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*Original Research*

# Mineralogical Characterization and Agronomic Evaluation of Zeolite, Phosphate Rock, and Perlite Mixtures as Substrates for Lettuce Cultivation

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**Abstract**

This study presents the characterization and results of applying a mineral mixture to lettuce cultivation, aiming to enhance nutritional input throughout the entire growth cycle of the plant. The mixture consists of three components: feldspathic rock, commercial expanded perlite (PER), and phosphate rock (PR). For the experimental development, two types of feldspathic rock were used: one extracted from the state of Hidalgo, Mexico (RH), and another from Veracruz, Mexico (RV). Both were characterized and applied independently. The feldspathic rocks from Hidalgo and Veracruz were subjected to a cation exchange treatment by immersion in an ammonium solution. Subsequently, they were mixed in different proportions with non-exchanged feldspathic rock, expanded perlite, and phosphate rock, resulting in six different mineral mixtures. Each mineral used was characterized: the crystalline phases were identified using X-ray diffraction (XRD), elemental composition was analyzed by X-ray fluorescence (XRF), and crystal morphology was examined via scanning electron microscopy (SEM). Only the ammonium-exchanged feldspathic rocks were analyzed for the texture and the cation exchange capacity using ICP-OES. The effects of the six mineral mixtures on lettuce cultivation were evaluated by measuring root length, fresh weight, and dry matter content. Results show that lower nutrient availability leads to increased

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root growth and higher dry matter percentage. Thus, the use of mineral substrates is proposed as a cost-effective and widely available alternative for lettuce crop nutrition.

**Keywords:** natural zeolite, phosphate rock, perlite, mineral substrates, cation exchange capacity, root growth, sustainable agriculture

## Introduction

Agriculture is a fundamental pillar for economic development and population growth, serving as the main source of income to combat hunger and poverty. In recent years, various strategies have been developed to optimize food production, including fertigation and controlled-release fertilizers, which enhance nutrient availability for plants [1].

However, soil fertility loss remains one of the main challenges, particularly due to nitrogen (N) and phosphorus (P) deficiencies – essential nutrients for plant growth. The imbalance of these elements has serious consequences for natural ecosystems and global food security [2, 3]. Additionally, after heavy rains or snowmelt, phosphorus concentrations drop abruptly due to erosion and surface runoff [4].

In this context, several studies have shown that the Green Revolution promoted massive fertilizer use, improving agricultural yields but also generating significant environmental and health issues. Excessive use of chemical fertilizers has been linked to phenomena such as water eutrophication, biodiversity loss, global warming, and soil and air pollution [5]. While conventional inorganic fertilizers can increase crop productivity, their intensive use has caused negative impacts such as soil degradation, water contamination, and accumulation of heavy metals like arsenic and cadmium [6, 7].

Faced with these challenges, there is a growing need for sustainable alternatives that ensure efficient nutrition without compromising environmental balance. In this context, the use of mineral substrates emerges as a viable option. Materials such as natural zeolite, phosphate rock, and perlite offer benefits like improved nutrient retention, reduced leaching, and increased nutrient uptake efficiency [8-10].

Natural zeolites, for example, possess a microporous structure that enables ion exchange, especially when enriched with ammonium ($NH_4^+$). This allows them to function as slow-release fertilizers, reducing ammonia volatilization and nitrate leaching, while improving soil water retention [11-13]. Argentina has significant geological potential in zeolitic minerals; however, applied research is needed to characterize their agronomic properties and determine field application doses. Moreover, their adsorption capacity makes them suitable materials for the remediation of contaminated soils, reducing the bioavailability of heavy metals [14]. Previous studies have shown that clinoptilolite and chabazite, when ammonium-exchanged, significantly enhance nitrogen availability for crops and reduce nitrate losses through leaching [15-17].

Phosphate rock, in turn, is a cost-effective source of gradually released phosphorus, essential for root development and biomass formation. Its direct application has been proposed as a sustainable alternative to soluble phosphate fertilizers, reducing processing costs and minimizing environmental pollution [18, 19].

Expanded perlite, an amorphous volcanic rock, is widely used as a substrate component due to its low density, high water-holding capacity, and excellent aeration – features that support root growth in both hydroponic and solid-substrate systems [20, 21].

Various studies have indicated that combining these materials can enhance both the nutritional and physical properties of agricultural substrates, promoting more efficient and environmentally friendly agriculture [12, 22-24]. However, despite their potential advantages, a critical limitation persists in both scientific literature and commercial practice: the incomplete or absent mineralogical characterization of the materials used. Often, rocks employed as nutrient sources are identified solely by commercial or empirical means, without scientific validation of their crystalline phases or actual chemical composition, which can lead to ineffective or misleading agricultural outcomes [9].

Accurate identification of mineral phases through techniques such as X-ray diffraction (XRD) and elemental chemical analysis is essential to ensure their functionality as slow-release fertilizers, as properties such as cation exchange capacity, nutrient solubility, and soil stability depend directly on mineralogy, not on the assigned commercial name.

In this context, the present study aims to evaluate the performance of mineral mixtures composed of ammonium-exchanged natural zeolite, phosphate rock, and perlite, in different proportions, as substrates in lettuce cultivation under a zeoponic approach. Their influence on root growth and biomass production is analyzed. Furthermore, detailed mineral characterization is prioritized as a key step in validating their agricultural applicability. This research seeks to provide evidence of the potential of these materials as sustainable alternatives to conventional fertilizers, especially in intensive cropping systems.

## Materials and Methods

### Minerals Used in Substrate Preparation

Samples of feldspathic rocks were collected in the states of Hidalgo and Veracruz, Mexico. The first sample, from the locality of Tzijay, municipality of Zimapán, Hidalgo (RH), was extracted at UTM coordinates 14Q 458,583.88 m E / 2,283,615.35 m N, at an altitude of 1938 m above sea level. The second sample, from the municipality of Huayacocotla, locality of Teximalpa, Veracruz (RV), was obtained at UTM coordinates 14Q 550,375.37 m E / 2,257,722.83 m N. The phosphate rock sample (RF) was extracted from the *La Negra* mine, located in the municipality of Pacula, Hidalgo (UTM 14Q 463,682.75 m E / 2,318,574.19 m N). Expanded perlite (PER), commercially acquired, was used due to its water retention and aeration capacity.

The experimental mixture included materials with a nutritional function (RH, RV, and RF), and PER as a physical substrate enhancer. To ensure sample representativeness, systematic collection was performed considering active outcrop zones. Subsequently, the rocks were subjected to primary crushing using an Allis Mineral jaw crusher and secondary crushing with a Quinn roller crusher. The samples were homogenized and sieved, obtaining granulometric fractions from -#16 to +#40 for RH and RV, and from -#30 to +#40 for RF. The phosphate rock (PR) was finely ground and sieved to ensure that all particles passed through a 200-mesh sieve (≤ 75 μm). This reduction in particle size significantly increased the specific surface area, thereby enhancing the contact between the mineral surface and the aqueous phase and accelerating the solubilization of phosphate ions. Finally, the RH and RV samples were washed with deionized water and dried in an oven at 90°C for 24 hours.

### Mineral Characterization

#### *Identification of Crystalline Phases*

Crystalline phases present in each sample were identified by X-ray diffraction (XRD), using an INEL diffractometer, model Equinox 2000, equipped with a Co-K$\alpha_1$ radiation source ($\lambda$ = 1.789 Å) and a curved detector. Operating conditions were: 30 kV voltage, 20 mA current, and an angular step of 0.03° (2θ). The scan was performed over a range of 5° to 50° (2θ).

#### *Scanning Electron Microscopy (SEM)*

The morphology of mineral particles was analyzed using a JEOL IT 300 scanning electron microscope (SEM). Images were acquired at a resolution suitable for assessing particle size, shape, and surface texture. Additionally, point chemical analyses were performed by energy-dispersive X-ray spectroscopy (EDS) using an Oxford Instruments system to identify the elemental composition of selected crystals.

#### *Cation Exchange Capacity (CEC)*

To determine the cation exchange capacity of the feldspathic rocks RH and RV, 0.5 g of each sample was placed separately in nylon mesh bags and immersed in 50 mL of a 1N ammonium nitrate ($NH_4NO_3$) solution. The samples were continuously stirred at room temperature for 24 hours. The resulting solutions, referred to as Sln-RH and Sln-RV, were analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES) using a Perkin Elmer Optima 8300 instrument.

During the process, $NH_4^+$ ions replace the cations originally present at the exchange sites ($Na^+$, $K^+$, $Ca^{2+}$, and $Mg^{2+}$), which are released into the solution. The experimental CEC was calculated based on the total concentration of these released cations, expressed in meq/100 g of sample.

#### *Substrate Preparation*

Six experimental substrates were formulated from mixtures of exchanged and non-exchanged feldspathic rock, phosphate rock (RF), and expanded perlite (PER). Three of them included feldspathic rock from the state of Hidalgo (RH) and were named SRH-20, SRH-40, and SRH-60. The other three incorporated feldspathic rock

Table 1. Proportions of the prepared zeoponic substrates, data shown as % by mass.

| Substrates (Rock mixture) | (% by mass) | | | |
|---|---|---|---|---|
| | Ammonium-exchanged feldspathic rock | Non-exchanged feldspathic rock | Phosphate rock | Expanded perlite |
| SRH-20 | 12 | 6 | 2 | 80 |
| SRH-40 | 24 | 12 | 4 | 60 |
| SRH-60 | 36 | 18 | 6 | 40 |
| SRV-20 | 12 | 6 | 2 | 80 |
| SRV-40 | 24 | 12 | 4 | 60 |
| SRV-60 | 36 | 18 | 6 | 40 |

from the state of Veracruz (RV), named SRV-20, SRV-40, and SRV-60.

For each type of feldspathic rock (RH and RV), the sample was divided in a 2:1 ratio, two parts were subjected to a cation exchange process with ammonium ions ($NH_4^+$), and one part remained unmodified. The exchange was performed by the batch method, using a 1N ammonium nitrate ($NH_4NO_3$) solution at 500 ppm, with constant stirring for 24 hours at room temperature. This pre-loading with $NH_4^+$ was carried out to utilize the capacity of feldspathic minerals to act as slow-release nitrogen reservoirs. Therefore, ammonium was incorporated only during the exchange process and not throughout the entire cultivation period, since the objective was to evaluate its gradual desorption and contribution to plant nutrition in comparison with conventional nutrient solutions.

The numerical proportion accompanying each substrate code (20, 40, 60) represents the total percentage of bioactive minerals (feldspathic rock and phosphate rock) in the mixture, with the remainder being expanded perlite. The specific compositions of each mixture are detailed in Table 1.

All substrates were prepared in triplicate to ensure experiment reproducibility.

*Application of Substrates in Lettuce Cultivation*

The experiment was conducted during the spring of 2022, using lettuce (*Lactuca sativa* L., Grand Rapids variety). Seeds were germinated in 1 L containers filled with a 2:1 (v/v) soil-to-sand mixture. After 15 days, seedlings that reached a height of 5 to 7 cm were transplanted into 1.5 L black polyethylene bags previously filled with the different formulated substrates.

The trial was carried out under controlled conditions in a zenithal greenhouse, with natural photoperiod and average daily temperatures of 15°C (minimum) and 27°C (maximum). Temperature was regulated using sliding curtains and hot-air extractors. Relative humidity was manually adjusted by irrigating the substrates.

Irrigation was applied through an automated drip system, using a nutrient solution prepared according to the formulation proposed by Steiner (1961). Volumes were applied as needed to maintain optimal substrate moisture without waterlogging.

Six experimental treatments were established, corresponding to the mineral mixtures (SRH-20, SRH-40, SRH-60, SRV-20, SRV-40, and SRV-60), plus a control treatment composed exclusively of expanded perlite (PER). In the control treatment, perlite acted solely as an inert physical support, while plant nutrition was entirely supplied by the Steiner solution throughout the cultivation period. This condition represents a conventional hydroponic baseline system against which the mineral substrates were compared. Each treatment was applied to nine plants, organized in three replicates of three experimental units each (n = 63).

The crop cycle lasted 45 days from transplanting to harvest. At harvest, three response variables were measured: (1) total root length (cm), (2) fresh weight (g), and (3) dry weight (g). Samples for dry weight were

Table 2. Oxide chemical analysis of the components of each substrate.

| Compound (% by mass) | RH | RV | RF | PER |
|---|---|---|---|---|
| $SiO_2$ | 73.38 | 70.02 | 12 | 72.43 |
| $TiO_2$ | 0.05 | 0.11 | 0.01 | -- |
| $Al_2O_3$ | 11.51 | 11.05 | 1.31 | 14.17 |
| $Fe_2O_3$ | 1.55 | 1.44 | 0.683 | 1.29 |
| MnO | 0.03 | 0.02 | 0.16 | -- |
| MgO | 0.72 | 1.45 | 0.06 | -- |
| CaO | 1.89 | 1.79 | 46.90 | 0.42 |
| $Na_2O$ | 0.92 | 0.44 | 0.11 | 4.27 |
| $K_2O$ | 3.98 | 3.25 | 0.079 | 4.82 |
| $P_2O_5$ | 0.03 | 0.03 | 33.70 | -- |
| F | -- | -- | 2.91 | -- |
| $SO_3$ | -- | -- | 0.288 | -- |
| $Cu_2O$ | -- | -- | -- | 2.13 |
| P x C | 6.89 | 10.43 | 1.78 | -- |
| Sum | 99.943 | 100.00 | 99.991 | 99.53 |

Note: *P × C = Loss on ignition.

placed in an oven at 90 °C for 72 hours until reaching constant weight.

## Results and Discussion

### Chemical Analysis by X-ray Fluorescence

The chemical composition of the minerals used in the substrates was determined by X-ray fluorescence (XRF), expressed as mass percentage of oxides. Feldspathic rock samples from Hidalgo (RH), feldspathic rock from Veracruz (RV), and phosphate rock (RF) were analyzed by XRF using a sequential-type spectrometer. Expanded perlite (PER), being an industrial product with amorphous characteristics, was analyzed by energy-dispersive X-ray spectroscopy (EDS) coupled with scanning electron microscopy. The results are presented in Table 2.

The feldspathic rocks RH and RV exhibit a high $SiO_2$ content (above 70%), characteristic of aluminosilicate materials such as zeolites and feldspars. Both contain significant amounts of $Al_2O_3$ (>11%) and notable levels of $K_2O$ (3.98-3.25%), indicating their potential as a potassium source for plants. They also contain oxides of Fe, Mg, and Mn, which function as essential micronutrients for plant growth.

Phosphate rock (PR) shows a high content of CaO (46.90%) and $P_2O_5$ (33.70%), consistent with its mineralogical composition dominated by fluorapatite. Traces of F and $SO_3$ were also detected, commonly present in this type of phosphate mineral. The presence of silica (12%) suggests associated silicate impurities.

In the case of expanded perlite (PER), its high $SiO_2$ (72.43%) and $Al_2O_3$ (14.17%) content is typical of this glassy, volcanic-origin material. Although it does not contribute significant nutrients, its porous structure and inert chemistry enhance moisture retention and aeration within the substrate. The detection of $Cu_2O$ may be due to impurities introduced during the industrial processing.

### Mineral Characterization by X-ray Diffraction

#### *Identification of Crystalline Phases*

Phase identification in each rock sample was carried out using diffraction patterns analyzed with Match!

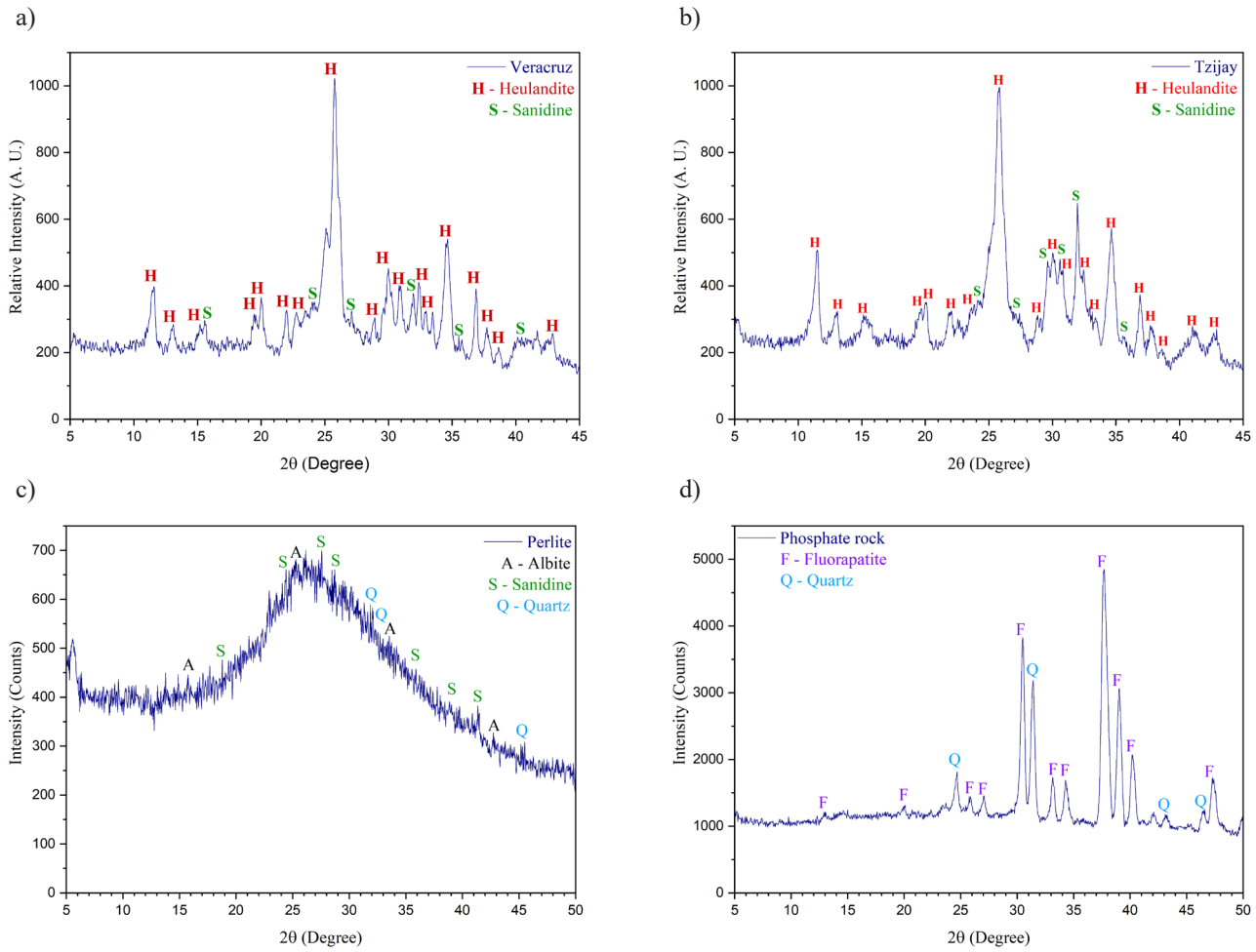


Fig. 1. Diffraction patterns of the analyzed samples: a) RV sample; b) RH sample; c) expanded perlite sample (PER); and d) phosphate rock sample (RF).

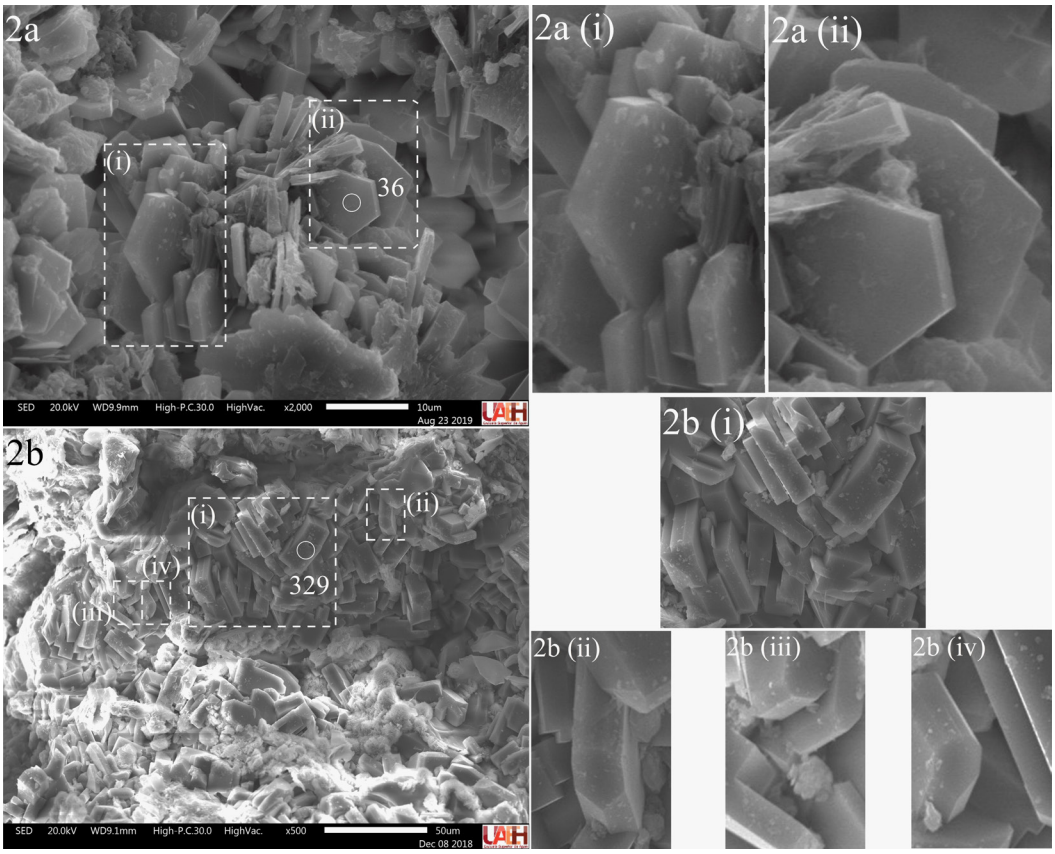


Fig. 2. a) Morphology of clinoptilolite crystals with enlargements in 2a(i) and 2a(ii), and b) feldspathic rock crystals with enlargements in 2b(ii), 2b(iii), and 2b(iv), showing their characteristic shapes and structural details.

software version 3.0. Fig. 1 shows the diffraction patterns for the feldspathic rocks from Veracruz (RV, Fig. 1a)) and Hidalgo (RH, Fig. 1b)), where two main phases were identified: the heulandite phase (PDF 96-210-6946) and the mineral species sanidine (PDF 01-084-1504 for RV and PDF 01-086-0682 for RH), along with clinoptilolite (PDF 01-070-1859). In the diffraction pattern of the expanded perlite (Fig. 1c)), a high content of amorphous material was observed, and the mineral phases identified were albite (PDF 83-1610), quartz (PDF 86-1629), and sanidine (PDF 20-2107). Finally, the phosphate rock sample (Fig. 1d)) primarily showed fluorapatite (PDF 77-1902) and quartz (PDF 83-2468) as the main mineral phases.

### *Recognition of Crystallites and Semi-quantitative Chemical Analysis*

Characterization by scanning electron microscopy (SEM) allowed observation of the mineral morphology in the substrates and enabled semi-quantitative chemical analysis through energy-dispersive X-ray spectroscopy (EDS). The obtained micrographs reveal the characteristic shapes of crystallites corresponding to each type of rock used in the zeoponic system.

Fig. 2a) shows the typical morphology of clinoptilolite, with magnified views of selected areas 2a(i) and 2a(ii), where pseudohexagonal crystals are observed, slightly tilted toward the upper and left edges. The crystals range from 2 to 10 µm in diameter and 2 to 3 µm in thickness, in agreement with previous reports [17] and crystallographic databases [25]; however, larger crystals with diameters up to 20 µm and thicknesses of 5 µm have also been documented [17].

Fig. 2b), corresponding to the feldspathic rock from Hidalgo, displays prismatic crystals with a box-like rectangular morphology, measuring between 15 and 25 µm in length and 3 to 12 µm in width, consistent with previously reported dimensions [26]. Some crystals exhibit angular terminations forming distinct triangular shapes (2b(ii)), a morphology already described in the literature [13], while others show additional planes on their lateral faces (2b(iii) and 2b(iv)), resulting in well-defined beveled structures, in agreement with specialized databases [13, 27]. Semi-quantitative EDS analysis revealed a composition dominated by Si, Al, and K in clinoptilolite, and by Si, Al, K, and Ca in the feldspathic rocks, confirming their aluminosilicate nature; phosphate rock (RF) crystals showed high levels of Ca and P, consistent with their phosphate composition.

### *Determination of the Structural Chemical Formula of Zeolite Crystals*

Based on the semi-quantitative analysis by energy-dispersive spectroscopy (EDS), two representative

Table 3. Semi-quantitative elemental composition obtained by EDS (atomic %) at representative points of samples RV (point 36), RH (point 329), and perlite.

| Element | RV | RH | PER |
|---|---|---|---|
| O | 49.07 | 49.7 | 56.77 |
| Si | 34.89 | 34.8 | 26.74 |
| Al | 8.14 | 8.6 | 6.48 |
| Ca | 3.76 | 2.8 | 0.92 |
| K | 2.42 | 2.6 | 4.00 |
| Mg | 1.09 | 0.9 | 1.22 |
| Na | ND | 0.6 | 3.17 |

Note: ND = Not detectable under analysis conditions. The data correspond to point analyses obtained by EDS coupled with SEM. Semi-quantitative values are expressed as atomic percent.

points were selected to calculate the structural chemical formula: point 36 in sample RV (Fig. 3a)) and point 329 in sample RH (Fig. 3b)). The results obtained are presented in Table 3.

To determine the chemical formula, the atomic data were normalized considering the characteristic ratio between oxygen, silicon, and aluminum in natural zeolites, based on the method proposed by Max H. Hey and Bannister (1934) [28], which assumes a unit cell containing 72 oxygen atoms. From these calculations, the following molar ratios were obtained:

Si/Al = 4.12 for sample RV

Si/Al = 3.89 for sample RH

These values are characteristic of clinoptilolite- and heulandite-type zeolites, respectively, which is consistent with the morphology observed in the micrographs.

The approximate chemical formulas for both samples, based on the number of cations per unit cell, are as follows:

Clinoptilolite (RV): $Ca_{2.19}K_{1.44}Mg_{1.05}[Si_{28.97}Al_{7.03}O_{72}]$

Heulandite (RH): $Ca_{1.61}K_{1.54}Mg_{0.86}Na_{0.6}[Si_{28.63}Al_{7.37}O_{72}]$

These formulas reflect the high proportion of silicon relative to aluminum, characteristic of zeolites with a high Si/Al ratio, which is associated with greater thermal stability and lower acidity. Additionally, the predominant presence of potassium and sodium as compensating cations is consistent with the geochemical environment of formation of these materials.

In Fig. 3a), the micrograph corresponding to expanded perlite (PER) is shown. Particles with a highly porous surface are observed, resulting from the rapid release of structural water during the thermal expansion process. This phenomenon generates a spongy and irregular structure, favorable for water retention and aeration in horticultural substrates. The particles exhibit irregular shapes with sizes ranging approximately between 70 µm and 500 µm, which is consistent with the typical characteristics of this amorphous volcanic material.

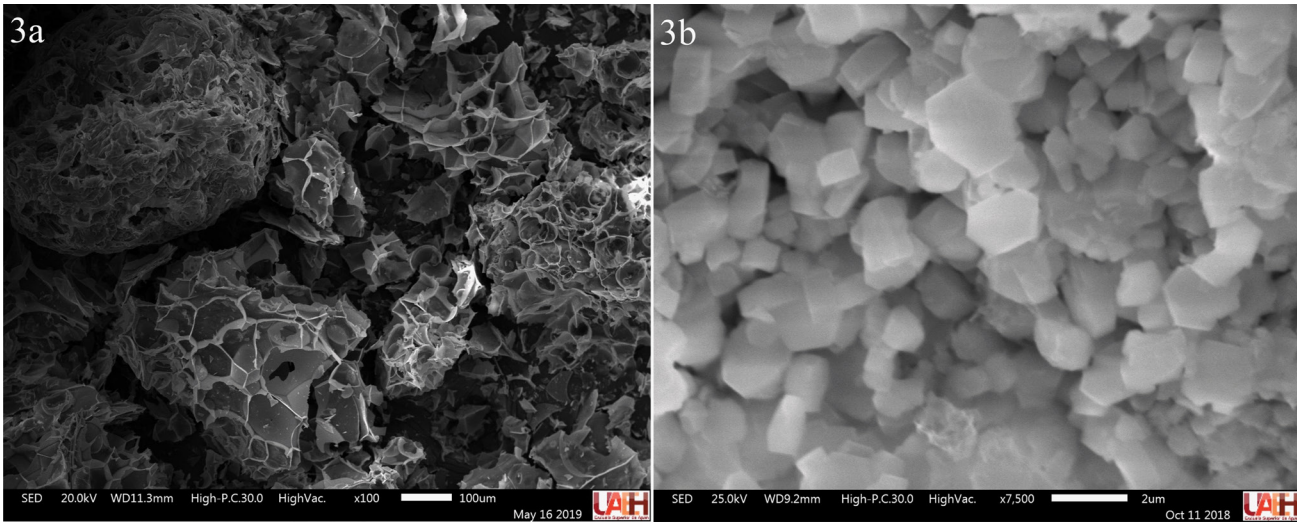


Fig. 3. Micrographs of samples a) PER and b) RF

Table 4. Cation Exchange Capacity results obtained by ICP-OES (meq/g).

| Ionic species | RH C.I.C. ($m_{eq}$/g) | RV C.I.C. ($m_{eq}$/g) |
|---|---|---|
| Ca | 0.44 | 0.27 |
| K | 0.20 | 0.27 |
| Mg | 0.11 | 0.07 |
| Na | 0.15 | 0.14 |
| Total | 0.90 | 0.75 |

In Fig. 3b), the microstructure of phosphate rock (RF) is shown. Crystals with hexagonal morphology and tabular habit, characteristic of minerals from the apatite group, are identified. These crystallites have dimensions smaller than 3 μm, and their distribution appears both isolated and in aggregates. This morphology is consistent with the previously determined chemical composition, dominated by CaO and $P_2O_5$, and suggests the predominant presence of fluorapatite as the main phase in the rock.

*Theoretical and Experimental Cation Exchange Capacity.*

The results of the analysis of the solutions resulting from the cation exchange with 1N $NH_4NO_3$, determined by inductively coupled plasma optical emission spectroscopy (ICP-OES), are presented in Table 4.

The RH sample showed a total cation exchange capacity (CEC) of 0.90 $m_{eq}$/g, higher than that of the RV sample, which was 0.75 $m_{eq}$/g. This behavior is consistent with the previously obtained Si/Al ratio (Si/Al = 3.89), associated with heulandite, whose structure typically offers a higher density of exchangeable cation sites.

However, when analyzing each ion species individually, the RV sample exchanged more potassium ($K^+$), with a value of 0.27 $m_{eq}$/g compared to 0.20 $m_{eq}$/g in RH, representing a 35% increase relative to RH. This result is interesting since the chemical composition by XRF shows a lower concentration of $K_2O$ in RH (3.98%) compared to RV (3.25%). This apparent contradiction may indicate that a greater proportion of potassium in RH is fixed in non-exchangeable phases, possibly associated with mica clays or potassium feldspars, limiting its release during the exchange process.

In both samples, calcium ($Ca^{2+}$) was the predominant exchanged cation, followed by $K^+$, $Na^+$, and $Mg^{2+}$, in that order. This pattern suggests that the active sites in the zeolitic structures have differential affinity for exchangeable cations, consistent with reports for clinoptilolite and heulandite in previous studies [11].

## Application of the Zeoponic Substrate

The results of the average root length and fresh and dry matter weight measurements are shown in Table 5.

All the evaluated zeoponic substrates (SRH-20, SRH-40, SRH-60, SRV-20, SRV-40, and SRV-60) showed higher performance than the control treatment, evident both in fresh and dry biomass of the lettuce plants cultivated. However, the difference in mass values between the different mineral mixture proportions (20%, 40%, and 60% bioactive rocks) did not follow a strictly proportional trend.

This non-linear behavior suggests that the effect of zeolite and phosphate rock content in the substrate on plant growth depends not only on the mineral percentage but also on the interaction between nutrient availability, water retention, and substrate aeration. For example, a high content of mineral phase may promote the release of cations and phosphorus; however, it can also reduce the soil's effective porosity and hinder gas exchange in the rhizosphere, mainly oxygen ($O_2$) and carbon dioxide ($CO_2$), which negatively affects root respiration and, consequently, root growth.

Table 5. Measurements taken from lettuce for each mineral mixture.

| Bioactive minerals (mass %) | Root length (cm) | | Fresh matter (g) | | Dry matter (g) | | Dry matter (mass %) | |
|---|---|---|---|---|---|---|---|---|
| | SRV | SRH | SRV | SRH | SRV | SRH | SRV | SRH |
| 20 | 29.917 | 29.224 | 281.621 | 224.308 | 22.195 | 14.655 | 7.88% | 6.53% |
| 40 | 27.632 | 29.294 | 423.913 | 400.198 | 26.389 | 24.053 | 6.23% | 6.01% |
| 60 | 24.377 | 26.731 | 474.308 | 427.866 | 25.434 | 26.336 | 5.36% | 6.16% |
| Control group | 15.21 cm | | 360.67 g | | 15.88 g | | 4.40% | |

In this context, the mixture with 40% bioactive minerals (SRH-40 and SRV-40) showed the most balanced results in terms of total biomass and root length, indicating that this proportion could represent a preliminary optimal point for designing zeoponic substrates. Still, further experimental research is required to accurately establish the ideal proportion, considering both nutritional efficiency and physical properties of the growing medium.

The rapid availability of phosphorus observed in this study can be attributed mainly to the particle size reduction of the phosphate rock. Since the material was ground and sieved to pass through a 200-mesh (≤75 μm) sieve, its specific surface area increased considerably, promoting a higher degree of contact between the mineral surface and the surrounding aqueous solution. This physical modification accelerates the dissolution kinetics of phosphorus-bearing phases compared to coarser fractions typically used in agronomic applications, where phosphorus release is known to be slower. Additionally, the acidic microenvironments generated by root exudates may have further contributed to the enhanced solubilization of phosphate ions, favoring their availability to lettuce plants during the relatively short cultivation cycle.

Additionally, substrates with feldspar rock from Hidalgo (SRH) tended to slightly outperform those from Veracruz (SRV), which can be attributed to their higher total cation exchange capacity, as previously discussed (Table 4), and differences in morphology or accessibility of active sites in the zeolitic structure.

The results indicate that the roots of lettuce plants grown in the mineral mixtures exhibited significantly greater length compared to the roots in the control treatment, where root growth was limited to 15.21 cm. This behavior suggests that the nutrient solution used in the control may contain an excess of nitrogen (N), potassium (K), and calcium (Ca), which is not optimal for hydroponic lettuce cultivation, since excessive availability of these nutrients in high fluxes can inhibit root development [29].

When analyzing only the three mineral mixtures, a decreasing trend in root length is observed as the proportion of bioactive substrate increases. This can be explained because, in systems with high water and nutrient availability, plants tend to develop shorter but healthier roots, as previously reported [30].

Additionally, in systems with solid substrates, nutrients are released gradually, which favors balanced root development in lettuce. This finding aligns with earlier studies [31], which indicate that greater root length is associated with a more vigorous root system efficient in water and nutrient uptake. Moreover, it has been reported that the use of substrates with controlled nutrient release improves root growth and plant yield [32]. The presence of perlite in the mixtures also contributes to increased water and nutrient availability due to its high retention capacity, thus benefiting root development.

The dry matter percentage in treatments with bioactive mineral mixtures was higher than in the control, which showed 4.4% by mass – a value similar to that reported in lettuce leaves (4.36% by mass) [33]. In particular, the SRV-60 treatment, with 20% by mass, exhibited the highest dry matter percentage, coinciding with the greatest root growth. It is well known that greater root length promotes biomass accumulation and improves plant nutrition, suggesting higher nutrient uptake efficiency [30, 33].

Finally, this study demonstrates that using natural mineral substrates such as zeolite and perlite offers significant advantages over inorganic fertilizers, especially in reducing contamination through leaching. Unlike chemical fertilizers, which can infiltrate and contaminate water bodies, natural minerals retain nutrients and prevent their loss. Controlled release of nitrates and phosphates is an essential characteristic of these materials, as confirmed previously [15], where zeolite in hydroponic substrates significantly reduced nutrient loss and improved nutritional efficiency. These results suggest that implementing natural mineral substrates not only improves lettuce growth and nutrition but also represents a viable strategy to mitigate environmental contamination caused by chemical fertilizers, contributing to the sustainability of modern agricultural systems.

## Conclusions

Natural feldspathic rocks containing zeolite, sourced from the states of Veracruz and Hidalgo, along with phosphate rock rich in fluorapatite, were characterized and evaluated for their potential as natural fertilizers. It was determined that both zeolites contain crystals belonging to the heulandite-clinoptilolite series, and that the mixture of these bioactive materials possesses physical and chemical properties suitable for use as slow-release fertilizers.

The substrates SRV-40 and SRH-40 proved to be the most effective compared to the control, demonstrating that the combination of zeolite, phosphate rock, and perlite significantly improves lettuce growth. This positive effect is attributed to the gradual nutrient release, moisture retention capacity, and optimal mineral balance in the substrate.

Compared to conventional fertilizers, these mineral substrates constitute a more sustainable and ecological alternative, as they reduce nutrient leaching and the environmental impact associated with synthetic fertilizers. Their application contributes not only to minimizing nitrate contamination but also to preserving natural resources, promoting more efficient and regenerative agriculture.

Finally, these findings highlight the sustainability of using natural minerals in agriculture. Unlike industrial fertilizers, whose production involves high energy costs and generates polluting emissions [34, 35], the

use of zeolite and perlite improves soil aeration and water retention, contributing to more sustainable and regenerative agricultural systems. This supports the exploitation capacity of the soil without compromising food sovereignty for future generations.

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## Conflict of Interest

The authors declare no conflict of interest.

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