Vera-Puerto et al., 2022). Nonetheless, incomplete compliance for chloride (and, to a lesser extent, sulfates) indicates that salinity-related constraints persist, with removal remaining partial but broadly consistent across configurations.

The compliance assessment with Chilean irrigation standard NCh 1333 was intentionally framed around the intended end use of the reclaimed effluent irrigation of ornamental plants and urban green areas thereby prioritizing parameters most directly linked to salinity, ionic charge, and overall physicochemical suitability. Although NCh 1333 specifies 31 parameters for irrigation water, this study evaluated seven based on available analytical data and study scope: pH, EC, TDS, chlorides, fluorides, sulfates, and fecal coliforms. The compliance grade of

Table 4

Evaluation of compliance with DS 90/2001.

Parameter		Zeo1+CA		Zeo2+CA		Zeo3+CA		Zeo4+CA	
		4.0 L/h	6.0 L/h	4.0 L/h	6.0 L/h	4.0 L/h	6.0 L/h	4.0 L/h	6.0 L/h
Acidity	pH	-	-	+	-	+	+	-	-
Electrical conductivity	EC	NA	NA	NA	NA	NA	NA	NA	NA
Total dissolved solids	TDS	NA	NA	NA	NA	NA	NA	NA	NA
Total suspended solids	TSS	+	+	+	+	+	+	+	+
Chloride	Cl ⁻	+	+	+	+	+	+	+	+
Fluoride	F ⁻	+	+	+	+	+	+	+	+
Nitrate	NO ₃ ⁻	NA	NA	NA	NA	NA	NA	NA	NA
Sulfate	SO ₄ ²⁻	+	+	+	+	+	+	+	+
Total phosphorus	tP	+	+	+	+	+	+	+	+
Total nitrogen	tN	+	+	+	+	+	+	+	+
Chemical oxygen demand	COD	NA	NA	NA	NA	NA	NA	NA	NA
Biochemical oxygen demand	BOD ₅	+	+	+	+	+	+	+	+

Compliance with water quality parameters was assessed according to the limits established in the Chilean Standard DS 90/2001. The symbol (+) indicates regulatory compliance, whereas (-) indicates non-compliance. NA refers to parameters not applicable, as they are not included in the evaluated standard or regulation. ND denotes parameters not detected during analysis, which were considered as regulatory compliance (+) for the purposes of the assessment.

these parameters is summarized in Table 5. Heavy metals were excluded likewise to DS 90/2001 because the tested water corresponds to secondary/tertiary-treated municipal effluent with no identifiable industrial inputs. Nonetheless, metals are explicitly recognized as a priority line for future work, particularly for agricultural reuse scenarios and where long-term accumulation in productive soils may occur.

Overall compliance patterns were highly configuration- and flow-dependent. For pH, full compliance was achieved by Zeo1+AC (4–6 L/h), Zeo2+AC (4 LPH), and Zeo3+AC (4–6 L/h), whereas Zeo2+AC (6 L/h) and Zeo4+AC (both flow rates) fell outside the regulatory range, limiting their direct irrigation applicability. In contrast, EC exhibited consistently high compliance (>99%) across all configurations, indicating effective salinity attenuation (with Zeo4+AC at 6 L/h reaching 100% compliance). However, none of the configurations met the TDS limit, highlighting dissolved solids as a cross-cutting constraint for irrigation reuse under NCh 1333 even when EC is substantially reduced.

Ion-specific criteria further differentiated system performance. Chloride compliance varied markedly: Zeo4+AC (6 L/h) achieved 100% compliance, while several configurations showed low (<50%) or null (0%) compliance, underscoring chloride as a critical limiting parameter for reuse. A similar trend was observed for sulfates, where Zeo4+AC (6 L/h) again achieved full compliance, whereas the remaining configurations only partially complied or failed entirely. Fluoride met the regulatory threshold in all cases, as concentrations were below the method detection limit, which was lower than the standard's maximum allowable value.

While Zeo4+AC operated at 6 L/h provided the most stringent compliance with ion-specific irrigation constraints (notably chloride and sulfate), Zeo1+AC at 4 L/h also emerged as a technically viable option due to its full pH compliance and consistently high EC compliance, albeit with only partial compliance for chloride and sulfate, which may require complementary control depending on site-specific irrigation sensitivity.

Despite these improvements, microbial contamination persisted in all cases, highlighting the necessity of a dedicated downstream disinfection step.

3.2.3. Stage 2A: Zeolite + activated carbon filtration + UV-C disinfection

Wastewater filtered through the Zeo1 + activated carbon system (4 L/h) and subsequently exposed to UV-C light radiation showed a sharp reduction in bacteriological indicators (Fig. 3). Fecal coliforms decreased by 99.8%, from 1.3×10^4 MPN/100 mL in the untreated control to 23 and 50 MPN/100 mL at flow rates of 1.0 and 1.5 L/min, respectively, well below the regulatory threshold for irrigation reuse (<1000 MPN/100 mL). Total coliforms followed a similar trend, declining to 23 and 240 MPN/100 mL (Fig. 3). These results confirm the strong disinfection capacity of UV-C light radiation after filtration, in line with reported efficiencies of commercial UV systems (Bick et al., 2001; Collivignarelli et al., 2021), and demonstrate its reliability for rural applications (Nguyen et al., 2019).

From a technical perspective, the 1.0 L/min flow rate provided superior performance, achieving full compliance with bacteriological standards and enhancing the effectiveness of UV-C disinfection. At this

Table 5

Evaluation of compliance with NCh1333.

Parameter		Zeo1+CA		Zeo2+CA		Zeo3+CA		Zeo4+CA	
		4.0 L/h	6.0 L/h	4.0 L/h	6.0 L/h	4.0 L/h	6.0 L/h	4.0 L/h	6.0 L/h
Acidity	pH	+	+	+	-	+	+	-	-
Electrical conductivity	EC	+	+	+	+	+	+	+	+
Total dissolved solids	TDS	-	-	-	-	-	-	-	-
Total suspended solids	TSS	NA	NA	NA	NA	NA	NA	NA	NA
Chloride	Cl ⁻	-	+	-	+	-	-	+	+
Fluoride	F ⁻	NA	NA	NA	NA	NA	NA	NA	NA
Nitrate	NO ₃ ⁻	+	+	+	+	+	+	+	+
Sulfate	SO ₄ ²⁻	+	+	+	+	-	-	+	+
Total phosphorus	tP	NA	NA	NA	NA	NA	NA	NA	NA
Total nitrogen	tN	NA	NA	NA	NA	NA	NA	NA	NA
Chemical oxygen demand	COD	NA	NA	NA	NA	NA	NA	NA	NA
Biochemical oxygen demand	BOD ₅	NA	NA	NA	NA	NA	NA	NA	NA

Compliance with water quality parameters was assessed according to the limits established in the Chilean Standard NCh 1333. The symbol (+) indicates regulatory compliance, whereas (-) indicates non-compliance. NA refers to parameters not applicable, as they are not included in the evaluated standard or regulation. ND denotes parameters not detected during analysis, which were considered as regulatory compliance (+) for the purposes of the assessment.

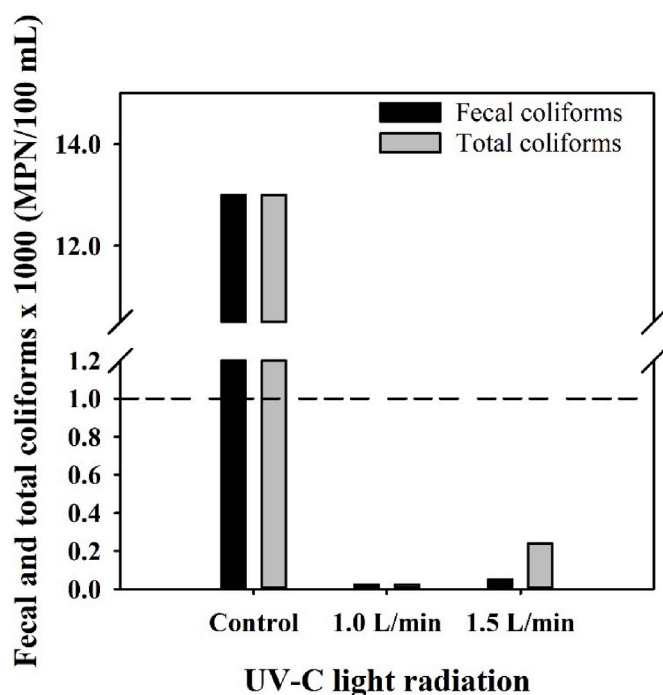


Fig. 3. UV-C disinfection of filtered wastewater. Fecal coliforms (black bars) and total coliforms (gray bars) in wastewater before and after filtration with zeolite and activated carbon and irradiation with UV-C light radiation at 1.0 and 1.5 L/min flow rate. Bars represent parameter concentrations. As parameters were determined from single measurements following standardized analytical methods, no error bars are shown. Analyses were based on single determinations conducted under ISO-certified procedures in an accredited DICTUC laboratory (Dirección de Investigaciones Científicas y Tecnológicas, Pontificia Universidad Católica de Chile). The dotted horizontal line indicates the maximum limit established by the Chilean standard (Fecal and total coliforms: <1000 MPN/100 mL; MPN: Most Probable Number).

lower flow, additional improvements were also observed in parameters such as TSS and COD, while BOD₅ remained unaffected (Table S4). Overall, the combination of zeolite-carbon filtration and UV-C disinfection proved effective for producing effluents suitable for safe agricultural reuse in northern Chile.

3.2.4. Stage 2B: Column filtration + UF membrane + UV disinfection

The stepwise treatment system, combining Zeo1 + activated carbon (4 L/h), ultrafiltration, and UV-C disinfection, markedly improved wastewater quality (Fig. 4; Table S5). Progressive reductions in TSS, BOD₅, and COD were observed across the treatment stages, meeting regulatory thresholds and confirming effective removal of particulate and organic matter (Fig. 4A–B). Bacteriological indicators showed the most significant improvements. Each treatment stage contributed to bacterial reduction, with UV-C achieving near-complete inactivation of both fecal and total coliforms (Fig. 4C). This highlights a strong synergistic effect between filtration and disinfection, ensuring microbial safety for potential reuse.

Nutrient dynamics revealed partial removal of total nitrogen, likely due to adsorption onto Zeo1 and AC and retention by UF, while tP decreased from 7.8 mg/L in the control to undetectable levels after treatment (Fig. 4D; Table S5). In contrast, non-standardized parameters such as EC, TDS, chloride, and sulfate remained largely unchanged.

Despite efficient performance for pollutant removal, it was observed that the UF exhibited a flux decline of up to 50% (Fig. S3), primarily due to membrane fouling. Considering that the system operates under a cross-flow configuration, the fouling rate is expected to be considerably higher for this type of treated water, which presents an elevated

bacteriological load. Such conditions promote the formation of deposits on the membrane surface, ultimately reducing the permeate flux and limiting the feasibility of UF for long-term application in rural wastewater treatment systems. Decline in water flux is a classic phenomenon of membrane fouling. Studies such as that by Choi et al. (2005) explain that fouling in systems with permeate flow is driven by a drag force that transports foulants toward the membrane surface and pores, resulting in pore blockage. Lin et al. (2009) detail that the severity of fouling depends on pore size and the mass of retained organic matter. In our case, the secondary effluent, even after zeolite and carbon filtration, contained a residual load that contributed to the obstruction of the UF membrane (0.03 µm), increasing hydraulic resistance. This finding validates the decision to discard UF in the pilot configuration. The simplicity of the system based solely on adsorption columns and UV-C emerges as a key advantage for rural applications, as it eliminates the operational complexity and maintenance costs associated with membrane cleaning or replacement, problems that are widely documented (Chapalaghi et al., 2022; Choi et al., 2005). For this reason, the scaled-up treatment train did not include the ultrafiltration (UF) membrane step; it comprised only fixed-bed column filtration followed by UVC disinfection.

3.3. From lab to field: Pilot-scale validation at La Higuera wastewater plant

The optimized system (Zeo1+AC + UV-C) was scaled up and validated under real operating conditions (Fig. 5). The integrated process significantly enhanced effluent quality. The TSS decreased from 6.3 ± 0.2 to 1.9 ± 0.5 mg/L ($\approx 70\%$ removal), while BOD₅ dropped from 26.5 ± 7.3 to 10.4 ± 1.0 mg/L, remaining well below the 35 mg/L limit. The COD was also reduced by 52.6% (50.4 to 21.4 mg/L). Bacteriological indicators showed dramatic improvements: fecal coliforms dropped from $12,707 \pm 12,431$ to 13 ± 4 MPN/100 mL, and total coliforms from $14,199 \pm 11,934$ to 17 ± 8 MPN/100 mL ($>99.9\%$ removal). Nutrient concentrations showed moderate reductions, with tN and tP decreasing by $\approx 14\%$ and 37% , respectively. Salinity (EC, TDS, Cl⁻, and SO₄²⁻) remained largely unchanged, consistent with their ionic nature. The pilot-scale results validated the technical feasibility and robustness of the system in rural Chilean conditions, confirming its potential for safe agricultural reuse.

The temporal decline in system efficiency (from 86% in July to 78% in October) is consistent with a common dynamic in fixed-bed zeolite systems: an initial high-removal phase driven by abundant available exchange/adsorption sites, followed by progressive site occupation and the approach to breakthrough as bed loading accumulates. This “capacity exhaustion” behavior is widely documented for natural-zeolite packed columns treating real wastewaters and is typically captured through breakthrough-curve concepts and fixed-bed modeling, where performance decreases as the mass-transfer zone migrates through the bed (Sheikh et al., 2023). In line with this (Bulacio Fischer et al., 2025b), report column operation with zeolite treating real treated wastewater and discuss how column performance is constrained by finite sorption capacity and operational conditions, supporting the interpretation that declining removal can reflect progressive saturation of active sites (Bulacio Fischer et al., 2025a). Accordingly, the decrease observed here can be interpreted as a capacity-limited trend rather than a sudden process failure, and similar limitations have also been highlighted in pilot-scale applications of natural-zeolite-based systems for nitrogen control (Yu et al., 2025).

The utilization of natural zeolites not only reduces costs and minimizes the environmental footprint associated with material transport (Nibe and Gaikwad, 2025) also aligns with the development of robust, context-appropriate treatment technologies. The abiotic nature of both the present system and the Fe-C/zeolite system described by (Yu et al., 2025) offers a distinct advantage for implementation in variable climates, such as the semi-arid region of La Higuera or during cold winters,

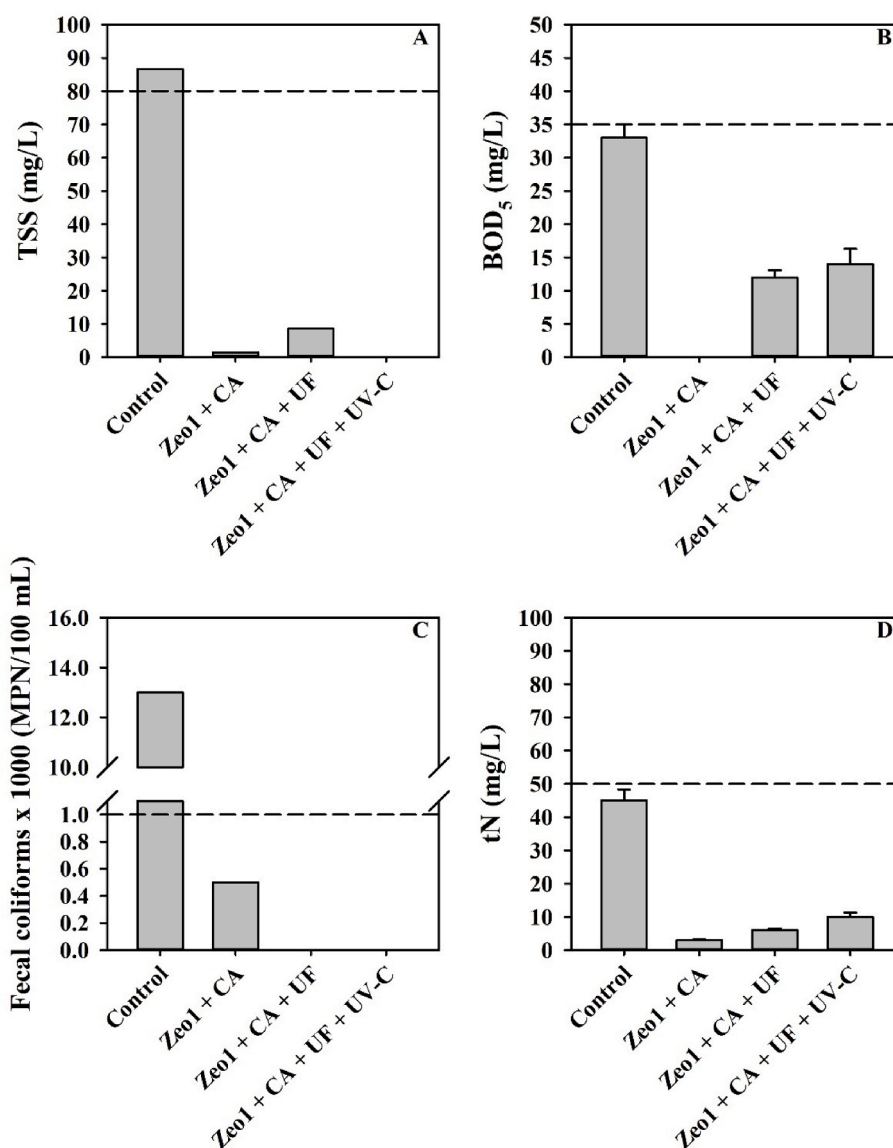


Fig. 4. Physicochemical and bacteriological characteristics of wastewater after filtration and disinfection. A) Total suspended solids (TSS; mg/L), B) Biochemical oxygen demand (BOD₅; mg/L), C) Fecal coliforms (MPN/100 mL), and D) Total nitrogen (tN; mg/L) in effluent after secondary treatment, after filtration with Zeolite (Zeol1), activated carbon (AC), ultrafiltration membrane (UF), and disinfection with UV-C light radiation. Bars represent parameter concentrations; error bars indicate standard deviation when replicate measurements were available. For parameters determined from single measurements following standardized analytical methods, no error bars are shown. Microbiological analyses were conducted under ISO-certified procedures in an accredited DICTUC laboratory (Dirección de Investigaciones Científicas y Tecnológicas, Pontificia Universidad Católica de Chile), under single measurements and no error bars are shown. The dotted horizontal line indicates the maximum limit established by the Chilean standard (TSS: 80 mg/L, BOD₅: 35 mg/L, Fecal coliforms: <1000 MPN/100 mL and tN: 50 mg/L; MPN: Most Probable Number).

as performance does not depend on sensitive microbial consortia, unlike conventional nitrification–denitrification processes. Recent full-scale column studies have affirmed that zeolite can sustain significant NH₄⁺ adsorption even under low effluent concentrations, reinforcing the technical feasibility of this strategy in rural settings (Paliaga et al., 2025). Ultimately, integrating zeolite-based nitrogen recovery supports the shift from conventional “treat-and-discharge” paradigms toward resource-oriented wastewater management, contributing directly to Sustainable Development Goals (SDGs) 6 (Clean Water and Sanitation) and 12 (Responsible Consumption and Production (Paliaga et al., 2025), and offers a scalable model for enhancing water security in water-stressed regions globally.

4. Limitations and system adaptability

The four-month pilot-scale validation confirmed the efficiency of the treatment system under fluctuating influent quality (e.g., BOD₅: 11–48 mg/L; tN: 56–80 mg/L). Because the pilot campaign spanned only ~3–4 months, the results primarily demonstrate short-term feasibility under real operating conditions. Longer-term operation across multiple seasons is still needed to confirm robustness and to characterize breakthrough/saturation dynamics. In addition, two critical challenges were identified. First, nitrogen removal efficiency was variable: while 86% reduction was achieved in July, performance declined to 78% in October, likely due to saturation of zeolite exchange sites. Zeolite media were operated in single-pass mode and no regeneration (chemical or thermal) was performed during the experimental period. Consequently, the reported nitrate/tN removals reflect the initial service capacity of

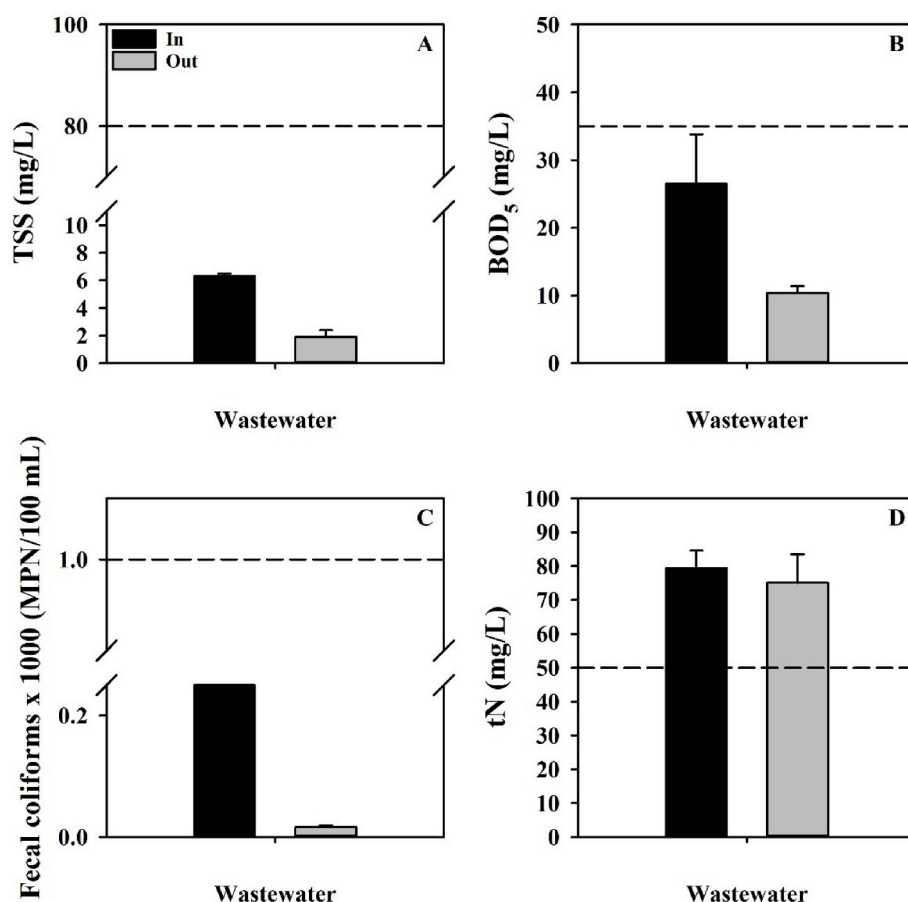


Fig. 5. Physicochemical and bacteriological characteristics of wastewater after scaling up treatment. A) Total suspended solids (TSS; mg/L), B) Biochemical oxygen demand (BOD₅; mg/L), C) Fecal coliforms (MPN/100 mL), and D) Total nitrogen (tN; mg/L) in effluent after secondary treatment, after filtration with Zeolite (Zeo1), activated carbon (AC), and disinfection with UV-C light radiation. Bars represent parameter concentrations; error bars indicate standard deviation when replicate measurements were available. For parameters determined from single measurements following standardized analytical methods, no error bars are shown. Microbiological analyses were conducted under ISO-certified procedures in an accredited DICTUC laboratory (Dirección de Investigaciones Científicas y Tecnológicas, Pontificia Universidad Católica de Chile), under single measurements and no error bars are shown. The dotted horizontal line indicates the maximum limit established by the Chilean standard (TSS: 80 mg/L, BOD₅: 35 mg/L, Fecal coliforms: <1000 MPN/100 mL and tN: 50 mg/L; MPN: Most Probable Number).

the packed bed and may decline over time as ion-exchange/adsorption sites become progressively exhausted, implying that full-scale application will require regeneration protocols or media replacement schedules to ensure sustained performance. Fouling in the packed beds of zeolite and activated carbon occurs due to the accumulation of organic and biological matter on the surface of the adsorbent granules, leading to pore blocking and surface clogging that reduce their long-term efficacy. This behavior highlights the need to consider complementary strategies such as: (a) UV disinfection as a pretreatment step to decrease the bacteriological load; (b) surface modification of the zeolite or activated carbon with nanoparticles to enhance antifouling properties (Chapalaghi et al., 2022); and (c) the implementation of periodic bed-regeneration protocols (e.g., saline regeneration for zeolite) or scheduled media replacement. Reported regeneration frequencies vary widely depending on influent composition and loading: for example, granular zeolite columns treating WWTP effluent for adsorption have been operated in short service cycles of ≈ 5 days followed by backwashing and in situ regeneration, while field-scale clinoptilolite systems for ammonium capture have shown much longer loading cycles (291, 110, and 52 days) with onsite regenerations between cycles (Fu et al., 2022). Accordingly, for rural secondary effluents where nitrogen species and suspended solids fluctuate seasonally, routine monitoring of effluent quality (e.g., tN/NH₄⁺ trends) and simple breakthrough indicators (including conductivity-based approaches) provides a defensible basis to trigger regeneration before substantial capacity loss compromises

compliance (Malovany et al., 2013). These actions would help preserve ion-exchange capacity and maintain the hydraulic permeability of the columns, mitigating a form of fouling that differs from membrane fouling but is equally relevant to the system's operational lifespan. Second, membrane-based configurations (Configuration B) did not yield significant improvements over simpler systems but introduced higher operational complexity, including fouling and the need for frequent cleaning. These findings suggest that, in rural contexts, technically simpler systems (zeolite-activated carbon filtration followed by UV disinfection) are preferable, balancing efficiency, robustness, and ease of maintenance. This aligns with the research trends identified for decentralized systems. Ribarova et al. (2024) note that operational reliability and regulatory compliance are key barriers to the adoption of decentralized systems, underscoring the importance of developing interoperable and user-friendly technologies. The inherent complexity of innovative solutions often represents an obstacle to their adoption when end-users are not technology experts. Future enhancements could explore the integration of intelligent monitoring systems, a growing field where AI-driven solutions provide effective technical support to overcome challenges in water quality monitoring (Liu et al., 2025).

5. Implications for agricultural reuse and sustainability

The monitoring campaigns showed average EC and TDS values of 1774 $\mu\text{S}/\text{cm}$ and 964 mg/L, respectively, which together indicate a

salinity level commonly associated with moderate restrictions for irrigation and, therefore, a potential suitability for moderately salt-tolerant crops under appropriate management (Table S8). As widely recognized, crop response to irrigation water salinity and, in hydroponic systems, to nutrient and salt concentration, is highly dependent on species and genotype, phenological stage, planting density, and site specific agronomic and climatic conditions (Pescod, 1992; Wortman, 2015). Accordingly, the EC levels observed here are broadly consistent with ranges reported as acceptable for several conventional crops and fall within thresholds commonly cited for hydroponic production systems (1000–3000 $\mu\text{S}/\text{cm}$; Table S8) (Pescod, 1992; Wortman, 2015). Similarly, the measured TDS concentrations are typically classified as imposing moderate limitations, compatible with irrigation of moderately salt-tolerant crops (Han et al., 2011; Kachi et al., 2016; Latifa et al., 2020). When benchmarked against widely used crop-specific thresholds for irrigation water salinity, this EC level exceeds the approximate “no-yield-loss” thresholds reported for grapevine (≈ 1000 $\mu\text{S}/\text{cm}$) and citrus (≈ 1100 $\mu\text{S}/\text{cm}$), suggesting a potential risk of yield reduction under long-term application unless adequate leaching and drainage are ensured. In contrast, the measured EC is close to the range generally considered manageable for more salt-tolerant perennial crops such as olive (often reported as $< \approx 2000$ $\mu\text{S}/\text{cm}$ for minimal salinity constraints), indicating that crop selection and irrigation management (e.g., leaching fraction) are key to enhancing practical applicability in the study area.

Despite this, EC and TDS can vary markedly in field settings due to irrigation practices, evapoconcentration, rainfall patterns, and soil properties, which may amplify salinity accumulation over time. Therefore, while these results support the feasibility of reuse, crop-specific tolerance thresholds and long-term impacts on soil salinity and structure should be carefully evaluated through continued monitoring (Menezes et al., 2014; Zhai et al., 2015).

In practice, sustainable implementation should incorporate routine assessment of key soil indicators, including ECe (electrical conductivity of the saturated paste extract) as a standard metric of root-zone salinity, and where sodicity is a concern SAR (sodium adsorption ratio) and ESP (exchangeable sodium percentage) to capture the risk of sodium-driven structural degradation. To complement these chemical indicators, infiltration-related metrics such as field infiltration rate, saturated hydraulic conductivity (Ksat), and aggregate stability should also be tracked, as they provide an early warning of reduced permeability and soil sealing. This monitoring framework enables timely corrective actions, including the targeted application of chemical soil amendments (e.g., gypsum or acidifying agents to increase calcium availability and improve soil structure), together with optimized irrigation scheduling/distribution and adequate drainage, which are essential for sustainable irrigation under saline and/or sodic conditions (Tessema et al., 2023; Wichelns and Qadir, 2015).

Beyond regulatory compliance, the presented system represents a model aligned with the principles of circular economy, energy efficiency, and social benefit. The pilot plant is distinguished by its operation, which is entirely powered by photovoltaic solar energy, ensuring optimal energy efficiency and autonomy in remote areas. The reliance on natural zeolites (Zeo1) and the system's low energy demand (UV-C disinfection) align not only with the Sustainable Development Goals, specifically SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production), but also with the vision for wastewater treatment plants of the future (Zhao et al., 2023).

Field trials in La Higuera also demonstrated the system's resilience to variability in influent quality and contamination peaks (e.g., TSS up to 303 mg/L), suggesting strong potential for replication in other rural Chilean regions facing similar hydrological constraints (e.g., Coquimbo, Nuble).

The pilot-scale validation of this system represents a significant contribution. A comprehensive literature review conducted by Ribarova et al. (2024) revealed a critical gap: no studies were identified that reported full-scale applications of circular treatment systems for onsite

domestic wastewater. This work, therefore, helps bridge the divide between laboratory research and practical implementation, advancing the Technology Readiness Level (TRL) for this category of solutions.

6. Economic feasibility and cost considerations

The economic feasibility of the proposed tertiary treatment system was evaluated according to local conditions such as population, water use, and operating costs; and compared with the cost data published for municipal water treatment plants and its implementation at rural scale (Ozgun et al., 2021; Zagklis and Bampas, 2022). La Higuera, a community of approximately 600 inhabitants, capital investment for equipment and works would range between US\$ 80,000 and 120,000 (2025 year). Additionally, operational and maintenance costs would estimate between US\$ 3000 and 6000 (2025 year), depending on the level of energy autonomy achieved through photovoltaic power. Under these conditions, the reuse cost would be approximately US\$ 0.10–0.18 per m^3 of reclaimed water. These costs are appropriate for the population characteristics and potential use of wastewater (Ozgun et al., 2021). The modular design of the system, implemented in a 20-foot container, facilitates deployment in space-limited localities and enables incremental expansion or retrofitting of existing wastewater treatment plants. From a socio-economic perspective, operation and maintenance costs are feasible to distribute among end users, considering the productive, social, and environmental benefits associated with wastewater reuse for agricultural irrigation. Overall, the cost structure supports the scalability, replicability, and long-term sustainability of the proposed system in rural and semi-arid regions, including benefits associated with wastewater reuse for agricultural purposes.

7. Conclusions

This study designed, optimized, and validated a low-cost hybrid tertiary treatment system for domestic wastewater reuse in the rural, water-stressed community of La Higuera, Chile. The modular train fixed-bed adsorption using locally sourced natural zeolite (Zeo1) operated in series with activated carbon, followed by UV-C disinfection proved robust, technically feasible, and well-suited for rural implementation.

Under optimal laboratory conditions (4 L/h), the process achieved near-complete removal of TSS and COD and up to 93% reduction of total nitrogen (tN), primarily attributed to ion-exchange mechanisms on the zeolite surface. At pilot scale, the system consistently reduced key parameters under real operational variability, including TSS ($\approx 70\%$), BOD_5 ($\approx 56\%$), and COD ($\approx 53\%$), confirming its effectiveness beyond controlled conditions. UV-C disinfection ensured $>99.8\%$ inactivation of fecal coliforms, decreasing concentrations from $>10^4$ MPN/100 mL to values consistently below the Chilean regulatory threshold (<1000 MPN/100 mL), thereby meeting a critical requirement for safe agricultural irrigation reuse.

From a sustainability perspective, the system advances circular economy principles by leveraging a local adsorbent (reducing costs and embodied carbon), operating fully on photovoltaic solar power, and reframing wastewater as a valuable resource, aligning with SDG 6 and SDG 12. The study also delineates key limitations and optimization pathways. Limited removal of dissolved salts (EC and TDS) indicates that the effluent is best suited for salt-tolerant crops or may require blending with other water sources. In addition, the observed decline in nitrogen removal efficiency over time (86% to 78%) suggests progressive saturation of ion-exchange sites, underscoring the need for simple regeneration or replacement protocols to ensure long-term technical and economic viability. Importantly, because the pilot-scale evaluation covered only ~ 3 –4 months, long-term performance claims remain preliminary, and seasonal variability as well as longer-term breakthrough/saturation behavior of the fixed-bed media should be assessed through extended multi-season monitoring.

Overall, this work demonstrates that a technically simple hybrid

system using local materials and renewable energy can provide a safe and sustainable irrigation water source for arid rural communities, offering a pragmatic and replicable model to strengthen water security in Chile and other water-stressed regions worldwide. The proposed modular train is transferable to other rural/decentralized WWTPs because key polishing targets (low residual BOD₅ and TSS) are comparable to values reported for decentralized domestic wastewater effluents in the international literature, while background ionic strength commonly falls in the same order of magnitude (EC $\approx$ 1500 μ S/cm) (Nivala et al., 2019). Site-specific adaptation is mainly required for (i) influent nitrogen loading/speciation, (ii) background salinity/TDS affecting adsorption and irrigation suitability, and (iii) local reuse regulations and monitoring requirements (Kootatatep et al., 2021).

CRediT authorship contribution statement

Christopher González: Writing – original draft, Methodology, Investigation. **Constanza Negrete:** Methodology, Investigation, Formal analysis, Data curation. **Aurelien Do:** Methodology, Funding acquisition, Formal analysis, Conceptualization. **Jaime Herrera:** Writing – review & editing, Data curation. **Iván Martínez Díaz:** Writing – review & editing, Formal analysis, Data curation. **Raúl Calderón:** Writing – review & editing, Project administration, Conceptualization. **Barbara Rodríguez:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2026.129143>.

Data availability

Data will be made available on request.

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