

Impact of electrochemically treated greywater on green wall and roof irrigation: Effects on soils and plants

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ABSTRACT

As part of a study on the treatment and reuse of greywater, the potential use of greywater for irrigating green walls and roofs was assessed, with the focus on its effects on the substrate and vegetation. The response of three ornamental species common in central Chile, *Chlorophytum comosum* (loose spider plant), *Dymondia margaritae* (silver carpet) and *Hedera helix* (common ivy), was evaluated under irrigation with untreated washing machine greywater, greywater treated by electrochemical processes and potable water (used as a control). The experimental work was conducted over 12 months using 60 pots installed on a green wall (20 per irrigation type), exposed to the climate conditions of Santiago de Chile. Periodic measurements were taken of the substrate (pH, electrical conductivity, organic matter and phosphorus) and of the plants (leaf count and size, presence of foliar spots and pigment analysis) to evaluate growth, health and signs of biological stress in response to the different irrigation waters. Irrigation with electrochemically treated greywater maintained soil pH within neutral ranges and limited salinity to levels suitable for moderately tolerant plants. In contrast, untreated greywater led to higher electrical conductivity values. No significant differences were detected in soil organic matter or phosphorus content among the different types of water. After an initial adaptation, plant growth with treated greywater matched or exceeded growth with potable water. There were no major alterations in pigment composition or visible stress symptoms. These results suggest that electrochemically treated greywater is a viable sustainable option for irrigating green walls and roofs.

1. Introduction

Accelerated urbanization has significantly reduced green space per inhabitant, raising global concern over declining environmental quality and urban well-being [1,2]. In response, green roofs and walls have emerged as efficient alternatives to conventional parks, requiring no additional land in densely built areas. These systems improve air quality, mitigate the urban heat island effect and promote biodiversity due to

new habitats for diverse species [3–5]. They also enhance building energy efficiency through natural insulation [6,7] and contribute aesthetically and psychologically to urban livability [8,9]. Although the benefits of green walls and roofs are well-known, large-scale implementation could put a significant strain on municipal water supply networks if alternative water sources for irrigation are not available [10,11]. As global water stress is expected to affect over half of the population [12], with many cities already competing for limited

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freshwater resources [13], integrating non-traditional water resources becomes crucial for sustainable irrigation. Such sources (desalinated water, rainwater, stormwater, treated wastewater and recovered condensates) can complement traditional supplies and reduce dependence on freshwater [14]. Several urban initiatives have already adopted these alternatives for irrigating green roofs and vertical gardens [15–21].

Urban areas provide an opportunity to recover domestic effluents for decentralized treatment and reuse, particularly treated wastewater. Domestic wastewater is typically divided into blackwater and greywater, each with distinct characteristics and reuse implications [22]. Blackwater, originating from toilets, contains high levels of pathogens and organic matter, thus requiring advanced treatment before reuse. Greywater, produced from bathing, laundry and dishwashing, constitutes most household wastewater and has lower pollutant loads [23]. With adequate treatment, it can be reused for several purposes, like toilet flushing and irrigation, reducing potable water demand and wastewater generation. Moreover, unlike other non-traditional water sources that are often seasonal or weather-dependent, greywater offers a regular and consistent supply, closely linked to domestic water consumption patterns [24].

A variety of technologies enable the safe and efficient reuse of greywater [25–30]. The choice of treatment depends on the reuse purpose, quality standards, space availability and costs. Simple methods include screening, sedimentation and filtration, while chemical and biological treatments (such as coagulation, adsorption, wetlands and biofilters) further remove pollutants and pathogens. Final disinfection, typically by chlorination, ozonation or ultraviolet radiation, ensures safety. Increasingly, hybrid systems integrate these processes to enhance performance and guarantee compliance with reuse requirements. Although electrochemical treatment of greywater is not among the most common approaches, it has significant advantages over alternative options.

Electrochemical advanced processes are promising technologies for greywater treatment because they are environmentally compatible, versatile, scalable, compact and reduce treatment time compared to other chemical and biological technologies [31,32]. When coupled with renewable energy sources, like photovoltaic systems, the energy demand of these electrochemical processes can be covered in a sustainable way. Electro-oxidation (EO) is widely applied due to its operational simplicity and the absence of pH adjustment requirements, enabling the in-situ generation of strong oxidants such as hydroxyl radicals. Most organic pollutants are degraded either directly at the anode or indirectly by electro-generated oxidants, leading to non-selective oxidation. EO can be combined with electrocoagulation (EC), a process in which sacrificial metal electrodes are polarized in an electrolytic cell so that soluble metal cations are released into the wastewater [33]. These cations hydrolyze and form coagulant species that destabilize colloids, adsorb pollutants and promote floc formation to eliminate the suspended solids present. The main advantages of EC in wastewater treatment are the lack of chemical addition and the generation of lower volumes of higher quality sludge [34]. These characteristics make electrochemical technologies an interesting option to treat greywater in order to be reused.

Previous studies that have applied electrochemical treatments to greywater can be mentioned. A work focused on EO evaluated the impacts of cell configuration, current density and cathode material on chemical oxygen demand (COD) removal and disinfection byproduct (DBP) formation in greywater [35]. The results demonstrated that divided EO cells equipped with boron-doped diamond (BDD) cathodes presented the most viable option for low energy COD removal without any accumulation of DBP in a greywater reuse scenario. The adequate identification of optimal EO operational parameters demonstrated effective removal of surfactants in a complex greywater matrix with energy consumption below 1 kWh/g COD [36]. The treatment of greywater from washing machines using EO with titanium and stainless steel electrodes reduced turbidity and conductivity, achieving a final pH value of 7.99 [37]. A high COD removal rate of 87.8% from high-load

greywater was achieved with an energy consumption of only 4.11 kWh/m³ when sand filtration pretreatment was coupled to a EC process utilizing aluminum as the sacrificial electrode [38]. Another study evaluated the influence of EC operating parameters (treatment time, current density and temperature) on the removal of biochemical oxygen demand (BOD₅), total suspended solids (TSS), turbidity and *E. coli* in synthetic greywater [39]. The optimal conditions removed 51.8% BOD₅, 83.7% TSS and 74.6% turbidity while for *E. coli* a maximum of 5.5 log reduction was achieved. The optimization of a real greywater treatment process by aluminum-based EC resulted in a maximum COD removal efficiency of 86.34% with current density being the most influential factor [40]. The use of finned electrodes achieved 85% chemical oxygen demand (COD) reduction, 90% surfactant removal and 95% turbidity reduction, demonstrating superior kinetics compared to conventional electrodes in EC systems [41]. Hybrid systems that combine EO and EC can enhance the treatment performance. An EC process based on an aluminum anode and an iron cathode coupled to an EO process using titanium with platinum coating mesh as an anode and stainless steel as a cathode led to COD, color, turbidity and TOC removal rates of 96.1%, 97.5%, 90.9% and 98%, respectively [42]. Even examples of more complex electrochemical processes, such as the application of bio-electrochemical reactors, have been reported [43].

The reuse of greywater for irrigation has been increasingly studied as a strategy to alleviate water scarcity and promote sustainable resource management [44–53]. Properly treated greywater can be a valuable source for irrigating ornamental plants, green roofs and some crops. Its effects on soil and vegetation depend on effluent quality and exposure time: moderate nutrients may enhance growth, while excessive salts or pollutants can harm soil structure and plant health.

On the one hand, studies have shown that long-term use of inadequately treated greywater may alter soil pH and electrical conductivity, negatively affecting plant development. One study assessed greywater irrigation on germination and seedling growth in red spinach (*Amaranthus dubius*), spiderwisp (*Cleome gynandra*) and black nightshade (*Solanum nigrum*) [54]. Greywater reduced seed vigor in all species, decreased germination in red spinach, limited shoot emergence in black nightshade and reduced growth and chlorophyll content in the latter two, alongside increased soil pH and conductivity. Compared with tap water or nutrient solution, greywater also reduced biomass in lettuce (*Lactuca sativa* L. cv. Iceberg) and radish (*Raphanus sativus* L. cv. French Breakfast), decreasing soil enzyme activity [55]. Tomato (*Solanum lycopersicum*) plants irrigated with tap water showed higher fruit weight and number than those irrigated with untreated or zeolite-treated greywater, although treatment improved performance relative to untreated greywater [56]. Similarly, untreated greywater reduced chlorophyll content and nutritional quality in pepper, lowering productivity compared to tap or treated water [57]. In silverbeet (*Beta vulgaris* var. *cicla*), greywater irrigation significantly increased soil pH and conductivity [58]. Additionally, greywater irrigation may increase phosphorus pollution risk, contributing to eutrophication and other environmental impacts, thereby limiting its sustainability [59].

On the other hand, with appropriate treatment and monitoring, greywater irrigation can yield neutral or even positive effects on plant performance without significant reductions in yield or biomass. A field study evaluating untreated and treated greywater (screening, sedimentation and solar disinfection) in chili peppers (*Capsicum frutescens*) and marigolds (*Calendula officinalis*) found that treated greywater was microbiologically safe and enhanced growth, particularly in chili [60]. Lettuce (*Lactuca sativa*) irrigated with greywater treated using shale and laterite showed germination rates above 50% for raw and shale-treated greywater, while lower values were observed for tap water and laterite-treated greywater [61]. The use of greywater in ten fall-planted geophytes (*Allium*, *Hyacinthus*, *Tulipa*, *Crocus*, *Narcissus*) did not significantly affect biomass, nutrient profile or visual quality, as only fresh biomass in *Allium* and *Hyacinthus* decreased, but with no impact on dry biomass or flowering [62]. Treated greywater (gravel filtration)

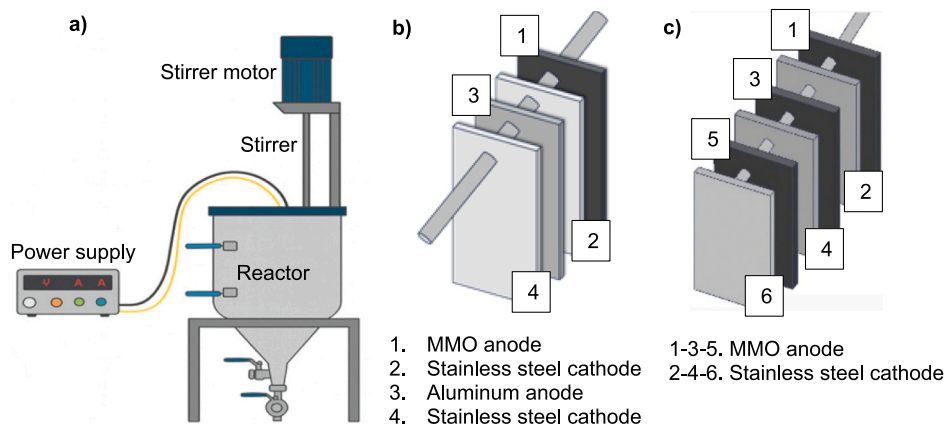


Fig. 1. a) Schematic of the electrochemical reactor, b) electrode configuration for EO + EC and c) electrode configuration for EO.

increased shoot biomass in mesquite (*Prosopis juliflora*), tamarugo (*Prosopis tamarugo*) and siris (*Albizia lebeck*), with no changes in protein content [63]. Similarly, irrigation of carrot (*Daucus carota sativa*), lettuce (*Lactuca sativa*) and pepper (*Capsicum annum*) showed no differences in growth or productivity compared to tap water, exhibiting similar bacterial counts on crop surfaces [64]. In pot trials with silverbeet (*Beta vulgaris* var. *cicla*) and carrot (*Daucus carota*), greywater increased growth, yield and nutrient content relative to tap water, although hydroponic solution performed best. However, greywater also raised soil electrical conductivity and promoted metal accumulation in soil and crops [65].

The use of greywater for irrigating green roofs and walls has been specifically investigated [11,66–69]. Greywater improved soil fertility, particularly phosphate availability, promoting the growth of minnieroot (*Ruellia tuberosa*), with increased height and biomass, although with reduced chlorophyll and higher leaf chlorosis [70]. The effects on substrate properties and six climbing species (*Akebia quinata*, *Gelsemium sempervirens*, *Jasminum azoricum*, *Pandorea pandorana*, *Trachelospermum jasminoides* and *Vitis × Ganzin* glory) were also assessed [71]. Greywater did not affect plant growth or pH, but increased substrate electrical conductivity. Similarly, heartleaf philodendron (*Philodendron hederaceum*), peace lily (*Spathiphyllum wallisii*) and Boston fern (*Nephrolepis exaltata*) grown on indoor living walls tolerated continuous greywater irrigation, with only minor reductions in green cover for peace lily after 30 weeks [72]. Despite increasing conductivity due to recirculation, plant performance remained largely stable. Green roofs planted with lippia (*Phyla nodiflora*) and blue rock bindweed (*Convolvulus mauritanicus*) on coal ash or perlite showed no growth differences between greywater and tap water irrigation [73]. However, drainage exhibited increased electrical conductivity and chemical oxygen demand, limiting direct reuse without dilution. In Al Ain (UAE), intensive and extensive roofs planted with reed canary grass (*Phalaris arundinacea*) and irrigated with untreated greywater showed better performance in intensive systems, likely due to deeper substrates [74]. Although some parameters met reuse standards, turbidity, organic matter, sodium and bacterial removal remained inadequate. Overall, safe application requires alignment between water quality, substrate characteristics and plant tolerance. Greywater reuse in green roofs and walls is feasible, but demands strict quality control and adaptive management.

The aim of this work was to analyze the potential of electrochemically treated greywater and its reuse in irrigation, specifically for green walls and roofs. Therefore, in this work, an electro-oxidation system was proposed to treat greywater in order to be reused for irrigation. This innovative development has demonstrated a satisfactory performance in the treatment of laundry greywater [75]. The impact of irrigation with treated greywater over an entire year on the growth of three plant species (loose spider plant, silver carpet and common ivy), which were identified as suitable candidates for Chilean green infrastructure, was

assessed and compared with untreated greywater and tap water. Additionally, the evolution of key substrate properties was monitored to evaluate the effects of irrigation using this advanced electrochemical system. Unlike previous studies, which were usually conducted under controlled laboratory conditions or short testing periods, this research was performed under real outdoor conditions, exposed to rainfall and climatic variations, providing a more comprehensive and realistic assessment of the long-term performance and environmental implications of electrochemically treated greywater reuse.

2. Materials and methods

2.1. Greywater characterization and treatment

The greywater was obtained from a domestic washer/dryer (Model MLSF-095B/W manufactured by Midea) operating with a mixed 20 °C cycle and drying program “D-2” and using a commercial detergent (Bio Frescura, Chile). The greywater produced washing each laundry load (which comprised approximately 7 kg of clothes) was subsequently fed into a 25 L electrochemical reactor for treatment. As shown in Fig. 1a, the reactor is made of 304 stainless steel, with a diameter of 36 cm, a total height of 40 cm (20 cm in the cylindrical part and another 20 cm in the conic bottom) and a thickness of 2 mm. It is equipped with a 304 stainless steel stirrer operating within a speed range of 0–350 rpm, driven by a 0.5 HP, 220 V motor. The system is connected to a power supply (Model HY3005E-2 manufactured by Ele-tech), which powers the electrodes depicted in Fig. 1b and Fig. 1c, which correspond to Mixed Metal Oxide (MMO) and aluminum anodes and stainless steel cathodes, each measuring 20 cm in length and 4 cm in width. The system was operated at a constant current intensity of 5 A under uncontrolled voltage for 2 h. The selection of these reactor conditions was based on previous preliminary works to characterize the performance of the designed system [75].

During the first seven months of the experiment, the system operated under an electro-oxidation (EO) mode, employing a cell configuration consisting of three MMO anodes and three stainless steel cathodes. From the eighth month until the end of the study, the system was operated in a combined electro-oxidation/electrocoagulation (EO/EC) mode. In this stage, a simplified electrode arrangement was used, comprising two stainless-steel cathodes and two anodes, one MMO and one aluminum. After treatment, in the case of the electro-oxidation and electrocoagulation processes, the clarified supernatant was recovered and employed for irrigation. The main characteristics of the untreated (GNT) and treated (GT) greywaters with EO and EO/EC are compiled in Table 1, as well as those of the control tap (P) water taken from the water supply network in the installations of the Department of Chemical and Bioprocess Engineering of the University of Santiago, Chile (USACH). Samples collected during electrolysis were filtered and stored at 4.0 ±

Table 1

Characterization of untreated and treated greywaters and control tap water.

Parameter	Untreated greywater	Treated greywater (EO)	Treated greywater (EO + EC)	Control tap water
pH	8.04	8.02	8.02	6.94
Electrical conductivity (mS/cm)	7.19	6.92	2.37	0.72
Turbidity (NTU)	15.47	3.56	0.35	0.50
TSS (mg/L)	3.40	2.13	–	0.15
COD (mg/L)	970	514	54	< DL*
Free chlorine (mg/L)	0.02	55.33	–	0.015
Total chlorine (mg/L)	0.02	58.67	–	0.015
NH ₄ ⁺ (mg/L)	12.53	7.43	–	–
NO ₃ ⁻ N (mg/L)	4.77	5.23	–	2.51

* Value below the detection limit

0.1 °C until analysis. Tap water was used as solvent and blank in all measurements. pH, electrical conductivity and total dissolved solids were measured with a multiparameter meter (Model MW804 by Milwaukee). Turbidity was determined using a portable turbidity meter (Model HI98703–02 by Hanna Instruments). Free chlorine, total chlorine, ammonium and nitrate were quantified with specific reagents (Hanna Instruments) and analyzed with a multiparameter photometer (Model HI83399–02 manufactured by Hanna Instruments). Chemical oxygen demand (COD) was determined according to Standard Method 5220-D using the same photometric equipment.

2.2. Irrigation experimental design

The system to represent green walls and roofs consisted of a metallic structure that enabled the installation of plastic pots, arranged on four faces with different cardinal orientations, each exposed to outdoor weather conditions and natural sunlight. The system was located at the installations of the Department of Chemical and Bioprocess Engineering of the University of Santiago, Chile (USACH). For meteorological study during the experimental period, data were obtained from the Chilean Meteorological Directorate (Climate Services), using daily records taken from the Quinta Normal Station (330020), situated less than 300 m away from the experimental installation. Each face contained 3 columns and 5 rows of pots, totaling 60 plant units.

These plastic pots, with an approximate volume of 20 L, were filled with leaf mold as substrate (Anasac Jardín, Tierra Biológica Compost). The three plant species selected were loose spider plant (*Chlorophytum comosum*), silver carpet (*Dymondia margaretae*) and common ivy (*Hedera helix*). Their selection was based on wide availability, low cost and resistance to the environmental conditions of the Metropolitan Region of Chile, which concentrates the majority of the country's population and is increasingly subjected to water stress. The plants used have two origins: while the spider plant and common ivy specimens were collected in a plant nursery located in Pomaire (a town of Melipilla, a peripheral commune of the Metropolitan Region of Santiago), the silver carpet specimens were collected at a plant nursery located in San Bernardo (a commune within the southern part of the Metropolitan Region).

These plants were systematically distributed along each column and row according to the scheme represented in Fig. S1. Images of the experimental set-up under initial and final conditions are shown in Fig. S2 in the Supplementary Material. The experiment lasted 12 months (from July 2024 to June 2025) with regular irrigation applied every other day. Irrigation considered three types of water distributed from left to right on each face as follows: raw greywater from washing machine use in the left column, electrochemically treated greywater in the central column and control tap water in the right column. The irrigation system was automated using independent 100 L tanks for both types of

greywaters, each equipped with a booster pump (Model CTM 60/A by Calpeda), a controller (Model Autumpump by BestFlow) and an irrigation timer (Model X301 3/4 Digital 1 station - battery by Edrop), which enabled the automatic opening and closing of the flow towards a hose circuit with sprinklers. Water was delivered to the upper row of each column, with the lower rows irrigated through runoff and dripping. For tap water, the same type of irrigation timer was used, connected directly to the drinking water supply network and to an identical irrigation circuit as those of both types of greywaters.

2.3. Plant analysis

In order to quantify the development of each plant, monthly records were taken, including counts and physiological measurements adapted to each species. For the spider plant, the parameters measured were number of leaves, leaf length and width, number of offshoots at the ends of stolons and number of colored leaves. For the silver carpet, the parameter measured was the percentage of pot area covered by vegetation. The growth of each plant over the pot was recorded monthly until the fifth month, as the plants reached maximum coverage and no further variations were observed. Coverage was visually assessed using a scale from 1 to 5, where 1 corresponded to the minimum coverage observed at the beginning of the experiment and 5 to the complete surface of the pot. The representation of this scale is provided in the Supplementary Material (Table S1). Finally, for the ivy, the parameters recorded were branch length, leaf length and width and number of colored leaves. The purpose of these measurements was to provide a detailed account of plant growth and health and to evaluate how each species responded over time to the experimental conditions.

Additionally, the pigment content of the leaves of the three species was measured at each plant pot to monitor the health status of the plants. The sampling was performed monthly during the first six months and subsequently every three months, based on the observed trends. The total content of chlorophyll a, chlorophyll b and carotenoids was determined using duplicate samples of 100 mg of fresh tissue from leaves that was ground to a powder using liquid nitrogen, mortar and pestle before extraction with 1 mL of ethanol (96% purity by Avalco). The extracts were centrifuged at 10,000 rpm for 10 min at 4 °C and the absorbance of the supernatant at 470, 649 and 665 nm was measured [76,77]. The exact equations used to assess the pigment concentrations as function of the measured absorbance values can be consulted in Table S2 in the Supplementary Material.

2.4. Soil analysis

Composite soil samples were taken from each pot at monthly intervals. Different depths were considered, covering the entire area of the pot while avoiding root damage. The depths of the samples ranged from 10 to 20 cm, including the surface level, with a total of approximately 10 to 12 g of moist soil. The samples were air-dried on aluminum foil for at least 48 h, until they reached a constant mass. Then, the samples were sieved through a 2 mm mesh and roots and other plant residues manually removed. For the measurement of pH and electrical conductivity (EC), soil suspensions prepared in a 1:2.5 w/v (weight/volume) soil-to-water ratio were prepared using distilled water. The distilled water production system consisted of a series of stages: first a sand filter, followed by a cationic resin and finally an activated carbon filter. Subsequently, the water passed through a reverse osmosis system and was stored, before finally passing through a mixed-bed resin. A potentiometric method was employed to determine pH and conductivity values, using a stirrer (Model 2D-400 by Finepce) and a multiparameter device (Model CX-701 by Elmetron) with a pH electrode (Model PY-41 by Alpha) and a conductivity electrode (Model EC-63 by Elmetron). For the analysis of phosphorus and organic matter content, sampling was conducted every three months rather than on a monthly basis. Available phosphorus was determined by extraction with sodium bicarbonate

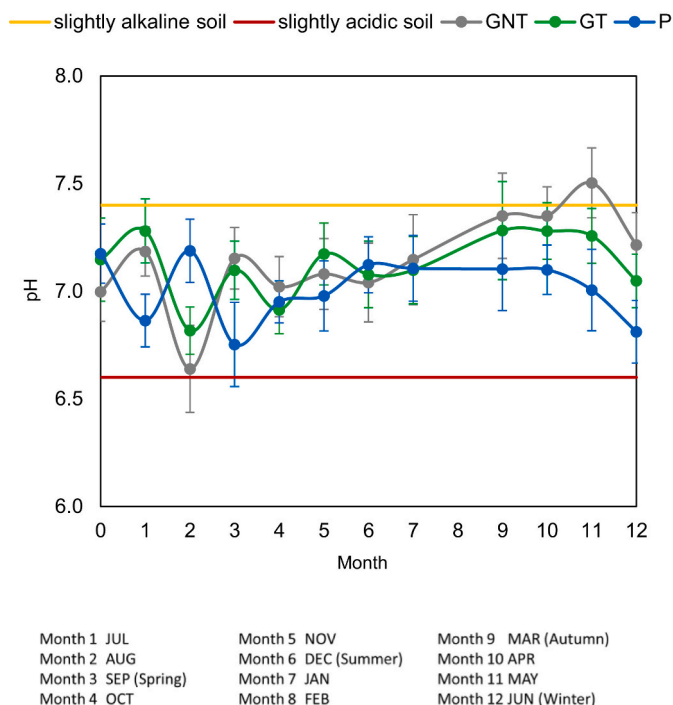


Fig. 2. Evolution of mean soil pH values over the experimental period under different types of irrigation water.

solution and colorimetric analysis based on the molybdenum blue complex according to the Olsen-P method [78]. Organic matter content was quantified by the Walkley-Black wet oxidation method [78], with colorimetric determination of reduced dichromate.

3. Results and discussions

3.1. Weather record

The register of the meteorological conditions reported during the period that covered the experimental test can be observed in Fig. S3, which includes data relative to precipitations, humidity, temperatures and solar radiation. Regarding rainfall, 346.8 L/m² were recorded during the year that lasted the experiment, but these precipitations were irregular: the rainfall registers during the first and second months of the period were 183.1 and 80.6 L/m² respectively, while during the last month 61.3 L/m² were registered. The joint contribution of these three months represented the 93.7% of the total rainfall, demonstrating that the precipitations out of the period from June to August (winter station in Chile) are scarce in the selected location. These rainfall events are expected to influence the measured parameters, as they can cause dilution, leaching and runoff or alter substrate moisture and nutrient levels, affecting plant response and system performance. In relation to humidity, the average value for the three wet months was 80.8%, but during the rest of the period the humidity level was clearly lower, with values consistently below 70% and even lower than 40% values during the summer (from the fifth to the eighth month of the experimental period). The average value during the rest of the year was 58.9%, which resulted in a global annual average humidity equal to 64.5%.

Minimal temperatures below 0 °C were registered thirteen times during the first three months of the experimental period, but the frosts experienced by the plants were not severe, since the lowest recorded temperature was −1.5 °C. In contrast, the maximum temperature was above 35 °C only three days through the year, being the highest recorded temperature 35.9 °C. The average temperature ranged from 4.6 °C to 25.5 °C, with a mean value equal to 15.7 °C. Extreme temperatures, both high and low, can cause physiological stress and tissue damage in plants,

adversely affecting their growth and overall vitality [79]. The total daily global radiation was used to represent the exposure to sunlight of the plants. Total daily global radiation refers to the amount of shortwave solar energy received on a horizontal surface from both direct sunlight and diffuse sky radiation, integrated over the course of a day. Solar radiation directly influences photosynthesis, stomatal activity and transpiration in plants [80,81].

High radiation levels enhance carbon assimilation and growth, while excessive radiation may cause photoinhibition, leaf temperature rise and water stress [82], especially when combined with high temperature, drought or salt stress [83]. Global radiation ranged from 200 to 10,668 W/m², with an average of 5966 W/m². From September to April (summer, late spring and early autumn in Chile), values were consistently above 6000 W/m². Analysis of the maximum hourly radiation showed 116 days exceeding 1000 W/m², a threshold typically associated with clear full-sunlight conditions. Thus, the site where the plants were located can be regarded as having very high solar availability.

3.2. Soil characteristics

The evolution of the pH values in the different soils is shown in Fig. 2. The range of mean values registered moved from 6.64 to 7.50, with both minimal and maximal points corresponding to untreated greywater. In the case of the treated greywater, the pH mean values ranged between 6.82 and 7.28. Accordingly, pH remained within neutral soil limits, without surpassing the upper bound for slightly alkaline soil (pH 7.4) or falling below the lower bound for slightly acidic soil (pH 6.6) [84]. On the one hand, the minimal pH value was achieved during the second month, just after one of the main rainfall episodes registered during the experimental test. The slightly acidic nature of rain, with values typically in the interval from 5.5 to 6.0 due to the dissolution of atmospheric carbon dioxide (which forms weak carbonic acid), can justify this reduced value [85].

On the other hand, the maximum value was attained during the eleventh month, just before a rainfall episode that occurred after a long period with limited precipitation. This final rainfall event in the last part of the investigated period caused once again a reduction of the pH (values decreased 0.2 points for the three types of water during the last month), which finished the experiment with values equal to 7.22, 7.05 and 6.81 for untreated greywater, treated greywater and tap water respectively. Therefore, meteorological conditions appeared to exert a stronger influence on substrate pH than the type of irrigation water. Indeed, seasonal changes in soil pH are well documented and arise from variations in moisture, temperature, plant development and microbial activity [86]. Despite the higher pH values of both untreated and treated greywater (both above 8.00) when compared to tap water (below 7.00), the irrigation with greywater did not cause a continuous trend towards increased pH values. Uneven evolutions with multiple peaks and valleys were observed, especially during the first half of the studied period, while the extended period with limited precipitations caused an increase in the pH values of the soils, exceeding the slightly alkaline soil threshold for the case of untreated greywater.

Previous investigations have reported the increase of pH in the soils irrigated with untreated greywater, especially when alkaline greywater with pH values above 9.5 was used [58,87]. Under these conditions, soil pH achieved values around 7.9, which implied a rise of 1.0 points when compared with the initial soil pH before the irrigation with greywater. In this work, where the pH value of the untreated greywater was close to 8.0, the rise in the soil pH was not so significant, but values above the limit that define a slightly alkaline soil were achieved. Therefore, the irrigation with untreated greywater in arid regions with limited rainfall could result in the alkalization of soil due to increased pH, especially when the most alkaline greywaters are employed, such those from laundry and kitchen sinks [88]. Other authors have reported that soil pH did not change in a relevant way as consequences of the irrigation with greywater and alkalization of the soil was avoided, but in most cases the

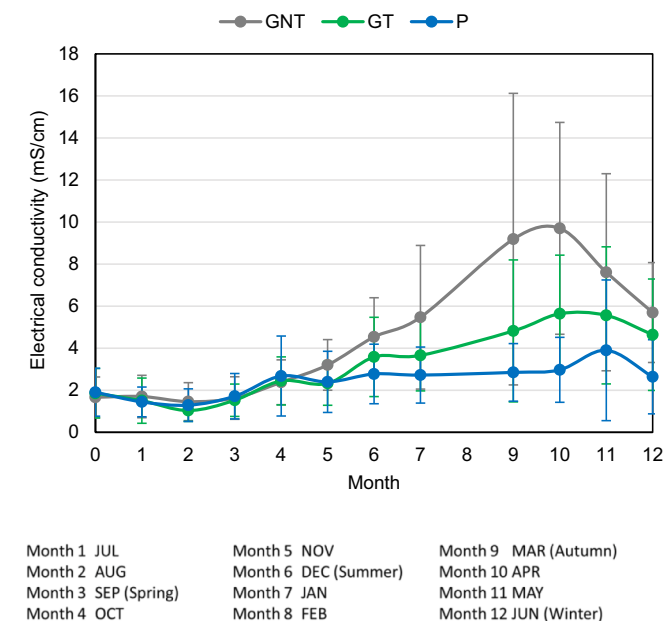


Fig. 3. Evolution of mean soil electrical conductivity values over the experimental period under different types of irrigation water.

samples employed were synthetic greywaters with pH values below 7.8 [71,73] or real greywaters with acidic characteristics and pH values lower than 6.7 [57,89]. Nevertheless, the electrochemical treatment applied in this work to the greywater assured that the pH did not exceed the slightly alkaline soil threshold.

The evolution of the electrical conductivity in the different soils is presented in Fig. 3. While very similar results were reported for the three types of water during the first five months of the test, with mean values below 3 mS/cm, after this point the electrical conductivity of the soils irrigated with treated greywater was higher than the control soils irrigated with tap water. Moreover, the untreated greywater exhibited the highest electrical conductivity values, reaching a maximum mean of 9.70 mS/cm in the tenth month, after a summer with limited rainfall. This value approached the 10 mS/cm salinity limit defined by the Maas-Hoffman classification for tolerant plants. Therefore, even these types of plants could be affected by irrigation with untreated greywater [90].

In the case of the treated greywater, the maximum mean was 5.64 mS/cm (once again achieved in the tenth month), which did not exceed the salinity limit of 6 mS/cm defined by the Maas-Hoffman classification for moderately tolerant plants. Nevertheless, the limit for moderately sensible plants, which is defined as 3 mS/cm, was surpassed when treated greywater was used for irrigation. In fact, this limit was also surpassed in soils irrigated with tap water, since the mean electrical conductivity in the eleventh month was 3.90 mS/cm. The initial values of salinity in the soils before starting the irrigation tests must be taken into account, since the electric conductivity was close to 2 mS/cm in all cases, which can be considered a value around the salinity limit defined for sensible plants. This situation could be explained by the higher electric conductivity of the tap water used in this work (0.72 mS/cm) when compared to other tests that employed control water with 50% lower salt content [65] or even an order of magnitude lower [89].

The increase of the soil electrical conductivity after irrigation with greywater is a frequently reported fact [54,58,91]. Even when greywater was alternated with potable water for irrigation, the soil salinity effectively rose [71]. Other authors have reported that the employment of untreated [92] and treated greywater [93,94] for irrigation did not produce a significant loss on soil quality due to increased salinity, while have observed reduced electrical conductivity in soils irrigated with greywater [95,96]. However, the accumulation of salts in soil can be

largely determined by irrigation practices and soil hydraulic behavior. For instance, independent outdoor cultivation configurations, such as pots, containers or garden beds, may benefit from surface runoff and leaching induced by rainfall, whereas continuous field crops or indoor systems are not subject to these processes. In addition, soil salinity accumulation in the sandy loam was about half and third of that in the loamy and clay loamy soil, respectively [91]. Therefore, the potential risks of increased soil salinity caused by irrigation greywater should be assessed specifically for each case study. The results of this study showed that the proposed electrochemical treatment of greywater reduced soil electrical conductivity compared to untreated greywater, yielding values suitable for irrigation of plants not sensitive to salinity.

The changes in the organic matter content in the soils were registered (Fig. S4). The use of just leaf mold as substrate avoiding mixing with other inorganic substrates resulted in high initial contents of organic matter, which ranged from 13.2% in the case of the pots to be irrigated with untreated greywater to 17.7% for the pots to be irrigated with control tap water. Over time, these initial differences tended to be balanced out. After 6 months of irrigation, the organic matter content of the soils was very similar for all three types of water: 17.0% for untreated greywater, 17.3% for treated greywater and 17.6% for tap water. These values corresponded to the summer and represented the maximum values achieved by soils irrigated with both types of greywater. The organic matter content decreased successively for samples taken after 9 and 12 months, finishing the experimental period at around 15%. These values were similar to those observed for control tap water. Different seasonal patterns in soil organic matter content have been identified [97–99], so it cannot be universally concluded that summer has higher organic matter than winter. The relationship depends on local environmental conditions, ecosystem types and soil management. However, there are examples where winter organic content is lower [100,101].

These small differences in the organic matter content of soils exposed to greywater when compared to control soils have been previously reported. Soil samples collected from greywater discharge zones and control soils in Nigeria presented similar organic matter contents at different depths [102]. Moreover, stable levels of organic matter content after long periods of irrigation with greywater have been registered too. Soil samples taken from a Jordanian home garden irrigated with greywater treated by a constructed wetland for 2 years exhibited just a slight decrease in the organic matter content, from 1.99 to 1.91% [96]. In some cases, a higher amount of organic matter present in greywater-irrigated soil samples has been evidenced by the greater amount of carbon and less oxygen present in comparison to the control samples [70]. This greater organic matter content can be enhanced when the irrigation with greywater is complemented with auxiliary techniques, such as mulching, where a layer of organic material (wood chips, bark or straw) is placed on the soil in greywater infiltration or irrigation systems to reduce evaporation, minimize odors and prevent direct human contact [103]. The supplementary organic matter from mulch applied to poor soils helped to retain water near the surface, reduced the loss of valuable nutrients and increased organic matter content [104]. The additional nutrients supplied by greywater can enhance microbial activity, leading to localized decreases in soil organic matter content, particularly in the upper soil layers [105]. Although more significant reductions of organic matter content were reported in a study carried out in different locations of USA, which achieved 70% decrease in a sampling point when compared to the corresponding control, these drastic alterations of the organic matter content are not frequent. Therefore, the results of this study did not identify any relevant modification of the soil organic matter content attributable to the irrigation with greywater.

Fig. S5 shows the variation of the available phosphorus (P) concentration in the soils for the three types of irrigation water. It is important to note the type of detergent used, as a phosphate-free product was selected. Consequently, the phosphorous content of the greywater was

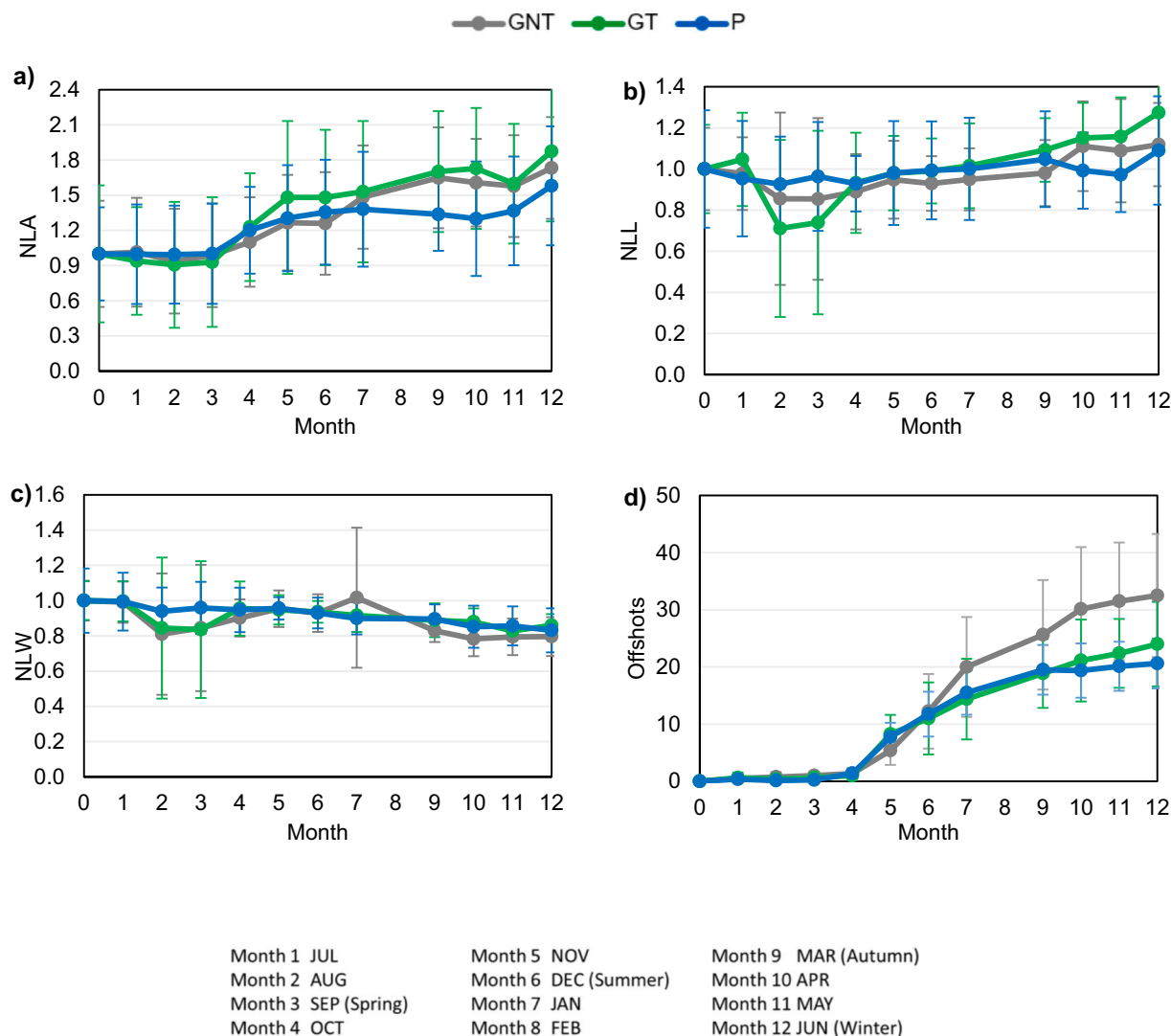


Fig. 4. Effects of irrigation water type on mean (a) normalized leaf amount (NLA), (b) normalized leaf length (NLL), (c) normalized leaf width (NLW) and (d) number of offshoots in spider plant.

lower than the typical values obtained when traditional detergents were employed and this could influence the P concentration in the soils. Initially, the three soils' values ranged from 280 to 300 mg/kg, moving to the interval from 300 to 320 mg/kg after three months of irrigation. However, after six months of irrigation a clear pattern emerged and persisted until the end of the experiment: the soil irrigated with control tap water had the highest P content, while the soil irrigated with untreated greywater had the lowest value. Due to the lack of phosphates in the detergent (the main source of phosphorous in greywater), the amounts of phosphorous provided by the three different types of water were assumed to be equivalent. Consequently, the lower P concentration in soils irrigated with greywater could be explained by the plants' higher P uptake when irrigated with greywater when compared to tap water. The additional supply of nutrients, such as nitrogen, provided by greywater could result in increased nutrient uptake from the soil. In fact, plants irrigated with greywater have been reported to exhibit higher concentrations of P and other micronutrients, such as Fe [106]. However, other factors can affect nutrient uptake from soils. For instance, increased plant biomass may enhance overall nutrient uptake. As it can be observed in the next section related to the plant growth, after acclimatization during the first months of the test period, plants irrigated with treated greywater exhibited comparable or even superior performance in leaf development, branch elongation and surface coverage

when the plants irrigated with control tap water. This additional plant biomass can contribute to achieve higher uptake of nutrients from the soil. Moreover, seasonal factors, mainly linked to weather conditions, can influence in the P content in soils. In this study, the maximal P levels were achieved during the summer (Month 6), a period characterized by the highest temperatures and no rainfall.

Temperature, precipitation and moisture modify P content in soils through processes such as leaching, mineralization and weathering [97,107,108]. A research study in Chinese forests demonstrated that the most important factor affecting soil total P distribution was the combined effect of temperature and precipitation, while the single effect of temperature had a higher explanation rate than the single effect of precipitation [109]. Nevertheless, temperature has contrasting effects on soil P availability and can interact in different ways to control soil P availability. While higher P levels in soils have been found in cold winter than in hot summer [99,110], a study that analyzed multiple worldwide distributed soil locations revealed that available P on high-sand soils was positively affected by mean annual temperature [111]. The lower P levels in soils during rainy periods have been more frequently reported, mainly due to leaching [112,113]. Other studies have identified that available P varied differently during the seasons but did not follow any particular trend [114].

A study that considered existing greywater recovery systems in

locations from the arid western region of the USA found no significant differences in total phosphorus values in soils after irrigation with greywater [115]. Some authors even found small decreases in the P content in the soils irrigated with greywater for 2 years [96]. Another Australian research group demonstrated that the total P concentration in soils after silverbeet harvest was not significantly influenced for any of the irrigation types investigated in the study (Irrigation with 100% greywater, irrigation with a 1:1 mixture of greywater and potable water and alternate irrigation with potable water and greywater in successive events) when compared with the control [58]. Significantly, higher soil P concentrations were observed under greywater irrigation in the absence of plants, indicating that plant presence reduces soil P through nutrient uptake. Although higher P concentrations have been reported in soils irrigated with greywater than those irrigated with control water due to the presence of detergents [116,117], these values were below the P concentration achieved in this study using the control tap water. Nevertheless, further investigation to get information related to the nutrient and VOC contents in plant tissues can be suggested to have a better understanding of the interactions among different nutrients.

A more detailed study of the main properties of the soils as a function of their vertical position on the experimental installation was carried out. Because of the experimental design (water was delivered only to the upper row of each column, being the lower rows irrigated through runoff and dripping), the irrigation conditions were not the same in each row. The pH (Fig. S6), electrical conductivity (Fig. S7), P concentration (Fig. S8) and organic matter content (Fig. S9) values of the soils in the different rows can be consulted. The irrigation system could have caused a displacement by leaching of some soil components from the upper rows to the lower ones. However, a deep analysis did not identify any relevant pattern in the evolution of the soil properties in the different rows. For instance, in the case of the electrical conductivity, a downward salt carryover from upper to lower rows could have appeared, but the data disaggregated by rows did not support this idea. Focusing on the untreated greywater, Row 1 had the highest initial electrical conductivity. However, after three months of irrigation, Row 4 had the highest value. However, after six months and until the end of the experimental period, Row 3 had the highest electrical conductivity. Row 3 was located at a higher level than Row 4, which previously had the highest electrical conductivity, fact that discarded the carryover from upper to lower rows. Plant size and the corresponding root system development can also influence soil properties. For instance, the silver carpet located in Row 3 was the plant with the lowest biomass. This reduced size may imply a lower nutrient uptake from the soil and could justify the higher electrical conductivity values found in Row 3 after six months when compared to the other rows, where plants with higher size were located.

Although the one-year monitoring period completed in this study has provided valuable and robust information about mid-term effects of irrigation with treated greywater, further investigation to consider long-term effects in soils should be carried out. Salinity increased moderately but remained within acceptable ranges, but cumulative impacts could occur under prolonged application (10–20 years) of greywater irrigation. Moreover, the effects of other chemical species not explicitly evaluated in this study (metals, specific organic pollutants ...) should be taken into consideration.

3.3. Plants growth

The growth of the different species was specifically treated to take into consideration the diversity of plants considered for green walls and roofs. Regarding the spider plants, all the plants survived the 1-year experiment with a healthy appearance (100% survival rate). When the normalized leaf amount (NLA) was evaluated (this normalization served to compensate for the different initial number of leaves in each plant), a first initial stage (which lasted the first three months) without increasing the number of leaves can be identified (Fig. 4a). In the case of the plants irrigated with both untreated and treated greywater a small reduction in

the number of leaves was reported during these months, which corresponded to the winter months in Chile. After this phase, in the period between Months 3 and 6, the spider plants increased the numbers of leaves, especially in the cases of the treated greywater and the control tap water. However, the plants irrigated with untreated greywater required additional time to achieve equivalent growth. For instance, after 6 months of experiment, the NLA value for the plants irrigated with untreated greywater was 1.26. Meanwhile, the values for control water and treated greywater were 1.36 and 1.48, respectively. During the second half of the experiment, however, the NLA values for the spider plants irrigated with both types of greywater were consistently higher than those for the control tap water, achieving the treated greywater the maximum value (1.87) at the end of the period, followed by untreated greywater (1.73) and control tap water (1.58). These results suggest that, although plants irrigated with greywater required an initial adaptation period to the specific characteristics, they exhibited greater growth than those irrigated with control tap water once acclimatized.

When the normalized leaf length (NLL) was investigated, similar results appeared. The spider plants irrigated with both types of greywater presented relative longer leaves than the ones irrigated with control tap water when the experimental period finished (Fig. 4b). Nevertheless, once again, during the first months of the experiment, the irrigation with greywater resulted less effective and resulted in shorter leaves when compared to the use of tap water (after three months the NLL value for control tap water was 0.96, while the values for untreated and treated greywater were 0.85 and 0.74 respectively). The analysis of the normalized leaf width (NLW) presented a similar pattern. Although this parameter presented a global decreasing trend (as spider plant leaves elongated while becoming narrower), the performance of plants irrigated with greywater during the first three months was clearly lower than that observed under control tap water (Fig. 4c): by the third month, the NLW value for control tap water reached 0.96, whereas both greywaters showed values of 0.84.

The selected spider plant species has stolons with offshoots (Fig. S10) which represent the youngest parts of plants with possibility of reproduction. In these plants, the production of offshoots at the ends of stolons is generally considered a sign of good health and vegetative vigor, since this asexual propagation strategy becomes more pronounced when the plant is well established and resources are sufficient. However, moderate stress conditions such as root confinement, slight nutrient limitation or presence of pollutants may also stimulate offshoot formation [118], so this indicator should be interpreted together with other physiological traits. The evolution of offshoot production in spider plants once again evidenced that specimens irrigated with untreated greywater required a longer acclimatization period (after five months they reached an average of 5.4 offshoots, whereas plants irrigated with control tap water produced 7.8), as seen in Fig. 4d. However, after six months of experimentation, offshoot production was similar across the three irrigation treatments (ranging from 11.0 for treated greywater to 12.2 for untreated greywater), but from this point onward the plants irrigated with untreated greywater accelerated their production and became the most productive group. The final value reached 32.5 offshoots, compared with 24.0 for treated greywater and 20.6 for control tap water. This exceptional performance of the plants irrigated with untreated greywater will be further discussed in the following subsection, together with the results concerning plant health, to better assess whether this higher number of offshoots reflects a positive or negative condition in spider plants.

A detailed analysis of the spider plants allocated at each cardinal point of the experimental installation was carried out to evaluate the potential influence of this variable (Fig. S11). The different orientations of the plants may result in varying exposure to sunlight and to meteorological factors such as wind or humidity. These environmental differences can have a direct impact on physiological processes, including photosynthesis, water loss through transpiration, temperature-induced stress, growth patterns and overall plant performance. In the present

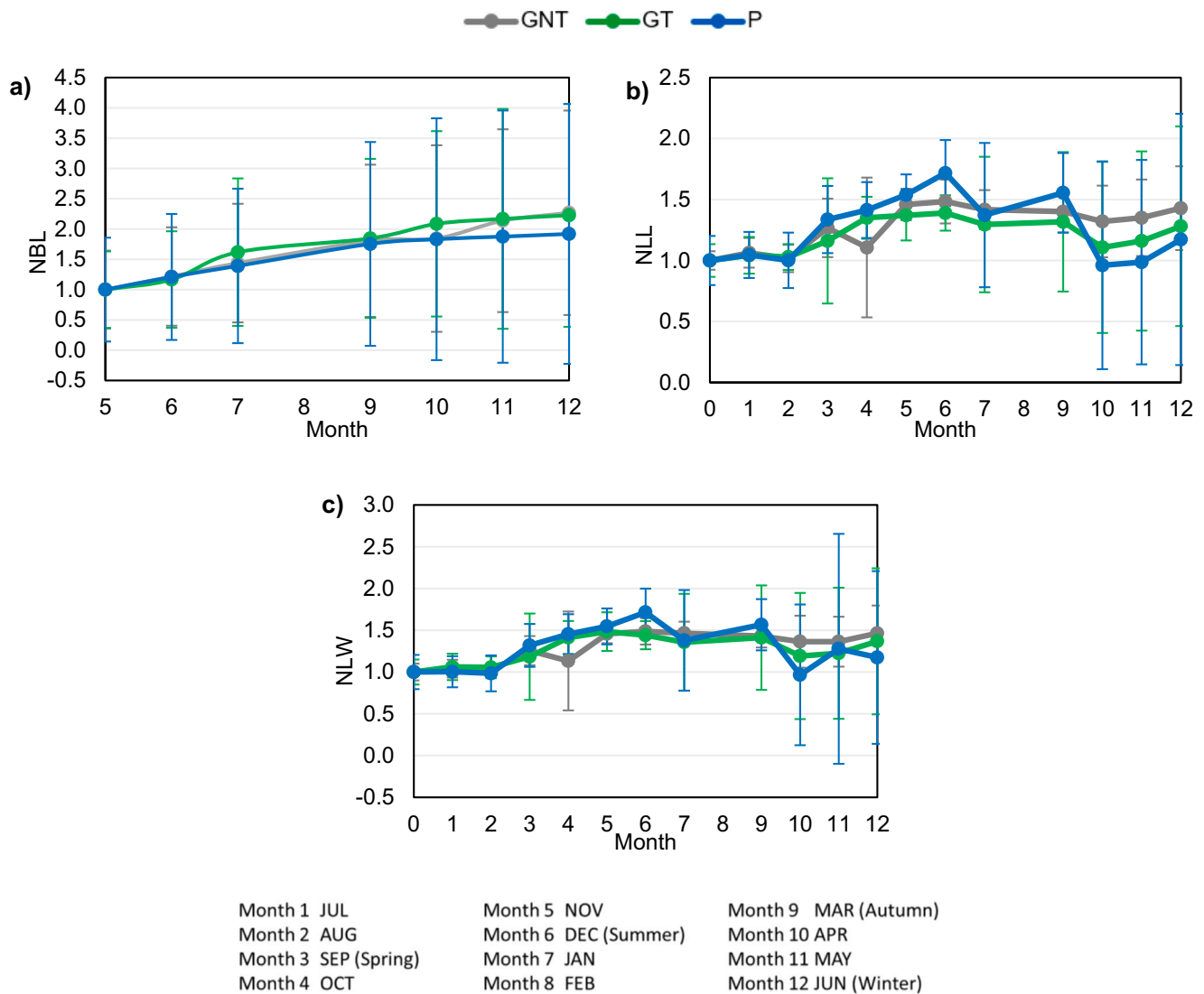


Fig. 5. Effects of irrigation water type on (a) normalized branch length (NBL), (b) normalized leaf length (NLL) and (c) normalized leaf width (NLW) in common ivy.

study, however, no clear or consistent pattern related to the different cardinal orientations was identified. Interestingly, the orientation that exhibited the highest plant growth, expressed in terms of the relative number of leaves, varied depending on the type of irrigation water. Specifically, plants irrigated with untreated greywater showed the best growth in the north orientation, those irrigated with treated greywater performed best in the west orientation, whereas the south orientation was associated with the highest productivity when control tap water was used. This different performance, without clear trends relating the cardinal orientations, the plant species and the types of water used for irrigation, could be explained just by the great variability of live systems.

Focusing on the ivy, five of the initial plants did not survive the one-year experiment (79.1% survival rate). All the dead plants were in the last row of the experimental installation, which had the lowest irrigation flow and sunlight exposure. Surprisingly, all the plants irrigated with untreated greywater survived: two dead specimens were irrigated with treated greywater and the other three with control tap water. Normalized leaf length (NLL) and width (NLW) values were recorded, and after the fifth month, the normalized branch length (NBL) was also considered. NBL is measured as the sum of the lengths of all the branches in a plant divided by the initial value of this sum (Fig. 5a). Both the NLL (Fig. 5b) and NLW (Fig. 5c) values were subject to a seasonal variation: they presented maximums during the summer (around the sixth month)

but the values decreased after this season, mainly due to the appearance of new smaller leaves to replace the older ones, which contributed to reduce the average value. Once again, as in the case of the spider plants, the delay that suffered the plants irrigated with both types of greywater can be observed. During the first half of the year, both the length and width of the leaves from plants irrigated with greywater were consistently smaller than the values corresponding to the control tap water. However, after this initial adaptation period, the values were much more similar and during the last three months of the experimental period the values of the plants irrigated with greywater surpassed their homologous irrigated with control tap water, with the plants irrigated with untreated greywater presenting the maximum value. In the case of the NBL values, as the recording started after five months, this delay stage was not taken into account and the three types of irrigation water presented quite similar results. Nevertheless, once again, the values for tap control water in the last three months were below those of the greywaters. The detailed analysis of the ivy plants located in the different cardinal orientations did not reveal any relevant trend (Fig. S12). While the south orientation was the most advantageous for the plants irrigated with both types of greywater, the plants irrigated with control tap water presented better performance in the west orientation of the experimental installation.

The silver carpet was the species specifically considered for the design of green roofs in this study. One plant, which was irrigated with

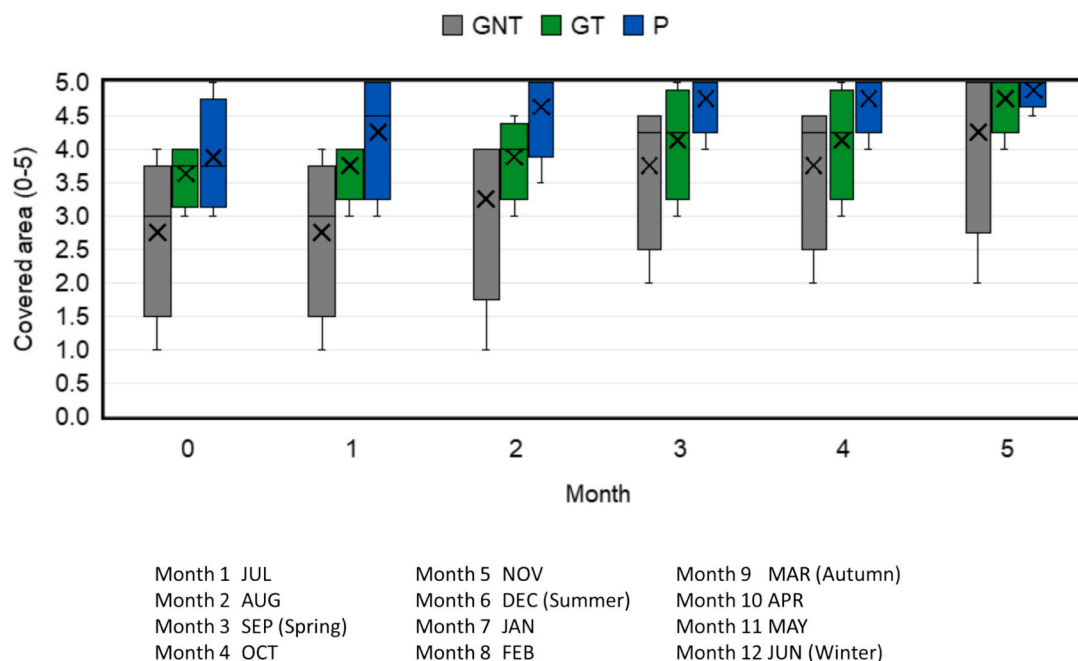


Fig. 6. Surface area covered by silver carpet under different irrigation water types.

untreated greywater, did not survive (91.6% survival rate). The growth pattern resembled that of the other species: plants irrigated with both types of greywater experienced an initial delay associated with the adaptation period (Fig. 6). This delay was more pronounced for untreated greywater, but the area covered by plants irrigated with treated greywater was also clearly lower than that of the tap water control during the first half of the experimental period. While some control plants achieved full pot surface coverage within the first month, those irrigated with greywater required at least five months to reach full coverage.

The joint analysis of the performance of the three species confirmed the adaptation period required by plants irrigated with both untreated and treated greywater. This period led to reduced short-term growth compared to the tap water control. However, after this initial stage, the growth of plants irrigated with greywater matched the control after six months and even surpassed it by the end of the one-year experimental period. While some studies reported no significant differences in short-cycle vegetables irrigated with freshwater or greywater, such as lettuce harvested after 40 days [119] or silverbeet after 60 days [58], lettuces irrigated with greywater for just 4 weeks showed lower productivity in terms of leaf area and weight relative to control water [120]. However, African leafy vegetables harvested 55 days after sowing exhibited significant delays in germination and reduced total biomass under greywater irrigation compared to tap water [54]. Similarly, pepper plants irrigated for 15 weeks with tap water showed higher fruit and biomass productivity than those irrigated with untreated greywater [57]. Reduced productivity has also been observed in longer-cycle crops, such as tomato grown for over six months, where greywater irrigation decreased both leaf and fruit yield compared to tap water [56]. In contrast, ornamental species developed adequately, maintaining their aesthetic value, when irrigated constantly and exclusively with greywater over an extended period of 30 weeks [72].

3.4. Plants health

Assessing plant health through photosynthetic pigment composition provides critical insight into physiological responses to environmental stressors, including irrigation water quality. Chlorophyll *a*, chlorophyll *b* and carotenoids are key indicators of photosynthetic efficiency and

photoprotective capacity and their relative proportions can reflect both seasonal acclimatization and stress adaptation [121,122]. Changes in pigment profiles were not significant and comparison of the control composition with those of the greywater treatments revealed no major differences. Pigment ratios indicate a general state of semi-dormancy (Table S3). Although chlorophyll *a* remains in higher concentrations than chlorophyll *b* and carotenoids are present in lower proportions, the pigment ratios display a slight decrease between month 0 and the subsequent sampling periods. The main general observation was the variation in chlorophyll forms in plants irrigated with greywater during the first months of the experiment. For instance, the percentage of chlorophyll *b* increased at the expense of chlorophyll *a* in spider plants irrigated with treated greywater in the first and second months, in ivy plants under the same treatment in the first and fourth months and in silver carpet plants irrigated with both untreated and treated greywater in the initial months. This modified pigment profile could be associated with the previously identified adaptation period, as samples collected during the second half of the experimental period showed only minor differences.

Species-specific responses were also evident. In spider plants (Fig. 7a), chlorophyll *a* declined from the first month onward, while chlorophyll *b* and carotenoids increased slightly. This pattern aligns with reduced photosynthetic demand during winter and was independent of irrigation type, indicating that seasonal cues dominated over water quality effects in driving physiological dormancy. Ivy (Fig. 7b) displayed a similar early-season chlorophyll *b* increase, again linked to low temperatures. However, from month seven onward, carotenoid concentrations rose appreciably across all treatments. This late-season elevation is likely a photoprotective response to increasing solar intensity combined with rising soil salinity, a known consequence of long-term greywater use [122]. Carotenoids mitigate oxidative damage by dissipating excess light energy and their accumulation underscores the plant's capacity to activate stress-defense mechanisms without visible damage. Silver carpet (Fig. 7c) showed the most uniform pigment response across irrigation regimes, though treated greywater caused the strongest early effect, possibly due to residual disinfectants or altered nutrient availability. In the latter half of the trial, carotenoid accumulation mirrored trends in ivy and spider plant and was again attributed to cumulative salinity stress and exposure to high summer temperatures

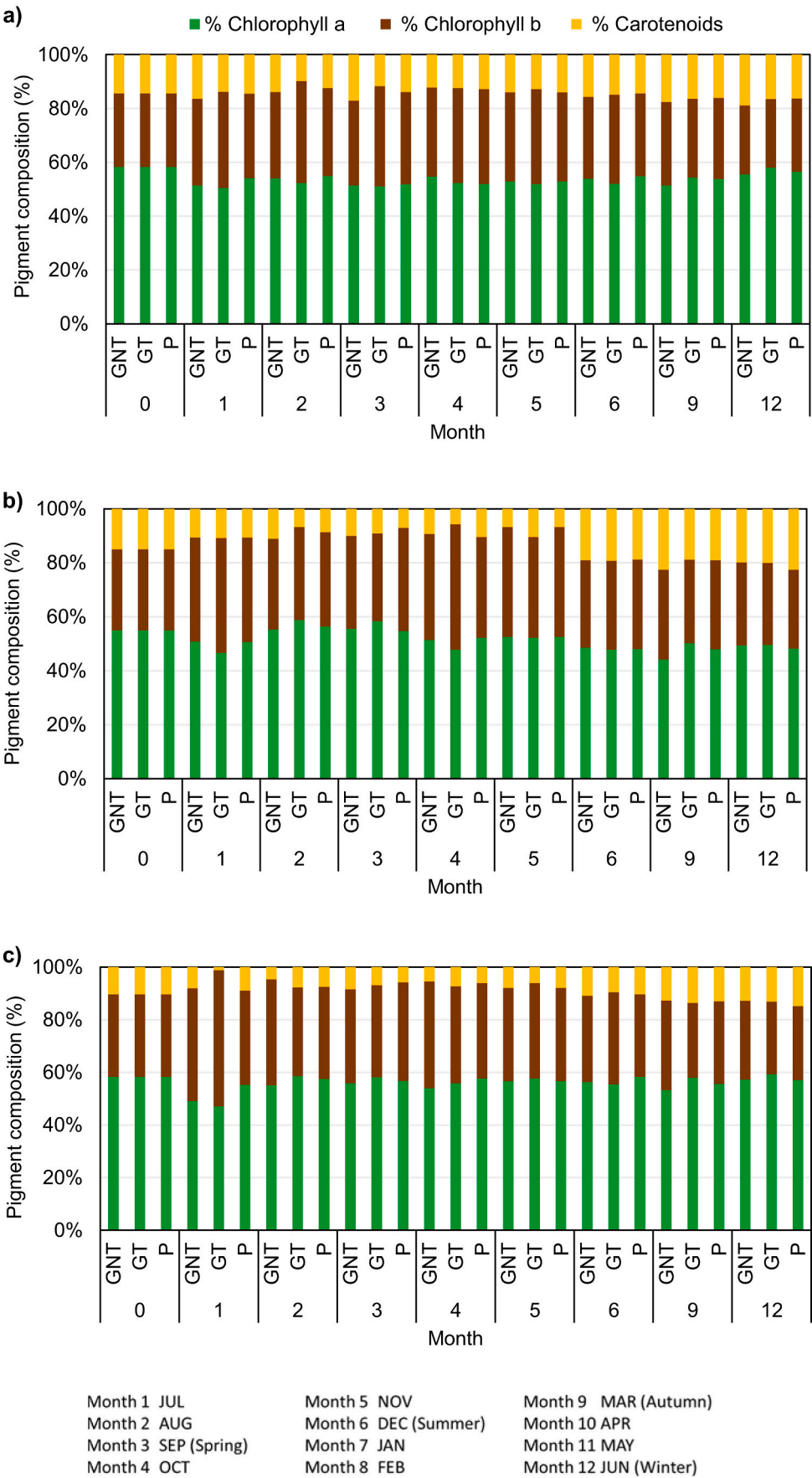


Fig. 7. Effects of irrigation water type on pigment concentration in: (a) spider plant, (b) common ivy and (c) silver carpet.

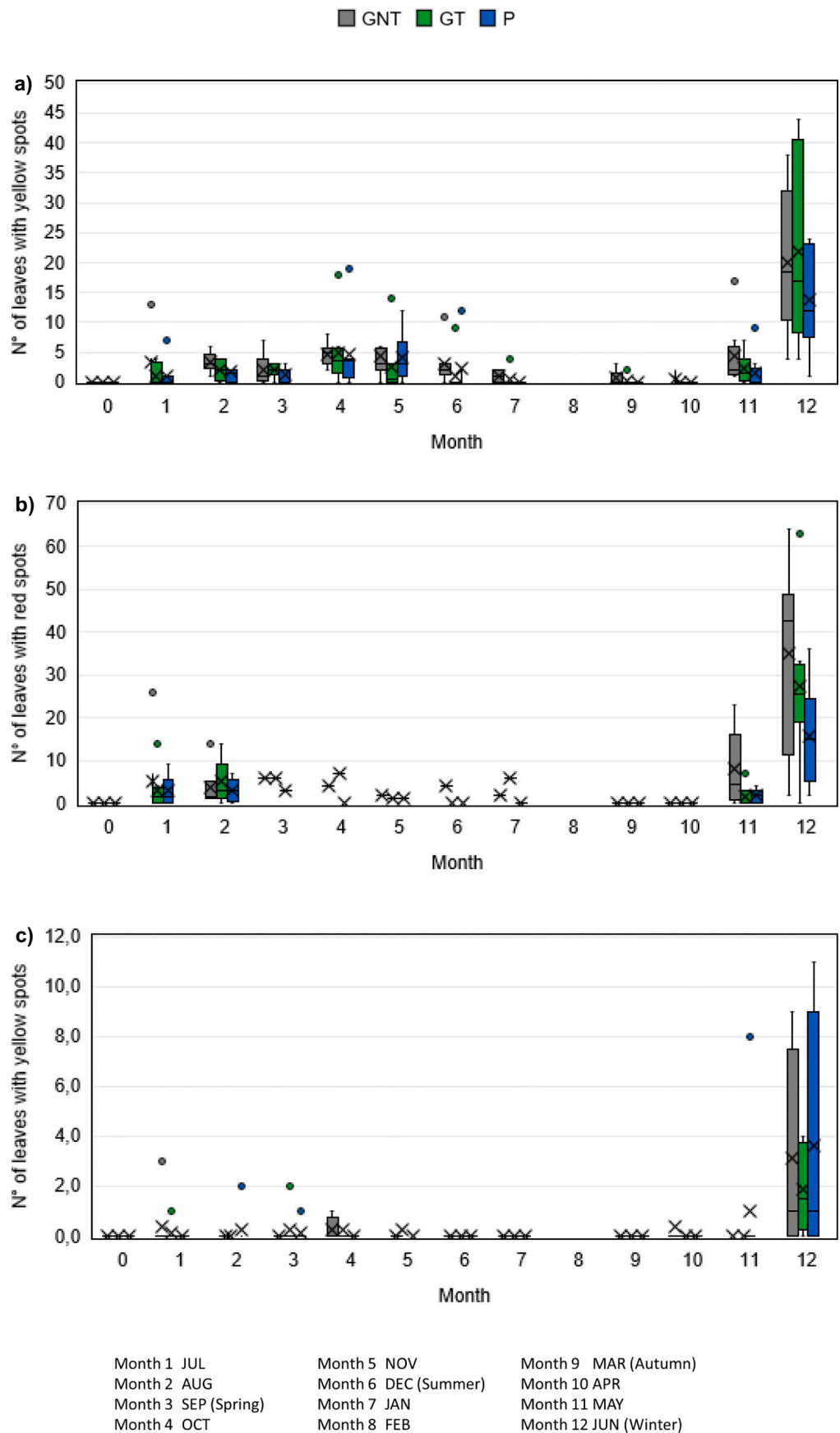


Fig. 8. Effects of irrigation water type on the number of leaf spots: (a) yellow and (b) red spots in spider plant and (c) yellow spots in common ivy. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[123].

Visual inspection of leaf surfaces revealed minimal symptomatology for most of the experimental period (Fig. 8). Incidence of chlorotic or necrotic spots remained low and comparable across all irrigation treatments until the final month, which coincided with the onset of winter. During this period, a modest increase in both yellow (chlorotic) and red (anthocyanin-associated or oxidative) spots was observed.

Notably, symptom expression varied by species and water type. In spider plants, treated greywater induced the highest number of yellow spots, whereas untreated greywater was associated with more red spots, potentially reflecting differential responses to salinity versus organic pollutants. Control plants also developed both spot types, albeit to a lesser extent. In ivy, surprisingly, the highest spot count occurred under tap water irrigation, suggesting that factors beyond water quality, such as microclimatic exposure or nutrient imbalances, may have contributed to visible stress.

This seasonal uptick in foliar symptoms aligns with the physiological slowdown associated with winter dormancy rather than acute toxicity. The absence of severe or progressive chlorosis throughout the trial indicates that neither untreated nor treated greywater imposed phytotoxic stress levels sufficient to compromise long-term plant health in these ornamental species.

These results contrast with studies on edible crops, where greywater irrigation frequently induces chlorosis and pigment degradation. For example, Wiel-Shafran et al. (2006) documented significant chlorosis in lettuce after only 30 days of untreated greywater irrigation, attributed to high salinity and surfactant content [124]. Similarly, Lubbe et al. (2016) and Veatch-Blohm et al. (2023) reported reduced chlorophyll concentrations in leafy vegetables and ornamentals under greywater regimes, respectively [54,62]. However, these effects often manifest in short-cycle or sensitive species grown under controlled or intensive conditions.

Conversely, several studies, particularly those involving resilient ornamentals or treated effluents, report neutral or even beneficial outcomes. Anangadan et al. (2024) observed only minor increases in leaf spotting and slight chlorophyll reductions in ornamentals irrigated with greywater over three months, consistent with our findings [70]. Moreover, treated greywater has been shown to enhance chlorophyll content in certain crops: Shqerat & Al-Tabbal (2025a, 2025b) reported increased total chlorophyll in tomato and pepper [56,57], while Abdulqader & Memduhe (2017) noted similar benefits in bean and watermelon [125]. Even in marigold, a common ornamental, Disha et al. (2020) found no significant pigment differences between treated greywater and control [60].

Taken together, the evidence suggests that ornamental species (particularly those adapted to variable environments) can maintain robust physiological function under long-term greywater irrigation. The transient pigment shifts and minor late-season spotting observed here reflect adaptive plasticity rather than pathological decline, reinforcing the suitability of these species for sustainable green infrastructure applications using reclaimed water.

4. Conclusions

Electrochemical treatment of greywater can be considered an efficient and robust alternative to conventional methods, since it substantially improves water quality parameters such as turbidity, suspended solids and chemical oxygen demand, while keeping pH values within a range compatible with irrigation, despite its higher electrical conductivity compared to tap water. These characteristics make it suitable for irrigation in urban green infrastructure, especially when the goal is to reduce potable water consumption.

From a soil perspective, using treated greywater did not significantly alter key parameters such as pH, organic matter content or phosphorus concentration. Seasonal meteorological variations, especially rainfall, influenced soil pH more than the type of irrigation water. Salinity

increased moderately but remained within acceptable ranges, indicating that the electrochemical process effectively mitigated salt accumulation compared to untreated greywater. Additionally, the absence of phosphates in the detergent formulation limited phosphorus inputs, avoiding the risks often associated with greywater reuse.

The one-year irrigation experiment revealed that the three selected ornamental species exhibited comparable survival rates and growth patterns when irrigated with either treated greywater or tap water. An initial adaptation period was observed for all species irrigated with both untreated and treated greywater. This period was manifested through slower growth during the first months. Once acclimatized, however, plants irrigated with treated greywater showed comparable or even superior performance in terms of leaf development, branch elongation and surface coverage. This behavior suggests that, with careful management of irrigation practices, treated greywater can sustain plant growth in vertical and horizontal greening systems without detrimental physiological impacts.

Overall, the results suggest that electrochemically treated greywater is a technically sound and environmentally sustainable option for irrigating green walls and roofs in urban areas facing water scarcity. Implementing it can reduce the demand for potable water, support the expansion of urban vegetation and contribute to climate adaptation strategies. However, successful application requires adequate system design, continuous monitoring of water quality and soil salinity and consideration of local climatic conditions to ensure long-term sustainability.

CRediT authorship contribution statement

Gabriel Illanes: Writing – review & editing, Writing – original draft, Investigation, Data curation. **Nadia Águila:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Julio Urzúa-Ahumada:** Writing – review & editing, Supervision. **Karen Manquían-Cerda:** Writing – review & editing, Methodology, Conceptualization. **Gustavo E. Zúñiga:** Writing – review & editing, Methodology, Conceptualization. **Roxana Arce:** Writing – review & editing, Methodology, Conceptualization. **Julio Romero:** Writing – review & editing, Methodology, Conceptualization. **Ricardo Abejón:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Esteban Quijada-Maldonado:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

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.jwpe.2026.110010>.

Data availability

Data will be made available on request.

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