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Nutrient chemistry in coconut-mineral mixed substrates for soilless culture

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Abstract: The use of substrate mixtures in soilless culture systems requires a comprehensive understanding of their chemical behavior, particularly regarding their capacity to supply or retain nutrients. This study evaluated the soluble and exchangeable fractions of coconut coir substrate mixed at five different proportions (100-0%, 75-25%, 50-50%, 25-75%, and 0-100%) with five mineral materials: coal slag, perlite, pumice, vermiculite, and zeolite. A total of 25 treatments were assessed under greenhouse conditions using carnation cuttings (*Dianthus caryophyllus* cv. Pomodoro) as a plant bioindicator. Results showed that vermiculite mixtures exhibited the highest cation exchange capacity (CEC) and significant sodium, manganese, and iron concentrations, while zeolite showed elevated levels of calcium and sodium in the exchangeable phase. Root development was positively correlated with soluble potassium, sodium, chloride, and sulfate levels. Treatments with equal proportions of vermiculite or pumice and coconut substrate (50:50) achieved the best rooting performance. These results highlight the importance of considering both soluble and exchangeable nutrient fractions to support substrate selection and fertigation management decisions in sustainable soilless crop production.

1. Introduction

Although substrate research has primarily focused on individual material characterization, synergistic effects in mixtures remain underexplored. The characterization of these mixtures is critical, as their properties determine a substrate's capacity to store and release water and nutrients, facilitate aeration, and influence root development (Gruda, 2019), with potential for substantial variability. Specifically, studies on the chemical properties of substrate materials have aimed to: (1) quantify nutritive element concentrations, (2) verify elevated levels of potentially phytotoxic elements (e.g., sodium - Na), and (3) assess heavy metal presence (Block *et al.*, 2008). These evaluations are typically conducted prior to plant growth applications, with analyses performed on unaltered, homogeneous solid phases. However, during plant growth, organic compounds may be secreted by plants or generated through cumulative organic matter decomposition processes (Silber, 2008). Consequently, newly formed solid surfaces become heterogeneous, and the mixture's chemical properties may significantly diverge from those observed during initial characterization of individual materials (Silber and Raviv, 1996).

Materials used as soilless cultivation substrates may be of organic or mineral origin. Compared to organic materials, mineral-based substrates exhibit higher stability, retaining their physical and chemical properties over longer periods, which is why their use is widespread, particularly in Europe. In Colombia, their adoption has not been extensive due to their high cost and limited availability (Monsalve *et al.*, 2021). Rice husks are the most used substrate material in Colombia, but in recent years, they have also been utilized in other sectors, such as concrete production, posing a threat to their future availability as agricultural substrates (Monsalve *et al.*, 2021). This has forced many farmers to seek viable alternatives to replace or supplement this material. In this regard, Monsalve *et al.* (2021) chemically characterized a wide range of organic and mineral materials with potential use in soilless cultivation, two organic substrates other than rice husks (coconut and oil palm-derived materials) were identified as particularly suitable, together with five mineral materials: coal slag, perlite, pumice, vermiculite, and zeolite. These materials, except oil palm, were therefore selected for further evaluation in the present study. Coconut fiber, obtained from the mesocarp or outer husk of the coconut fruit (*Cocos nucifera*), specifically from the fibrous layer located between the hard inner shell and the outer layer of the coconut (Satyanarayana *et al.*, 1982; Abad *et al.*, 2002), is widely used due to its favorable structure and availability. Physically, coconut fiber has a tubular structure with concentric microfibrils, a low density (around 0.69 g/cm^3), high water retention capacity, good aeration, and good hydraulic conductivity which promotes root development in plants (Asiah *et al.*, 2004; Abad *et al.*, 2005; San Andres *et al.*, 2023). Moreover coconut substrate has revealed to be successfully used for consecutive monoculture of tomato given that the reuse did not induce phytotoxicity for the plants (Capodilupo *et al.*, 2015). Chemically, the fiber is mainly composed of cellulose, hemicellulose, and lignin, which give it strength and durability; it also contains small amounts of waxes, fats, and minerals such as silica and metal oxides (Brígida *et al.*, 2010).

Coal slag is a byproduct of coal combustion in thermoelectric plants and steel furnaces (Serna, 2012). It has been successfully used in crops such as tomatoes (Peña *et al.*, 2013) and carnations (Quintero *et al.*, 2012), both alone and in mixtures. Although considered inert, it may exhibit phosphorus fixation or excess boron (Martínez and Roca, 2011). Perlite is a thermally expanded volcanic aluminum silicate that forms a porous, lightweight, and sterile structure. With its low density, high water retention capacity, and excellent aeration properties, it is widely used as an inorganic substrate in soilless cultivation. These physical and chemical characteristics make perlite highly favorable for optimal root development and overall plant growth (Doğan and Alkan, 2003; Markoska *et al.*, 2018 a, 2018 b). Perlite is chemically inert, meaning it does not react with fertilizers or other compounds present in the substrate, and it maintains its stable composition over time. In addition, its high porosity and low density promote water retention and aeration, while its chemical inertness helps prevent salt accumulation, as it does not release soluble ions into the medium (Markoska *et al.*, 2018 a, 2018 b; Reka *et al.*, 2019). Silber *et al.* (2012) demonstrated that its Zn adsorption capacity depends on pH, ionic strength, and temperature. In hydroponic systems and in the production of vegetables such as lettuce and cucumber, perlite has been shown to promote crop development and quality. Moreover, compared to soil cultivation, perlite-based soilless cultivation of lettuce showed microbiological and qualitative performance better than those grown in soil (Pace *et al.*, 2018). However, when used as the sole substrate, it may require careful management of fertilization and irrigation to prevent nutrient leaching (Gul *et al.*, 2007; Stoian *et al.*, 2022; Yang *et al.*, 2023). Pumice is a pyroclastic volcanic material (Huang *et al.*, 2025), extremely lightweight (Hosniyeh *et al.*, 2024), primarily composed of SiO_2, Al_2O_3, Fe_2O_3, CaO, Na_2O, K_2O, and H_2O (Boodt *et al.*, 1974). Vermiculite, a thermally expanded mica, exhibits numerous significant physical and chemical properties, including developed porous structures, high water retention, low density, and elevated cation exchange capacity due to its mineral structure (Hao *et al.*, 2023). Its use is recommended as an alternative for mixing with other substrates (Schneider *et al.*, 2018). Zeolites, particularly clinoptilolite, are crystalline aluminosilicates with high porosity and cation exchange capacity, allowing them to retain and gradually release nutrients (Głąb *et al.*, 2023), as confirmed by Eshghi *et al.* (2014) who found that it absorbs and slowly releases nitrogen to the culture medium.

Due to their large surface area, high water retention, and high cation exchange capacity, the application of zeolite and vermiculite is highly relevant as inorganic soil amendments in agriculture (Jarosz *et al.*, 2022; Głąb *et al.*, 2023).

Some countries, including Colombia, lack specific regulations for the use of substrates in horticultural crop production, international standards have been proposed for the most relevant chemical properties. Table 1 summarizes the recommended optimal levels. Nevertheless, the substrates used throughout the world differ significantly as to their makeup, while attempting to adhere to a specific set of principles. These principles are quite complex, relating to physical and chemical factors of solids, liquids, and gases in the root zone of the plant (Raviv *et al.*, 2019).

Given the diversity in chemical behavior of these materials, it is important to understand not only their individual properties but also how they interact when combined in substrate mixtures. Therefore, the objective of this study is to characterize the soluble and exchangeable fractions of the organic coconut substrate and the mineral materials coal slag (CS), perlite (PE), pumice (PM), vermiculite (VE), and zeolite (ZE), mixed in different organic-mineral proportions, using carnation (*Dianthus caryophyllus* L.) as a plant of interest. Carnation was selected due to its high sensitivity of early root development to substrate chemical properties, its widespread use in commercial soilless cultivation systems, and its relevance as a bioindicator species for evaluating substrate agronomic suitability during the rooting stage.

2. Materials and Methods

Treatments, design, and sample preparation

The study was conducted at the facilities of Flores Aurora S.A.S., located in the municipality of Suesca (Cundinamarca, Colombia), at coordinates 05°03.740′ N and 73°50.201′ E, an elevation of 2,584 meters above sea level, and an average ambient temperature of 14°C. The experiment was established in a chapel-type greenhouse adapted to function as a humidity chamber, maintaining relative humidity levels above 80% and an average internal temperature of 30°C. Five mineral materials [coal slag (CS), perlite (PE), pumice (PM), vermiculite (VE), and zeolite (ZE)] were evaluated in mixtures with coconut substrate (CS) at five CS mineral ratios: 100-0, 75-25, 50-50, 25-75, and 0-100. All chemical and plant-related evaluations were performed once, at the end of the rooting period (24 days after establishment). A completely randomized design (CRD) was applied in a 5×5 factorial arrangement with two factors: substrate type (five mineral materials) and proportion (five mixing levels), resulting in 25 treatments and 75 experimental units, with three replicates per treatment.

Each experimental unit consisted of a plastic tray (0.6 × 0.3 × 0.15 m; surface area = 0.18 m^2; volume = 0.03 m^3), containing 104 carnation cuttings.

Prior to mixture preparation, the coconut coir substrate was pre-treated by the manufacturer through washing with potable tap water for a period ranging between 30 and 60 minutes. This washing process aimed to reduce the concentration of soluble salts, particularly sodium and chloride, which are commonly elevated in coconut-based substrates.

Exchangeable, soluble, and available phase characterization

For the exchangeable phase, K^+, Ca^{2+}, Mg^{2+}, and Na^+ were extracted with 1 M ammonium acetate (pH 7) and analyzed via absorption atomic spectroscopy AAS. Cation exchange capacity (CEC) was determined by replacing NH_4^+ with NaCl, followed by volumetric titration. Soluble-phase parameters included electrical conductivity (EC, measured at 25°C), pH (potentiometric method), phosphate (PO_4^{3-}) using the stannous chloride colorimetric method, sulfate (SO_4^{2-}) with the barium chloride method, chloride (Cl^-) by silver nitrate titration, and K^+, Ca^{2+}, Mg^{2+}, and Na^+ using (AAS). Total N content was determined by high-temperature combustion using an elemental analyzer, P by colorimetric titration with molybdate and ammonium vanadate. Available Cu^{2+}, Fe^{2+}, Mn^{2+}, and Zn^{2+} were extracted using DTPA and analyzed by AAS.

Plant growth suitability

Carnation cuttings (*Dianthus caryophyllus*, cv. Pomodoro) were used as a bioindicator of substrate suitability for plant growth. All mineral components were sieved to a particle size ≤2 mm prior to planting. The rooting phase lasted 24 days, which corresponded to the entire duration of the experiment, from cutting establishment to final chemical and plant evaluations, during which no fertilization was applied. This plant was selected due to the rapid growth cycle of the species, its relevance in Colombian soilless cultivation systems, and the high sensitivity of root development to substrate properties. This approach enabled the evaluation of both the rooting efficiency and substrate-plant interaction across a wide range of substrate mixtures.

Rooting percentage was evaluated by removing 10 cuttings per experimental unit and counting those showing visible root emergence and physical anchorage to the substrate. Each rooted cutting was assigned a value of 10%, so that the presence of roots in all 10 cuttings corresponded to 100% rooting. This approach was selected as a practical and standardized indicator of rooting success, commonly used in commercial carnation propagation to rapidly assess substrate suitability. Root dry weight was determined after drying the roots at 70°C for 48 h. Root formation and biomass accumulation were considered the main quality indicators for cuttings, based on grower-established standards for transplant readiness.

Statistical analysis

A correlation matrix was used to explore associations between chemical parameters and plant growth viability. In addition, a principal component analysis (PCA) was conducted as an exploratory multivariate approach to assess overall relationships among chemical variables and to identify potential collinearity patterns within the dataset. Treatment differences were analyzed using one-way ANOVA and Tukey's HSD test. Prior to ANOVA, normality and homogeneity of variances were tested using the Shapiro-Wilk and Bartlett tests, respectively. All statistical analyses were conducted using R (version 4.4.3) (R Core Team, 2025), with the mvoutlier (Filzmoser and Gschwandtner, 2021), Hmisc (Harrell, 2025), and agricolae (de Mendiburu, 2023) packages.

3. Results and Discussion

Soluble phase

The soluble-phase chemical properties of the evaluated substrates and mixtures revealed marked differences associated with mineral type and mixing proportion, while remaining within agronomically acceptable ranges for early plant establishment. Both pH and electrical conductivity (EC) values fell within the recommended limits for soilless substrates (Table 1), indicating no immediate chemical constraints for root development. Among individual mineral substrates, vermiculite (VE) exhibited the highest pH (7.37), whereas pumice (PM) showed the highest EC (0.26 dS m^{-1}) (Fig. 1). At the treatment level, VE25 reached the maximum pH (7.5), while PM50 presented the highest EC (0.30 dS m^{-1}) (Table 2).

Table 1 - Recommended optimal levels for the chemical characteristics of substrates used in soilless culture

Parameter	Value	Source
pH	5.5 a 7.0	Ansorena, 1994; Sonneveld and Voogt, 2009
EC (dS m^{-1})	<2.0	Ansorena, 1994; Nelson, 2012
CEC ($cmol_c$ kg^{-1})	>20	
N- NH_4 (mg L^{-1})	<30	Sonneveld and Voogt, 2009
N-NO_3 (mg L^{-1})	<200	Sonneveld and Voogt, 2009
P (mg L^{-1})	<30	Nelson, 2012
PO_4 (mg L^{-1})	<92	Nelson, 2012
K (mg L^{-1})	<250	Sonneveld and Voogt, 2009
Ca (mg L^{-1})	<200	Nelson, 2012
Mg (mg L^{-1})	<70	Raviv and Lieth, 2008
Na (mg L^{-1})	<100	Abad *et al.*, 2002; Sonneveld and Voogt, 2009
Cl (mg L^{-1})	<5	Sonneveld and Voogt, 2009
SO_4 (mg L^{-1})	<70	Nelson, 2012

Although statistically significant differences in pH were observed among mixtures, none reached values considered detrimental to plant growth. In soilless systems, maintaining pH within a slightly acidic to circumneutral range (≈5.5-7.0) minimizes the risk of nutrient deficiencies or toxicities, while even small variations within this interval can influence nutrient solubility and ionic equilibria in the root zone (Huang *et al.*, 2025). The moderate EC values observed across all treatments contrast with reports describing coconut-based substrates as inherently saline (Abad *et al.*, 2001; Machado and Bui, 2021) and can be attributed to the pre-washing of the coconut coir.

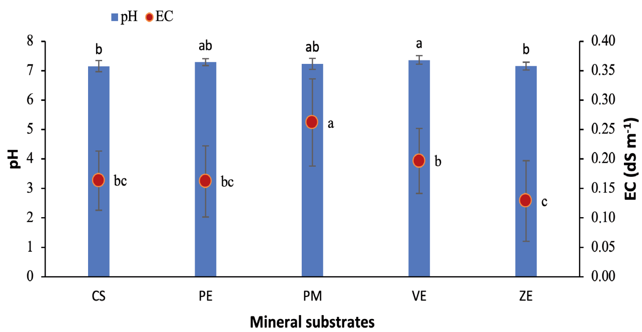

Fig. 1 - Comparison of pH and electrical conductivity (EC) of the evaluated substrates and substrate mixtures. Data correspond to all coconut-mineral (100-0%, 75-25%, 50-50%, 25-75%, and 0-100%) mixtures (namely, coal slag (CS), perlite (PE), pumice (PM), vermiculite (VE), and zeolite (ZE) evaluated at the end of the rooting period (24 days). Bars represent mean values (n= 15), and error bars indicate the standard deviation. Different letters indicate significant differences according to Tukey's test (P<0.05).

This pretreatment effectively reduced the concentration of readily soluble salts, confirming its relevance for ensuring the suitability of coconut fiber in nursery and propagation systems (Gbollie *et al.*, 2021). Similar EC stability under non-fertigated conditions was previously reported by Monsalve *et al.* (2021) for the same materials prior to plant establishment.

Soluble cation concentrations exhibited a clear dominance of sodium (Na^+) over potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) across all mineral substrates. Vermiculite showed the highest Na^+ concentration (336 mg L^{-1}), exceeding recommended thresholds (Table 1), followed by pumice (216 mg L^{-1}) (Fig. 2). This pattern reflects the combined influence of the intrinsic Na content of coconut coir and the contribution of specific mineral components. Vermiculite also exhibited the highest soluble K^+ (61.9 mg L^{-1}) and Mg^{2+} (35.1 mg L^{-1}), while

Table 2 - pH, electrical conductivity (EC), and soluble nutrient concentrations (K, Ca, Mg, Na, PO_4^{3-}, SO_4^{2-}, Cl^-) of the evaluated treatments

Treatment	Soluble phase								
	pH	EC dS m^{-1}	K mg L^{-1}	Ca mg L^{-1}	Mg mg L^{-1}	Na mg L^{-1}	PO_4^{3-} mg L^{-1}	SO_4^{2-} mg L^{-1}	Cl^- mg L^{-1}
CS0	7.3 ab	0.3 abc	42.3 abcdefg	4.3 f	2.8 d	148.6 defgh	16.7 c	72.5 defghi	117.5 fg
CS25	7.3 ab	0.1 cde	28.5 cdefg	8.2 ef	4.3 d	164.9 defg	49.4 a	102.9 cdefg	172.3 ef
CS50	7 b	0.2 bcde	14.3 defg	30.2 cdef	12.6 d	137.3 defgh	29.3 b	141.1 bc	178.3 ef
CS75	7 b	0.1 cde	12.4 defg	36.2 abcd	12.8 d	110.9 efgh	16.6 c	135.5 bcde	169.9 ef
CS100	7.2 ab	0.1 cde	9 efg	57.4 ab	12.6 d	84.6 fgh	9.5 cdef	80.8 cdefghi	132.8 fg
PE0	7.3 ab	0.3 abc	42.3 abcdefg	4.3 f	2.8 d	148.6 defgh	16.7 c	72.5 defghi	117.5 fg
PE25	7.3 ab	0.1 cde	32.3 bcdefg	6.9 ef	3.5 d	162.1 defg	8.9 cdef	117.7 cdef	180.7 ef
PE50	7.3 ab	0.2 bcde	46.9 abcdef	6.9 ef	5.5 d	217.4 cdef	13.7 cde	130.7 bcde	244.9 de
PE75	7.4 ab	0.1 cde	14.6 defg	17.7 cdef	9.7 d	127.6 efgh	4.4 cdef	68.7 efghi	157.9 ef
PE100	7.3 ab	0.1 de	10.1 efg	38.8 abc	8.5 d	66.6 gh	0.4 f	39.1 ghi	104.1 fg
PM0	7.3 ab	0.3 abc	42.3 abcdefg	4.3 f	2.8 d	148.6 defgh	16.7 c	72.5 defghi	117.5 fg
PM25	7.3 ab	0.3 ab	77.1 ab	15.5 cdef	6 d	270 bcd	11.6 cdef	82 cdefghi	348.1 bcd
PM50	7.1 b	0.3 a	72.5 abc	61.1 a	14.8 d	344 bc	15.7 cd	84.7 cdefgh	328.6 bcd
PM75	7.1 ab	0.3 abc	49.1 abcde	19.4 cdef	14.3 d	247.3 bcde	7 cdef	198.7 ab	268.8 cde
PM100	7.4 ab	0.2 abcde	6.7 efg	32.1 bcde	8 d	67.6 gh	2.7 ef	19.7 hi	101.1 fg
VE0	7.3 ab	0.3 abc	42.3 abcdefg	4.3 f	2.8 d	148.6 defgh	16.7 c	72.5 defghi	117.5 fg
VE25	7.5 a	0.2 bcde	84.6 a	12.1 def	12.2 d	310.2 bc	14.7 cde	133.1 bcde	357.4 bc
VE50	7.3 ab	0.2 abcd	63 abc	22.7 cdef	33.2 c	525 a	33 b	216.1 a	415.4 b
VE75	7.3 ab	0.2 bcde	57.6 abcd	26.3 cdef	51.7 b	330.5 bc	9.5 cdef	139.1 bcd	412.4 b
VE100	7.4 ab	0.2 abcde	62.1 abc	26 cdef	75.7 a	364.5 b	6.2 cdef	75.6 cdefghi	560.7 a
ZE0	7.3 ab	0.3 abc	42.3 abcdefg	4.3 f	2.8 d	148.6 defgh	16.7 c	72.5 defghi	117.5 fg
ZE25	7.1 ab	0.1 cde	6.9 efg	30.3 cdef	13.7 d	107.7 fgh	3.7 def	57.6 fghi	179.1 ef
ZE50	7.2 ab	0.1 de	3.1 fg	25.7 cdef	8.5 d	93.1 fgh	4 def	84.9 cdefgh	113.7 fg
ZE75	7.1 ab	0.1 de	2 fg	21.7 cdef	6.5 d	85.6 fgh	2.3 ef	76.1 cdefghi	94.5 fg
ZE100	7.0 b	0.1 e	0.7 g	11.2 cdef	3.4 d	22.7 h	0.3 f	15.9 i	27.9 g

Data correspond to all coconut-mineral mixtures evaluated at the end of the rooting period (24 days). Values represent mean values (n = 3). Different letters within each column indicate significant differences among treatments according to Tukey's test (P<0.05).

no significant differences were detected for Ca^{2+} among mineral substrates (Fig. 2).

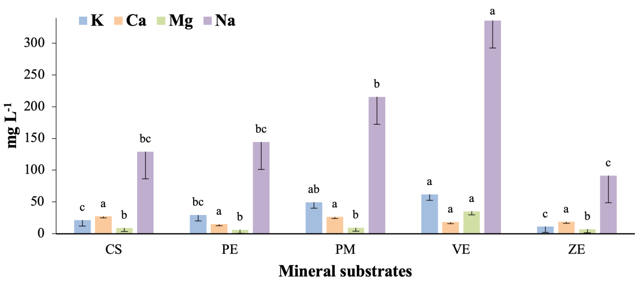

Fig. 2 - Comparison of soluble K^+, Ca^{2+}, Mg^{2+}, and Na^+ concentrations in the evaluated substrates and substrate mixtures. Data correspond to all coconut-mineral (100-0%, 75-25%, 50-50%, 25-75%, and 0-100%) mixtures (namely, coal slag (CS), perlite (PE), pumice (PM), vermiculite (VE), and zeolite (ZE)evaluated at the end of the rooting period (24 days). Bars represent mean values (n = 15), and error bars indicate the standard deviation. Different letters indicate significant differences according to Tukey's test (P<0.05).

At the mixture level, the soluble ionic composition was strongly modulated by both substrate type and proportion. Treatment VE50 displayed the highest Na^+ concentration (525 mg L^{-1}), whereas VE25, PM50, and VE100 reached the maximum levels of K^+ (84.6 mg L^{-1}), Ca^{2+} (61.1 mg L^{-1}), and Mg^{2+} (75.7 mg L^{-1}), respectively (Table 2). These results indicate that increasing the proportion of high-CEC minerals such as vermiculite enhances the capacity of the substrate to retain and subsequently release soluble cations into the soil solution, thereby modifying the ionic environment encountered by roots during the rooting phase. Regarding anions, chloride (Cl^-) was the dominant soluble species in several substrates, with particularly high concentrations in vermiculite (372.7 mg L^{-1}) and pumice (232.9 mg L^{-1}) (Fig. 3). Coal slag exhibited the highest phosphate (PO_4^{3-}) concentration (24.3 mg L^{-1}), whereas vermiculite showed the highest sulfate (SO_4^{2-}) levels (127.3 mg L^{-1}). At the treatment scale, VE100 reached the maximum Cl^- concentration (560.7 mg L^{-1}), CS25 exhibited the highest PO_4^{3-} content (49.4 mg L^{-1}), and VE50 presented the highest SO_4^{2-} concentration (216.1 mg L^{-1}) (Table 2).

Despite the elevated concentrations of Na^+ and Cl^- in several mixtures (particularly those containing vermiculite) the EC values remained within acceptable limits for soilless cultivation. This apparent decoupling between individual ion concentrations and bulk EC highlights the importance of evaluating specific ionic composition rather than relying solely on EC as an indicator of salinity risk. The high variability observed for Cl^- (Fig. 3) likely reflects the heterogeneous chemical nature of organic-mineral mixtures, where differences in mineralogy, particle size distribution, and water-holding capacity influence ion mobility and leaching dynamics.

In coconut coir-mineral systems, the soluble-phase composition is governed by the interaction between substrate chemistry and irrigation water, allowing highly mobile ions such as Cl^- to accumulate or be displaced depending on water management practices (Knaus *et al.*, 2025; Malík and Tlustoš, 2025). Vermiculite, characterized by high porosity, fine texture, and strong water retention, can promote localized accumulation of mobile anions within the rhizosphere, generating spatial heterogeneity in ion distribution. Comparable behavior has been documented in soil systems, where Cl^- profiles are strongly influenced by texture and water fluxes rather than uniform fertilizer inputs (Li *et al.*, 2025; Svensson *et al.*, 2023).

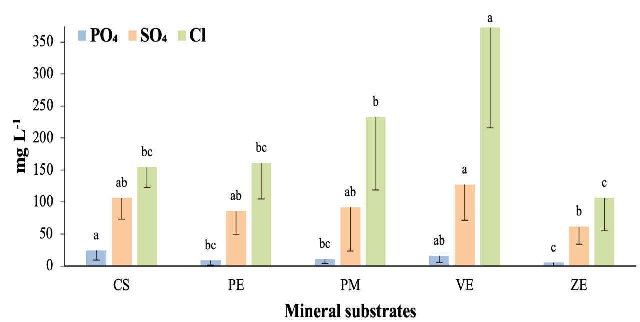

Fig. 3 - Comparison of the PO_4^{3-}, SO_4^{2-}, and Cl^- concentrations in the evaluated substrates and substrate mixtures. Data correspond to all coconut-mineral (100-0%, 75-25%, 50-50%, 25-75%, and 0-100%) mixtures (namely, coal slag (CS), perlite (PE), pumice (PM), vermiculite (VE), and zeolite (ZE) evaluated at the end of the rooting period (24 days). Bars represent mean values (n= 15), and error bars indicate the standard deviation. Different letters indicate significant differences among treatments according to Tukey's test (P<0.05).

While the Cl content in vermiculite substantially exceeded optimal limits (Table 1) and this material also contained high levels of Na and SO_4, these did not impact EC, which, as noted earlier, remained within acceptable ranges for all mixtures. The high variability observed in this anion (Fig. 3) may be due to the intrinsic chemical heterogeneity of the materials of mineral and organic origin, where differential leaching during irrigation can cause marked fluctuations in the root zone. In soilless cultivation systems using coconut coir-vermiculite mixtures, the substrate functions as a reservoir of mobile nutrients, whose final ionic composition is determined by the combined effects of irrigation water chemistry and the intrinsic chemical properties of the substrate, allowing salts to accumulate or be released depending on water management practices (Knaus *et al.*, 2025; Malík and Tlustoš, 2025). Vermiculite, characterized by a high water- and nutrient-holding capacity, fine texture, and elevated porosity, promotes the formation of local gradients in the substrate solution, which can facilitate the localized accumulation of highly mobile ions such as Cl^- within the rhizosphere (Knaus *et al.*, 2025; Malík and Tlustoš, 2025). Field experiments in potato production have shown that Cl^- leaching is strongly influenced by soil texture (loam vs. sandy loam) and by precipitation or irrigation patterns, resulting in highly variable vertical Cl^- profiles even under identical applications of chloride-based fertilizers (Li *et al.*, 2025). Similarly, landscape-scale studies across moisture gradients have documented pronounced spatial heterogeneity of Cl^- in soils and associated vegetation, driven primarily by local hydrology and profile position rather than uniform chloride inputs (Svensson *et al.*, 2023).

Overall, the soluble-phase results demonstrate that coconut-mineral mixtures exhibit distinct ionic signatures that depend on mineral identity and mixing ratio. These differences are agronomically relevant, as they directly affect the chemical environment experienced by roots during the early establishment phase and must be considered when designing fertigation strategies to avoid ionic imbalances or unintended nutrient accumulation.

Exchangeable phase

Among the mineral substrates, vermiculite (VE) showed the highest average CEC (76.1 $cmol_c$ kg^{-1}) as well as the highest Mg content (54.3 $cmol_+$ kg^{-1}) in the exchangeable phase. Zeolite (ZE) exhibited the highest concentrations of Ca (43.2 $cmol_c$ kg^{-1}) and Na (32.2 $cmol_c$ kg^{-1}). No significant differences were observed in K concentration among the evaluated mineral substrates (Fig. 4).

The 100% coconut coir substrate (treatments: CS0, PE0, PM0, VE0, and ZE0) displayed the highest CEC (103.3 $cmol_c$ kg^{-1}), followed by treatments combined with vermiculite (VE25, VE50, VE100, and VE75) with values of 84.9, 68.5, 66.8, and 57 $cmol_c$ kg^{-1}, respectively (Table 3).

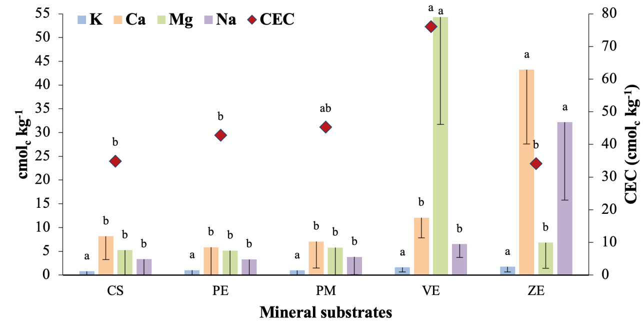

Fig. 4 - Comparison of cation exchange capacity (CEC) and exchangeable K^+, Ca^{2+}, Mg^{2+}, and Na^+ in the evaluated substrates and substrate mixtures. Data correspond to all coconut-mineral (100-0%, 75-25%, 50-50%, 25-75%, and 0-100%) mixtures (namely, coal slag (CS), perlite (PE), pumice (PM), vermiculite (VE), and zeolite (ZE) evaluated at the end of the rooting period (24 days). Bars represent mean values (n= 15), and error bars indicate the standard deviation. Different letters indicate significant differences among treatments according to Tukey's test ($P<0.05$).

The results indicate that many evaluated mixtures contain soluble and exchangeable cation concentrations that must be considered in fertigation programs, particularly those with a high cation exchange capacity (CEC>20 cmolc kg^{-1}), such as coconut coir-vermiculite mixtures, which promote favorable cation adsorption conditions in the medium to long term. Coconut coir exhibits a relatively high CEC (≈32-96 meq 100 g^{-1}) and the ability to adsorb and gradually release Ca^{2+}, Mg^{2+}, K^+, and Na^+, providing temporal nutrient buffering (Huang *et al.*, 2025; Malík and Tlustoš, 2025), while vermiculite, a 2:1 phyllosilicate with a very high CEC and permanent charges, can retain K^+, Ca^{2+}, and Mg^{2+} within its interlayer spaces and gradually release them (Huang *et al.*, 2025; Malík and Tlustoš, 2025). In mixed substrates, materials with elevated CEC enable essential cations such as K^+, Ca^{2+}, Mg^{2+}, and NH_4^+ to be temporarily retained in the exchange complex and subsequently released into the substrate solution for plant uptake, rather than being rapidly lost through leaching (Monsalve *et al.*, 2021). Consequently, a high CEC in soilless substrates reduces ionic concentration fluctuations, increases the temporary storage capacity for NH_4^+ and K^+, and improves fertilizer use efficiency (Monsalve *et al.*, 2021; Xu *et al.*, 2021), while systems with higher effective CEC exhibit lower cation leaching and greater buffering capacity during leaching events by acting as reversible sinks and sources of exchangeable cations (Guarnieri *et al.*, 2021; Ng *et al.*, 2022). However, this

Table 3 - Cation exchange capacity (CEC) and exchangeable K^+, Ca^{2+}, Mg^{2+}, and Na^+ of the evaluated treatments. Data correspond to all coconut-mineral mixtures evaluated at the end of the rooting period (24 days)

Treatment	Exchangeable phase				
	CEC cmolc kg^{-1}	K cmolc kg^{-1}	Ca cmolc kg^{-1}	Mg cmolc kg^{-1}	Na cmolc kg^{-1}
CS0	103.3 a	2.9 a	16.7 d	17.2 d	10.7 d
CS25	36 fgh	0.6 b	8.9 fgh	5.3 e	3.4 g
CS50	16.6 i	0.2 b	6.6 ghij	2.1 e	1.2 h
CS75	10.5 i	0.2 b	4.7 hijkl	0.9 e	0.8 h
CS100	8.2 i	0.1 b	3.9 hijkl	0.7 e	0.6 h
PE0	103.3 a	2.9 a	16.7 d	17.2 d	10.7 d
PE25	39.8 efg	0.8 b	4.6 hijkl	4.1 e	2.5 gh
PE50	37.1 fgh	0.7 b	5.1 hijkl	3.5 e	2.2 gh
PE75	21.2 hi	0.4 b	2.1 jkl	0.8 e	0.6 h
PE100	12.7 i	0.3 b	0.8 l	0.2 e	0.5 h
PM0	103.3 a	2.9 a	16.7 d	17.2 d	10.7 d
PM25	50.1 def	1 ab	7.2 fghi	5.6 e	3.9 g
PM50	36.5 fgh	0.4 b	6.4 hijk	4.3 e	2.2 gh
PM75	21.2 hi	0.4 b	3.3 ijkl	1.6 e	1.4 h
PM100	15.2 i	0.2 b	1.6 kl	0.3 e	0.9 h
VE0	103.3 a	2.9 a	16.7 d	17.2 d	10.7 d
VE25	84.9 b	1.9 ab	14.7 de	46.7 c	8.2 e
VE50	68.5 bc	1.4 ab	12 def	65.4 b	6.1 f
VE75	57 cde	1 ab	11.4 efg	80.6 a	4.2 fg
VE100	66.8 cd	0.9 b	5.4 hijkl	61.7 b	3.5 g
ZE0	103.3 a	2.9 a	16.7 d	17.2 d	10.7 d
ZE25	22 ghi	2.8 a	46.8 b	5.4 e	39.2 b
ZE50	19.6 hi	1.3 ab	54.6 a	4.3 e	46.9 a
ZE75	15.6 i	0.9 b	59.5 a	4.1 e	48.3 a
ZE100	10.2 i	0.8 b	38.5 c	3.1 e	15.8 c

Data correspond to all coconut-mineral mixtures evaluated at the end of the rooting period (24 days). Values represent mean values (n = 3). Different letters within each column indicate significant differences among treatments according to Tukey's test (P<0.05).

buffering effect is conditional on the saturation state of the exchange complex and the cation composition of the nutrient solution, as coconut coir may initially sequester Ca^{2+} and Mg^{2+} if not properly pre-saturated, thereby altering ionic equilibria (Malík and Tlustoš, 2025).

Na levels in the mixtures exceeded recommended thresholds (Table 2), consistent with Jenagathan (2008), who reported that coconut-based materials exhibit the highest Na concentrations. Excess Na+ is a persistent challenge in organic substrates of coastal origin, as it competes with K+ for root absorption sites; this ionic imbalance alters osmoregulation and cell turgor, restricting tissue expansion and compromising both plant growth and photosynthetic efficiency (Munns *et al.*, 2020; Balasubramaniam *et al.*, 2023). Elevated Na was particularly notable in vermiculite-containing mixtures, where Na concentrations increased proportionally with vermiculite content (Table 3), suggesting an additive effect between the Na contributions from coconut substrate and vermiculite. Vermiculite is a 2:1 phyllosilicate characterized by a high cation exchange capacity (CEC, ~ 80-150 meq/100 g) and a significant ability to adsorb cations within its interlaminar structure (De Jesus Andrade *et al.*, 2025). This allows the mineral to sequester and concentrate monovalent cations, such as Na^+, from the substrate solution, releasing or re-adsorbing them in response to shifts in chemical equilibrium (Yan *et al.*, 2024; Andrade *et al.*, 2025). In systems influenced by NaCl, Na^+ effectively displaces Ca^{2+} from the interlaminar spaces, leading to a substantial increase in the Na_2O content within the vermiculite matrix (Feng *et al.*, 2020).

When blended with coconut coir-which inherently contributes high levels of exchangeable Na^+ and K^+ due to its coastal origin and post-harvest processing (Heller and Nunez, 2022; Malík and Tlustoš, 2025) vermiculite functions as a "cationic sponge". This mineral component can fix a portion of the Na^+ released by the coir while simultaneously releasing its own Na^+ if the mineral was previously sodified by process water or fertilization (Feng *et al.*, 2020; Yan *et al.*, 2024; Andrade *et al.*, 2025). Consequently, characterization studies of soilless media confirm that the addition of expandable minerals (such as vermiculite or zeolites) to coir-based substrates markedly enhances cation retention, thereby modifying the ionic profile of the substrate solution available for plant uptake (Petmuenwai *et al.*, 2024; Yan *et al.*, 2024).

Available and total nutrients

Coal slag (CS) showed the highest phosphorus concentration (187.5 mg kg^{-1}), with a highly significant difference compared to other mineral substrates (Fig. 5). Consistent with the high native phosphorus content of coal slag [0,4% (Monsalve *et al.*, 2021)], which was the highest among all tested materials. Similarly, CS-based treatments (CS100, CS75, CS50, and CS25) showed the highest phosphorus concentrations, with values of 311.8, 265.7, 215.6, and 112.4 mg kg^{-1}, respectively (Table 4). This consistent enrichment across both the pure

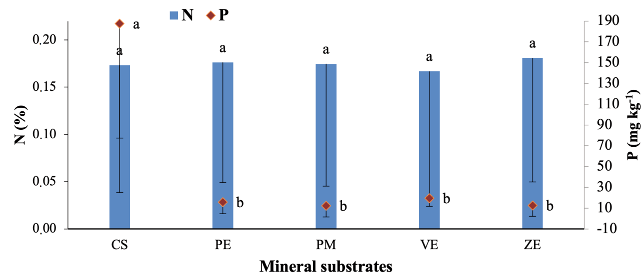

Fig. 5 - Total N and P content in the evaluated substrates and substrate mixtures. Data correspond to all coconut-mineral (100-0%, 75-25%, 50-50%, 25-75%, and 0-100%) mixtures (namely, coal slag (CS), perlite (PE), pumice (PM), vermiculite (VE), and zeolite (ZE) evaluated at the end of the rooting period (24 days). Bars represent mean values (n= 15), and error bars indicate the standard deviation. Different letters indicate significant differences among treatments according to Tukey's test (P<0.05).

Table 4 - Total nitrogen (N), phosphorus (P), and available micronutrient concentrations (Fe, Mn, Cu, and Zn) of the evaluated treatments

Treatment	Total		Available micronutrients			
	N	P	Fe	Mn	Cu	Zn
	%	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
CS0	0.4 a	32.1 d	25.6 bc	45.6 b	4.8 efghi	17.3 a
CS25	0.3 b	112.4 c	33.4 b	24.6 cde	8.2 cdefghi	20.1 a
CS50	0.2 bc	215.6 b	26.3 bc	12.5 cdef	18.8 bc	15.3 ab
CS75	0.1 ef	265.7 ab	22.6 cd	9.4 def	20.1 ab	13.2 abcde
CS100	0 ef	311.8 a	17.3 cde	5 ef	30.6 a	7 cdefgh
PE0	0.4 a	32.1 d	25.6 bc	45.6 b	4.8 efghi	17.3 a
PE25	0.3 b	9.6 d	6.8 efghi	17.6 cdef	5.8 efghi	14.2 abcd
PE50	0.2 c	17.9 d	9.8 efghi	20.2 cdef	7.4 defghi	8.4 bcdefg
PE75	0.1 ef	13.5 d	9.5 efghi	12.3 cdef	12.2 bcdefgh	4.2 fgh
PE100	0 ef	6 d	1.8 i	2.1 f	18.1 bcd	1.7 fgh
PM0	0.4 a	32.1 d	25.6 bc	45.6 b	4.8 efghi	17.3 a
PM25	0.3 b	8.9 d	13 defgh	26.1 bcd	4.3 fghi	5.6 efgh
PM50	0.2 cd	8.3 d	14.7 def	20 cdef	8.6 cdefghi	8.6 bcdef
PM75	0.1 de	6 d	6.1 fghi	10.3 cdef	13.4 bcdefg	6.5 defgh
PM100	0 ef	6 d	2.4 hi	2.7 f	15.7 bcde	1.3 fgh
VE0	0.4 a	32.1 d	25.6 bc	45.6 b	4.8 efghi	17.3 a
VE25	0.2 bc	20.9 d	50.4 a	80.1 a	7.1 defghi	14.7 abc
VE50	0.2 cd	14.5 d	55.5 a	100.7 a	11.6 bcdefgh	8.2 bcdefgh
VE75	0.1 ef	12.5 d	52.2 a	97.2 a	13.7 bcdef	4.6 fgh
VE100	0 ef	17.4 d	13.6 defg	30.2 bc	13.3 bcdefg	5 fgh
ZE0	0.4 a	32.1 d	25.6 bc	45.6 b	4.8 efghi	17.3 a
ZE25	0.3 b	6.8 d	6.3 fghi	13.5 cdef	2.4 ghi	2.9 fgh
ZE50	0.2 bc	7.6 d	3.2 ghi	11.5 cdef	1.2 hi	1.4 fgh
ZE75	0.1 ef	6.3 d	2.4 hi	7.1 def	0.3 i	0.3 gh
ZE100	0 f	10.5 d	2.1 i	1.8 f	0 i	0.3 h

Data correspond to all coconut-mineral mixtures evaluated at the end of the rooting period (24 days). Values represent mean values (n = 3). Different letters within each column indicate significant differences among treatments according to Tukey's test (P<0.05).

mineral material and its mixtures indicates that CS contributes substantial native P to the substrate system, which becomes relevant when evaluating both nutrient supply potential and risks of over-fertilization under standard fertigation regimes. This finding is particularly relevant within a circular economy framework, as coal slag functions not only as a physical support but also as a slow-release source of native P for recycled industrial by-products used as substrate components (Jupp *et al.*, 2020; Yu *et al.*, 2022).

No significant differences in nitrogen concentration were observed among substrates (Fig. 5), but differences were detected among treatments. The highest nitrogen concentration (0.4%) was found in the 100% coconut substrate (Treatments: CS0, PE0, PM0, VE0, and ZE0) (Table 4), consistent with its organic nature (Monsalve *et al.*, 2021). This pattern is expected because the N contribution from inorganic substrates through native nutrient release is typically minimal during crop cycles. As Silber (2008) explains, with few exceptions (such as when using phosphate rock), this contribution is negligible. Organic substrates, however (particularly compost) contain substantial nitrogen quantities, making their concentration in these growth media potentially significant. In this context, coconut coir-based treatments provide an intrinsic N baseline that may influence early-stage nutrient conditions even in the absence of fertigation.

Among micronutrients, Mn stood out for its high concentration in vermiculite-containing mixtures (70.8 mg kg^{-1}) (Fig. 6), increasing proportionally with vermiculite content. This trend was reflected in its high standard deviation (Fig. 6). These findings correspond with vermiculite's naturally high Mn concentration - the highest among evaluated materials [390.2 mg kg^{-1} (Monsalve *et al.*, 2021)], which notably exceeded optimal levels (Table 1). According to Kebabi *et al.* (2017), vermiculite exhibits a high adsorption capacity for manganese (Mn), which could explain the elevated concentrations of this element. This behavior is consistent with the characteristic cation retention properties of vermiculite, which have been exploited for the removal of metals such as manganese from various compounds. This substrate also contained the highest iron concentration (39.5 mg kg^{-1}), compared to other materials (Fig. 6), consistent with both its natural concentration (Monsalve *et al.*, 2021) and chemical structure. This behavior aligns with

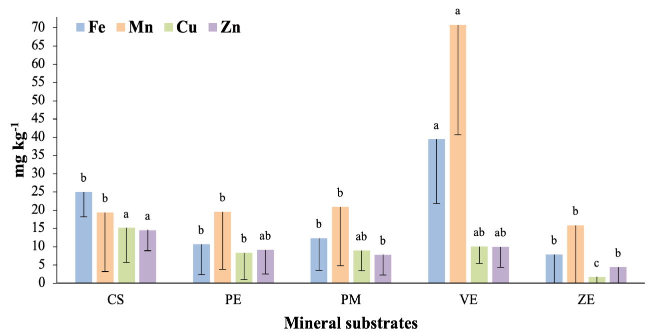

Fig. 6 - Available Fe, Mn, Cu, and Zn concentrations in the evaluated substrates and substrate mixtures. Data correspond to all coconut-mineral (100-0%, 75-25%, 50-50%, 25-75%, and 0-100%) mixtures (namely, coal slag (CS), perlite (PE), pumice (PM), vermiculite (VE), and zeolite (ZE) evaluated at the end of the rooting period (24 days). Bars represent mean values (n = 15), and error bars indicate the standard deviation. Different letters indicate significant differences among treatments according to Tukey's test (P<0.05).

vermiculite's characteristic cation retention properties, which is further utilized for metal removal (e.g., Mn) from various compounds (Kebabi *et al.*, 2017). CS accumulated the highest amounts of copper (15.2 mg kg^{-1}) and zinc (15 mg kg^{-1}). Among treatments, those containing VE (VE100, VE75, VE50, and VE25) consistently showed the highest Fe and Mn concentrations, while CS-based treatments (CS25, CS50, CS75, and CS100) exhibited the maximum Cu and Zn levels (Table 4). These results reveal a clear mineral "signature" in the available micronutrient fraction, which complements what was observed previously for exchangeable bases and reinforces the importance of mineral selection when designing coconut-mineral mixtures.

As with exchangeable bases, N, P, and micronutrient concentrations must be considered in substrate fertilization programs. Failure to account for the native nutrient content of soilless substrates may result in excessive nutrient inputs when standard fertigation programs are applied indiscriminately. Elevated concentrations of soluble and exchangeable ions, such as Na^+, Cl^-, or NO_3^-, can lead to ionic toxicity or nutrient imbalances in plants. In addition, surplus nutrients not retained or absorbed by the crop may be leached from the root zone, increasing the risk of nutrient losses to drainage water and subsequent environmental contamination. Therefore, accurate characterization of substrate nutrient fractions is essential to adjust fertigation strategies, improve nutrient use efficiency, and minimize both agronomic and environmental risks.

To further explore potential multicollinearity among the evaluated chemical variables, a principal component analysis (PCA) was conducted as an exploratory tool (data not shown). The analysis did not reveal a dominant principal component structuring the dataset, as more than 70% of the total variance was only explained after the fourth principal component (PC4), indicating a complex multivariate system without a clear dimensional reduction. This result reflects the heterogeneous chemical behavior of the coconut-mineral mixtures, where soluble, exchangeable, and available nutrient fractions respond differently depending on substrate composition and proportion. The only consistent association identified was between exchangeable Na^+ and Ca^{2+}, which is mechanistically consistent with cation exchange processes and competitive interactions within high-CEC substrates. This relationship supports the interpretation that substrate mixtures with elevated exchange capacity can simultaneously retain multiple base cations, modifying the ionic balance of the substrate solution available for plant uptake.

Plant growth suitability

Plant growth suitability was evaluated through two key parameters: rooting percentage and root dry weight (RDW). All treatments and substrates achieved 100% rooting success, with no variability among treatments; therefore, no statistical differences were detected, and the data are not shown. Results indicate all substrates would be suitable for plant growth, as they exhibited 100% survival rates even without nutrient solution application, consistent with conventional management practices for indicator plants (carnation cuttings). However, significant differences were observed in root dry mass accumulation (RDW), with vermiculite and perlite-containing substrates showing particularly notable results (Table 5). Statistical differences were observed among the evaluated treatments. The highest RDW value was recorded for VE (1.92 g), followed by PE (1.88 g), PM (1.7 g), and CS (1.65 g). ZE showed the statistically lowest weight (1.61 g). Overall, treatment VE50 (2.41 g) demonstrated the best performance, followed by PM50 (2.21 g) and VE100 (2.09 g) (Table 5). The study site owner reported that carnation cuttings with root dry weights exceeding 1.0 g are considered adequate for field transplantation. This suggests that, except for PM100, all mixtures are appropriate for use as substrates in such production systems. Additional factors, including economic and environmental considerations, should be evaluated to determine the most viable mixture.

Pearson correlation analysis revealed highly significant relationships between root dry matter accumulation and soluble concentrations of K, Na, SO_4^{2-}, and Cl^- (Table 6).

The positive correlations observed between root dry weight and soluble Na^+ and Cl^- concentrations in the present study (Table 6) may appear counterintuitive, given the well-documented negative effects of salinity on plant growth. However, these results are consistent with previous

Table 5 - Root dry weight (RDW) of carnation cuttings grown in the evaluated substrate mixtures

Treatment	RDW (g)
CS0	1.67 fgh
CS25	1.69 fg
CS50	1.77 defg
CS75	1.73 efg
CS100	1.38 hi
PE0	1.67 fgh
PE25	1.88 cdef
PE50	1.91 cdef
PE75	2.06 bcd
PE100	1.88 cdef
PM0	1.67 fgh
PM25	1.78 defg
PM50	2.21 ab
PM75	2.00 bcde
PM100	0.83 j
VE0	1.67 fgh
VE25	1.68 fg
VE50	2.41 a
VE75	1.75 efg
VE100	2.09 bc
ZE0	1.67 fgh
ZE25	1.77 defg
ZE50	1.51 ghi
ZE75	1.75 efg
ZE100	1.34 i

Data correspond to all coconut-mineral mixtures evaluated at the end of the rooting period (24 days). Values represent mean values (n= 3). Different letters within each column indicate significant differences among treatments according to Tukey's test ($P<0.05$).

Table 6 - Pearson correlation matrix between root dry weight (RDW) and the evaluated chemical variables (n = 75)

Phase	Parameter	RDW
Soluble	pH	-0.02
	EC	0.22
	K^+	0.43 ***
	Ca^{2+}	0.06
	Mg^{2+}	0.36 **
	Na^+	0.63 ***
	PO_4^{3-}	0.21
	SO_4^{2-}	0.55 ***
	Cl^-	0.55 ***
Exchangeable	CIC	0.14
	K^+	-0.04
	Ca^{2+}	-0.18
	Mg^{2+}	0.31 **
	Na^+	-0.15
Total	N	0.08
	P	-0.19
Available micronutrients	Fe	0.24 *
	Mn	0.31 **
	Cu	0.31 **
	Zn	0.09

* = P<0.05), ** = P<0.01, and *** = P<0.001.

physiological evidence indicating that root biomass in carnation is less sensitive to salinity stress than shoot growth. Kwon *et al.* (2019) demonstrated that increasing NaCl concentrations (up to 200 mM) caused severe reductions in plant height (≈ 68.3%), stem dry weight, flower weight, and leaf area (≈ 57.6%), while root dry weight was not significantly affected, even under high salinity. As a consequence, NaCl stress reduced the shoot-to-root ratio, mainly due to stronger suppression of shoot growth rather than root development.

In the study of Kwon *et al.* (2019), sodium concentrations above 2,299 mg L^{-1} significantly affected shoot-related traits, whereas root and leaf dry weights remained comparatively stable, suggesting a degree of root tolerance to elevated Na^+ and Cl^- levels. This differential sensitivity supports the interpretation of our results, where mixtures exhibiting higher soluble Na^+ and Cl^- concentrations (particularly VE50 and PM50), which also showed the highest root dry weight, did not impair early root development. Instead, moderate salinity in these substrates may have promoted osmotic adjustment and preferential allocation of assimilates to roots, allowing carnation cuttings to maintain or even enhance root biomass during the rooting phase.

Correlation analysis suggests that the accumulation of K, Na, SO_4, and Cl is associated with enhanced root development (Table 6), which is consistent with the performance of vermiculite-containing mixtures that exhibited the highest concentrations of soluble K, SO_4, and Cl. Overall, mixtures combining equal proportions of vermiculite and pumice with coconut substrate showed the best performance, in agreement with reports indicating improved growth and yield in raspberry plants when pumice is combined with coconut fiber (Zhao *et al.*, 2024) and superior root development and net photosynthetic rates in wasabi seedlings grown in vermiculite (Hoang *et al.*, 2019). Although Na^+ and Cl^- are commonly regarded as stress-inducing ions, evidence from ornamental potted plants exposed to moderate salinity (NaCl 4.5-7.5 dS m^{-1}) indicates that osmotic adjustment can be achieved through the accumulation of Na^+ and Cl^- together with organic osmolytes, allowing tolerant species to maintain acceptable growth despite increased ion levels (García-Caparrós *et al.*, 2016; García-Caparrós and Lao, 2018). Similarly, studies in *Callistemon citrinus* and *Viburnum lucidum* under moderate NaCl conditions have shown that vacuolar compartmentalization of Na^+ and Cl^- constitutes a tolerance mechanism, whereby these ions act as low-cost osmotic solutes while cytosolic homeostasis is preserved through organic osmolytes and K^+ (Cirillo *et al.*, 2019).

Therefore, the positive Na^+ and Cl^- root growth relationships observed here should not be interpreted as an absence of salinity risk, but rather as an indication that, at the concentrations and exposure duration evaluated, these ions may contribute to short-term osmotic regulation without limiting root formation. This reinforces the importance of distinguishing between early rooting responses and long-term plant performance, as well as the need for careful fertigation management when using high-CEC substrates such as vermiculite-based mixtures.

4. Conclusions

This study demonstrates that mixing coconut substrates with mineral substrates substantially modifies the chemical environment of soilless growing media, with clear implications for nutrient availability, retention, and early root development. Among the evaluated materials, vermiculite and pumice-based mixtures, particularly at equal proportions (50:50), showed the most favorable balance between cation exchange capacity, soluble nutrient availability, and root dry weight, indicating a high agronomic suitability for carnation propagation.

The results highlight the importance of considering both soluble and exchangeable nutrient fractions when designing fertigation programs for soilless systems. Substrates with high cation exchange capacity, such as coconut-vermiculite mixtures, can temporarily retain nutrients and buffer ionic fluctuations, potentially improving fertilizer use efficiency. However, the elevated concentrations of Na^+ and Cl^- observed in some mixtures underline the need for careful fertigation management, including appropriate substrate washing, monitoring of irrigation water quality, and the possible use of calcium-based amendments to mitigate ionic imbalances.

Coal slag mixtures contributed significant amounts of native phosphorus, suggesting a potential role of this material as a supplementary P source within circular economy strategies. Zeolite-containing mixtures enhanced Ca and Na retention, confirming their capacity to modify the cationic composition of the substrate exchange complex. Overall, the combination of organic and mineral components proved advantageous, as mixing different mineral substrates with coconut coir allowed complementary chemical properties to interact, resulting in improved substrate performance compared with single-material systems.

This study was intentionally focused on the chemical characterization of substrate mixtures and their agronomic viability, using rooting percentage and root dry weight as indicators of suitability. A limitation of the work is that plant physiological responses were assessed only at the end of the rooting period, without time-series measurements or detailed analyses of plant ion content and root architecture. These aspects should be addressed in future studies to better capture dynamic substrate-plant interactions and long-term crop performance.

In practical terms, the findings provide growers with quantitative information to support substrate selection and fertigation adjustment, particularly when using coconut-mineral mixtures under commercial soilless cultivation. Future research should evaluate the long-term behavior of these mixtures under fertigation, their economic feasibility, and their environmental performance under commercial production conditions.

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The authors wrote the manuscript themselves. Artificial intelligence tools were used solely to enhance the writing style and assist in translating the manuscript into English. The AI did not contribute to the development of scientific content, data interpretation, or the formulation of conclusions. The authors take full responsibility for the accuracy and integrity of the manuscript.

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