Physicochemical Characteristics of Leachates from Soilless Substrates for Tomato (*Solanum lycopersicum* L.) Seedling Production

Características fisicoquímicas de los lixiviados de sustratos sin suelo para la producción de plántulas de tomate (*Solanum lycopersicum* L.)

Jorge Alonso Alcalá Jáuregui [1*], Claudia Tiscareño Villa [1], Ángel Natanael Rojas Velázquez [1], Idrissa Diedhiou [2], María Flavia Filippini [3], Daniela Cónsoli [3], Eduardo Martínez Carretero [4], Juan Carlos Rodríguez Ortiz [1], Hugo Magdaleno Ramírez Tobías [1]

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Abstract

Assessing agricultural water quality is fundamental to minimizing and mitigating irrigation's environmental impacts. Leachate dynamics and physicochemical parameters as environmental stress indicators were evaluated. For tomato (*Solanum lycopersicum* L.) seedling production, we used soilless substrates. The study evaluated four treatments: T1 (100% coconut fiber), T2 (75% coconut fiber + 25% perlite), T3 (100% peat moss), and T4 (75% peat moss + 25% perlite). A controlled irrigation regime lasted 16 days, including fertilizer and fungicide applications. We collected and analyzed 192 leachate samples for eight parameters. Measured parameters included pH, electrical conductivity (EC), total dissolved solids (TDS), Na^+, NO_3^-, K^+, and Ca^{2+}. T3 showed the highest average volume retained (AVR). T2 exhibited the highest average leachate volume (AVL). Nitrate concentrations were higher in T4 and lower in T1, exceeding regulatory limits. Concentrations of Na^+, K^+, and NO_3^- posed contamination risks. These findings highlight the need for improved monitoring to enable safe agricultural reuse.

Keywords
Substrate mixtures • total dissolved solids (TDS) • nitrates • reference levels

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1 Universidad Autónoma de San Luis Potosí. Facultad de Agronomía y Veterinaria. Km. 14.5 Carretera San Luis-Matehuala Apdo. Postal 32 CP 78321 Soledad de Graciano Sánchez. S. L. P. México. * jorge.alcala@uaslp.mx
2 EARTH University. Limón Province. Mercedes. Costa Rica.
3 Universidad Nacional de Cuyo. Facultad de Ciencias Agrarias. Catedra Química Agrícola. Almirante Brown 500. M5528AHB. Chacras de Coria. Mendoza. Argentina.
4 IADIZA (CONICET). Geobotánica y Fitogeografía. Mendoza. Argentina.

Resumen

La evaluación de la calidad del agua para uso agrícola es fundamental. Minimiza el impacto ambiental del riego y mitiga estos problemas. Este estudio evaluó la dinámica de los lixiviados y los parámetros fisicoquímicos como indicadores de estrés ambiental. Utilizamos sustratos sin suelo para la producción de plántulas de tomate (*Solanum lycopersicum* L.). El estudio evaluó cuatro tratamientos: T1 (100 % fibra de coco), T2 (75 % fibra de coco + 25% perlita), T3 (100% turba) y T4 (75% turba + 25 % perlita). Se aplicó un régimen de riego controlado durante 16 días, incluyendo aplicaciones de fertilizantes y fungicidas. Recogimos y analizamos 192 muestras de lixiviados para ocho parámetros. Los parámetros medidos incluyeron el pH, la conductividad eléctrica (CE), los sólidos totales disueltos (STD), Na^+, NO_3^-, K^+ y Ca^{2+}. T3 mostró el mayor volumen medio retenido (AVR). T2 presentó el mayor volumen medio de lixiviados (AVL). Las concentraciones de nitrato fueron más altas en T4 y más bajas en T1, superando los límites reglamentarios. Las concentraciones de Na^+, K^+ y NO_3^- planteaban riesgos de contaminación. Estos hallazgos ponen de relieve la necesidad de mejorar la supervisión para permitir una reutilización agrícola segura.

Palabras clave

Mezclas de sustratos • sólidos disueltos totales • nitratos • niveles de referencia

Introduction

Assessing agricultural water quality is fundamental to preventing and mitigating environmental impacts. Agriculture dominates groundwater and surface water use. These resources are being overexploited worldwide (Moxey, 2012; Ongley, 1996; Yadav, 2024). Water scarcity is a priority in arid areas, particularly considering crops´ use 65% of applied water (Wahb-Allah & Al-Omran, 2012). Major impacts include agricultural leaching, erosion, and excessive nutrient losses, mainly caused by high nitrate concentrations.

Nitrate is a key indicator for evaluating agri-environmental policies (Kronvang *et al.*, 2020; Moxey, 2012; OMS, 2006). Considering irrigated areas will likely increase, to mitigate water shortages, we must increase water efficiency and use marginal water (reclaimed, saline, or drainage) for irrigation. Fertigation enables this approach (UNESCO, 2025). Considering that about 25% of the world's surface water is polluted, monitoring quality parameters is necessary. However, in Mexico, official information about agricultural impacts on water resources is scarce. Data on pollution sources and inputs like fertilizers are limited (Aguilar & Pérez, 2008). Tomato is one of the most important vegetables in the world, with a per capita consumption of 20.2 kg (Pérez-Díaz *et al.*, 2020).

Tomato production is the most significant national crop impacting water use. Mexico is the world's leading red tomato (*Solanum lycopersicum* L.) exporter, cultivating 49,522.18 ha and producing 3,636,927.46 tons. Sinaloa (19.6%), San Luis Potosi (12%), and Michoacan (9.8%) are the main producers (SEDARH, 2025). Exports mainly go to the United States and Canada (99.7%) (SIAP, 2022). Global demand will likely reach 11.78 million metric tons by 2030.

Average annual water requirements for tomatoes are 1,813 m^3/ha. Requirements vary by system: 1,040 m^3 for non-technified open fields and 8,461 m^3 for technified ones (Rincón *et al.*, 2016). Intensive tomato cultivation requires balancing fertigation efficiency and water quality. This balance is necessary for proper application and minimizing environmental impacts (Banjaw *et al.*, 2017). Fertigation increases water use efficiency. In San Luis Potosi and Soledad de Graciano Sanchez (Mexico), groundwater availability for 5,000 ha is limited. Consequently, farmers use water from deep and shallow aquifers, alongside domestic and industrial wastewater (Sarabia-Meléndez *et al.*, 2011). Irrigated areas suffer from waterlogging, desertification, salinization, and erosion. Water quality degradation from salts, agrochemicals, and toxic leachates is a serious problem (Moxey, 2012). Currently, soilless growing systems prioritize water and fertilizer efficiency. These systems respond to soil pathogens while allowing optimal plant growth control and high productivity (Gonnella & Renna, 2021). Global concern grows over recovering and recycling nutrients in food production. This is due to increasing natural resource consumption (Lucero-Sorbazo *et al.*, 2022). Agricultural water waste contains nutrients, pesticides, sediments, organic matter, pathogens, and heavy metals (Mateo-Sagasta *et al.*, 2017).

Quality analysis considers electrical conductivity (EC), total dissolved solids (TDS), pH, ions, and bacteria (Diaz *et al.*, 2025). Studies have evaluated leachates in horticultural crops using substrates like vermicompost, sand, perlite, coconut fiber, and peat moss (Salas *et al.*, 2003). Coconut fiber has a bulk density of 0.03-0.09, a pH of 4.9-6.1, and high-water retention. Perlite density ranges from 0.08 to 0.12 with a pH of 7 to 7.5. Peat moss has a density of 0.2-0.5, a pH of 4-7, and high-water retention (Mateo-Sagasta *et al.*, 2017). Current technologies in agroecosystems must reduce the harmful effects of chemical fertilizers and improper waste disposal. Transforming agricultural practices provides solutions to immediate and long-term problems (Shanmugavel *et al.*, 2023). This study evaluated the environmental implications of tomato (*Solanum lycopersicum* L.) seedling production. We quantified leachate volumes and characterized their physicochemical properties in different soilless substrates.

Materials and Methods

The study was conducted in the greenhouse at the Environmental Engineering Laboratory. This laboratory belongs to the Faculty of Agronomy and Veterinary, UASLP, Mexico. The site is located at km 14.5 of the San Luis Potosí-Matehuala highway, Ejido Palma de la Cruz. Its geographical coordinates are 22°14’05’’ N and 100°51'48” W, at an altitude of 1,836m ASL.

Physical Characterization of Substrates

We established a completely randomized experimental design with four treatments and three replications. The treatments included coconut fiber, perlite, and commercial peat moss. They were prepared as follows: T1 (100% coconut fiber), T2 (75% coconut fiber + 25% perlite), T3 (100% peat moss), and T4 (75% peat moss + 25% perlite). We used technical data for Kekkilä DSM 05 peat moss (LiTEC, 2025) and AGROLiTA™ perlite (Agrolita de México, 2023). Table 1 presents relevant information from these sheets. The coconut fiber was sieved before characterization. Measured parameters included bulk density, real density, particle size distribution (PSD), thickness index, pH, and EC. We followed UNE-EN 13041 standards for these determinations (AENOR, 2022). PSD was determined using a mechanical sieve with mesh sizes from 4.76 mm to 0.15 mm. We weighed the remaining fraction in each sieve. The thickness index was the sum of weights for fractions larger than 1 mm. Particles were classified by diameter: fine (<1 mm), medium (1-2.38 mm), and coarse (>2.38 mm). Total porosity was calculated using real and bulk density. All substrate analyses were performed at the faculty's Water and Soil Laboratory. Table 1 summarizes fiber characterization.

Table 1. Summary of some physical and chemical characteristics of the substrates used in the experiment.

Tabla 1. Relación de algunas características físicas y químicas de los sustratos utilizados en el experimento.

Commercial peat substrates	Commercial perlite substrates	Coconut fiber substrate
Blond-brown peat (Sphagnum type)	Actual density (g/m^3): 0.35	Thickness index: fine
Particle size 0-6 mm	Apparent density (g/m^3): 0.12-0.23	Apparent density: 1.47 g/mL
Fertilization: 0.3 kg/m^3 (N-P-K and microelements)	Porous space % volume: 34-85%	Actual density: 1.5 g/mL
Additives: Calcium carbonates (Ca, Mg) and humectant (W)	pH: 6.5-7.5	Porosity (PT): 2%
		pH: 6.1
pH: 5.5 (saturated paste method)	The chemical composition indicates different percentages of silicon, aluminum, iron, sodium, potassium, calcium, and others.	Electrical conductivity: 1000 µS/cm
Electric conductivity: 1.3 mS/cm (saturated paste method)		Particle size distribution in ranges: 0.34 for 0.15 mm mesh to 15.46 g for 2.0 mm mesh

Peat moss and perlite data come from commercial technical sheets (LiTEC, 2025; Agrolita de México, 2023). Laboratory tests determined coconut fiber characteristics.

Los datos de la turba y la perlita provienen de fichas técnicas comerciales (LiTEC, 2025; Agrolita de México, 2023). Las pruebas de laboratorio determinaron las características de la fibra de coco.

Physical and Chemical Characterization

We determined pH and EC values using a HANNA HI99300 multiparameter meter. The saturation extract method used a 1:1 volume ratio of distilled water and substrate (300 mL each). We filtered the extract using 100 mm filter paper under vacuum. We ensured that the filtrate was clear to maintain reading accuracy.

Seedling Preparation

All substrates were prepared in 4-liter containers. We used four 200-cell seed trays (66 × 32 × 4 cm). Each treatment included three replicates, divided into 40-cell sections (5 × 8). Empty cell rows separated the treatments. We left edge cells empty to reduce the edge effect. Three individual trays under each seedbed collected residual water. We sowed two commercial tomato (*Solanum lycopersicum* L.) seeds per cavity. Normal irrigation continued until germination exceeded 60%. Subsequently, seedlings received 16 days of programmed irrigation. This included three applications of Amistar® Gold fungicide and Gro Green (20-30-10) fertilizer.

Irrigation Application

The irrigation program lasted 16 days with a frequency of every three days. We applied 750 mL of water per seedbed. Irrigation was controlled using 100 mL beakers and 5 mL syringes. The total volume was divided among the four treatments and their respective cavities. We prepared a four-liter solution for each application using 0.5 mL of fungicide and 1.5 mL of fertilizer. Each replicate received 750 mL of this solution via a foliar application. Fertilizer and fungicide were applied on days nine and fifteen. On day sixteen, we applied only the fertilizer solution. The irrigation water was pre-characterized using the same physicochemical parameters as the crop. Initial water quality values were Na^+ (24.50±7.72 mg L^{-1}), NO_3^- (55.3±42.6 mg L^{-1}), K^+ (14.25±2.06 mg L^{-1}), and Ca^{2+} (59.5±33.9 mg L^{-1}). We also measured pH (7.55±0.23), EC (231.50±7.07 µS cm^{-1}), and TDS (115.0±3.46 ppm). Reference levels for irrigation water quality (CSR Laboratorio, 2023) indicate that EC values between 400 and 700 µS cm^{-1} pose no risk. Values below 400 or above 3000 µS cm^{-1} are risky. TDS (0-500 ppm) and pH (6.5-8.4) are within acceptable ranges. For Ca^{2+}, levels below 150 mg L^{-1} are acceptable, but values above 70 mg L^{-1} require caution. Na^+ (0-70 mg L^{-1}) and K^+ (0-20 mg L^{-1}) levels are safe. For NO_3^-, values of 0-20 mg L^{-1} are safe, while 130 mg L^{-1} is risky. Consequently, initial NO_3^- levels (20-130 mg L^{-1}) require vigilance during the experiment.

Volumetric and Physicochemical Parameters

We collected leachates approximately four hours after post-irrigation to prevent evaporation. Based on previous studies (Yescas *et al.*, 2011), we calculated several volumetric parameters. These included Total Volume Applied (TVA), Total Volume Retained (TVR), Total Volume Leached (TVL), and Leaching Retention Index (LRI). We measured TVL using 300 mL and 20 mL test tubes. TVR was calculated as TVA - TVL. We estimated the average retained volume (AVR) and average leached volume (AVL) by dividing TVR and TVL by the number of irrigations. LRI was calculated as TVR/TVA, and we also estimated the leaching percentage (PL = TVL/TVA*100). We measured pH, TDS (ppm), and EC (µS cm^{-1}) using HQ40dMulti and HANNA HI99300 meters. LAQUAtwin portable meters measured Na^+, NO_3^-, Ca^{2+}, and K^+ ions (mg L^{-1}). We estimated the total leachate volume (mL) using all samples and replicates over the 16 days.

Statistical Analysis

We performed statistical analyses using Minitab® software. A one-way analysis of variance (ANOVA) was conducted for selected parameters. We used Tukey's test ($p \leq 0.05$) for mean comparisons. Additionally, we employed correlation and principal component analysis (PCA). These analyses explore relationships among variables and identify underlying patterns in the dataset.

Results and Discussion

Volumetric Indicators of Leachate

We analyzed 192 leachate samples. The total volume applied (TVA) was 48,000 ml. The total volume leached (TVL) reached 13,112 mL, resulting in a total volume retained (TVR) of 34,888 mL. This TVR represented 27.31% of the applied irrigation water. Tukey's test ($p \leq 0.05$) showed significant differences among volumetric variables for all treatments. T2 (75% coconut fiber + 25% perlite) yielded the highest TVL, AVL, and PL values. Conversely, T3 (100% peat moss) exhibited the highest TVR, AVR, and LRI (table 2). On average, T3 retained 579.87 mL (AVR). T2 showed the highest average leaching (AVL) with 247.75 mL and the highest percentage leached (PL). Differences between T3 and T2 were notable. T3 retained 77.31% of the TVA, resulting in an LRI of 0.77. This retention was 1,242 mL higher than T2. T2 obtained the lowest AVR and highest TVL, representing 33.03% of the TVA (3,964.0 mL).

Table 2. Relationship of leachate indicator behavior in the treatments and application of irrigation (n=64).

Tabla 2. Relación entre el comportamiento del indicador de lixiviados en los tratamientos y la aplicación de riego (n=64).

Treatment	Irrigation days	TVA	TVR	TVL	AVR	AVL	PL	LRI
		mL	mL	mL	mL	mL	%	
T1 100% coconut fiber	16	12,000	8,409	3,591	525.56 bc	224.43 ab	29.92	0.701
T2 75% coconut fiber + 25% perlite	16	12,000	8,036	**3,964**	502.25 c	**247.75 a**	**33.03**	0.670
T3 100% peat moss	16	12,000	**9,278**	2,722	**579.87 a**	170.12 c	22.68	**0.773**
T4 75% peat moss + 25% perlite	16	12,000	9,165	2,835	572.81 ab	177.18 bc	23.62	0.764

Different letters within a column indicate significant differences (Tukey, $p \leq 0.05$). Variables include total volume applied (TVA), total volume retained (TVR), total volume leached (TVL), average volume retained (AVR), average volume leached (AVL), leaching percentage (PL), and leaching retention index (LRI).

Letras distintas en una misma columna indican diferencias significativas (Tukey, $p \leq 0.05$). Las variables incluyen: volumen total aplicado (TVA), volumen total retenido (TVR), volumen total lixiviado (TVL), promedio del volumen retenido (AVR), promedio del volumen lixiviado (AVL), porcentaje de lixiviación (PL) e índice de retención de lixiviación (LRI).

Substrate characterization determined moisture content. Water retention occurred in both individual and combined substrates. The retention order was coconut fiber > coconut fiber + perlite > peat moss > peat moss + perlite > perlite. This order influences leachate indicators. Pore space and porosity distribution differ among substrates. These differences affect leachate volume regardless of irrigation frequency. Combining coconut fiber or peat moss with perlite increases porosity. Coconut fiber has 84.42% total porosity and 61% retention capacity. Peat moss mixed with perlite shows 81.82% porosity and 53.80% retention capacity (Quesada & Méndez, 2005). All four substrates contained fine particles. Real densities ranged from 1.5 to 1.53 g mL^{-1}. In dry particles, most water passes quickly through pores before retention. Conversely, in wet particles, leached volume depends only on substrate characteristics (Yescas *et al.*, 2011). Tomato irrigation requirements in greenhouses range from 200 mL per plant initially to 1,500 mL at maximum demand (Flores *et al.*, 2007). Coconut fiber gravimetric humidity can reach 960%. Mixing it with inorganic materials significantly reduces this humidity (Gutiérrez-Castorena *et al.*, 2011). Organic and inorganic mixtures at a 75:25 ratio retain the highest volumetric moisture (up to 98%). Coconut fiber contributes most to this retention. Mixtures at a 50:50 ratio retain 60-82%, while pure inorganic materials retain the least (Gutiérrez-Castorena *et al.*, 2011).

Soilless systems typically show higher water and fertilizer losses. However, recirculating drains could reduce contamination (Salas *et al.*, 2003).

Physicochemical Parameters

We performed a correlation analysis on 192 samples. Out of 28 interactions, 13 were significantly negative, and 9 were significantly positive ($p \le 0.05$). The strongest positive correlations were TDS-EC ($r^2=0.964$), TDS-K^+ ($r^2=0.783$), and EC-K^+ ($r^2=0.779$). The strongest negative correlation was pH-K^+ ($r^2=-0.418$). pH and EC are key parameters for substrate selection. They affect seedling rhizosphere development. These parameters and their interactions require constant analysis (Quesada & Méndez, 2005). Tukey's test ($p \le 0.05$) showed significant mean differences among parameters. These differences vary by treatment and irrigation day (table 3 and figure 1, page 7). T2 (75% coconut fiber + 25% perlite) recorded the highest average leachate volume (82.58 mL). T3 (100% peat moss) showed the lowest volume (57.75 mL). This 24.83 mL difference represents a 142.9% increase in leachate volume. Regarding physicochemical parameters (table 3), T1 (100% coconut fiber) had the highest concentrations of EC, TDS, Na^+, and K^+. T4 (75% peat moss + 25% perlite) showed the highest NO_3^- concentrations. Previous studies on coconut fiber and sargassum evaluated pH, EC, and Na^+, K^+, and Ca^{2+} content. Immersing these materials in water decreased harmful salts like Na^+ and Cl^-. However, soluble K^+ content also reduced by more than 50%. Continuous water application effectively leached salts, resulting in lower EC values (Rodríguez *et al.*, 2016). Another study compared coconut fiber powder with peat. Results showed differences between coconut fiber sources. Coconut fiber pH was slightly acidic. Salinity varied between 39 and 597 mS m^{-1} in saturated extracts. Nitrogen and calcium concentrations were low, while phosphorus and potassium concentrations were high. Chloride and sodium concentrations were also high (Abad *et al.*, 2002).

Table 3. Results of mean concentrations of physicochemical parameters in leachate according to treatment (Tukey, $p \le 0.05$, n=192).

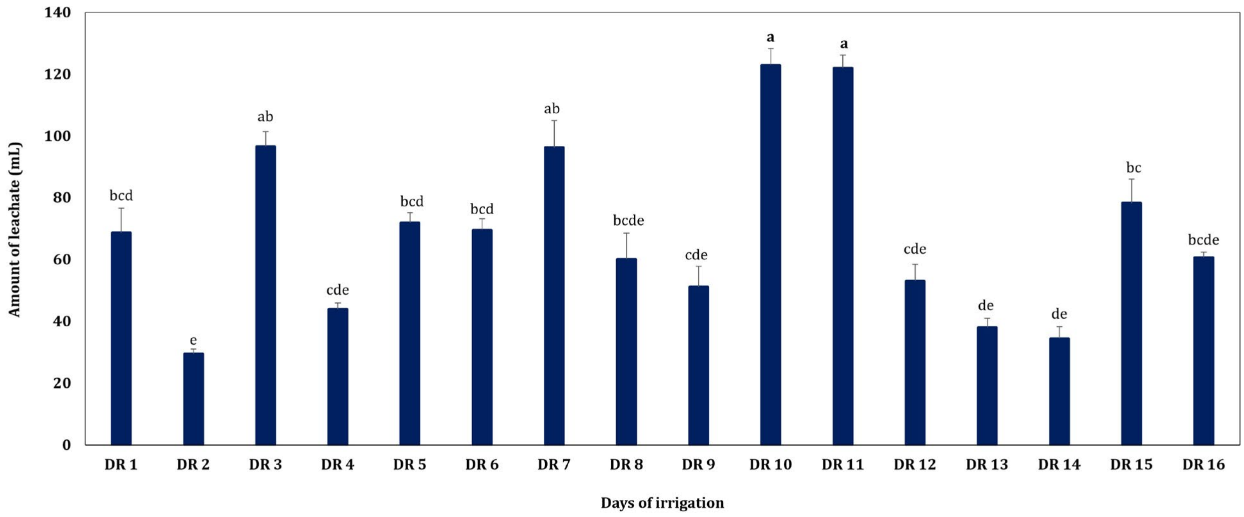
Tabla 3. Resultados de las concentraciones medias de los parámetros fisicoquímicos en lixiviados de acuerdo con el tratamiento (Tukey, $p \le 0,05$, n=192).

Means with different letters in the column indicate significant differences. Average of normal irrigation water applied: Na^+ (24.50 ± 7.72 mg L^{-1}), NO_3^- (55. 3 ± 42.6 mg L^{-1}), K^+(14.25 ± 2.06 mg L^{-1}), Ca^{2+} (59.5 ± 33.9 mg L^{-1}), pH (7. 55 ± 0.23), EC (231. 50 ± 7.07 µS cm^{-1}), and TDS (115. 0 ± 3.46 ppm).

Medias con letras diferentes en columna indican diferencia significativa. Promedio del agua normal de riego aplicada: Na^+ (24,50 ± 7,72 mg L^{-1}), NO_3^- (55,3 ± 42,6 mg L^{-1}), K^+ (14,25 ± 2,06 mg L^{-1}), Ca^{2+} (59,5 ± 33,9 mg L^{-1}), pH (7,55 ± 0,23), EC (231,50 ± 7,07 µS cm^{-1}) y TDS (115,0 ± 3,46 ppm).

Treatment	Parameters							
	Amount of leachate mL	Na^+ mg L^{-1}	NO_3^- mg L^{-1}	K^+ mg L^{-1}	Ca^{2+} mg L^{-1}	pH Scale	EC µS cm^{-1}	TDS ppm
	Mean	**Mean**	**Mean**	**Mean**	**Mean**	**Mean**	**Mean**	**Mean**
T1 100% coconut fiber	74.81 a	**126.79 a**	251.04 b	**899.72 a**	17.91 b	6.34 b	**617.50 a**	**312.70 a**
T2 75% coconut fiber + 25% perlite	**82.58 a**	105.47 ab	259.96 b	620.43 b	23.95 b	**6.80 a**	561.75 a	285.70 a
T3 100% peat moss	57.75 b	84.85 b	342.33 a	81.25 c	**116.06 a**	6.60 ab	277.41 b	149.45 b
T4 75% peat moss + 25% perlite	59.06 b	87.50 b	**358.54 a**	59.47 c	111.27 a	6.47 b	288.00 b	143.93 b

Irrigation on the tenth day showed the highest volume (122.91 mL). The second day recorded the lowest volume (29.41 mL). This 93.50 mL difference represents a 417.91% increase. Table 4 (page 7) highlights the days with maximum concentrations. EC, TDS, and Na^+ were highest on the fourth day. NO_3^- and Ca^{2+} peaked on the thirteenth day. Significant differences exist in Na^+, K^+, Ca^{2+}, and NO_3^- contents, pH, and EC between coconut fiber and peat moss mixtures (Quesada & Méndez, 2005). Consequently, parameter variations relate to substrate combinations and nutrient solutions.



Means with different letters in the column indicate significant differences.
Medias con letras diferentes en columna indican diferencias significativas.

Figure 1. Amount of leachate according to the day of irrigation application in tomato seedling crop substrates (Tukey, p≤0.05; n=192).

Figura 1. Cantidad de lixiviados de acuerdo con el día de aplicación del riego en los sustratos del cultivo de plántulas de tomate (Tukey, p≤0,05; n=192).

Table 4. Concentration of physicochemical parameters in leachate according to irrigation day (Tukey, p≤0.05; n=192).

Tabla 4. Concentración de parámetros fisicoquímicos en lixiviados de acuerdo con el día de riego (Tukey, p≤0,05; n=192).

Irrigation day	Na^+	NO_3^-	K^+	Ca^{2+}	pH	EC	TDS
	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	Scale	µS cm^{-1}	ppm
	Mean	Mean	Mean	Mean	Mean	Mean	Mean
First	108.50 b	246.66 bcd	**994.00 a**	70.06 bcd	6.15 cdef	687.25 a	343.16 a
Second	73.25 b	238.33 bcd	951.50 ab	51.83 bcd	6.12 cdef	591.50 abc	295.25 abcde
Third	77.66 b	285.83 bcd	511.33 bcde	49.00 bcd	5.62 f	637.16 ab	318.25 ab
Fourth	**448.33 a**	386.66 bc	218.91 de	54.58 bcd	6.05 ef	**723.58 a**	**358.16 a**
Fifth	88,667 b	189.33 d	848.917 ab	60.66 bcd	6.35 bcdef	582.83 abc	312.58 abc
Sixth	79.58 b	287.50 bcd	746.75 abc	84.41 bc	5.83 f	416.41 cdef	208.16 def
Seventh	80.25 b	327.50 bcd	609.75 abcd	76.33 bcd	6.06 def	417.50 cdef	208.16 def
Eighth	31.50 b	335.00 bcd	256.91 de	75.08 bcd	6.84 abc	303.25 def	151.25 ef
Ninth	72.00 b	162.08 d	233.58 de	79.41 bcd	**7.22 a**	303.50 def	159.58 ef
Tenth	67,083 b	218.91 cd	153.75 de	72.00 bcd	7.20 a	224.16 f	111.16 f
Eleventh	48.16 b	303.75 bcd	49.83 e	12.75 d	6.74 abcde	335.00 def	166.58 ef
Twelfth	45.250 b	143.29 d	82.75 e	17.33 cd	6.81 abcde	301.00 def	193.25 ef
Thirteenth	111.50 b	**935.00 a**	316.66 cde	**164.50 a**	7.150a	229.33 ef	131.50 f
Fourteenth	110.08 b	416.25 b	338.33 cde	97.83 ab	7.08 ab	229.33 bcd	238.16 bcde
Fifteenth	101.83 b	188.21 d	199.91 de	65.58 bcd	6.95 ab	421.33 cde	211.16 cdef
Sixteenth	74.83 b	183.20 d	130.66 e	45.41 bcd	6.68 abcde	323.50 def	160.83 ef

Different letters within a column indicate significant differences (Tukey, p ≤ 0.05). Average irrigation water values: Na^+ (24.50±7.72 mg L^{-1}), NO_3^- (55.3±42.6 mg L^{-1}), K^+ (14.25±2.06 mg L^{-1}), and Ca^{2+} (59.50±33.9 mg L^{-1}). Measured pH (7.55±0.23), EC (231.50±7.07 µS cm^{-1}), and TDS (115.0±3.46 ppm). Fertilizer and fungicide were applied on days nine and fifteen. On day sixteen, only fertilizer was applied.

Letras distintas en una misma columna indican diferencias significativas (Tukey, p ≤ 0,05). Valores promedio del agua de riego: Na^+ (24,50±7,72 mg L^{-1}), NO_3^- (55,3±42,6 mg L^{-1}), K^+ (14,25±2,06 mg L^{-1}) y Ca^{2+} (59,50±33,9 mg L^{-1}). El pH fue de 7,55±0,23, la CE de 231,50±7,07 µS cm^{-1} y los STD de 115,0±3,46 ppm. El fertilizante y el fungicida se aplicaron los días nueve y quince; el día dieciséis solo se aplicó fertilizante.

Substrate characteristics influence these values. Fungicide and nutrient applications on days nine and fifteen also affect them (table 4, page 7). The first stage showed several contrasts among treatments and variables (figure 2). Although T2 obtained the highest leaching percentage (LP), pH was the only parameter of interest. In contrast, T1 (100% coconut fiber) showed higher TDS and EC values. This may be associated with coconut fiber particle release.

DR: irrigation day; TVR: total volume retained; AVR: average volume retained; LRI: leaching retention index. Source: Own elaboration.

DR: día de riego; TVR: volumen total retenido; AVR: volumen medio retenido; LRI: índice de retención de lixiviación. Fuente: Elaboración propia.

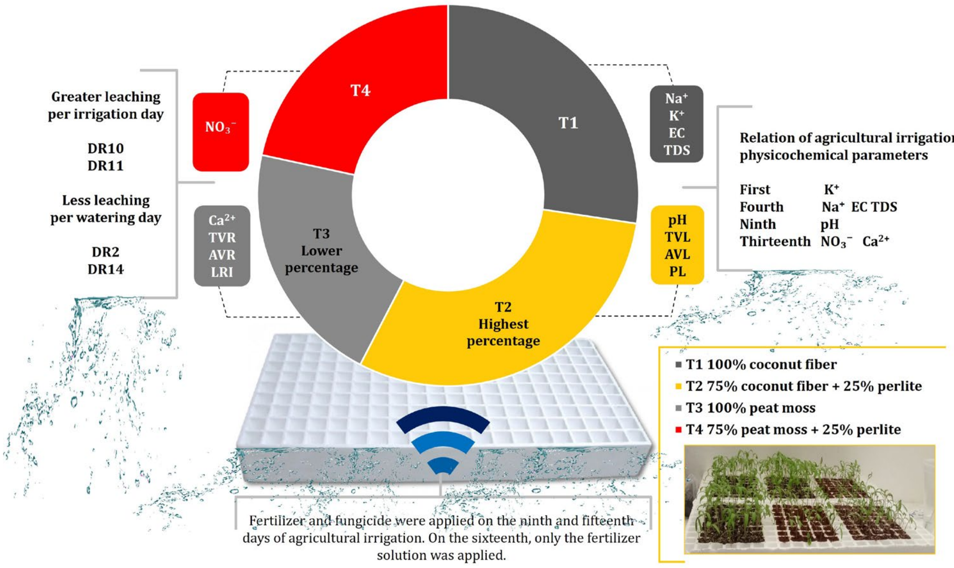


Figure 2. Volumetric variables and physicochemical parameters by substrate and irrigation day in tomato seedlings.

Figura 2. Variables volumétricas y parámetros fisicoquímicos según sustrato y día de riego en plántulas de tomate.

NO_3^- leaching in T4 (75% peat moss + 25% perlite) is relevant. Leachate concentrations did not increase despite the applications on day sixteen. This suggests seedling growth influenced parameter variations. Agronomic variables like root and stem size support this. Root size variations were not significant, ranging from 7.3 cm to 7.8 cm. However, the stem was significantly larger in T3 (6.66 cm) and smaller in T2 (4.6 cm). This analysis addresses the need for environmental impact studies on substrates. It focuses on waste, recycling, and remediation in horticulture (Kader *et al.*, 2024).

This evaluation considered the following criteria: a) the highest and lowest amount found per treatment and irrigation days. b) the variation relative to the average concentration in the applied irrigation water. c) the percentage variation of the parameter over the highest amount and its reference level. These results are described below (table 5, page 9).

pH

Values ranged from 6.34 (T1) to 6.80 (T2). Over 16 days, leachate pH ranged from 5.62 to 7.22. This increase may relate to the first fungicide and nutrient applications. The original irrigation water averaged 7.55, which is within FAO quality guidelines (Aguilar Ibarra & Pérez Espejo, 2008). Treatment variation was 90.06%, while irrigation day variation reached 95.62%. These levels pose no risk for agricultural irrigation (CSR Laboratorio, 2023). In substrate management, pH decreases as particle size increases (Mixquititla-Casbis *et al.*, 2022). Optimal nutrient absorption occurs between pH 5.0 and 6.5 (Durán *et al.*, 2009). Substrate type, water alkalinity, and root activity affect these values. Fertilizer reaction also influences pH changes (Barbaro *et al.*, 2018).

Table 5. Physicochemical parameter concentrations by treatment, irrigation day, and reference levels.
Tabla 5. Concentraciones de parámetros fisicoquímicos según tratamiento, día de riego y niveles de referencia.

Parameter	Increased quantity in treatments	Lower quantity in treatments	Difference	Increased quantity on irrigation day	Less quantity in irrigation day	Difference	Normal irrigation water applied	% variation in treatments over the largest quantity	% variation in days of irrigation over the highest quantity	Reference level for water
pH Scale	6.80	6.34	**0.46**	7.22	5.62	1.62	7.55	90.06	95.62	No risk for agricultural irrigation water. e.
EC μs cm^{-1}	617.5	277.41	**340.09**	723.58	224.16	**499.42**	231.50	266.73	312.56	No risk for agricultural irrigation water. b and e.
TDS ppm	312.7	143.93	**168.77**	358.16	111.16	**247.00**	115.00	271.91	311.44	The permissible limit is not exceeded. c and e
mg L^{-1}										
Na^+	126.79	84.85	**41.94**	448.33	31.5	416.83	24.50	517.51	1,829.91	Possible risk of toxicity. b, c, and e
Ca^{2+}	116.06	17.91	**98.14**	164.50	12.75	151.75	59.50	195.05	276.47	No risk for agricultural irrigation water. b
K^+	899.72	59.47	**840.25**	994.00	49.83	994.17	14.25	6,313.82	6,975.43	Danger of irrigation contamination. b
NO_3^-	358.54	251.04	107.50	935.00	143.29	772.92	55.30	648.35	1,690.77	With danger of contamination a.b.c.d and e

a: Programa Regulatorio Agrícola (2013); b: CSR Servicios (2006) and CSR Laboratorio (2023); c: NOM-127-SSA-1994 (DOF, 2022); d: Federal Law on Water Rights (CONAGUA, 2020); e: FAO Irrigation Guidelines (Ayers & Westcot, 1994).

a: Programa Regulatorio Agrícola (2013); b: CSR Servicios (2006) y CSR Laboratorio (2023); c: NOM-127-SSA-1994 (DOF, 2022), d: Ley Federal de Derechos de Agua (CONAGUA, 2020); e: Directrices de Riego de la FAO (Ayers & Westcot, 1994).

Electrical Conductivity (EC)

EC values ranged from 277.4 to 617.5 µS cm^{-1}. T3 (100% peat moss) recorded the lowest value, while T1 (100% coconut fiber) showed the highest. The difference reached 340.1 µS cm^{-1}. EC also varied by irrigation day. The highest value (723.5 µS cm^{-1}) occurred on day four. The lowest (224.1 µS cm^{-1}) occurred on day ten. This range (0.25-0.75 dS m^{-1}) indicates moderate salinity (C2) according to the Riverside classification (Thorne & Peterson, 1996). These waters are usable with moderate leaching (Ayers & Westcot, 1994). Generally, special salinity control is unnecessary for moderately salt-tolerant plants (Cortés-Jiménez *et al.*, 2009). EC levels below 1,000 µS cm^{-1} are risk-free. Values between 1,000 and 1,575 µS cm^{-1} indicate risk, while higher values pose danger (CSR Laboratorio, 2023). Our results show no salinity risk to crops. Substrate EC should ideally remain below 1 dS m^{-1} to facilitate fertilization and avoid phytotoxicity (Barbaro *et al.*, 2018). Coconut fiber (0.90 dS m^{-1}) and perlite (0.01 dS m^{-1}) report low EC. This parameter varies by substrate type and tomato growth stage (Yescas *et al.*, 2011).

Total Dissolved Solids (TDS)

TDS values ranged from 143.93 to 312.70 mg L^{-1}. T4 recorded the lowest value, while T1 yielded the highest. This difference (168.77 mg L^{-1}) is higher than the irrigation water average (115.0 mg L^{-1}). The highest TDS (358.16 mg L^{-1}) occurred on day four, and the lowest (111.16 mg L^{-1}) on day ten. Treatment variation reached 271.91%, while irrigation day variation was 311.44%. None of these values exceeded the 1,000 mg L^{-1} permissible limit (NOM-127-SSA-2021). TDS concentration relates to anions and cations, expressed as EC (Sarabia Meléndez *et al.*, 2011). For irrigation water, values up to 500 mg L^{-1} pose no issue (CSR Laboratorio, 2023). FAO guidelines (Ayers & Westcot, 1994) also consider levels up to 450 mg L^{-1} safe for agricultural use.

Sodium (Na^+)

Leachate Na^+ concentrations varied by treatment. T1 yielded the highest value (126.79 mg L^{-1}), and T3 the lowest (84.50 mg L^{-1}). Regarding irrigation days, Na^+ peaked on day four (448.33 mg L^{-1}) and was lowest on day eight (31.50 mg L^{-1}). Both results exceeded the irrigation water average (24.50 mg L^{-1}). Treatment variation was 517.51%, while irrigation days showed a 1,829.9% increase. Sodium levels in coconut fiber (363.65 mg L^{-1}) are lower than in materials like sargassum (Gayosso-Rodríguez *et al*., 2018). Several mechanisms influence Na^+ accumulation. These include roots, sodium-rich irrigation water, organic amendments, and fertilizers. Mineralization of organic matter and upward ion movement via evapotranspiration also contribute. Perlite, of volcanic origin, contains 1-4% Na_2O (Camacho *et al*., 2021). The 200 mg L^{-1} limit (NOM-127-SSA1-2021) was only exceeded on irrigation day four. Na^+ levels below 70 mg L^{-1} are risk-free. Levels between 70 and 300 mg L^{-1} pose a risk, and values over 300 mg L^{-1} indicate toxicity (CSR Laboratorio, 2023). Based on this criterion, treatments suggest toxicity risks. FAO guidelines (Ayers & Westcot, 1994) also indicate restrictions above 69 mg L^{-1}.

Calcium (Ca^{2+})

Leachate Ca^{2+} values varied by treatment. They ranged from 17.91 mg L^{-1} (T1) to 116.06 mg L^{-1} (T3). Similarly, Ca^{2+} varied by irrigation day, ranging from 12.75 mg L^{-1} (day 11) to 164.50 mg L^{-1} (day 13). Differences across treatments (93.15 mg L^{-1}) and irrigation days (151.75 mg L^{-1}) exceeded the irrigation water average (59.5 mg L^{-1}). T3 (100% peat moss) exceeded this average by 1.9 times. Previous studies report calcium concentrations lower than materials like henequen bagasse (Gayosso-Rodríguez *et al*., 2018). Peat moss mixtures typically contain calcium levels < 100 mg L^{-1} (Garbanzo-León and Vargas-Gutiérrez, 2014). Optimal substrate calcium levels should exceed 200 mg L^{-1} (Martínez-Florián & Roca, 2011). Treatment variation was 195%, and irrigation day variation was 276.47% relative to the applied water. FAO guidelines indicate that Ca^{2+} usually ranges from 0 to 401 mg L^{-1} (Ayers & Westcot, 1994). Ca^{2+} can counteract negative sodium effects, reducing sodicity risks. However, high Ca^{2+} levels increase water hardness and pipe clogging risks. Levels of 50 mg L^{-1} are risk-free, while values over 250 mg L^{-1} pose clogging dangers (CSR Laboratorio, 2023).

Potassium (K^+)

Leachate K^+ concentrations were high. T1 (100% coconut fiber) showed the highest value (899.72 mg L^{-1}), while T4 (peat moss + 25% perlite) showed the lowest (59.47 mg L^{-1}). This created an 840.25 mg L^{-1} difference across treatments. Potassium levels also varied by irrigation day, from 994 mg L^{-1} (day 2) to 49.83 mg L^{-1} (day 13). Both results exceeded the irrigation water average (14.25 mg L^{-1}). T1 exceeded this average by 63.13 times. Potassium levels over 100 mg L^{-1} represent a contamination danger (CSR Laboratorio, 2023). This increase primarily results from the mineral composition of coconut fiber, a rich potassium source (Rincón *et al*., 2016).

Nitrates (NO_3^-)

The highest NO_3^- concentration was 358.54 mg L^{-1} (T4), and the lowest was 251.04 mg L^{-1} (T1). Values ranged from 143.29 mg L^{-1} (day 12) to 935 mg L^{-1} (day 13). Differences across treatments (107.49 mg L^{-1}) and irrigation days (791.70 mg L^{-1}) were higher than the irrigation water average (55.3 mg L^{-1}). T4 showed a 6.48-fold increase, while T1 increased 4.53 times. These levels exceed the 10.0 mg L^{-1} permissible limit (NOM-127-SSA-2021) and the 5.0 mg L^{-1} Federal Water Rights Law limit (CONAGUA, 2020; DOF, 2022; Valles *et al.*, 2017). Nitrate levels must be considered during fertilization. For example, 700 m^3 ha^{-1} of irrigation water at 25 mg L^{-1} contributes 40 kg of N ha^{-1}. This could save fertilizer and reduce contamination risks (Sarabia-Meléndez *et al.*, 2011). Surface waters typically have low NO_3^- (0-18 mg L^{-1}), but high levels result from agrochemicals and industrial effluents (Valdés, 2015). NO_3^- levels between 50 and 100 mg L^{-1} pose risks, while values over 100 mg L^{-1} indicate high contamination (CSR Laboratorio, 2023; OMS, 2006). Excessive irrigation promotes leaching and increases nitrate contamination (Salas *et al*., 2003). In this study, T4 exceeded the 10 mg L^{-1} nitrogen threshold by 5.5 times and T1 by 7.9 times. All samples exceeded the FAO severe restriction level of 30 mg L^{-1} (Ayers & Westcot, 1994). This indicates a high contamination risk for nearby soil and water. High NO_3^- accumulation in plants can also affect consumers. NO_3^- can transform into NO_2^- in the human body, potentially causing methemoglobinemia in infants or forming carcinogenic compounds (Valdés, 2015).

Principal Component Analysis (PCA)

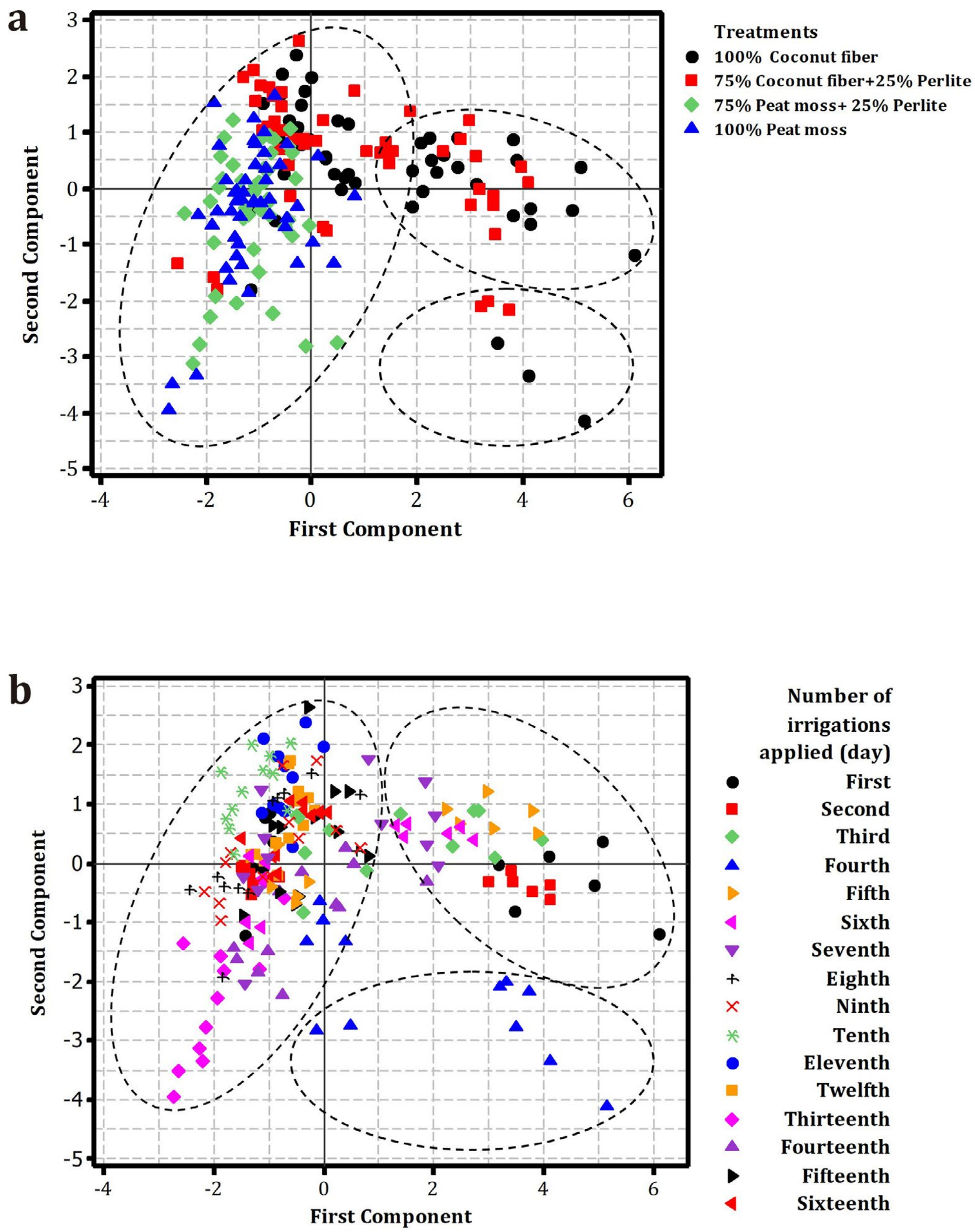
The PCA used 192 samples. It identified associations between parameter groups with positive and negative interactions. Figures 3a and 3b (page 12), show data associations by treatment. We observed three groups based on the treatments. Group one includes T1 (100% coconut fiber) and T2 (75% coconut fiber + 25% perlite). Group two includes T3 (100% peat moss) and T4 (75% peat moss + 25% perlite).

Figures 4a and 4b (page 13), show the vector analysis. This analysis presented three data groups and distinguished their influence on parameter behavior. This corroborates the correlation between variables, especially the relationship between EC and TDS.

Component Variation

The first three principal components (PC) explained 72.9% of the variation. PC1 accounted for 42.2%, PC2 for 19.4%, and PC3 for 11.2%. In PC1, EC (0.522), TDS (0.519), and K^+ (-0.453) explained the most significant variation. For PC2, leachate volume (0.541) was a positive factor, while NO_3^- (-0.481), Na^+ (-0.476), and Ca^{2+} (-0.472) were negative. For PC3, variations were driven by Ca^{2+} (0.523), leachate volume (0.285), and pH (-0.758).

These results confirm two main groups defined by treatments T1/T2 and T4. Data dispersion from the central axis is evident. This may result from the specific data groups in each PC (figures 3a and 3b, page 12; figures 4a and 4b, page 13). Nutrient solutions and fungicide applications likely influenced cluster behavior. Overwatering causes nutrient solution leaching, and economic losses for farmers. Overwatering also causes drastic changes in substrate pH and EC. Additionally, it leads to growing medium saturation, decreased photosynthesis, and nutritional imbalances. Excessive water promotes pathogen development and results in poor-quality fruits (Yescas *et al*., 2011). Monitoring these parameters is mandatory to control environmental risks to soils, plants, surface water, and groundwater (Alcalde-Sanz & Gawlik, 2017). Developing environmentally friendly substrates and control systems is essential for sustainable production (Tuxun *et al.*, 2025).

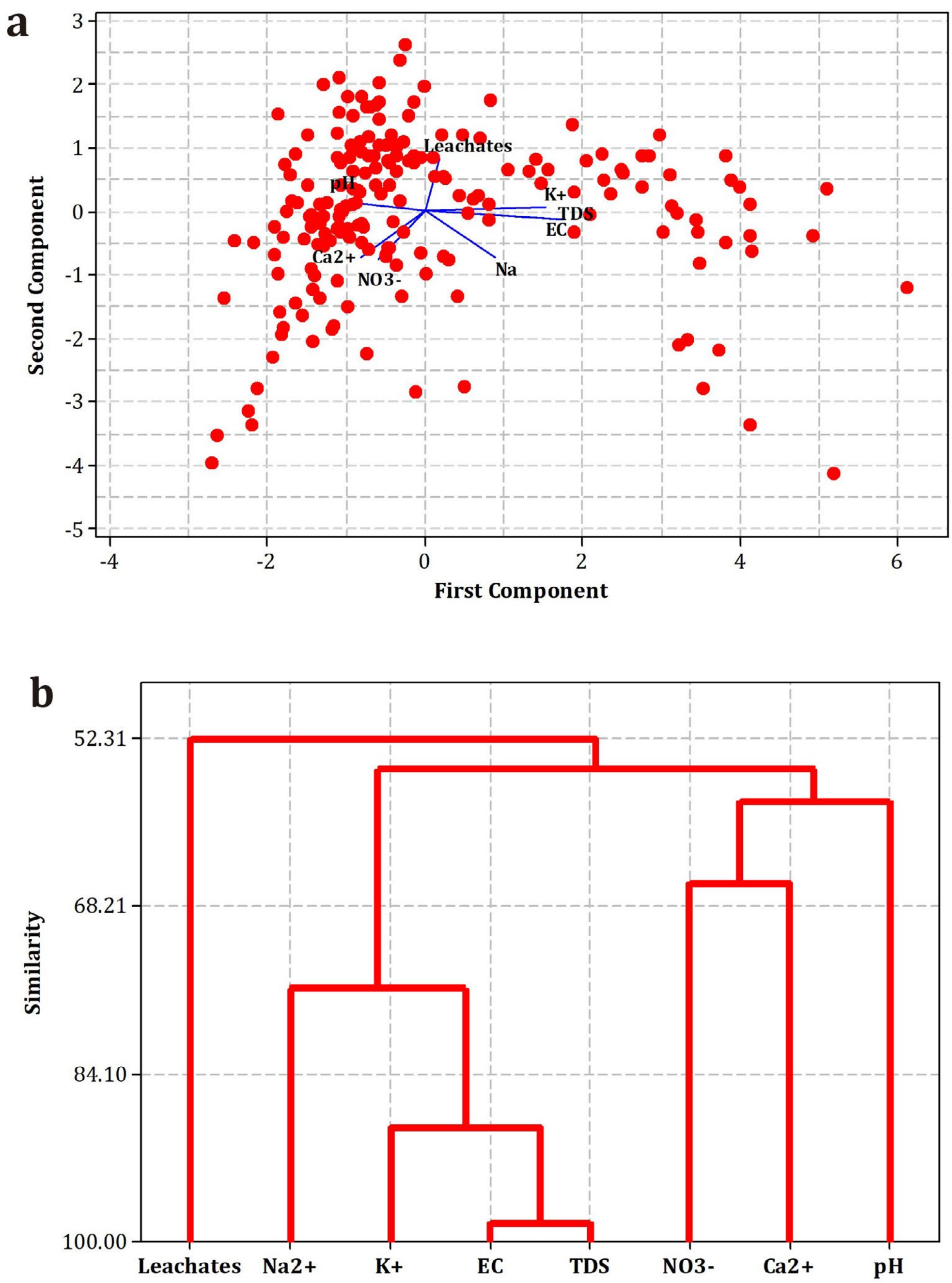


a) Irrigation application days b) derived from the physicochemical parameters evaluated in irrigation application and leachates.

a) Días de aplicación del riego b) derivada de los parámetros fisicoquímicos evaluados en la aplicación del riego y los lixiviados.

Figure 3. Distribution of PCA points between treatments.

Figura 3. Distribución de puntos del PCA entre los tratamientos.



(a) Percentage similarity between parameters in leachates (b).

(a) Porcentaje de similitud entre parámetros en los lixiviados (b).

Figure 4. Physicochemical parameter distribution by treatment from PCA.

Figura 4. Distribución de parámetros fisicoquímicos por tratamiento mediante PCA.

Conclusions

Agricultural substrate use affects the volume and quality of residual leachates. This relationship is key to tomato seedling production. We observed significant variations in volumetric variables, particularly in applied, retained, and leached irrigation volumes. Physicochemical parameters also varied between applied and residual water. The 75% coconut fiber and 25% perlite treatment showed the highest water loss through leaching.

This included total volume, average loss per irrigation, and drainage percentage. Conversely, this treatment had the lowest water storage capacity. In contrast, peat moss retained the largest amount of water, highlighting its superior moisture storage ability. These findings emphasize the critical role of substrate composition on water use efficiency. Excessive leaching has significant environmental implications. Substrate management must be adjusted to minimize water losses and reduce contamination risks. All treatments produced over 20% leachate despite controlled watering. This underscores the necessity of increasing water use efficiency to align with sustainable management standards. Fertilizer application days showed no exceptionally high values. However, variations occurred throughout the 16 days of irrigation. Substrate retention, leaching, or seedling root absorption likely caused these variations. The increase in certain physicochemical parameters is significant. Coconut fiber substrates showed prominent levels of sodium, potassium, EC, and TDS. TDS behavior was notable, increasing by 270% between treatments and over 300% across irrigation days. EC increased by over 260% between treatments and 310% across irrigation days. The pH increased by up to 90% between treatments and over 95% across irrigation days. Sodium increased by over 500% between treatments and 1,800% across irrigation days. Potassium increased by more than 6,000% between treatments and 6,900% across irrigation days. Similarly, calcium increased between 195% and 270%, with peat moss showing the highest values. The most important finding was high NO_3^- accumulation in the peat + perlite combination. This posed a significant environmental hazard. Concentrations exceeded the original irrigation of water by 600% to 1,600%. Detected levels of potassium, sodium, and nitrates pose a contamination risk. These levels indicate potential toxicity for agricultural irrigation. Our results highlight the need to monitor leachate dynamics. Leachate monitoring is an important indicator of environmental impact. Substrate management must change to reduce contamination danger. Future studies should focus on large-scale validation and more physicochemical factors. Creating treatment plants and securing leachate reuse are also primary objectives.

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